NATIONAL NETWORK FOR CRITICAL TECHNOLOGY ASSESSMENT

SECURING AMERICA'S FUTURE

A Framework for Critical Technology Assessment

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SECURING AMERICA'S FUTURE

A Framework for Critical Technology Assessment

A report by the National Network for Critical Technology Assessment

Praise for *Securing America's Future: A Framework for Critical Technology Assessment*

"If the US is to win the global race for innovation advantage, smart technology policy will be needed. And that depends on in-depth technology analysis. That is why the new analysis from the National Network of Critical Technology Assessment is so important."

—Rob Atkinson, President, Information Technology Innovation Foundation (ITIF)

"Solutions to many of the challenges confronting our nation—from the environment to health care, from national security to the economy—require technology advances. Herein is a pathway to such advances."

—Norman Augustine, Former Chair and CEO, Lockheed Martin; Former Under Secretary of the Army

"The US is embedded in an international economy, facing massive trade deficits in manufactured and advanced technology goods. Yet we have been flying blind, failing to track our competitors and where they and we stand on emerging technologies. This report provides the roadmap on how we must act to turn that problem around. It's important to both national and economic security that we adopt it."

—William Bonvillian, Fellow, American Association for the Advancement of Science (AAAS); Lecturer, Massachusetts Institute of Technology (MIT)

"Well-targeted technology investments have enormous potential, reaching from innovation to social well-being to national security. I am thrilled to see the novel ideas in Erica Fuchs's Hamilton Project proposal take the next step toward becoming a national capability through this year's National Network for Critical Technology Assessment. This sort of artful and strategic collaboration is necessary to confront obstacles and seize opportunities ahead."

—Wendy Edelberg, Director, The Hamilton Project, Brookings Institution

"This is an impressive set of analyses on topics of key national importance, especially given the short time frame under which they were completed. Policymakers will value these targeted assessments in their own right, and perhaps even more as a successful proof of principle that data analytical methods have great promise for steering national technology investments and policies."

—Gerald Epstein, Contributing Scholar, Johns Hopkins Center for Health Security; Former Assistant Director for Biosecurity and Emerging Technologies, Office of Science and Technology Policy

"A meaningful national technological assessment requires new research methods, new collaborations, new institutions, and a new sense of urgency. This report from the NNCTA responds to these imperatives and provides a compelling direction for future work."

—Adam Falk, President, Alfred P. Sloan Foundation

"This insightful report makes a compelling and well-documented case for a national office that spans agency missions, capable of deep analysis of critical technologies, the US position in these technologies, and the risks to continued US leadership and access. The country's economic and national security are dependent on a number of key technologies, and a better and earlier understanding of these dependencies and the risks to them has become mandatory."

—John Hennessy, Professor and President Emeritus, Stanford University

"This study demonstrated how networked teams of scholars and practitioners could effectively use models, tools, and datasets to aid decision makers who fund critical technology development and implementation. Multidisciplinary and geographically diverse teams brought new insights regarding necessary factors for critical technology assessment, particularly when there are national security, economic competitiveness, and social well-being considerations. The NNCTA report should be a resource to stakeholders in the government and private sector."

—Kaye Husbands Fealing, Dean and Ivan Allen Jr. Chair, Ivan Allen College of Liberal Arts, Georgia Institute of Technology

"Turning innovation into economic opportunity necessitates clear insights and a strategic direction. This report on assessing critical technologies provides policymakers with a needed blueprint for guiding investments in research and innovation."

—Farnam Jahanian, President, Carnegie Mellon University

"Virtually every goal we have as a nation, including national security, faster productivity growth, and shared prosperity, requires scientific and technological advances. If you want to learn how we can make better and more informed decisions about how to achieve these goals, read this report!"

—Tom Kalil, Former Deputy Director, Office of Science and Technology Policy

"US leadership in the critical technology areas that will be required for our global competitiveness can no longer be taken for granted. Using examples in several key technology areas, this must-read report shows how analytics can help inform our citizens, Congress, and federal agency leaders on where investments are needed to secure our future."

—Willie E. May, AAAS President-Elect; Vice President of Research, Morgan State University; Former Director, National Institute of Standards and Technology

"NNCTA's pilot year has demonstrated that we can—and must—develop and deploy analytical tools, processes, and human expertise to make decisions about our investments in the critical technologies that underpin our economic competitiveness, national security, and the equitable translation of the benefits of technology to all of society. The science of technology management is as important as any specific technology."

—J. Michael McQuade, Former Senior Vice President S&T, United Technologies Corporation; Former Vice President of Research, Carnegie Mellon University

"NNCTA's report highlights the urgent need to restructure how we deploy national funds to support the commercialization of technologies critical to US advantage."

—Katie Rae, CEO and Managing Partner, The Engine

"This framework outlines a path forward that will enable us to invest in and accelerate America's technological leadership. These recommendations have the potential to inform and reshape the way our nation innovates, taking us on a path toward a brighter, more technologically resilient future. As an investor and serial entrepreneur, I see this as an exciting proposition, and vital to a thriving economy."

—Matthew Rogers, Founder and CEO, Mill, Founder Nest, and Incite.org

"The importance of investing in the nation's technology future has never been greater. At the same time, the options are limitless and we need data-driven approaches to focus investments to the most promising areas. This report of the pilot year of the NNCTA demonstrates the potential of using the latest methods of machine learning and AI to harvest insights from data, guided by cross-disciplinary domain experts to put us on a firm footing for the future."

—Rich Uhlig, Senior Fellow and Corporate Vice President, Director of Intel Labs

"The United States has the best innovation ecosystem in the world; harnessing this innovation to produce needed national security capabilities at the speed of relevance is where we sometimes struggle. This Critical Technology Assessment pilot shows a possible path forward on how to better focus our innovation efforts on the most important things."

—Steven Walker, CTO, Lockheed Martin; Former Director, DARPA

EXECUTIVE SUMMARY

Over the past half-century, the longstanding US dominance of the global geopolitical balance of scientific, economic, and production capabilities has diminished. The United States also faces serious challenges on the home front, where economic inequality has increased and social mobility has declined. Technological change and globalization are central to all these concerns. Yet little is understood about pathways to simultaneously advance both US competitiveness in critical technologies and the well-being of all citizens.

Against this backdrop, the CHIPS and Science Act (US Congress 2022) introduced unprecedented legislation requiring the formulation of a US national technology strategy, led by the White House Office of Science and Technology Policy, to focus limited federal dollars to achieve national security, economic, and societal ends, given the interdependence of technologies and the impact of associated policies and investments across agency-specific missions. Congress charges the National Science Foundation's (NSF) Technology Innovation and Partnerships (TIP) Directorate to work in consultation with the interagency working group in identifying and evaluating societal, national, and geostrategic challenges facing the United States and investments in key technologies that could help address those challenges.

Responding to the legislative mandates will not be easy: Building the intellectual foundations, data, and analytic tools to inform NSF TIP's mission will require mobilizing, synthesizing, and integrating capabilities distributed across the country among different researchers, disciplines, and institutions. There is not a mature field of national technology strategy nor a widely agreed upon field of critical technology assessment. National investments in key technologies need to be guided by analytic and physical science expertise frequently found in academia and industry, and not easily attracted by individual agencies. National strategy in technology needs to (i) be based on knowledge that spans multiple government departments and (ii) take into account their missions. The United States lacks the data and infrastructure needed for timely situational awareness of global technology and production capabilities, rigorous methods to quantify the potential value of innovations (including considering geopolitical dynamics), and tools for quantifying opportunities across national objectives to simultaneously enhance national security, economic prosperity (including jobs), and social well-being (including health, environment, and equity).

Building the intellectual foundations, data, and analytic tools needed for critical technology assessment requires mobilizing, synthesizing, and integrating capabilities distributed nationwide among researchers, disciplines, and institutions.

In response to this gap, the NSF TIP-funded pilot National Network for Critical Technology Assessment (NNCTA) brings together leading scholars from across the nation to begin to build the intellectual foundations, analytic tools, and data needed to respond to this charge: specifically, to produce a vision for critical technology assessment that outlines (i) current capabilities (with demonstrations thereof) to help inform Congress and agency leaders on how to prioritize limited national resources—and in particular investments in research and innovation—to have the greatest impact on US societal, national, and geostrategic challenges; (ii) gaps in those capabilities; and (iii) the national investment and organizational form necessary to achieve that vision.The pilot activities highlight that there is both an art and a science to effective critical technology assessment, and that such assessment is essential to ensure that the country smartly invests and enacts necessary policies to achieve short- and long-term security, prosperity, and broad-based social well-being. Effective assessment is not top-down coordination or optimization of investments that copies competitor nations' style and approach, nor can it be solely a curiosity- (for science) or market- (for technology) driven approach that fails to acknowledge the stakes and the outcomes for the nation and its people.

Assessment is essential to ensure that the country smartly invests and enacts necessary policies to achieve short- and long-term security, prosperity, and broad-based social well-being.

As Congress recognized in the creation of TIP, something disruptive is needed in how we fund the pathway from translational discovery to commercialization. In addition, for TIP to be effective in fulfilling its charge, something disruptive is also needed in how the nation conducts critical technology assessment (CTA): the federal government will need to intentionally design a rapid CTA function for Congress and the executive branch alike. This program must embrace the accelerating pace of innovation, draw on the nation's rich variety of institutions, disciplines, and agencies, and exploit their analytic power and technical expertise. Such work will be best led by a single organizational unit charged to think across national objectives and technology interdependencies, engaging topic-specific program managers trained in the art of critical technology assessment to identify the most important problems, match methods to problems, and mobilize and orchestrate the distributed national capabilities both within and outside government.

The NNCTA pilot year activities (summarized in the next section) demonstrate that data and analytics can meaningfully inform national technology strategy, but the necessary capabilities do not sit with one discipline, investigator, or type of organization. The novel pairings and cross-disciplinary collaborations that were effective in this pilot year had to be orchestrated (a hallmark of the efforts undertaken by DARPA program managers). This orchestration is an "art" that, if done well, yields a whole greater than the sum of the parts: creating a dynamic exchange between a 30,000-foot machine-driven and a bottom-up expert-driven perspective to benefit from both; combining data across scholarly areas and institutions to transcend gaps; marshaling different disciplines and methods to solve different aspects of a policy problem; setting up different perspectives on the same policy problem to enhance understanding through complementary or contradictory insights; creating teams to combine disciplines and models in a way that produces otherwise unavailable novel findings; identifying transition partners; and transparently engaging throughout and communicating the final findings across the variety of relevant stakeholders. The analytic methods leveraged in specific fields are the frontiers of science—whether economics, computer science, sociology, political science, psychology and decision science, or engineering.

The pilot year investigations also revealed that the most appropriate methods and data are not static but closely linked with (i) the status of a technology's discovery, diffusion, and adoption; (ii) US global competitiveness in the knowledge, production, and use relevant to the technology; and (iii) the state of the policy process with respect to the technology. Understanding the most important problems to tackle in a particular area, and how to match methods across disciplines to those problems, requires deep knowledge of the industrial, technological, and policy contexts. Program managers with the talent to identify and understand national challenges as well as top researchers' activities across disciplines, and to provide the orchestration needed to address those challenges, are rare. The nation should cultivate them by investing in nontraditional educational programs and professional fellowships to build human capital with problem-oriented policy skills that leverage analytic rigor, interdisciplinary methods, and contextual and phenomenological depth—in short, to develop a community of practice in (rapid) critical technology assessment.

Based on these observations and our pilot year demonstrations, we recommend that the United States invest in a rapid critical technology assessment entity to provide the executive and legislative branches with the tools needed to inform national technology strategy. This CTA program would, as part of its primary functions, support NSF TIP in its annual roadmapping and OSTP in its Quadrennial National Technology Strategy, serve Congress and the executive branch with analytics to inform critical technology strategy across national (and agency-specific) missions writ large, and serve as a trusted source of technology assessment capability to government, industry, nonprofits, and the public. The program should focus on problems that span national missions, taking account of technology and policy interdependencies and of win-wins or tradeoffs across national objectives (or individual agency missions).

The federal government will need to intentionally design a rapid CTA function for Congress and the executive branch alike.

The CTA program would orchestrate the analytics necessary to inform national technology strategy. The program should draw heavily from the DARPA model in terms of its dynamism and the independence and discretion of talented program managers to choose problems and orchestrate top performers to address those problems. It should also, like DARPA, push the frontier of analytic capabilities, then transfer those capabilities eventually into the executive and legislative branches. Unlike DARPA, however, the program should not undertake high-risk analyses but be grounded in a simultaneously disciplined and innovative analysis process, pushing the frontier of scientific and analytic capabilities.

The core CTA function would be conducted by a program manager with both area-specific expertise (e.g., technical depth, such as in AI or semiconductors) and institutional and disciplinary breadth. Program managers would, as at DARPA, have limited terms to help keep the organization nimble and up-to-date and also to facilitate these positions as a stepping stone to follow-up leadership positions. The CTA entity would involve and draw on agency and organizational expertise across the government. It would fund problem-oriented research and also serve a business development role in supplementing nonspecific funds with matching contracts from relevant executive or legislative branches (e.g., for issues that cross departmental missions in semiconductors, involving the Departments of Commerce, Defense, and Energy; or, in the case of novel data infrastructure, NCSES, the International Trade Commission, and/or the US Census Bureau). In addition to the CTA entity's advisory board, which should include leaders from government agencies as well as from academia and industry, each program manager should have an area-specific advisory committee, and run workshops that bring together relevant thought leaders and stakeholders from academia, industry, government, and nonprofits to launch and inform analytic programs.

Overseeing the program managers, in a way similar to DARPA office directors' integrational role, would be a government director and a technical director. The government director would identify relevant national challenges across departments for which there likely is particular value in analytics, including in quantifying tradeoffs or win-wins across missions. The technical director would identify opportunities for collaboration or integration across the topic areas. The government and technical directors, along with the CTA program director, would together be responsible for one of the most challenging and important functions: where to focus the limited analytic resources—identifying the topic areas for program managers, reducing or eliminating funding of some areas as appropriate, and bringing on new program managers and funding in newly needed topics.

The CHIPS and Science Act calls for a new federal capacity to fortify the nation's leadership and ability to determine policies and investments that will ensure national security, global competitiveness, economic prosperity, and social well-being. To effectively operationalize this mandate will require something truly disruptive. This report of the pilot National Network for Critical Technology Assessment provides evidence of what analytics can accomplish, and the critical components for a path forward as effective and disruptive as legislators envisioned.

PILOT YEAR AREA DEMONSTRATIONS OF HOW ANALYTICS CAN INFORM NATIONAL TECHNOLOGY STRATEGY

Global Competitiveness

Type of critical technology assessment Situational awareness of US versus other nations' capabilities in science and technology (S&T) knowledge and production (and inputs such as funding and human capital)

Lead performers Yong-Yeol (YY) Ahn, James Evans, Joshua Graff Zivin, Cassidy R. Sugimoto

The United States today lacks sophisticated and systematic mechanisms to assess its global competitiveness in science and technology (S&T) relative to other countries in ways needed to effectively execute the country's defense, trade, commerce, and other missions (NASEM 2019). Large language models (LLMs) are revolutionizing the type of competitiveness assessments possible. At the same time, the types of on-the-ground open intelligence programs (ONR Global, NSF Satellite offices, World Technology Evaluation Center [WTEC], Asian Technology Information Program [ATIP]) needed to complement these models have been discontinued or downsized.

As an example, prior to this year's NNCTA analysis, the understanding has been that even if China has surpassed the United States in the total *number* of scientific publications, the United States is more creative and more likely to have high-impact breakthroughs like CRISPR that lead to new fields. But work by scholars in the National Network finds that China has the highest share globally of disruptive scientific papers (defined as those that initiate a new line of research in a field) and papers that lead to the emergence of new fields. That said, Chinese and US researchers also collaborate more on scientific publications than any other two nations, and this collaborative research represents a significant fraction of each country's scientific output. Causal analysis shows that both countries would substantially reduce their production of scientific knowledge if collaborations were cut off.

While these are initial measures that require further exploration with experts at field- and paper-specific levels, the findings are sufficiently concerning to deserve much greater attention. Such research will benefit from the development of a systemized approach that combines the most advanced LLM and machine learning capabilities with the knowledge of global experts in each field and, where opportunities exist (such as natural experiments), runs causal analyses to understand how policy interventions could influence outcomes in ways that strengthen US global standing in cutting-edge research.

This systemized approach should also be applied domestically to inform legislators and agencies of regional capabilities that could support US competitiveness and ways to advance them. In particular, our results show that in certain critical fields (such as computing), the United States is failing to engage the full talent base: Underrepresented female and minority scientists and technologists whose work is objectively superior are failing to get funding because of biases in the funding process. These underrepresented groups often do more interdisciplinary work and work with novel foci. Similarly, some high-risk, high-reward research is not funded in the federal peer review process. Early-stage higher-risk research may be more likely to be funded by philanthropic foundations, but their funding is not systematic and their missions do not necessarily address national needs. Tools leveraging current analytic capabilities and knowledge in decision science should be further developed and used to help mitigate federal peer review biases in real time to ensure that important innovative research is funded and domestic capability is strengthened.

Overall these results suggest that the United States needs a better system for identifying and funding underrepresented researchers and innovative, higher-risk approaches.

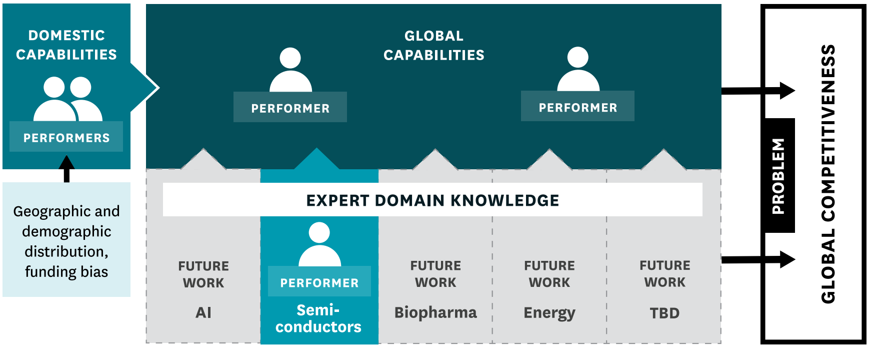
Program management Connect 30,000-foot insights from sophisticated data science models to contextual expert knowledge; red-teaming workshop; synthesis across researcher results

Methods LLMs, machine learning, end-of-program workshop to evaluate and red-team results with analytic, technology, and industry experts

Data Scientific publications, expert surveys

Criticality dimensions measured S&T competitiveness, social well-being

Challenges for future critical technology assessment Insufficient situational awareness of global technology and production capabilities (including product-level supply chains) and relevant human capital inputs



Artificial Intelligence

Type of critical technology assessment Emerging technology, high economic and security impact

Lead performers Lee Branstetter, Erik Brynjolfsson, Thema Monroe-White, Dewey Murdick, Dashun Wang

Academics, policymakers, industry experts, and the public have feared that artificial intelligence (AI) will lead to a loss of jobs, and productivity gains have proven difficult to measure. Using novel data and measurement techniques, we demonstrate that AI has the potential to substantially increase scientific discovery, productivity, output, and employment across the US economy, but the invention/diffusion process is still in early stages and not all firms, regions, demographics, or scientific fields are benefiting.

Many scientific fields are not benefiting from AI's potential to accelerate scientific discovery through machine-driven synthesis of knowledge, optimization of experimentation, and other mechanisms. Policy can support scientific and technology disciplines in discovering (through collaboration with AI experts) and training (through education) in the best uses of AI in their fields. The following measures can address gaps in leveraging AI to accelerate scientific discovery:

- Fund and facilitate cross-department collaborations between scientific and engineering disciplines and AI experts.
- Fund the development of university curriculum in the best uses of AI in their scientific and engineering fields.
- As shown by previous analyses, expand the AI-related professoriate immediately by (i) broadening opportunities for foreign graduates of related US PhD programs to remain in the United States and (ii) increasing funding and support programs that facilitate female and underrepresented groups in their graduate study in AI-related fields.

Firms that are farther ahead in AI adoption are growing in revenue and employment, but those benefits are concentrated in large firms and limited geographic regions and demographics. The United States needs to find ways to diffuse AI capabilities more broadly so that its benefits are more widespread.

- To support smaller enterprises in adopting and benefiting from AI, expand the ranks of AI workers with the skills needed to work at the disciplinary frontier, through advanced education of domestic students, attraction of outstanding foreign-born talent through immigration, and support programs for female and underrepresented groups to pursue AI-related fields.

- To enable more regions and demographics to benefit from AI, authorize funding to staff AI office and workforce support initiatives, like the National Artificial Intelligence Initiative Office for Education and Training; develop a federal framework of technical and nontechnical AI work roles and competencies; create a National AI Research Resource (NAIRR) to provide greater access to the computational resources and datasets for academics, nonprofit researchers, and startups from diverse backgrounds; and establish federal grant programs for AI industry-academia partnerships, AI-related degree and nondegree programs at community colleges and minority-serving institutions, and equipment at AI labs and related facilities.

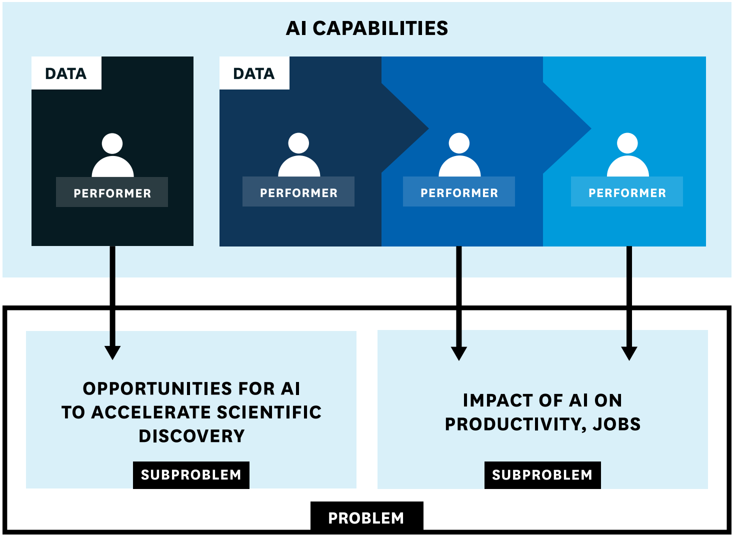
Program management Compare different datasets held by different performers to overcome sample and data limitations

Methods LLMs, machine learning, surveys, descriptive statistics, econometrics

Data Publications, patents, Bureau of Labor Statistics Survey, US Census data

Criticality dimensions measured Economic well-being (S&T competitiveness, productivity, jobs)

Challenges for future critical technology assessment Inadequate availability of and access to timely data—including from private sources—given the rapid rate of technology change; sharing of data and algorithms; broader geographic and demographic participation; algorithm bias



Semiconductors

Type of critical technology assessment Nascent evolving technology with high economic and security impacts; vulnerable supply chain for existing technology

Lead performers Yong-Yeol (YY) Ahn, Christophe Combemale, Hassan Khan, M. Granger Morgan, Neil C. Thompson

Regaining US competitiveness in semiconductors requires a multipronged approach. First, targeted investments in worker training will be necessary to overcome challenging labor and skill gaps in certain regions identified for new leading-edge domestic semiconductor facilities. Advanced analytic tools can and should be used to identify specific regional mismatches in skill demand and supply and inform necessary regional training and retraining programs. Second, the United States is behind competitor nations in enabling researcher access to commercial production technologies. Firms should be required to increase such access (e.g. improve their shuttle run and multi-project wafer offerings for US researchers) if receiving subsidies for US-based facilities. Last, given the stakes for the economy and security, advances by competitor nations, and insufficient funding for a broad enough portfolio given uncertainties, the United States should increase funding for next-generation (beyond-CMOS) semiconductor devices beyond that in the CHIPS and Science Act.

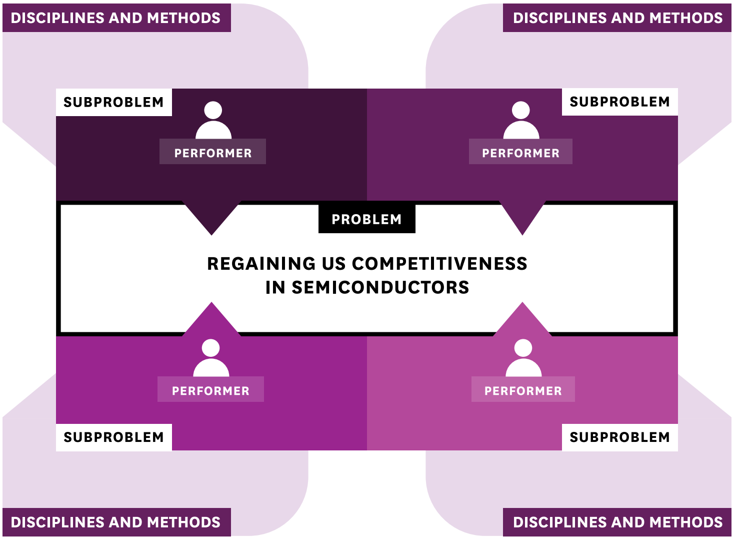
Program management Identify the most important problem and problem subcomponents, and then identify and leverage different performers with different methods and disciplines on different components of the problem; midway workshop to elicit stakeholder input and feedback from industry and government

Methods Expert elicitation, local labor skill gap modeling, productivity measurement, LLMs, engineering-economic models

Data Expert survey results, publications, O*NET data, productivity data from the US Bureau of Labor Statistics, USPTO patent data, the International Technology Roadmap for Semiconductors, and data on CPU and GPU characteristics

Criticality dimensions measured Economic well-being (S&T competitiveness, productivity, jobs)

Challenges for future critical technology assessment Small numbers of (i) analysts who can conduct the labor constraint analysis and (ii) nonstakeholder analysts who can pair advanced analytic capabilities with deep technical and industrial knowledge


DISCIPLINES AND METHODS
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SUBPROBLEM
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REGAINING US COMPETITIVENESS
IN SEMICONDUCTORS
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DISCIPLINES AND METHODS
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Biopharmaceuticals

Type of critical technology assessment Commodity product for which loss of access would have high social and security impacts

Lead performers Rena Conti, Baruch Fischhoff, Marta Wosińska

Pharmaceuticals are the most used medical care in the United States, yet their supply chains are not resilient, resulting in quality deficits and shortages that pose risks for patients and the medical system. The risks of supply deficits apply across pharmaceutical products and are concentrated among generic (off-patent) drugs, including "critical generics" used by a large fraction of the population as well as by particularly vulnerable populations. Advanced manufacturing technologies (AMTs)—such as continuous manufacturing, modular manufacturing, advanced batch processing, and digital twins—offer advantages in ensuring product quality and reliability of the manufacturing process, yet the private sector does not adopt such technologies in pharmaceuticals in general or where they are frequently needed at the generic drug level.

The public is aware of, concerned about, and affected by access issues, but appears to not be aware of quality issues. The federal government needs a multipronged approach, including revised regulation of generic drugs (and in particular the FDA production safety approval process) to facilitate AMT adoption, expanded surveillance to improve tracking and regulation of drug precursors and quality, improved public awareness of drug quality issues in fragile supply chains, and early public input on expectations around quality, price, availability, and policies to address these.

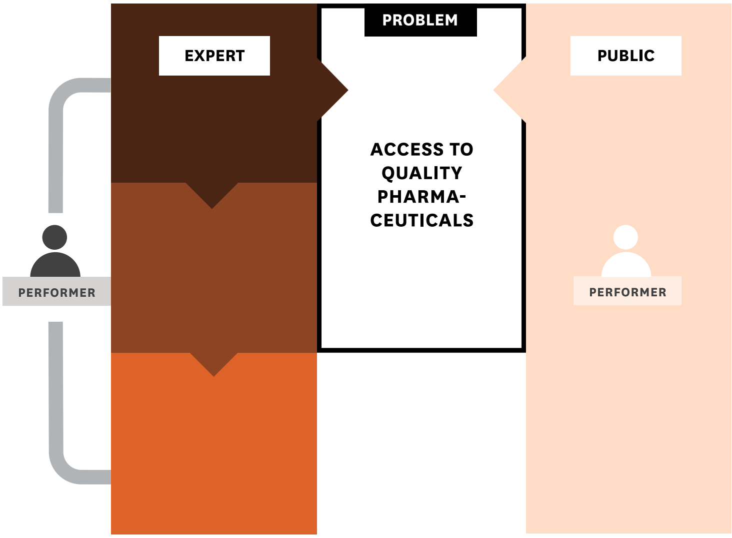
Program management Put side-by-side the results of performers with different disciplines, perspectives, and methods; workshop engaging leaders from academia, industry, and government to launch analytics

Methods Interviews, economics, descriptive statistics, expert elicitation; citizen surveys for public awareness, early input

Data Expert interviews; IQVIA pharmaceutical market data; USP data on supplier locations and drug raw materials; FDA data on drugs that have had supply shortages; expert and citizen survey results

Criticality dimensions measured Social well-being (health, demographics of populations affected)

Challenges for future critical technology assessment Limited government and nonstakeholder analyst access to product-level supply chain data in pharmaceuticals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Energy Storage and Critical Materials

Type of critical technology assessment Emerging product for which loss of access would have high social and economic impacts (and possibly security impacts)

Lead performers Elsa Olivetti, Kate S. Whitefoot

Policymakers' and industry's planned transition from conventional to battery electric vehicles (BEVs) is likely to face significant battery material supply chain risks as early as 2030. Simulations of 2030 scenarios show that lithium and cobalt supply shocks due to geopolitical disputes or natural disasters could have impacts similar in magnitude to the recent semiconductor shortage. Impacts would include significant increases in new vehicle prices (both conventional and electric), nearly a million US households unable to purchase a new vehicle, consumer surplus losses of approximately $24 billion, and significant lost wages for battery cell and pack production line workers.

The projected vulnerabilities to lithium and cobalt supply shocks can be avoided with supply chain diversification and increased adoption of cobalt-free batteries: Simulations suggest that encouraging additional supply of lithium domestically or in locations with lower risk of trade restrictions will mitigate the negative impacts of trade or other geopolitical disputes. Increasing the use of cobalt-free batteries (such as lithium-iron-phosphate) in the large majority of BEV sales significantly reduces the negative impacts of cobalt supply shocks. Immediate actions exist for increasing adoption of cobalt-free batteries and the future supply of lithium, and investments in innovations in novel lithium processing and cobalt-free battery chemistries could strengthen these alternatives.

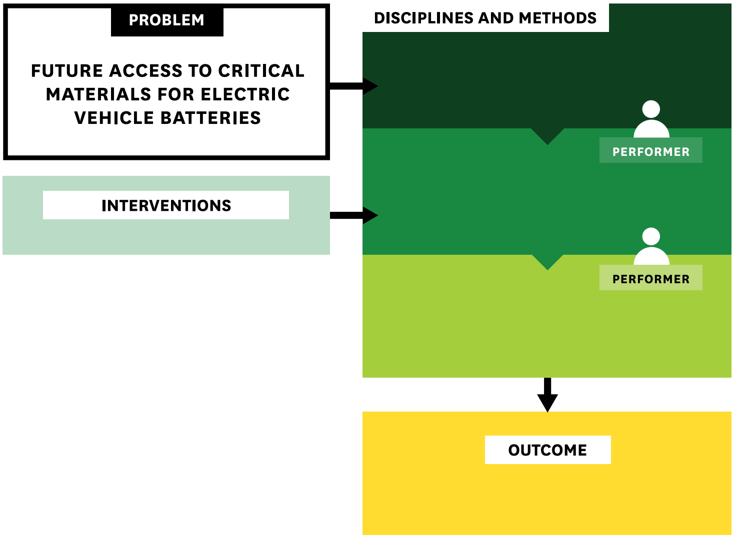
Program management Team two previously unconnected performers

Methods Industrial organization modeling, scenario modeling, supply chain modeling, engineering-economic models

Data Global mine supply data from S&P; historic data on material demand, prices, mining production, and mining costs; design, process, production, and labor hour data collected from private firms and published by Argonne National Laboratory; data on the automotive market from Ward's

Criticality dimensions measured Economic well-being, social well-being (consumer surplus losses, jobs)

Challenges for future critical technology assessment Need to bring together scholars with industrial organization economics and engineering analytic expertise, and make policymakers aware of the possibilities of such analysis


PROBLEM
FUTURE ACCESS TO CRITICAL MATERIALS FOR ELECTRIC VEHICLE BATTERIES
INTERVENTIONS
DISCIPLINES AND METHODS
PERFORMER
PERFORMER
OUTCOME

Cross-Cutting Insights for Critical Technology Assessment from the Area Demonstrations

Across demonstration areas, many scholars, government labs, and nonprofits (including FFRDCs) have a deep bench of data and models. The US government must develop a disruptive new program to tap into and integrate this expertise.

Advanced analytics today can be used to inform

- US global competitiveness in scientific funding and its collaboration networks
- US domestic funding biases that are failing to leverage the full bench of talent
- Technology commercialization pathways, including policy, investment, and other interventions—technical, human capital, infrastructure, regulatory, and citizen awareness and participation—to overcome bottlenecks. Following are examples of options identified this year to overcome technology commercialization bottlenecks:
  - Identify infrastructure gaps and increase access to that infrastructure to boost innovation;
  - Identify skill gaps in specific regions and training or worker mobility interventions to overcome these gaps;
  - Identify public, technical, and regulatory bottlenecks to the introduction of new technologies in commodity products, and opportunities to overcome those bottlenecks.
- Investment and policy interventions that could reduce supply chain vulnerabilities, and the value of that reduced vulnerability for national objectives in security, the economy, and social well-being.

US CTA capability is hampered by the following gaps:

- Building situational awareness of global technology and production capabilities is even more challenging than analyzing scientific and inventive capabilities through publications and patents: the data currently don't exist, and therefore few scholars or practitioners are rigorously addressing these problems. A CTA function must invest in these capabilities and develop a framework to determine where and how frequently they should be applied.
- The data needed for analytics to inform policy and investment in a timely fashion for rapidly moving critical technologies such as AI are lacking. Public-private partnerships must be established to create these datasets to inform critical questions in national technology strategy. There are analogous needs to coordinate data across the private sector and government in a timely fashion in certain critical technology supply chains.

The inclusion of equity in each analysis requires resources. Equity is not a single field of study, and experts with complex analytic, technical, and phenomenological knowledge are needed to address issues in algorithmic bias, energy equity, health equity, and equity and discrimination in labor and training (e.g., conscious and unconscious recruiting bias, macro- and microaggressions in STEM fields), among others. CTA leadership (the director, government director, and technical director) will also need to ensure that program managers maintain a cross-mission focus involving all three dimensions of criticality (security, the economy, social well-being), and that all analyses include the geographic and demographic implications of policies and investments.

US CTA capability will require the following institutional innovations:

- Leveraging the best of the nation's analytic capabilities to address the full portfolio of CTA challenges, opportunities, and needs will require integration of capabilities across a range of performers from academia, industry, and nonprofits such as FFRDCs.
- To scale this year's project and performer selection and orchestration activities, area-specific program managers should have deep contextual (technical and industrial) expertise in their topic area, experience in a diversity of institutions (academia, industry, and government), and an ability to understand leading analytic capabilities. There is a shortage of this type of human capital.
- To ensure policy relevance and impact of selected projects, program managers should be charged with (i) scanning globally and domestically for US challenges and gaps and (ii) scanning the nation's top talent for analytics to address those challenges, identifying multiple stakeholder agencies to partner with on specific analytic projects, and ensuring government transition partners for the outcomes.
- To simultaneously maintain relevance to policy and develop buy-in from relevant government stakeholders in the legislative and executive branches, members of Congress, the executive branch, and government agencies should be allowed to cofund analytic undertakings.
- The lack of a field of critical technology assessment means there is also a lack of human capital with the skills necessary both to perform the analytics needed for national technology strategy development and to serve as program managers of the work conducted across the country in each area. New education programs and professional fellowships are needed to invest in building this human capital.

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DIRECTOR'S NOTE

Erica R.H. Fuchs

This year of leading the National Network for Critical Technology Assessment has made me appreciate, in ways not possible in my life as a professor, that all great endeavors are the product of an extraordinary team. First, I express my utmost thanks to the NSF TIP team—Erwin Gianchandani, Tess DeBlanc-Knowles, and Jeff Alstott—for taking a bet on this pilot, believing in what this could be, and astutely managing our cooperative agreement. We wouldn't be here without your funding, participation, and guidance throughout the year. Thanks also to the Alfred P. Sloan Foundation leadership, Adam Falk and Danny Goroff. Danny, in particular, has become a mentor, advocate, and friend. The National Network would never have come into being without the work of Timothy McNulty, Associate Vice Provost of Government Relations at Carnegie Mellon University. Tim has been my trusted advisor, strategy architect, and cheerleader from day one, before the first testimony. Thank you, Tim, for believing in me before I believed in myself. Likewise, thank you to Farnam Jahanian, Theresa Mayer, William Sanders, and Peter Adams for their personal and institutional support necessary to pull rabbits out of hats on this one-year high-speed project. I cannot thank enough Shay Lynn Myers, our Network Coordinator and Event Director. Shay again and again came through under the most challenging circumstances. Thank you, Shay, for never questioning my crazy demands, being a friend and moral support to everyone on our team, and always having my back. Thanks to my research group, in particular Nikhil Kalathil, Afonso Amaral, Elina Hoffmann, Anthony Cheng, and Alex Newkirk. Repeatedly when we would have otherwise been unable to make it to the deadline without more technical heft you carried us over the finish line. Thank you for your endless enthusiasm and being my professional family. Thank you to Joel Predd for walking the first 8 months with me, to Matt Sanfilippo for being a partner and identifying key midway participants, to Rhonda Kloss and David Delo for managing an unusually large number of subcontracts, and to Dan Giamatteo and Sam Boyer for moving administrative hurdles to enable me to hire on a very compressed timeline. In the final 5 months, our team expanded in significant ways. Thank you to Natalie Ross, Project Manager, for jumping on the moving bullet train and seamlessly executing the multiple moving parts of our quality and communications review and report production process. Thank you, Natalie, for architecting cohesion across our diverse and dispersed team, and becoming the heart of our small internal group. Thank you, Rachel Losego, for expertly managing my unmanageable schedule. Thank you to Adam Jaffe for your expertise and decisiveness as our review moderator and editor-at-large. Likewise, great thanks to William (Bill) Bonvillian for serving as our sage senior advisor on DC communications. Thank you to Cameron Fletcher, our technical writer and editor, a magician at combining text from multiple sources into beautiful prose with a single voice and communicating complex concepts without any loss of precision. Thank you, Cameron, for being an ally and intellectual partner on the team. We are incredibly fortunate to have worked with Courtney Jo Fraser, Design Strategy Director at Opus Design. Courtney Jo, your intelligence and vision for communicating complex thoughts in figures is extraordinary—so many times it was only after working together that I realized, "Oh, so that's what we're doing!" Thank you to project coleads James Evans and Dewey Murdick. Your commitment and engagement were invaluable. Thank you to our Advisory Council for your consistently thoughtful engagement, enthusiasm, advocacy, and steering throughout the year. Thank you to Jared Cohon for your mentorship throughout my career, whether rough or calm waters, to Richard Lester for early on encouraging me to think big, and to Peter Blair and Tom Kalil for always being willing to hop on the phone as I traveled new territory. On the personal front: Thanks to Sachiyo Minegishi, for our Sunday afternoon strategy calls and ongoing friendship finding our way through life. Last, my utmost thanks to my family: my husband David Andersen (and his unfailing support of my professional ambitions), my fantasy-loving book-reading 11-year-old daughter Aria Andersen-Fuchs, and my never-ending-energy 5-year-old son Sebastian Andersen-Fuchs. Efforts such as this year inevitably have a high cost on family, and you have borne the brunt of that cost. Thank you for, each in your own way, always reminding me what matters most in life.

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CHAPTER 1: INTRODUCTION

Over the past half-century, the global geopolitical balance of scientific, economic, and production capabilities has shifted away from US dominance. At the same time, the United States faces serious challenges on the home front, where economic inequality has increased and social mobility has declined. Technological change and globalization are central to all these concerns. Policymakers need new tools to develop policies to simultaneously advance both US competitiveness in critical technologies and the well-being of all citizens.

Against this backdrop, the CHIPS and Science Act introduced unprecedented legislation. First, it mandated that the Office of Science and Technology Policy (OSTP) write a Quadrennial National Technology Strategy. Second, it mandated the National Science Foundation's (NSF) Technology Innovation and Partnerships (TIP) Directorate to, "In consultation with the interagency working group…identify and annually review and update a list of 1) Not more than 5 United States societal, national, and geostrategic challenges that may be addressed by technology [and] 2) Not more than 10 key technology focus areas…and evaluate the relationship between US societal, national, and geostrategic challenges and the key technology focus areas."

Responding to the legislative mandates will not be easy: Building the intellectual foundations, data, and analytic tools to inform NSF TIP's mission will require mobilizing, synthesizing, and integrating capabilities distributed across the country among different researchers, disciplines, and institutions. There is not a mature field of national technology strategy nor a modern, widely agreed upon field of critical technology assessment. National investments in key technologies need to be guided by analytic and physical science expertise frequently found in academia and industry, and not easily attracted by individual agencies. National strategy in technology should both be based on knowledge that spans multiple government departments and take into account multiple departments' missions.

Further, the necessary data and tools to inform NSF TIP's mandated mission are inadequate. The United States lacks timely situational awareness of global technology and production capabilities, rigorous methods to quantify the potential value of innovations (including considering geopolitical dynamics), and tools for quantifying opportunities across national objectives to simultaneously enhance national security, economic prosperity (including jobs), and social well-being (including health, environment, and equity).

In response to the legislative mandate of the CHIPS and Science Act, the NSF-funded National Network for Critical Technology Assessment (NNCTA) brings together leading scholars from across the nation to demonstrate how analytics can help inform Congress and agency leaders on strategic directions for and specific investments in research and innovation that could have the greatest impact on US societal, national, and geostrategic challenges. The goals of the 1-year pilot were to produce a vision for critical technology assessment based on current data and analytic capabilities (and demonstrations thereof), to identify gaps, and to determine the investment and organizational form necessary to achieve that vision.

Pilot Year Activities Designed to Meet the Charge

To meet the pilot year charge, the National Network for Critical Technology Assessment undertook four types of activities, as shown in **figure 1-1:** The Network (1) identified and executed selectively coupled research projects that demonstrate (i) current and prospective analytic capabilities for critical technology assessment (CTA) and (ii) how multidisciplinary lenses yield a whole greater than the sum of its parts; (2) prototyped a series of structured workshops convening experts from academia, industry, government, and nonprofits around the demonstrations' analytics for specific policy problems; (3) leveraged the demonstrations, workshops, and consensus-building sessions to build the intellectual foundations for critical technology assessment; and (4) developed a quality and communications review process to draw, from a broader base of analytic activities, recommendations for analytic and policy next steps. These activities were undertaken at a pace uncommon in academic research projects but necessary to have policy relevance (e.g., initial PI-specific demonstrations at 6 months, integration across demonstrations at 9 months), and executed in a way to make the planned and in-process work as open and transparent as possible to NSF TIP and executive branch policy decision makers.

We unpack the processes used for each of these activities below.

DEMONSTRATION SELECTION

The Network's pilot year activities include both top-down and bottom-up approaches (**figure 1-2**). A top-down "30,000-foot" view could enhance awareness of US global competitiveness and inform potential actions to improve it by assessing different countries' production of scientific knowledge and its commercialization (i.e., in the development and marketing of products), including factors such as human capital and sources of funding. A similar domestic analysis can shed light on capabilities at the regional, state, or even county level.

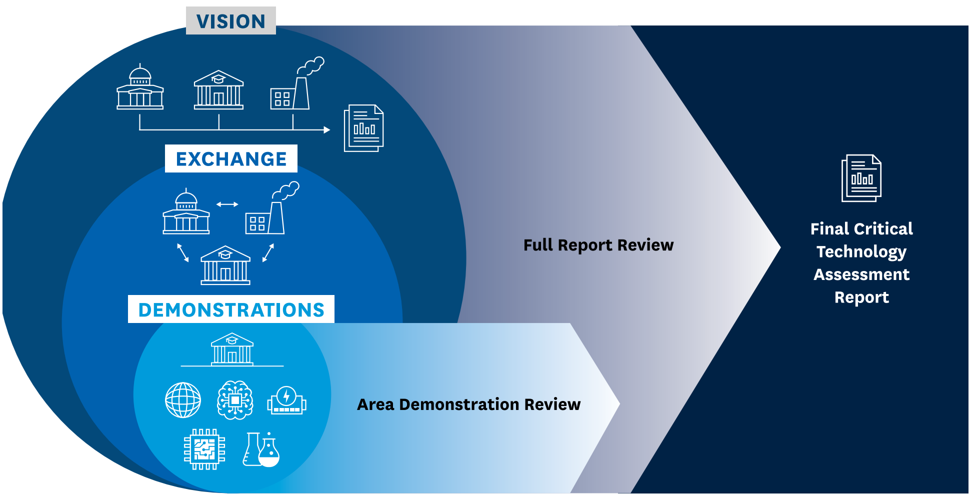

FIGURE 1-1. The area demonstrations—in situational awareness (global competitiveness), artificial intelligence, semiconductors, biopharmaceuticals, and energy and critical materials—were led by performers in academia. Their work was informed throughout by exchanges with experts in government, industry, and nonprofits. The vision for critical technology assessment drew on lessons across the demonstrations; elicited input on the data, analytic tools, and intellectual foundations for critical technology assessment during the exchange workshops; and a survey of and structured discussions and debate with network members and the Advisory Council. The area demonstrations were reviewed for research integrity and the full report was reviewed for quality and effective communication. (For process details see **figure 1-4**.)

Framework for Demonstration Selection

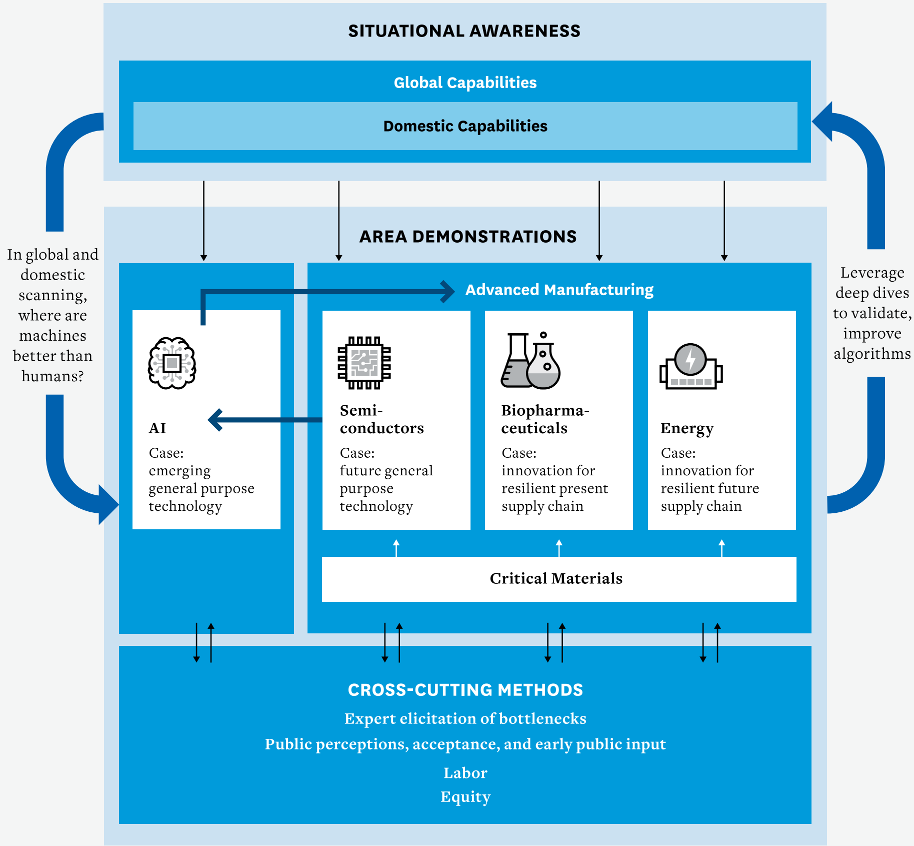

FIGURE 1-2. Framework that informed demonstration selection for the pilot year activities of the National Network for Critical Technology Assessment. The thick blue arrows show technological interdependencies explored between AI and semiconductors: advances in next-generation semiconductors are necessary to continue to advance AI, and AI holds the potential to accelerate scientific discovery, development, and commercialization of advanced manufacturing products in semiconductors, biopharma, and energy.

Situational awareness of the funding and production of scientific knowledge is matched with "bottom-up" area demonstrations in four technical areas highlighted in the list of "key technologies" in the CHIPS and Science Act and listed in a wide range of publications as "critical": artificial intelligence (AI), semiconductors (investments needed in leading-edge semiconductor device production and the future of computing devices, specifically "beyond CMOS"[1]), biopharmaceuticals (innovations in advanced manufacturing technologies for pharmaceuticals and in particular supply chain issues in generic drugs), and energy and critical materials (future battery supply chain issues with the ramp-up of electric vehicles). The area demonstrations represent different types of both technology criticality and assessment challenges.

The AI demonstration looks at the scientific discovery, productivity, and labor impacts of an emerging "general purpose technology" (GPT) with increasing but uneven adoption and with high security, economic, and social impacts. The semiconductor demonstration considers a potential future GPT, next-generation beyond-CMOS devices to advance computing performance, not yet adopted. The biopharmaceutical demonstration studies innovation and adoption of advanced manufacturing technologies to reduce pharmaceutical, and particularly generic drug, supply chain vulnerabilities. The energy and critical materials demonstration analyzes innovations in battery chemistries and critical material processing, along with potential policy interventions, to reduce future supply chain vulnerabilities.

The selected areas are important but not necessarily more so than others. Rather, they are used to demonstrate relevant methods for critical technology assessment and identify opportunities to advance US CTA capabilities. Chapter 5 explains differences in the CTA methods and data for each case.

Finally, looking at the pilot year's charge to identify gaps, it is not coincidental that three of the area demonstrations—semiconductors, biopharmaceuticals, and energy storage—involve advanced manufacturing technologies. While data are available from global publications and patents (each of which can be used to represent knowledge), data on global production capabilities (and supply chains) and on global human capital capa-bilities related to production are limited. At the same time, US manufacturing has been negatively impacted by trade and import competition and has low venture capital funding (compared to software), comparatively high R&D expendi-tures, and higher wages for high school–educated workers, and in some cases offshore manufacturing may have a negative impact on innovation (Fuchs and Kirchain 2010, Fuchs 2014, Fuchs et al. 2019, Autor et al. 2020). Commercial-ization of new technologies involving advanced manufacturing such as semiconductors, biotechnology, and energy technologies has been identified as an area of US weakness on which there is to be a particular focus by NSF TIP. Advanced manufacturing is also itself one of the key technologies listed in the CHIPS and Science Act.

DEMONSTRATION OF CROSS-CUTTING THEMES AND METHODS

The aim during the pilot year was to demonstrate in one topic area themes and analytic methods that could in future work be applied to multiple areas. Cross-cutting themes that could be applied throughout include human capital constraints (labor) and geographic and demographic diversity (equity). Cross-cutting methods relevant across cases include expert and public surveys about bottlenecks to commercialization and access.

Table 1-1 illustrates the following intersections. The situational awareness research and findings benefit by leveraging expert knowledge from the area lead in semiconductors. As shown in the "area demonstration connections" row of the table, the AI work shows the importance of assessing interactions between technologies (e.g., AI accelerating scientific discovery in semiconductors, biopharmaceuticals, and energy technologies), and the semiconductor work quantifies the potential value of next-generation (beyond-CMOS) computing devices for the economy, including advances in AI. The semiconductor area demonstrates the value of using formal expert elicitation methods to identify opportunities to overcome commercialization bottlenecks.

[1] CMOS = complementary metal-oxide semiconductor

The biopharmaceutical area illustrates the relevance of understanding public awareness and gathering early public input. The energy area clarifies the role of innovation to reduce supply chain vulnerability; in future work this lens could be applied to semiconductors and biotech.

Multiple areas demonstrate CTA methods involving labor inputs and outputs: The semiconductor area quantifies region-specific labor constraints that may prevent commercialization in this technology. The AI area considers the impact of emerging technology on labor outcomes. The energy area demonstrates the impact of supply chain vulnerabilities on labor outcomes. Multiple areas demonstrate CTA methods to quantify equity impacts: The situational awareness demonstration indicates the need for tools to help overcome demographic and geographic biases in funding. The AI demonstration shows geographic and demographic disparities in AI capabilities. The energy area explores the potential impacts of supply chain vulnerabilities on energy equity.

Limitations for competitiveness of demographic and geographic distribution of scientific funding

		ARTIFICIAL INTELLIGENCE	SEMICONDUCTORS	BIOPHARMA	ENERGY AND CRITICAL MATERIALS
Situational awareness		( )	x	( )	
Commercialization bottlenecks	Expert elicitation		x		
	Public perception & early input			x	
Labor			x		
Equity		x			
Area demonstration connections		AI's potential to accelerate scientific domains relevant to semiconductors, biotechnology, energy	Next-generation semiconductor device development limits advance in AI		Access and lack of innovation to reduce supply chain vulnerabilities in critical materials affects scale-up of electric vehicles

TABLE 1-1. Intersections of cross-cutting themes and analytic methods. See text for elaboration. x = direct intersection; () = 30,000-foot insights on competitiveness (without yet engagement with area experts)

In addition, the research questions demonstrated in one area how situational awareness could inform the area demonstration and vice versa, and in two areas how analytics could inform the relationships between technology areas. Future work should leverage analytic methods demonstrated in one area in multiple areas, as relevant to the most pressing questions in those contexts, and should draw on more disciplines and methods—including computer science, political science, and history—than could be demonstrated in this pilot year.

SELECTING QUESTIONS AND ORCHESTRATING MULTIDISCIPLINARY LENSES AND PERFORMER COMBINATIONS

Doing these analytics well is a science that should leverage the top talent across the nation. As important as this science is the art of matching of data and methods to problems, the orchestration and synthesis of insights across national analytic capabilities, and the selection of the performers and problems. The specific questions asked and the orchestration of the performers to address them are presented in chapter 4. The performers were brought together in quarterly meetings and charged in break-out sessions with identifying immediate and longer-term opportunities for integration.

MULTILATERAL EXCHANGE

NSF TIP's 1-year $4M pilot award for a National Network for Critical Technology Assessment enabled the first step of bringing together top academics from across the country to define a vision for critical technology assessment, considering current capabilities, gaps, and the national investment and organizational form needed to realize that vision. But to be successful, both the analytics and a CTA vision must also involve practitioners from industry, government, and nonprofits. Industry and government stakeholders are essential contributors who need to inform not only the data and analytics but also the questions asked. Moreover, in multiple cases industry has essential data or analytic capabilities not available in government or academia.

Network leads sought and received an award from the Sloan Foundation for a series of workshops and other mechanisms to convene or otherwise engage in a multilateral dialogue with practitioners in industry, government, and nonprofits. The workshops provided a forum to discuss the proposed demonstrations and an opportunity for the practitioners to comment on the associated data, analytics, questions, and policy problems; to potentially team up with the academics in solving challenges; and to inform the vision for the future of critical technology assessment. In total we held eight workshops: one workshop for each area demonstration, one cross-cutting workshop for labor and equity, and two workshops to engage in multilateral dialogue on the analytic results with industry and government leaders and build a cross-area vision of critical technology assessment with performers.

ELICITING THE INTELLECTUAL FOUNDATIONS FOR CRITICAL TECHNOLOGY ASSESSMENT

The Network developed a process to elicit the intellectual foundations for critical technology assessment from multiple contributors and built consensus around those intellectual foundations and a vision for critical technology assessment. Structured feedback was elicited in a 1-hour session at the end of each workshop as well as through a survey and series of exercises conducted by the Network and Advisory Council at the midway meeting. In total, there were more than 100 workshop participants spanning academia, industry, government, and nonprofits (**table 1-2**) and 25 participants in the survey of network and Advisory Council members. Based on this input, the authors identified chapters for the vision section of the report, and requested within-Network and external experts (in all cases multiple individuals per chapter) to contribute initial written content for those chapters. These authors presented their sections at the third quarterly meeting with assigned discussants, and each chapter was discussed by the full Network. The contributions were merged into a single document and each chapter draft shared with the full Network for feedback (provided both in writing and in a Zoom meeting to which all Network members were invited). Contributors to the vision chapters are listed in **appendix table 1A-1.**

TABLE 1-2. Industry, government, and nonprofit organizations that participated in multilateral exchange on the area demonstrations through area workshops, as discussants, or in meetings or conversations about the analytics.

Area demonstration	Multilateral exchange participants
Global Competitiveness	Defense Advanced Research Projects Activity (DARPA), Lockheed Martin, National Science Foundation (NSF), Office of Naval Research (ONR) Global, Office of Science and Technology Policy (OSTP)
Artificial Intelligence	Bureau of Labor Statistics (BLS), Microsoft, National Artificial Intelligence Initiative Office (NAIIO), National Science Foundation (NSF), Office of Science and Technology Policy (OSTP), OpenAI, US Department of Labor (DOL)
Semiconductors	Booz Allen Hamilton, Council of Economic Advisors (CEA), Defense Advanced Research Projects Activity (DARPA), Department of Defense (DOD), Department of Commerce (DOC), Denso, Federation of American Scientists, Ford, Global Foundries, Intel, Lockheed Martin, Microsoft, National Security Council, NVIDIA Corporation, Office of Science and Technology Policy (OSTP), President's Council of Advisors on Science and Technology (PCAST), RAND, Semiconductor Industry Association (SIA), SRI International, Western Digital
Biopharma-ceuticals	Acumen BioPharma, Association for Accessible Medicines (AAM), CMIC Group, Domestic Policy Council (DPC), Food and Drug Administration (FDA), National Commission on Biotechnology, National Economic Council (NEC), North Ocean Ventures, Office of Science and Technology Policy (OSTP), President's Council of Advisors on Science and Technology (PCAST), World Health Organization (WHO)
Energy and Critical Materials	Advanced Manufacturing Office (AMO), Defense Advanced Research Projects Activity (DARPA), Department of Energy (DOE), The Engine, Electric Power Research Institute (EPRI), LowerCarbon Capital, Office of Management and Budget (OMB), Office of Science and Technology Policy (OSTP), US House Committee on Science, Space, and Technology, Anonymous: automakers (3), think tanks and policy experts (3), mining companies (2), domestic and international government agencies (9)

REPORT REVIEW AND PRODUCTION

To cull from a number of recommendations for analytic and policy next steps we undertook two reviews: (1) of the area demonstrations and (2) of the full report. In both cases, we requested input on the research integrity, policy readiness and significance, and relevance and communication for stakeholders in Washington. For the area demonstrations, we also enlisted reviewers who were stakeholders or could otherwise comment on stakeholder response. For policy readiness, reviewers were asked to comment on whether the findings should be implemented, were an important policy-relevant finding needing support to progress to policy action, or a provocative early finding needing more research (**figure 1-3**).

The 21 reviewers across the five area demonstrations were drawn from academia, industry, and government, with at least one reviewer in each category for each area. The 23 reviewers for the full report were experts from academia, industry, government, and nonprofits with extensive experience in and knowledge of the federal policymaking process. All the reviewers generously provided thoughtful, useful critiques that helped refine the technical content and clarity of this report.

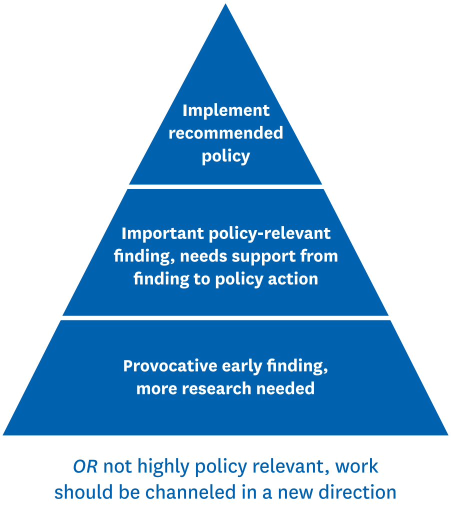

FIGURE 1-3. Quality and communications review of policy readiness.

SUMMARY OF PILOT YEAR ORGANIZATIONAL INNOVATIONS

The NNCTA pilot year activities involve six organizational innovations:

- **Project selection:** Multidisciplinary lenses on a single problem, top talent, novel collaborations, depth in specific technologies
- **Relevance to policy:** Bend academia closer to government; multilateral input from academia, industry, government (workshops, 6-month and 9-month feedback, review)
- **Speed:** Demonstrations in 6 months, integration in 9 months, synthesis and reporting at 12 months
- **Transparency:** Information shared during the analytic process with academia, industry, government stakeholders
- **Recommendations:** Quality and communications review to select from a number of recommendations for analytic and policy next steps
- **Vision for critical technology assessment, organizational form, investment:** Network consensus based on elicitations and consensus-building meetings begins to build the multidisciplinary intellectual foundations necessary for critical technology assessment, including
  - a CTA framework,
  - accommodation of different data and data solutions to different problems, and
  - Network sustainability and organizational form.

The timeline for the pilot year is shown in **figure 1-4**.

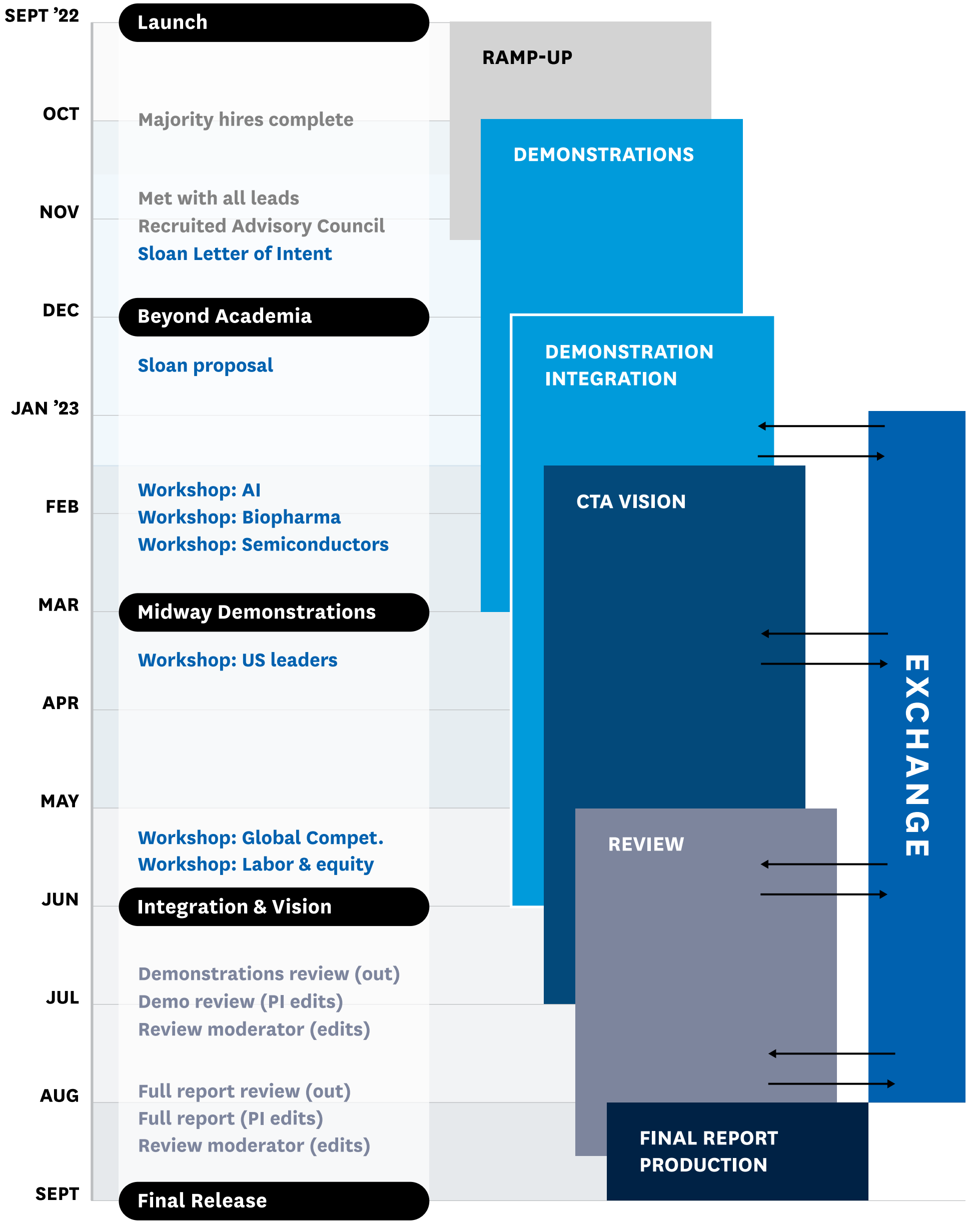

FIGURE 1-4. Timeline for the pilot year of the National Network for Critical Technology Assessment. PI = project lead

CHAPTER 2: CURRENT AND HISTORICAL US CAPABILITIES IN CRITICAL TECHNOLOGY ASSESSMENT

The sources and breadth of published science and technology (S&T) knowledge have expanded at unprecedented rates for the past half-century.[1] The institutions to support policymakers in light of this expansion have not kept up. Further, as S&T knowledge expands, of necessity it becomes ever more specialized, understood mostly by those working in narrow domains, who may have little contact with or knowledge of other domains. Policymakers need trusted sources of analysis, guidance, and insight with direct utility for issues they must address in a timely manner. There is much that critical technology assessment might do to clarify what makes some technologies more critical than others. Such information could assist policymakers in setting priorities, whether for R&D spending, foreign economic policies (trade and investment), taxation, public health, or economic development.

Context: Government Advisory Resources Past and Present

Compounding the challenges of rapid technical advances and specialization is the complex system of missions and activities across federal agencies and other actors.

Science and technology have been recognized as important to national security, the economy, and social well-being especially since the start of World War II, when the United States found itself technologically lagging behind Britain and Germany. The years following the war saw establishment of new S&T capabilities in the executive branch, legislative branch, and external sources. These included the Office of Naval Research (ONR; 1946), National Science Foundation (NSF; 1950), Air Force Office of Scientific Research (AFOSR; 1951), President's Science Advisory Committee (1957; later reconstituted as the President's Council of Advisors on Science and Technology, PCAST), and Advanced Research Projects Agency (ARPA, later DARPA; 1958). Other sources of advice and analytical expertise for the executive branch include the private RAND Corporation, the independent National Academies of Sciences, Engineering, and Medicine (NASEM; formerly the National Research Council), the federal National Science and Technology Council (NSTC) and Office of Science and Technology Policy (OSTP), and statistical agencies such as the Bureau of Economic Analysis (BEA) and Bureau of Labor Statistics (BLS). In the executive branch, dozens of agencies and subagencies have their own missions and often their own policy shops and considerable independence.

Congressional members and their staff are highly knowledgeable and talented, but do not necessarily have the numbers or depth and breadth in technical issues facing the US government, must less the US S&T enterprise as a whole. Congress can call on the Government Accountability Office (GAO), Congressional Budget Office (CBO), and Congressional Research Service (CRS) for studies touching on S&T, each with varying focuses and internal expertise. GAO, which reports to Congress and is charged with investigating "matters relating to the receipt, disbursement, and application of public funds," has published 30-plus "technology assessments" over the past 20-plus years; its products often reflect an accounting perspective given the agency's role, although with the creation of its Science, Technology Assessment, and Analytics (STAA) office, GAO has been conducting studies

[1] The many publications of Derek J. de Solla Price, beginning in the early 1960s and culminating in *Little Science, Big Science...and Beyond* (Columbia University Press, 1986), mapped increases in the formal literature.

more closely based on S&T aspects of policy. CBO produces useful reports on R&D budgets and planning, and on regulatory measures and their costs, occasionally delving more deeply into S&T-related issues, while grounding its work in government finance. CRS provides meticulous reviews, focusing on legislative content, both enacted laws (and agency regulations based on them) and proposed legislation. From 1974 to 1995, Congress was also able to draw on the congressional Office of Technology Assessment (OTA). OTA's mandate included, but went well beyond, policy for S&T and it addressed the S&T components of wider policy issues.

Challenges and Limitations

Because multiple agencies and subagencies, with substantial R&D budgets and technical expertise, share responsibility for identifying and either supporting or regulating technologies, overlapping jurisdictions can create boundary issues, compounded by asymmetrical access to technical expertise. It is difficult to coordinate or harmonize among agencies with overlapping responsibilities and there is limited sharing of their terms, methods, data, and information, sometimes because of security restrictions. There is also limited capacity for monitoring what goes on among agencies and subagencies on almost any issue, much less monitoring and sorting through outside advice, developments, analysis, and opinion. All of this makes cross-agency coordination difficult and challenges policymakers and analysts in efforts to extract and synthesize useful guidance.

The Office of Science and Technology Policy (OSTP) is statutorily charged with advising the president on S&T, coordinating the implementation of S&T priorities across the federal government, and engaging with partners from academia, industry, civil society organizations, and other government bodies. Over the past several decades OSTP funding has ranged between $5 million (2021) and $10 million (1993), not including additional funding sourced from NSF (for the Science and Technology Policy Institute) and DOE (for PCAST). While OSTP is solely an advisory and coordinating body, it has at times enhanced its leverage by joining with the Office of Management and Budget (OMB), which, given its primary function of budget oversight, can influence agency actions through budgetary approvals.

Finally, data gathering and analytical capacity to support policymakers in science and technology (S&T) decision making may have been reduced in the past 3 decades, particularly in light of the increasing depth and breadth of S&T issues and growing amount and variety of data needed for effective decision making. For example, the Defense Logistics Agency for a period funded selected defense-relevant product and technology tracking by the US Census Bureau (information that is lacking in trade data, which is often by weight or dollars), but it is not clear that an alternative replaced that effort. As a result, a 2020 supply chain study, for example, was left to rely heavily on information from trade associations, news media, and nongovernment organizations with possible stakeholder agendas (USITC 2020).

Need and Opportunity for Overarching Independent Technical Analysis

Effective critical technology assessment demands deep knowledge of specific technologies that is difficult for anyone to acquire and keep up with other than direct participants. But the engineers and scientists who are engaged day-to-day in developing potentially critical technologies and who have the deepest knowledge may themselves have, or work for employers with, stakeholder interests. And unlike science, where results are regularly peer reviewed and published, understanding of new technology is particularly difficult because it requires (i) unpublished private sector knowledge retained in business firms (much of which is proprietary); (ii) a combination of scientific, economic, and market-related expertise; and (iii) tacit "know-how."

Organizations such as the National Academies of Sciences, Engineering, and Medicine can enlist national and international expertise. Their consensus reports, based on input from 12 to 18 committee members, typically take 2–3 years to produce. OTA had analytic capabilities and could tap deep reservoirs of knowledge about technology (including through short-term external contracts), but since its defunding in 1995 these capabilities have not been replicated elsewhere.

Finally, federally funded research and development centers (FFRDCs), such as RAND (which in the 1990s housed the government's Critical Technologies Institute), MITRE, SRI, and the Institute for Defense Analyses, as well as national labs can often play important roles in technology assessment.

In short, it is a significant and pervasive challenge for work on critical technology assessment to leverage the full set of data and the S&T expertise dispersed across the country in academia and industry, and to combine sophisticated analytics with knowledge that gets inside the "black box" of technology. The federal government, agencies, and policymakers are in deep need of clear evidence informed with technical depth and analyses that can be used to guide decisions about parsing R&D budgets, proffering industrial supports and subsidies as in the CHIPS and Science Act, developing and applying export controls, or evaluating potential risks to national security.

CHAPTER 3: NATIONAL OBJECTIVES, TECHNOLOGY CRITICALITY, AND TECHNOLOGY ASSESSMENT

There is bipartisan interest in investing in "critical technologies," but the United States does not have an operational definition of "criticality," let alone the data, intellectual foundations, or policy roadmap that could translate that definition into a recommended portfolio of policies and investments. Policymakers lack methods to evaluate the criticality of specific technologies for national objectives ranging from national and economic security to the social well-being of all citizens (in terms of health and the number, quality, and distribution of jobs, for example). And even if a critical technology is identified, consensus does not exist regarding mechanisms such as secrecy, openness, domestic capabilities, international alliances, and the role of government investment that can best promote their development in the United States while protecting against their exploitation by adversaries.

Unfortunately, past approaches to identifying critical technologies have proven inadequate. Reports and lists have often been little more than reflections of stakeholder interests, and have struggled to find their way to supporting meaningful policy (cf. Mogee 1991, Knezo 1993, Bimber and Popper 1994, Wagner and Popper 2003). Nonetheless, a number of entities (cf. CFR, OSTP, DOD) have produced recent lists of "critical" or "key" technologies (**box 3-1**), and the CHIPS and Science legislation mandates that NSF's Directorate for Technology, Innovation, and Partnerships (TIP) annually update a list of 10 key technologies and how they might address US domestic and international challenges.

In the 1990 Defense Authorization Act (PL 101-189, signed into law in November 1989), Congress defined "critical technologies" as "essential for the United States to develop to further the long-term national security or economic prosperity." As revealed during the pandemic, this definition does not include public health or look beyond technology development to address related aspects such as product access.

For this project, we define a technology as critical with respect to three different but overlapping national missions (for detailed descriptions, see **appendix 3A**):

- US national security and that of our allies,
- US economic well-being, and
- US social well-being.

The Role of Technology in Advancing National Missions

Technological progress has long been considered central to all three missions. Technological superiority is considered a foundational element for the US military and warfighter (IMTI 2009). For example, the Allied victory in World War II has been attributed in part to the ability of the American (and Soviet) mass production industry to turn out military aircraft, tanks, and other weapons systems in unprecedented quantities thanks to inventions in materials, electricity, and the assembly line (Hounshell 1985). Today, uncrewed and autonomous systems—whether missiles, drones, or combat robots—have changed the nature of warfare, and AI more broadly is expected to continue to revolutionize conflict. One study concluded that, thanks to IT's ubiquity (e.g., as a general purpose technology) and its regular performance improvements (Moore's law), more than 90% of increases in total factor productivity in the 1990s in the United States and worldwide could be attributed to technological progress in microprocessors (Jorgenson et al. 2015).

Disruptive technologies can also transform the rules of the game in firm and national competition and international comparative advantage in ways that transcend classic productivity measurements, as has been seen with the invention of the car, the internet, and wireless communication (**box 3-2**).

Finally, the social benefits of technological advances are so numerous and so transformative to daily life that they increase the quality of life in ways that can be hard for economists to measure. Such were the effects of electricity, pasteurization, and semiconductors; more modern examples might include mRNA vaccines, ubiquitous computing, and AI.

Strategies, Tradeoffs, and Wins for National Objectives

Predicting the future of technology is challenging, but it is possible to set desirable objectives, map out technology pathways that with high probability can help to achieve those objectives, and work to coordinate relevant actors. Well-defined and transparent technology assessment methods can assist policymakers in developing strategies and identifying both tradeoffs and win-win solutions across national objectives for stakeholders with different values or weighting of national objectives.

Common methods in strategic analysis for technology policy include scenario analysis (Cornelius et al. 2005), wargaming (McHugh 1966, Rubel 2006), stress tests (Simchi-Levi and Simchi-Levi 2020, Ivanov and Dolgui 2022), and engineering analytic (technoeconomic) modeling (Busch and Field 1988, Morgan 2017), among others. The latter has shown promise in supporting the designation of commercialization pathways for emerging technologies, by identifying labor skill and quantity requirements as well as technology advances (such as improvements in process yields) required to lower costs (cf. Liu et al. 2021, Combemale et al. 2022).

BOX 3-1

History of Technology Criticality Designation and Listings

The concept of technology "criticality" has focused primarily on national security but at times expanded to include economic competitiveness and societal well-being, including public health. First came the notion of militarily critical technologies and, later, families of technology deemed critical for economic competitiveness. Early DOD compilations included lists and hundreds of pages of analysis. Early export control policies targeted sales of high-technology goods to the Soviet Union, Warsaw Pact countries, and China. High-performance computers, and their hardware components and software, were of particular concern as dual-use (military and civilian) technologies, especially given their role in calculations for early nuclear weapons. More recently, technologies such as semiconductors and software in end-systems essential to socioeconomic functioning (e.g., the internet, air traffic control, the electrical grid) as well as products associated with energy security have been considered critical. A 1976 Defense Science Board report (DOD 1976, pp. 1, 3) emphasized embedded (intangible) industrial knowledge, not just goods produced with such knowledge, stating that "Design and manufacturing know-how are the principal elements of strategic technology control," adding "there is unanimous agreement that the *detail of how to do things* is the essence of the technologies" (emphasis in original). That said, most critical technology lists focus on products and technologies. They are usually developed by consensus committees, which face the challenges of quantifying criticality for different missions and balancing stakeholder interests inherent in agency missions as well as S&T expertise. **Table 3B1-1** summarizes three recent critical technology lists. Eleven of the 18 rows have significant overlap across the lists, which also share a focus on national security.

TABLE 3B1-1. Recent critical technology listings, 2022 and 2023

Governmentwide "Critical and Emerging Technologies"	DOD "Critical Technologies"	CHIPS and Science "Key Technologies"
Advanced computing	Advanced computing and software	High performance computing, semiconductors, and advanced computer hardware and software
Advanced engineering materials	Advanced materials	Advanced materials science, including composites, 2D materials, other next-generation materials, and related manufacturing technologies
Advanced gas turbine engine technologies		
Advanced manufacturing		Robotics, automation, and advanced manufacturing
Advanced and networked sensing and signature management Communication and networking technologies Networked sensors and sensing	Integrated network Systems-of-systems FutureG	Advanced communications technology and immersive technology Data storage, data management, distributed ledger technologies, and cybersecurity, including biometrics
Advanced nuclear energy technologies		
Artificial intelligence	Trusted AI and autonomy	Artificial intelligence, machine learning, autonomy, and related advances
Autonomous systems and robotics		
Biotechnologies	Biotechnology	Biotechnology, medical technology, genomics, and synthetic biology
Directed energy Hypersonics	Directed energy, hypersonics	
Financial technologies		
Human-machine interfaces	Human machine interfaces	
Quantum information technologies	Quantum science	Quantum information science and technology (S&T)
Renewable energy generation and storage	Renewable energy generation and storage	Advanced energy and industrial efficiency technologies, such as batteries and advanced nuclear technologies, including but not limited to for the purposes of electric generation

Governmentwide “Critical and Emerging Technologies”	DOD “Critical Technologies”	CHIPS and Science “Key Technologies”
Semiconductors and microelectronics	Microelectronics	See top row
Space technologies and systems	Space technology	
		Natural and anthropogenic disaster prevention or mitigation

NOTE: Entries appear as in the source documents (L to R columns): *Critical and Emerging Technologies List Update* (Executive Office of the President, Feb 2022), p. 2; *National Defense Science & Technology Strategy 2023* (Department of Defense [unclassified version released May 9]), p. 3; HR 4346 (“CHIPS and Science Act”), July 22, 2022, Sec. 10387, pp. 560-61.

In terms of quantifying tradeoffs, for example, one assessment showed that compulsory secrecy during World War II protected sensitive technology but also resulted in restricted commercialization and limited follow-on innovation, with effects persisting through at least 1960 (Gross 2019). In terms of identifying win-wins across national missions or stakeholders with different values, past assessments have shown, for example, that (i) for safety-critical robust semiconductors, improved access to raw materials and intermediate inputs can benefit both the economy (sales and jobs in the automotive sector) and national security (chips for missiles) (Berger et al. 2023); and (ii) in the case of high-end semiconductors for communications, research suggests that reshored manufacturing can enhance US technological leadership and increase both the number and quality of US jobs (Combemale and Fuchs 2021, Combemale et al. 2022).

However, although scenarios can be cognitively compelling, they can also lead users to focus too narrowly on specific outcomes and ignore other potential futures. Various methods of horizon scanning are often important ways to make sure needed alternatives are analyzed, and are one of multiple places where LLM approaches may be particularly powerful.

Anticipating Future Technology Impacts

Technologies that are critical to each or all of the three missions can be readily identified. The challenge lies in anticipating which will be critical in the future. This requires thinking carefully and systematically about the various ways current and future technologies and their capabilities may evolve, and about the consequences of that evolution. **Box 3-3** discusses prior work and future opportunities.

Critical technology assessment is not, however, primarily about making predictions. Rather, it should acknowledge the ongoing challenge of decision making under uncertainty; provide analysis, tools, and data to support better-informed decisions in the face of inevitable uncertainty; and identify strategies that will increase the odds of realizing desired outcomes.

Measuring Policy Impacts

Measuring the impact of specific policies designed to address critical technologies presents at least two challenges. First, given the length of the innovation pipeline, it may take 10–30 years or more to know whether the desired outcome has been achieved. This time horizon is much longer than political cycles.

BOX 3-2

The Role of Technology in Competitiveness

The US balance of trade in goods and services has been negative for the past half-century. US-based firms in multiple industries including steel, semiconductors, and automobiles have struggled, sometimes successfully and sometimes not, as international rivals eroded their positions. These industries differ in their structure, work systems, supply networks, and technologies. Government policies on cross-border trade, foreign investment, and industrial supports and subsidies also vary. All these factors influence competitive outcomes for individual firms, either at the margins or centrally. To be competitive, technologies must be introduced at meaningful scale in products or processes—in a word, commercialized. In the United States this is the work of private firms, which may be manufacturers or providers of intangible outputs such as financial services and health care.

Two cases illustrate the impacts of technology use, one benefiting a US industry, the other advantaging international competitors. The US petrochemicals industry adopted technological innovations and plants grew in size because of steady improvements in process modeling, advances in catalysis, and computerized process controls. In microelectronics, foreign semiconductor firms gained advantages in high-volume production by fine-tuning their processes, superseding US capabilities in quality and reliability and thus cutting into the once-dominant market shares of US-based manufacturers. Impacts were initially felt in commodity devices such as memory chips, and later in the leading process nodes for the most advanced chips. Many services also benefit from technological innovation. For example, hospitals are using onsite 3D printers to create lifesize models of organs for the development and practice of complex surgeries and to create dental implants and prosthetics. Businesses pursue technical knowledge for product and process innovation in part through internal R&D—in 2022 Alphabet spent nearly $40 billion on R&D and Amazon some $73 billion[1]—and in part through strategic funding, search, and leverage of technology from outside sources, whether Silicon Valley startups, spinoffs from academic research, defense R&D and procurement, or from overseas. Technological advances are not without costs, however. Impacts of trade and technology on workers have been widely documented, although detailed analysis of how different technologies may have different impacts and the specific implications for training have been challenging to obtain because of the aggregate level of public data, the siting of necessary knowledge in firms, and the significant technical and product expertise needed. Implementing the necessary training is also resource-intensive.[2]

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1 From 10-K reports filed with the Securities and Exchange Commission, online. Amazon terms its entry "technology and content," but it is the same accounting category as for the R&D spending reported by other firms.

2 See https://data.oecd.org/socialexp/public-spending-on-labour-markets.htm. Over the years the United States has spent less on worker training than other members of the Organization for Economic Cooperation and Development, excepting only Mexico. More generally, see, e.g., Barnow and Smith (2015).

Second, it can be particularly difficult to set up policy experiments that have a counterfactual, especially for singular large-scale investments such as developing a new aircraft or building a particle accelerator.

Notwithstanding these challenges, it is essential to learn from past policies and to set up as effective a system as possible and then retrospectively assess the efficacy of policy actions (Manski 2013). In some cases, it may be possible to obtain focused or short-term metrics—such as the net short-term change in employment resulting from a program. Well-designed policies for critical technologies can be expected to also have synoptic or longer-term consequences. In this case, while it may be possible to show correlation, controlling for large numbers of other changes can make it difficult or impossible to demonstrate causation. Examples of the two types of metrics in the three domains of criticality are shown in **appendix table 3A-1**.

Demonstrating Critical Technology Assessment

The 1-year NNCTA pilot focused on demonstrating the potential for analytics to inform national RD&D investment and other policy issues for critical technologies in four technology areas:

- artificial intelligence (AI),
- semiconductors (chips),
- biopharmaceuticals (generic drugs), and
- energy storage (batteries) and critical materials

Developing measures of criticality was not the primary objective, but demonstration efforts in each of the four areas ended up providing a variety of short-term quantitative and qualitative measures. **Appendix tables 3A-2** and **3A-3** show the domains of criticality addressed by each area.

BOX 3-3

Forecasting Technology Outcomes

John A. Alic, Tom Mitchell, M. Granger Morgan

In the world of technology, as in human affairs more generally, the future is deeply uncertain. Technology forecasts involve complex technological and social systems whose interactions and outcomes can be difficult to predict. The high-profile case of solar energy demonstrates the challenge, where the price in 2019 was lower than expert assessments of cost in 2030 (Savage et al. 2021) (**figure 3B3-1**) and then cost estimates based on experience curve analysis (Candelise et al. 2013). For useful predictions to be possible, stable patterns must exist (Makridakis et al. 1998). When the pattern does change, as happens with some major innovations—solid-state electronics in place of vacuum tubes, jet engines in place of reciprocating powerplants, fiber-optic communications in place of digital electronics—prediction will at best be suggestive and highly uncertain until some new pattern has emerged and been validated.

This sort of uncertainty poses a fundamental problem for critical technology assessment. Major or radical innovations—"breakthroughs"—are a chief goal of innovation policy. Although rare, when they emerge the existing pattern is dissolved, rendering the future unknowable. Until a new pattern is established, guesses or at best informed technical judgment will be the sole basis for anticipating future trends.

How long the period of high uncertainty will last is usually also unknowable. For high-temperature superconductivity, for example, no new pattern is visible despite decades of advances in both theoretical understanding and experimental demonstration. Similarly, no one can reasonably predict if and when lithium-ion electric vehicle batteries will be superseded by some alternative electrochemical family. Moore's law, on the other hand, was put forward in 1975, quickly accepted, and by about 1980 the only question was how long the newfound trend would last and what would come next.

In thinking about technological forecasting, it is important to not conflate the idea of *identifying relevant technology directions and their potential implications* with the idea of *predicting exactly when a specific technical advance will occur.*[3]

[3] National technology strategy benefits greatly from knowledge of the potential directions to be taken. For example, it is quite useful to learn from experts—even if the timing and exact uses are not yet clear—that more general versions of AI large language models will be trained on vast quantities of videos and not just text, and that this training may revolutionize systems for video surveillance and self-driving vehicle technology.

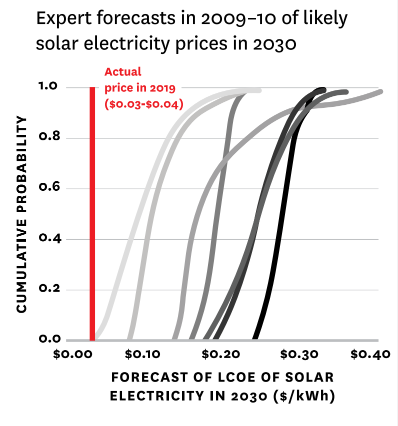


FIGURE 3B3-1. Underestimation of progress in reducing the future levelized cost of a technology (solar electricity) is illustrated by these cumulative distribution functions of the cost of solar photovoltaics in 2030 as assessed by seven energy experts in 2009–10. None of the forecasts included the actual price a decade later in 2019 (far left). Adapted from Savage et al. (2021).

A generalized sense of the directions of technological advances that are likely to have substantial impacts on society and the economy underlies the many critical technologies lists put forward in recent years, as well as individual policies such as those embodied in the CHIPS and Science Act pieces of legislation and documents intended as guides to policy thinking (e.g., the *National Artificial Intelligence Research and Development Strategic Plan: 2023 Update,* released by the White House in May 2023). The sounder the grasp of policymakers and policy influencers concerning factors and forces likely to affect technological directions and the pace of advance, along with possible constraints such as resource availability (e.g., for lithium-ion electric vehicle batteries) or the availability of skilled labor (e.g., for quality control in the manufacture of COVID vaccines), the more likely their decisions and actions will have positive effects on the economy, the labor force, and the population as a whole. This sort of forecasting is far easier than attempting to predict the timing of technological, production, or cost advances.

There is important ongoing research into other technological forecasting methods and applications (Nagy et al. 2013, Meng et al. 2021, Trancik 2021, Ziegler et al. 2021, Makridakis et al. 2023), including work in decision sciences demonstrating that certain individuals (or "superforecasters") can be consistently more accurate than experts or the general public (e.g., Tetlock and Gardner 2015). It's also too early to tell how advances in machine learning and natural language processing may be able to improve prediction capabilities, and research is needed to understand how and where they can contribute to technology prediction. To date, however, both technological enthusiasts and policy promoters habitually underestimate the technical obstacles that must be overcome before commercialization and therefore the time from demonstration of a new technology to its practical realization. As Simon Kuznets (1972, p. 437), 1971 Nobel laureate in economics for work including pioneering studies of innovation, explained: "a major technological innovation requires a long period of sustained improvement, and many significant complementary innovations (some of them also major but derivative) before its ramified and significant effects...are realized." This truth is part of the basis for evolutionary theories of innovation (Nelson and Winter 1982, Mokyr 1996), and it has substantial implications for forecasting and policy.

In summary, regardless of method, technological forecasting of exact times of precise technical developments is in general extremely difficult, should always include a range of uncertainty, and should not be the primary focus of near-term critical technology assessment efforts.[4] However, predictions of the general direction(s) in which technology will change and analyses of what will be the gating factors in these technological advances (and therefore policy actions that can make a difference) require much less precision and, taken with appropriate caution, can be of great use in providing insight and guidance to decision makers.

[4] For additional readings on the challenges of predicting technology outcomes see Albright (2002), Alic (1999), Apreda et al. (2019), Halal (2013), Kott and Perconti (2018), Fye et al. (2013), and Jaxa-Rozen and Trutnevyte (2021).

CHAPTER 4: DEMONSTRATIONS OF HOW ANALYTICS CAN INFORM NATIONAL TECHNOLOGY STRATEGY

The Pilot Year Demonstrations

The pilot year demonstrations of the value of analytics to inform investments in S&T addressed the following questions:

- How can the United States effectively track worldwide investment, production, position, and trajectory in critical science and technology (S&T)? Specifically, can we develop **situational awareness** of relative national capabilities in S&T? Where are the next scientific discoveries and technological disruptions most likely to occur? Who, domestically, has capabilities but is left out of scientific discovery and commercialization?
- What are the most effective ways to measure the implications of innovations in **artificial intelligence** for prosperity, jobs, and equity? What is the potential for AI to drive advances in scientific research? Which firms adopt AI-related technologies and what are the effects of adoption? What does the US AI workforce look like and how can it be leveraged and expanded?
- What is the optimal implementation of CHIPS funding in **semiconductors** to achieve the legislation's stated objectives, given financial, technical, and human capital constraints? What is the potential value of investments in next-generation (beyond-CMOS) semiconductor technologies and what investments are needed to overcome bottlenecks to commercialization and scale-up of these technologies?
- In **biopharmaceuticals,** are there innovations in advanced manufacturing technologies that could improve supply chain resilience in critical medicines? What products are "critical" and "vulnerable" from patient, provider, and public health perspectives and amenable to technological intervention? How might expert and public perceptions of criticality differ? What are the most effective strategies for communication with the public?
- In **energy** and **critical materials,** what would be the impacts of future battery material supply issues on the US automotive industry, consumers, and manufacturing jobs? What potential actions could mitigate these supply issues?

A Whole Greater Than the Sum of the Parts: Integrating Disciplines, Methods, and Data

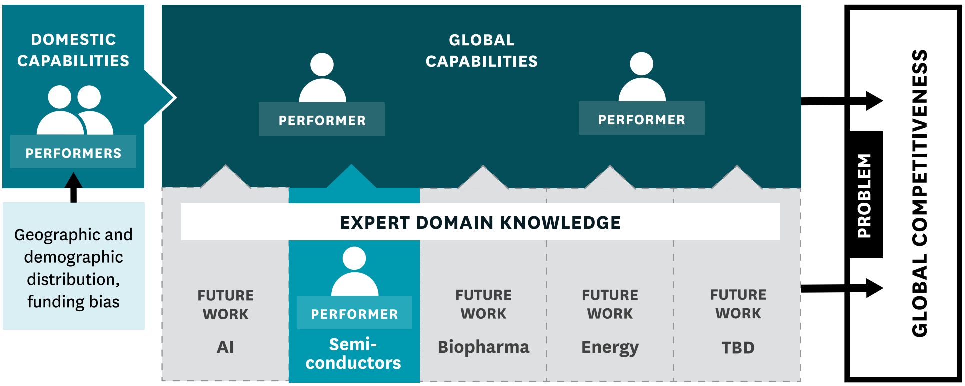
The analytic approaches to these questions were crafted to include contributions from researchers in different disciplines with different data and methodological expertise. Most of the researchers (more than 80%) had not interacted before the award. Indeed, a significant benefit of the Network approach is the side-by-side focusing of different disciplinary, analytic, and data lenses on specific policy problems as well as interdisciplinary collaboration and discovery among researchers who have not interacted in the past. **Figure 4-1** unpacks how each question brought together researchers from different disciplines and with different methods and data to provide insights where the whole was greater than the sum of the parts. Individual investigator summaries of their contribution to each area are in **appendix 4A-1.**

Demonstration of Cross-Cutting Methods and Themes

The aim during the pilot year was to demonstrate in one topic area selected themes and types of analytic methods that could eventually be applied to multiple areas. Cross-cutting themes that were demonstrated in selected cases but could be applied throughout included assessments of human capital constraints (labor) and geographic and demographic diversity (equity). Cross-cutting methods demonstrated in a single case included expert and public surveys about bottlenecks to commercialization and access. (Other methods such as scenario modeling, industrial organization, large language models, and econometrics were also used by researchers throughout.) In addition, the research questions demonstrated in one area how situational awareness could inform an area demonstration and vice versa, and in two areas how analytics could inform the relationships between area demonstrations. (See **table 1-1** in chapter 1.)

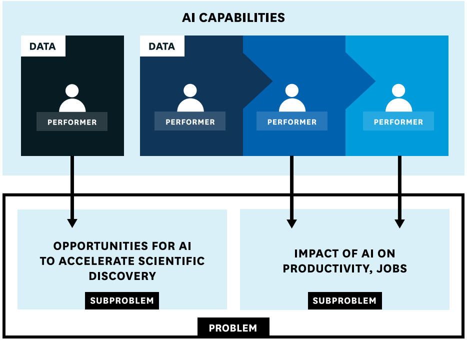
GLOBAL COMPETITIVENESS

30,000 foot search by algorithms informed by and interpreted through expert domain knowledge.



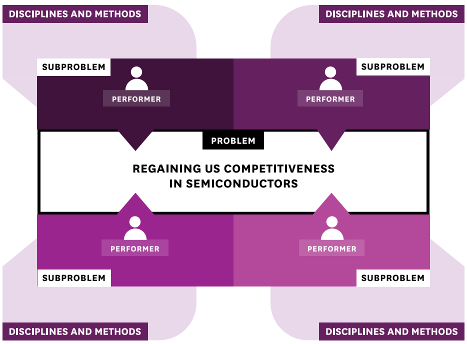
ARTIFICIAL INTELLIGENCE

Different data point in same direction (complementing weaknesses)



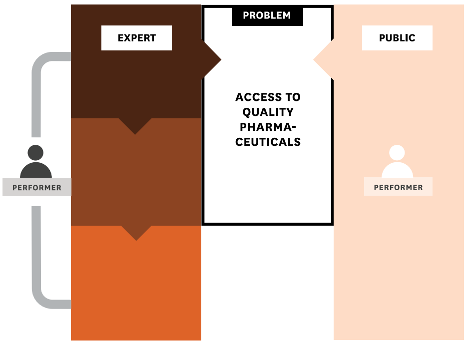
SEMICONDUCTORS

Different disciplines, methods solve different aspects of policy problem



BIOPHARMACEUTICALS

Different disciplines, methods offer different perspectives on same problem



ENERGY AND CRITICAL MATERIALS

Combination of disciplines, methods produce novel findings

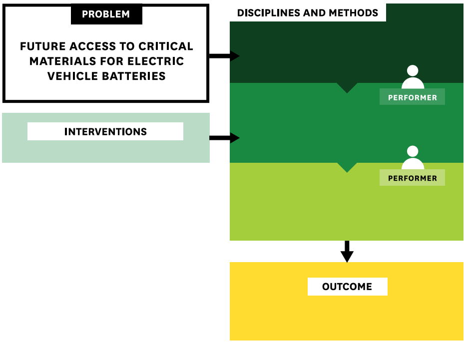


FIGURE 4-1. Dimensions of integration: Bringing together multidisciplinary lenses for a whole greater than the sum of the parts.

INTEGRATED SUMMARY:

GLOBAL COMPETITIVENESS

There is growing evidence that China is matching or overtaking US leadership of emergent and disruptive science in an increasing number of fields of science, engineering, and medicine. At the same time, the United States and China are each other's most frequent collaborators. A better understanding of these results and of the US S&T funding ecosystem is important to ensure a robust and innovative US research portfolio. Philanthropic foundations are playing a significant role in funding basic science, including riskier scientific endeavors; better data on these investments would help optimize national investment. Also needed, to enhance US competitiveness with a more robust national system of innovation, are better data on biases in government and other funding processes that might preclude investments from funding our top talent, regardless of demographic or institutional affiliations.

Type of critical technology assessment Situational awareness of US versus other nations' capabilities in science and technology (S&T) knowledge and production (and inputs such as funding and human capital)

Lead performers Yong-Yeol (YY) Ahn, James Evans, Joshua Graff Zivin, Cassidy R. Sugimoto

Program management Connect 30,000-foot insights from sophisticated data science models to contextual expert knowledge; red-teaming workshop; synthesis across researcher results

Methods LLMs, machine learning, end-of-program workshop to evaluate and red-team results with analytic, technology, and industry experts

Data Scientific publications, expert surveys

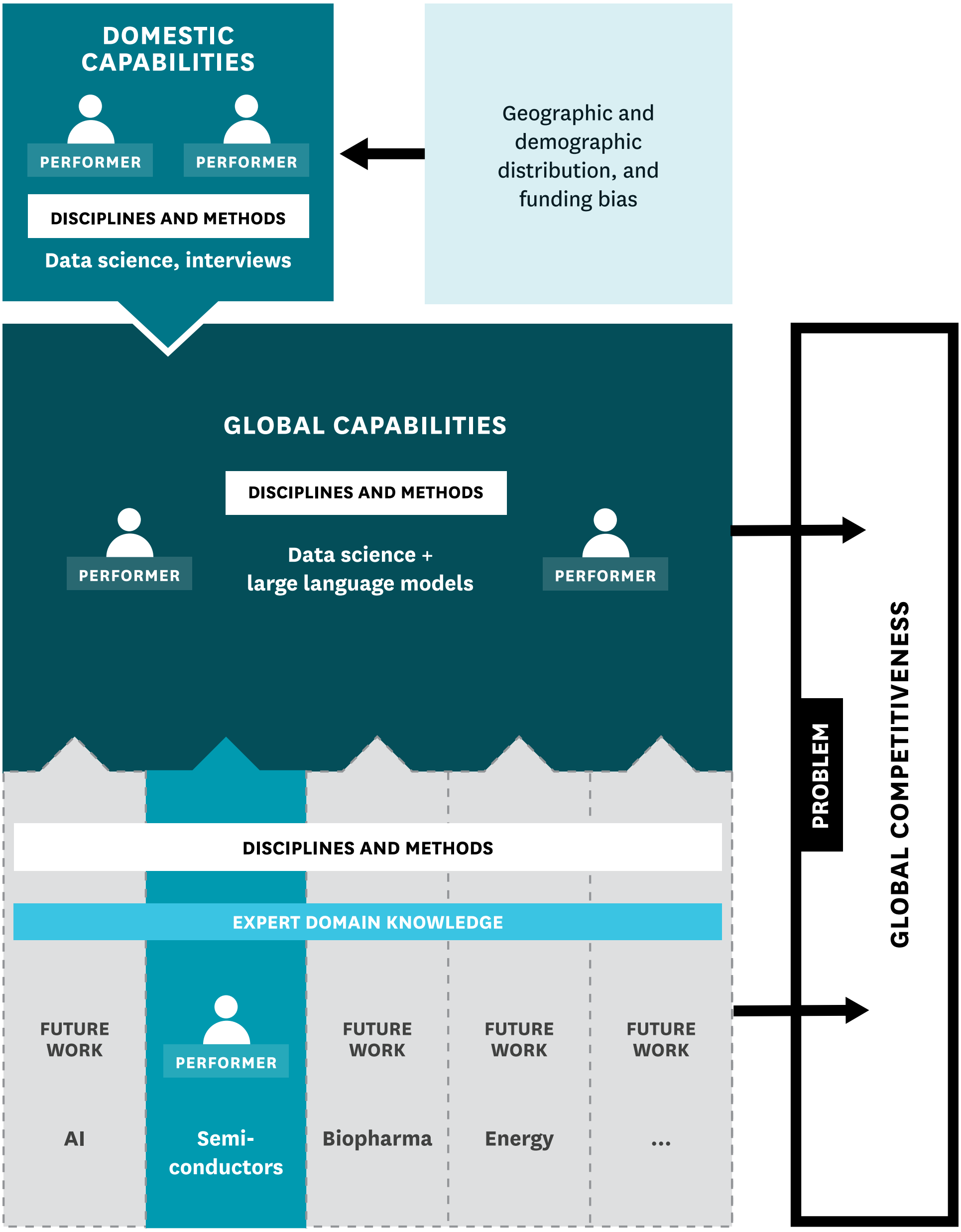
Criticality dimensions measured S&T competitiveness, social well-being

Challenges for future critical technology assessment Insufficient situational awareness of global technology and production capabilities (including product-level supply chains) and relevant human capital inputs

Additional contributors: Sadamori Kojaku, Jeffrey W. Lockhart, Lili Miao, Namrata Narain, Amit Seru, Filipi Nascimento Silva

GLOBAL COMPETITIVENESS

30,000 foot search by algorithms informed by and interpreted through expert domain knowledge.



GLOBAL COMPETITIVENESS

FINDING: China has the highest share globally of disruptive scientific papers and papers that lead to the emergence of new fields.

RECOMMENDATIONS: These findings should be explored at the level of individual scientific fields and individual papers to better understand these provocative, and potentially concerning, early results, what exactly the measures are indicators of, and area-specific implications. The United States should also begin discussions on how best to proactively and ongoingly evaluate and balance its portfolio of support for mature versus emerging science, with an emphasis on cultivating new directions.

FINDING: US and Chinese researchers collaborate on scientific publications in strategic areas (e.g., biotechnology, computing, materials engineering). Collaborative work between US and Chinese researchers represents a significant fraction of each country's publications.

RECOMMENDATIONS: Research should be expanded to understand how breaking or enhancing US-Chinese collaborations could affect scientific outcomes, access to strategically important knowledge, and global competitiveness. The United States should begin immediately to monitor networks of strategic partnerships across the globe to identify existing high-yield international collaborations and potentially fruitful or compromising collaborative ties.

FINDING: The NSF underfunds women, particularly women of color in computing, and does not fund the highest-impact work. Minority and White women tend to undertake research in different topic areas than White men, and thus could enhance the novelty and robustness of the US research portfolio.

RECOMMENDATION: To help overcome reviewer and citation bias, provide targeted funding to women and minoritized scholars in computing, with a focus on strategic areas.

FINDING: Foundations may be playing a significant role in funding basic science, including early funding of riskier scientific endeavors.

RECOMMENDATION: Explore mechanisms for information sharing between public and philanthropic funders to help optimize national investment in emerging and disruptive areas.

Research Questions

How can the United States effectively track worldwide investment, production, position, and trajectory in critical science and technology (S&T)? Specifically, can we develop situational awareness of relative national capabilities in S&T? Where are the next scientific discoveries and technological disruptions most likely to occur? Who, domestically, has capabilities but is left out of scientific discovery and commercialization?

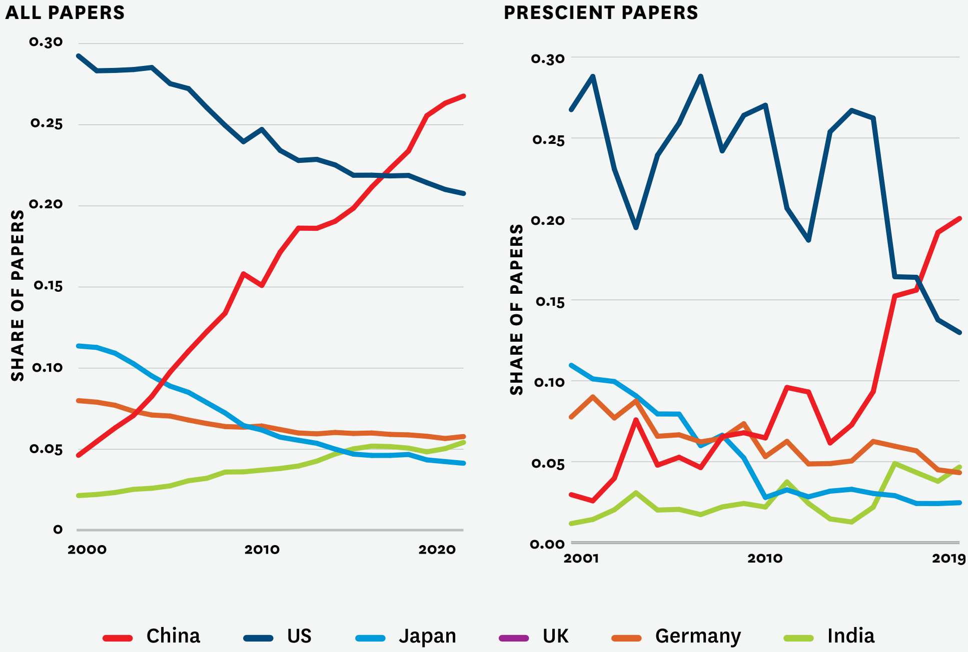
Motivation/Framing

Global situational awareness of emerging technical capabilities is critical to understand what advances are happening, where, and how, and their relevance to national security, health, and environmental challenges. Technological change also drives economic activity, creating new jobs while automating and sometimes resulting in the outsourcing of others. Understanding these changes is key to ensuring sustainable prosperity, security, and equity, buffering against shocks, and reducing the risk of being surprised by other countries' advances. Robust innovation also requires an understanding of how US research promotes or disenfranchises marginalized intersectional identities. Because researchers of different backgrounds can bring new perspectives into science and innovation, it is strategic to have a diverse pool of contributors. Diversity is associated with higher productivity (Hamilton et al. 2012, Smith-Doerr et al. 2017), innovation (Hofstra et al. 2020), and research topics that advance social change (Kozlowski et al. 2022). Therefore, our work seeks both to contextualize US S&T and to explore the degree to which the United States is training and resourcing the full capacity of the nation. The NNCTA work seeks to identify distinct dimensions of S&T leadership. We take three complementary approaches that evaluate national contributions to unfolding global scientific and technological advances both across all areas and within the selected critical strategic areas: AI, biopharmaceuticals, energy and critical materials (batteries for electric vehicles), and next-generation semiconductors. We note that leadership cannot be measured directly, so we employ surrogate measures, recognizing the danger that such proxies may become misleading policy goals in and of themselves.

Our first approach identifies the leadership of each country's scientists in emerging versus established or dissolving areas of science and technology by building a model that embeds more and less probable research pathways through an evolving network of research ideas and scientists. This model reveals that gradual "tectonic shifts" among scientific concepts can predict the emergence of new areas as their component ideas and techniques move toward catalysis (Sourati and Evans 2023). It also directly predicts which scientists and nations are poised to lead in these emerging areas.

Our second approach builds a distinctive model to capture the global prescience versus predictability or irrelevance of scientific contributions by modeling the probability of each combination of concepts through their projection in an embedding of scientific work that evolves over time. In prior work, we showed that papers that are surprising in the year they are published are more likely to become high-citation or hit papers (Shi and Evans 2023). Here we extend that to show which countries produce "prescient" papers that start out surprising when published and become the norm for subsequent research. Insofar as our first approach identifies leadership in areas predicted to emerge based on existing S&T currents, our second identifies leadership in areas that pivot S&T toward new, unexpected directions that violate existing currents.

Our third approach identifies the degree to which emergent and prescient work become recognized as disruptive, in the sense of catalyzing new directions of research. We use the citation-based "disruption index" to quantify the extent to which a new publication displaces by eclipsing prior work in the network of citations (Funk and Owen-Smith 2017, figure 3a). Based on scholars' tendency to cite a work instead of the sources it draws on, the disruption index characterizes how the novelty of a current work has become appreciated by the scientific community. Unlike the other two approaches, this identifies work attributed downstream for new directions responsible for pivots in the pattern of scientific attention.



US security and economic prosperity require (i) prompt and geographically and demographically distributed investment in emerging, critical technologies that forge national leadership and (ii) engagement of the full capacity of the US S&T workforce (e.g., Chetty et al. 2019). Our research aims to (i) elucidate the current global landscape of national funding and scientific publications via analysis of content (text) and context (metadata); (ii) use generative artificial intelligence and mechanistic models to forecast the position of nations in the global S&T ecosystem; (iii) develop interactive analysis platforms that display each nation's comparative present and future advantage across research fields; (iv) analyze the landscape of individual critical technologies, beginning with post-CMOS semiconductor technologies, to demonstrate the value of this approach; and (v) explore (a) the degree to which national investments sponsor and cultivate a diversity of US talent, using NSF investments as an initial case study, and (b) how nongovernment investments (starting with foundations) are advancing discovery and commercialization of critical technologies. These analyses presume that cutting-edge scientific research is necessary for the development and implementation of critical technologies. Our Vision for Future Analytic Work (below) describes causal analyses to explore this.

Methods and Sources of Data

During the pilot year we focused on the use of publication and citation data and metadata (e.g., authors, institutions, funders) from the Web of Science, Microsoft Academic Graph, and OpenAlex. Use of open datasets will be increasingly necessary to fulfill the OSTP's mandates on open science. In ongoing research, we are also exploring the use of Dimensions (by Digital Science), international patent databases, international publication databases with more coverage of distributed S&T production (e.g., in Chinese), and

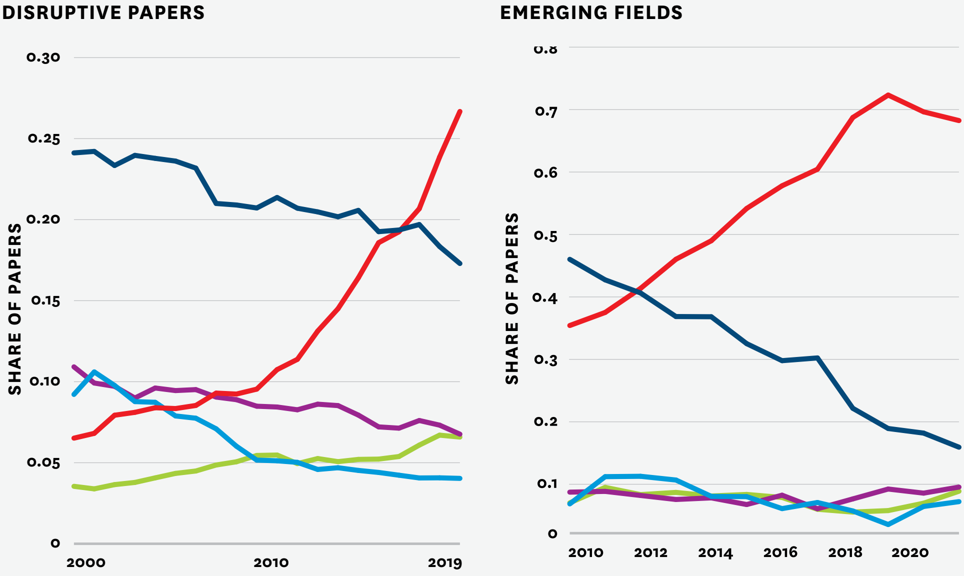


FIGURE 4-2. Chinese scientists lead the emergence of new fields related to critical areas, the production of low-probability work that becomes high probability in the future (prescient), and disruptive scientific advances perceived as the beginning of critical research directions.

downstream databases of products and companies. We relied on machine learning and AI technologies to encode and analyze large-scale unstructured data from article text, metadata, and related S&T artifacts; statistical physics tools to evaluate large-scale networks of collaboration, affiliation, and citation; and data science (scientometrics) and statistical approaches to compare and test national and international patterns of activity and inclusion. We use these data to (i) evaluate the international system of collaboration with bibliometric methods; (ii) assess the global and national distribution of funding with statistical analysis; (iii), using AI methods, describe the leadership of scientists in *emerging* S&T areas and (iv) identify *prescient* research that combines technologies and concepts ahead of their time (**table 4-1**); (v), using bibliometric methods, assess S&T *disruption*—the degree to which it becomes recognized as having catalyzed new directions of research; and (vi) examine the degree to which NSF is fully resourcing the country's talent. Selected examples of emerging areas (denoted by the terms used in our keyword search) are in **appendix 4A-2.**

Integrative Findings

A major global change in 21st century science and technology (S&T) is the rise of China's participation and the simultaneous decline in US leadership in various S&T fields. There is evidence to suggest that China has taken the lead both in producing top scientific research and in the number of scientists engaged in that research relative to the United States, Europe, and the rest of the world. China has also massively accelerated its disruptive science over the past 2 decades, with a higher than average proportion of papers ahead of their time and catalysis of emerging S&T areas, recognized by global researchers with disruptive citation patterns (**figures 4-2, 4-3**). China has been slower in its growth of developmental work across established areas, where the United States maintains (decreasing) leadership.

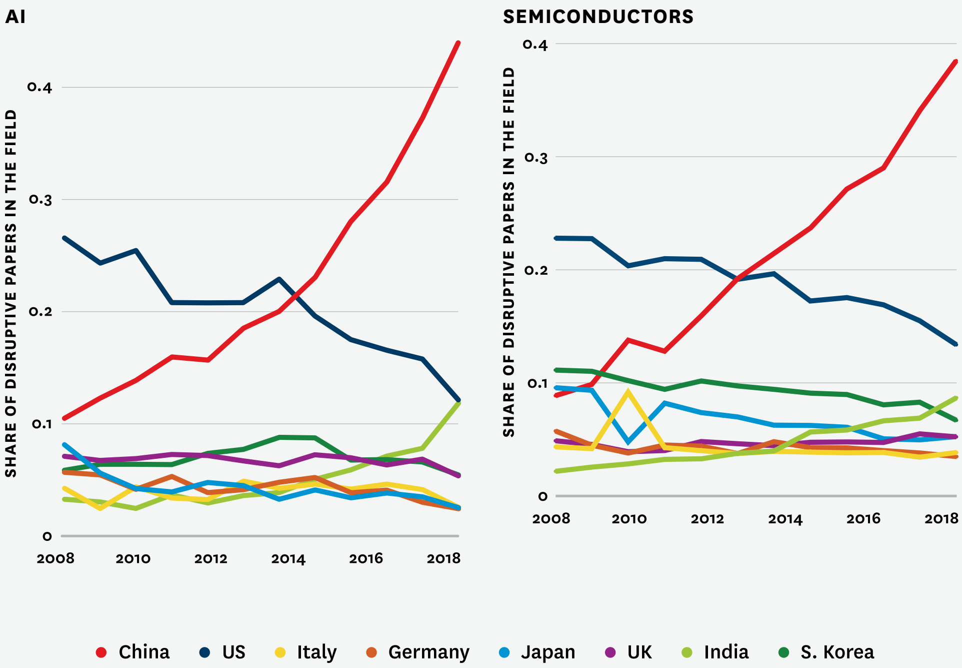


TABLE 4-1. Selected examples of high-prescience papers

Papers	Notes
Wright J, Yang AY, Ganesh A, Sastry SS, Ma Y. 2009. Robust Face Recognition via Sparse Representation. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 31(2):210–27	Extremely well cited paper on facial recognition technology
Gao X, Cui Y, Levenson RM, Chung LWK, Nie S. 2004. *In vivo* cancer targeting and imaging with semiconductor quantum dots. *Nature Biotechnology* 22:969–76	Extremely well cited paper on cancer imaging and semiconductor technology
O'Boyle NM, Banck M, James CA, Morley C, Vandermeersch T, Hutchison GR. 2011. Open Babel: An open chemical toolbox. *Journal of Cheminformatics* 3:33	Paper introducing a research tool that became widely adopted in chemistry
Basar E, Di Renzo M, De Rosny J, Debbah M, Alouini M-S, Zhang R. 2019. Wireless Communications Through Reconfigurable Intelligent Surfaces. *IEEE Access* 7:116753–73	Highly cited paper bridging two areas of research to enable next generation wireless technology

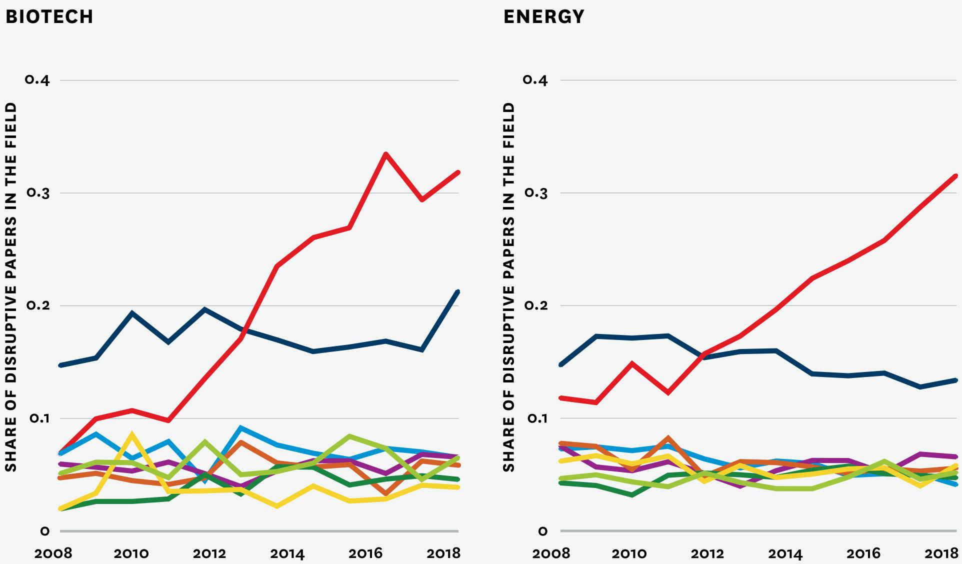


FIGURE 4-3. Since 2008 China has come to dominate disruptive scientific advances perceived as the beginning of critical research directions, with leadership differing by field and specific topics.

The United States retains global leads in interstitial areas that link other regions of critical research (e.g., social science that links AI and biotech), but is markedly less focused on emerging areas and prescient and disruptive research, which will shape technological leadership over the long term. For all figures, we note that changes in global shares are occurring in a context of absolute growth for all categories (including disruptive papers and for all major S&T contributors).

In interpreting these results, two factors are important to note. First, research by multiple Network authors documents a high rate of US-China collaboration (**box 4-1**), although those collaborations have recently stagnated. In 2018 China overtook the United States and Europe in the number of top 1% most cited papers; if all papers with both US and Chinese coauthors are removed, China first overtakes the United States in 2022. Including collaborations with US allies, such as Europe, the United States retains a greater number of the top 1% of most cited papers.

We also document a shift since 2010 in global sponsorship (funding) of the most cited and disruptive papers. The United States is the most critical research partner (in terms of coauthorship and funding) for other countries, but is less likely to fund the most disruptive and impactful domestic S&T research, especially in basic physical sciences and engineering.

We illustrate this with the case of post-CMOS technologies for semiconductors, in which the US and Chinese positions have reversed over the past decade. China now leads in most active post-CMOS technologies.

THE CASE OF POST-CMOS TECHNOLOGY DEVELOPMENT

We analyzed the 2022 *International Roadmap for Devices and Systems* (*IRDS*) report, which documents key post-CMOS technologies and a significant shift in dominance from the United States to China in emerging, prescient, and disruptive publications (**figure 4-4**).

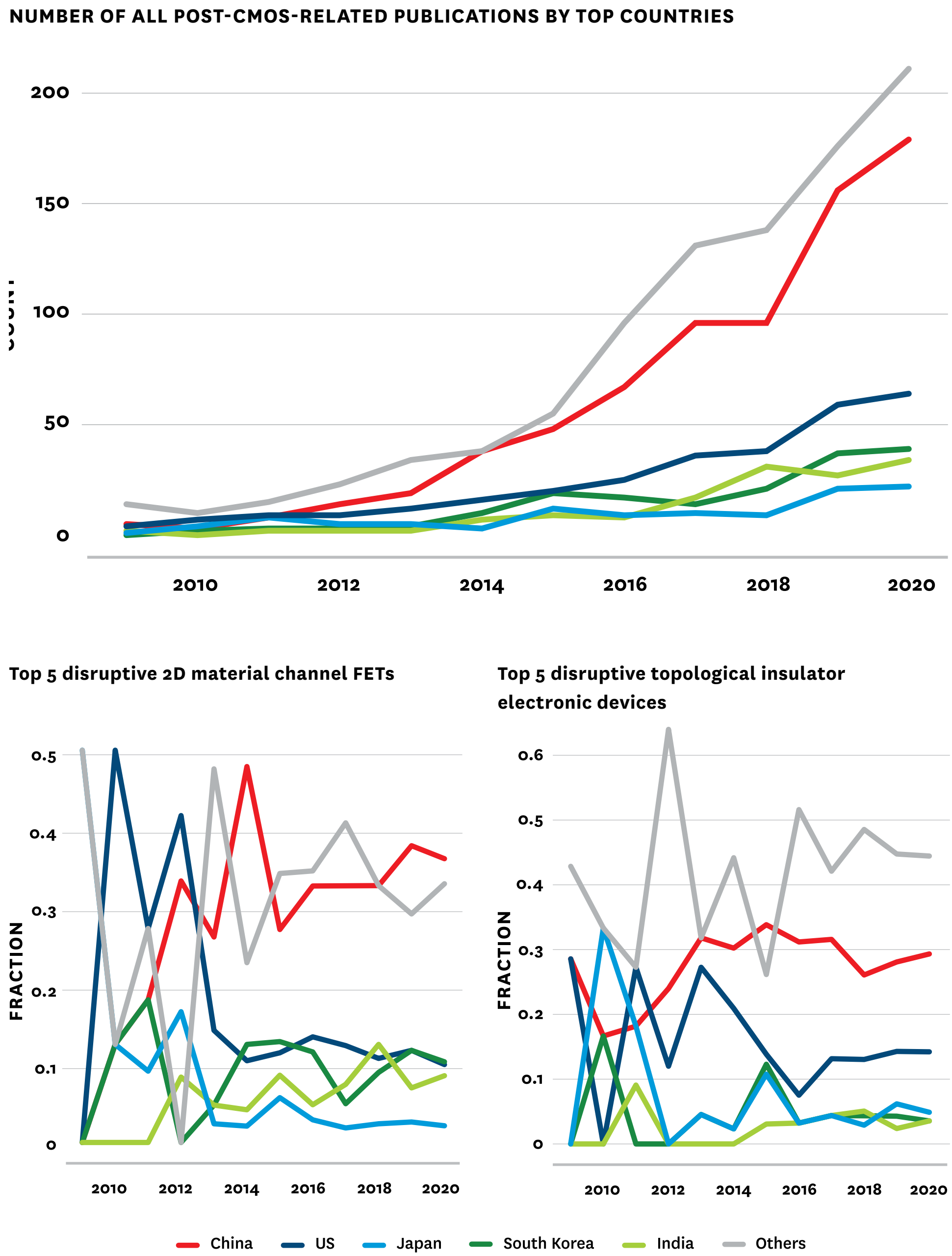


FIGURE 4-4. China has overtaken the United States in the number of beyond-CMOS semiconductor device publications (2010–20). Driving this trend, the beyond-CMOS semiconductor areas that have experienced the largest publication surge in the past 10 years are 2D material channel field effect transistors (FETs) (e.g., those based on graphene) and topological insulators. In both, the US and China have traded places, and China leads in terms of both the quantity and the disruptiveness of papers.

The two technology areas that illustrate this shift and have experienced the largest surge in the past 10 years are 2D material channel field effect transistors (FETs) (e.g., based on graphene) and topological insulators. While the United States retains a comparative advantage around publications on quantum physics applied to topological insulators, China has the greatest quantity of papers and the most disruptive papers across all subfields of 2D material channel FETs and other areas relevant to topological insulators. Nevertheless, US institutions still occupy the central position in the global collaboration network for beyond-CMOS.

FUNDING OF SCIENCE AND TECHNOLOGY

The quantity, direction, and nature (open-ended, mission-oriented) of scientific discovery and technology development as well as the associated human capital are foundational inputs to S&T outcomes. We examined (i) the degree to which national investments support and cultivate a diversity of US talent (using NSF investments as an initial case study) and (ii) how nongovernment investments (starting with foundations) may complement government funding in advancing discovery and commercialization of critical technologies.

Demographic Diversity in Funding and Outputs

The CHIPS and Science Act has been called "the most comprehensive effort in history to create opportunities in science and technology (S&T) for women, people of color, and other underrepresented groups" (Fechner 2022). In particular, the authorization to NSF, including the funding for a new Directorate for Technology, Innovation, and Partnerships, cites a specific mission to broaden participation in science and technology (S&T) (Sec. 10303).

Past research has shown that Black and Asian investigators are less likely to be awarded an R01 on the first or second attempt, Blacks and Hispanics are less likely to resubmit a revised application, and Black investigators who do resubmit have to do so more often to receive an award (Ginther et al. 2011). Past research has also shown that women in research teams are significantly less likely than men to be credited with authorship (Ross et al. 2022). Because grant funding (e.g., NSF, NIH) depends on publication track records, the lack of publication credit for women affects grant outcomes as well.

Our findings extend this research to show that, even when using publications and citations as a measure, the US scientific workforce and NSF funding of scientific work are not representative of the country's scientific talent (**figure 4-5**). The denominator in this figure is "other funded authors." To fully understand the potential loss of valuable talent, other populations should be considered, such as all authors, all those employed in S&T occupations, or all doctoral degree holders. Inclusion of baccalaureate degrees reveals even starker disparities; for example, women have been matriculating at higher rates than men for decades, but do not have parity in funding. Funding disparities have serious strategic implications for innovation, which is enhanced by both the engagement of geographically and demographically diverse researchers and collaborations of diverse teams.

Black and Latinx researchers and White women tend to bring a different topic profile to science and technology, and on teams, different perspectives combine to produce insights that are not equally obvious to everyone, potentially increasing the impact of technological innovations (Hamilton et al. 2012, Smith-Doerr et al. 2017, Hofstra et al. 2020, Kozlowski et al. 2022).

Finally, although we used citations throughout this work as a measure of scientific impact, citation counts themselves are not without bias. Our research shows that Black and Latinx authors and White women are undercited across all fields. Prestigious institutions reinforce dominant topic profiles and citation disparities, and minoritized researchers at these institutions are more likely to pursue traditionally White male topic profiles. Historically Black colleges and universities (HBCUs), Hispanic serving institutions (HSIs), and women's colleges amplify the participation (and topic composition) of minoritized scholars (**figure 4-6**). Research is clear on the bias that women and underrepresented minorities experience in the publication, citation, and funding decision-making processes.

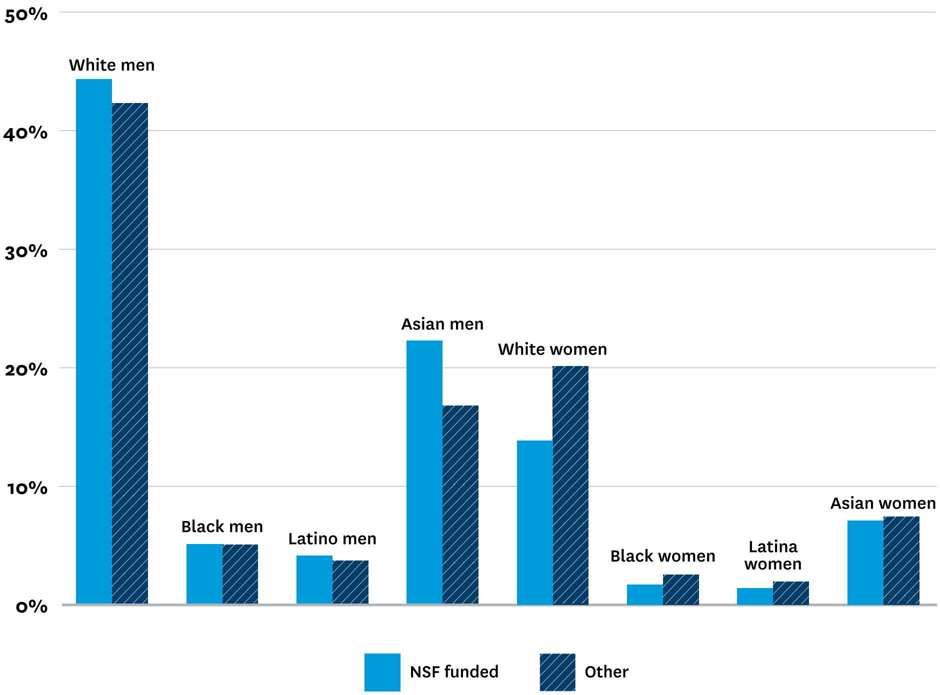


FIGURE 4-5. Distribution of authors by race and gender in NSF-funded and other articles, using an algorithmic approach described in Kozlowski et al. (2022).

Systemic and organizational change will be necessary to change these dynamics. More work is needed to understand which policies will have the greatest success in increasing the participation of women and minoritized groups in grants, and future CTA activities should carefully develop methods and data platforms, and perhaps experiments or scenarios to test the impacts of funding policies to increase such participation. A recent National Academies report also recommends that "Federal funding agencies, private philanthropies, and other grant-making organizations should provide increased opportunities for grants, awards, and other forms of support to increase understanding of how the policies, programs, and practices of…HBCUs and Tribal Colleges and Universities support students and faculty" (NASEM 2023, p. 9).

More than a decade ago a study recognized the higher probability of women and minoritized researchers having to resubmit proposals before getting funding, and suggested that assistance with the grants submission and resubmission process may be a policy lever for diversifying the scientific workforce (Ginther et al. 2011). NSF itself should explore how real-time tools on bias and best practices from decision sciences may help overcome biases in the review process.

NSF should also assess how the institutional portfolio for funding and deconcentration of funding across institutions may change the direction and rate of scientific outcomes to yield higher rates of engagement with minoritized scholars (particularly by increasing funding to minority-serving institutions). One experiment could be to leverage NSF grants to determine whether funding increases not only yield higher participation of minoritized groups but also increase productivity in, say, AI products and processes because of improved outcomes for a broader spectrum of customers. NSF's Committee on Equal Opportunities in

Science and Engineering (CEOSE 2023) has repeatedly stated that the United States needs an ADVANCE-like program for African American, Latinx, and Native American professors to yield any increase in grants, publications, and other indicators for those groups. If CEOSE's proposal is implemented, a CTA program could work with NSF to design the program to measure the impacts of these interventions.

Private Investment in Science and Technology

In terms of nongovernment investment, philanthropy and private seed funding are a unique feature of the US innovation ecosystem that could advantage the production of emergent and disruptive S&T and its commercialization. Before World War II, philanthropy was a major supporter of both higher education and scientific research in the United States; as public funding of science and technology grew after the war, philanthropic organizations reduced their support (NASEM 2020). In the past few decades, however, developments in technology and in the structuring of new and growing businesses have again been creating large individual fortunes, and private philanthropic giving to S&T research has been increasing as wealthy entrepreneurs turn from their businesses to social concerns (NASEM 2020). It is difficult to calculate a precise number, but our estimates suggest that philanthropy accounts for 15–25% of extramural R&D spending in the United States.

While the patterns characterizing US federal funding of S&T and university research are closely monitored (and the subject of spirited policy debates), understanding of the philanthropic ecosystem for S&T research is often limited to summary statistics provided by philanthropic sources and fails to account for the complete spectrum of philanthropic support for scientific institutions, making it difficult to characterize systemic patterns.

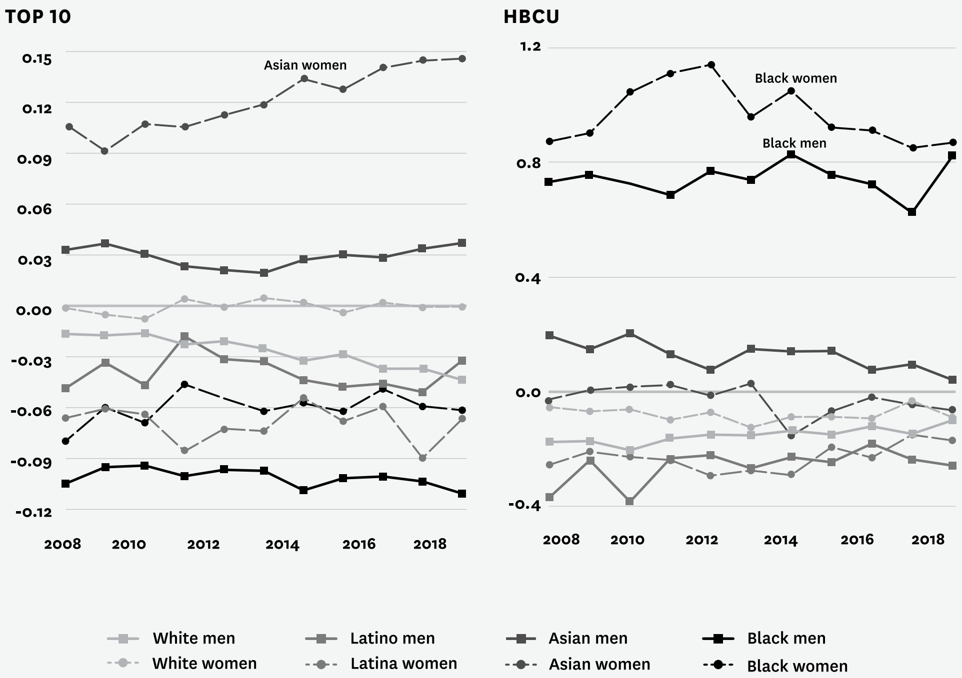
Philanthropy contributed up to 44% of basic research funding at US universities in 2016 and has been credited with the support of high-impact outcomes such as the work of Chemistry Nobel Prize recipients Frances Arnold and Jennifer Doudna. But much research tends to be limited to only the largest philanthropic gifts. In interviews by Joshua Graff Zivin and team, many foundations report funding risky research that federal agencies fund only later. Graff Zivin's work suggests that philanthropy generally invests in basic science and that its investment in critical tech is quite small and focused on AI, robotics, and data.

Options and Tradeoffs for the US Government

Our work begins to illuminate the vast array of information the United States could develop to guide its technology policy and strategic awareness toward enhancing its international leadership in science and technology. Analyses to date have relied on measures such as counts of publications; advanced modeling with high-quality data could enable much deeper understanding and foresight into not only the technical innovation landscape but also the policy options for advancing technological development. Infrastructure for such intelligence is extremely sparse, and creating a centralized database of US government-funded research to track outcomes will be a difficult task.

The United States could be a world leader in developing advanced infrastructure for monitoring and evaluation of scientific research and technological development. Such infrastructure requires long-term investment to build, maintain, and make accessible to analysts. For example, the National Center for Science and Engineering Statistics has maintained meticulous data on a narrow set of education and occupation measures in the S&T workforce since the 1920s, but these rich data are often not made available in a way that allows for integration across datasets or robust external analyses. As a result inferences and algorithms are used on variables such as race because, although these data are already collected, they are not made available in ways that allow for intersectional analyses.

Funding for related initiatives or expansions comes at the cost of long-term investment, not only to collect and maintain data on the S&T workforce, funding, or outputs but also to link them in ways that enable advanced analyses and strategic insights.



Those insights could guide US S&T policy to improve policy goals like efficiency and equity and maximize advances in strategic areas like environment, energy, health, AI, and semiconductors.

Our findings also suggest more direct policy options and tradeoffs. US S&T investment could evaluate its research portfolio to rebalance the distribution of risk, allowing more direct funding for higher-risk emerging and unexpected work with the potential to open up new areas. The United States could also target funding to younger and minoritized scientists, smaller and flatter teams, and high-risk collaborations between areas that correlate with emerging and prescient work near the innovation interface. We do not advocate US adoption of China's near exclusive targeting of specific S&T domains, as the United States still leads in global collaboration and its diverse domestic funding supports interstitial areas that will contribute to combinatorial advances in years to come. US educational and research funding needs to overcome its neglect of potentially high-performing women and minoritized scholars in computing and other areas in science, technology development, and commercialization.

Finally, our results suggest that philanthropy is playing a significant role in basic science and some role in critical technologies and early funding of riskier science. Although less is known about local foundation funding of regional ecosystems and commercialization-relevant activities, research shows that foundations' funding streams are generally locally concentrated and, as reported in their tax documents, support training programs, local incubators, and other physical infrastructure that could play a catalyzing role in commercialization and its location (Shekhtman et al. 2022). Dialogue and data on the size and scope of foundations' role throughout the S-curve (both basic science and technology commercialization) could help inform strategies for both public and private foundation funding so that, ideally, the two types of investment might complement each other.

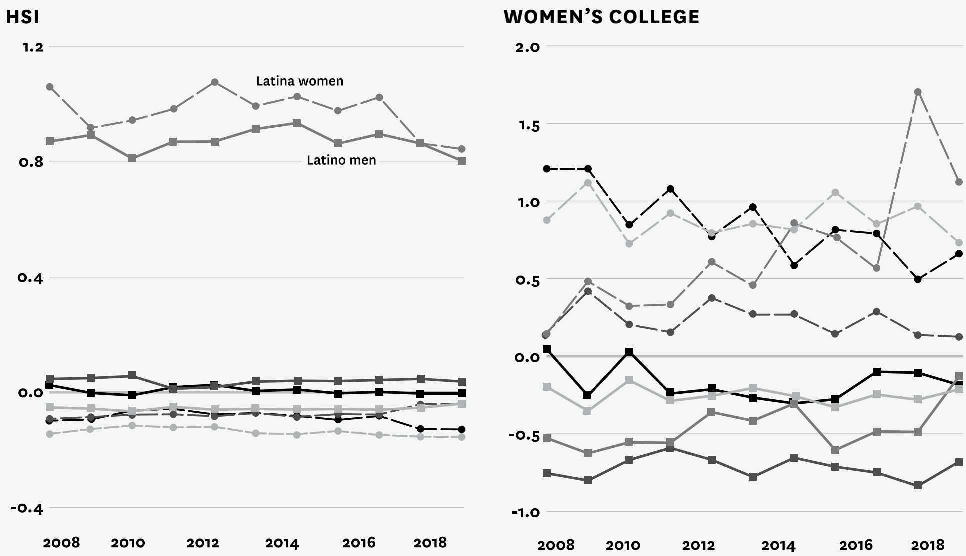


FIGURE 4-6. Authorship representation of racial and gender groups at different kinds of institutions, relative to their representation in the population, 2008–18. HBCU = historically Black college or university; HSI = Hispanic serving institution

Vision for Future Analytic Work

Future analytical and data-driven work on situational awareness could inform (i) national technology strategy by leveraging global S&T data linked across funders, researchers, and performing organizations; and (ii) the design and use of the most advanced analytical and predictive methods in order to

- validate bibliometric measures of prescience and disruptiveness with qualitative methods such as expert assessments.
- identify the current position, direction, and capacity of each national innovation system in terms of science, technology, and use in and impact on society.
- predict the future position, direction, and capacity of each national innovation system in terms of science, technology, and use in and impact on society.
- identify natural experiments in funding and focus that allow causal evaluation of R&D investments and organizations needed to yield sustained progress and leadership in areas critical to national prosperity and security.
- ongoingly evaluate the US portfolio of research investments, comparing S&T funding support across general and mission-driven agencies as well as nongovernmental sources, S&T areas, and the demographic distribution of funding recipients in order to advise on strategic investments to diversify the S&T workforce.
- identify natural and controlled experiments to unleash US talent, and harness international talent by expanding pathways to broaden participation in science, technology, and downstream development and commercialization.

This program will require a commitment to data infrastructure and continuous innovation in adapting emerging methods for inference and prediction to produce actionable S&T intelligence that guides more effective S&T policy. Open infrastructures will need to be built and supported in order to nimbly address contemporary issues, engage expertise, and make results available to all stakeholders. In the immediate future, we will better leverage the structured predictions of transformer models designed to forecast S&T futures and generatively simulate alternatives that could guide policy experiments and commitments. These and future efforts would support the development of a US S&T infrastructure that both informs and benefits from sustained leadership in the world.

It will be particularly important as this work proceeds to test and evaluate the quality of the relationship between the indicators and the underlying concepts. In the pilot year effort, the similarity in general trends revealed by the different indicators—each based on distinct underlying data—provides evidence that something real is being measured. Going forward, it will be crucial to evaluate in detail trends by S&T domain. For example, in the 1980s, it was initially not clear whether a rise in patenting indicated an increase in the rate of invention or changes in the patenting process itself. Researchers showed that the acceleration was present across essentially all fields of technology and concluded that this represented an increase in propensity to patent rather than an increase in invention. This example highlights the possibility of misinterpreting indicators and the importance of designing policy to stimulate desired outcomes, rather than indicator increase (Godin 2002, 2004).

Potential Broader Lessons for Critical Technology Assessment

Our first-year pilot demonstrated a number of striking potential early indicators "hiding in plain sight." By systematically analyzing data within and across scientific and technological areas and annotating valuable data from research artifacts (e.g., assaying metadata for countries, author identities, and funding agencies), our team generated insights contrary to conventional wisdom, pointed to new policy considerations, and illuminated critical tradeoffs. Some of these insights, such as China's growing strength in emerging critical S&T areas, flouted our expectations.

We believe that these pilot investigations have demonstrated the power that could be achieved through sustained investment in data linkage and analysis that takes advantage of emerging intelligence technologies and insights. Such analyses can clarify certainty and uncertainty to guide S&T investments and enable the United States to maintain its support of global public goods and a reservoir of diverse capacities while taking advantage of the new opportunities and combinations this capacity provides.

BOX 4-1

US and Chinese Research Depend on Collaborations

China's spectacular surge as a major economic and technological actor has raised concern in the West that the country could soon overtake Western advanced economies. An alternative view is that, absent democracy and freedom, China will not be able to fully transition from imitation-based growth to growth based on frontier innovation, and may even face the possibility of falling into a "middle income trap." Evidence suggests that China's research performance owes much to US collaborations. A main source of information on the scientific production of Chinese researchers and their coauthors is the Scopus bibliometric database, which covers 43,132 scientific journals, 78 million publications, and 16 million authors. **Figure 4B1-1** depicts the evolution since 2000 of the top 1% cited scientific publications for US and Chinese researchers. It also shows the number of top publications excluding papers with a "collaborator" from the other country, defined as a coauthor based in the other country or a coauthor based in the same country who previously published papers in the other country.

To provide more direct evidence of the dependence of Chinese research on US collaborations, information from the Scopus database is used to analyze how the China Initiative shock has affected the volume, quality, and direction of Chinese research. Launched in November 2018 by the Trump administration, the China Initiative was meant to "protect US intellectual property and technologies against Chinese Economic Espionage." In practice, it made administrative procedures more complicated and funding less accessible for collaborative projects between Chinese and US researchers, and some US-based researchers faced criminal investigations for lack of compliance with disclosure and funding regulations. The Initiative had a negative effect on the average quality of both the publications and coauthors of Chinese researchers with prior US collaborations. Moreover, this negative effect is stronger for Chinese researchers who demonstrated higher research productivity and/or worked in US-dominated fields and/or topics before the shock. Finally, Chinese researchers with prior US collaborations, in particular those in basic research, pulled away from US researchers after the shock. The fact that these Chinese researchers do not switch to new Chinese coauthors (or to coauthors from the rest of the world) suggests that a main beneficiary of the policy should be Europe.

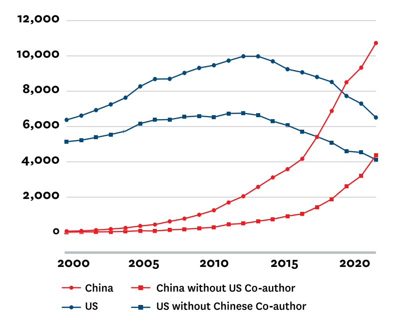


FIGURE 4B1-1. Chinese research hinges on US collaborations

This discussion draws from Aghion et al. (2023). Scopus data provided by Elsevier through ICSR Lab, subject to the license of CC-BY-NC-ND.

INTEGRATED SUMMARY:

ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI) has the potential to substantially increase productivity, output, employment, and scientific discovery across the US economy, but the invention/diffusion process is still in early stages and not all firms, regions, demographics, or scientific fields are benefiting.

Type of critical technology assessment Emerging technology, high economic and security impact

Lead performers Lee Branstetter, Erik Brynjolfsson, Thema Monroe-White, Dewey Murdick, Dashun Wang

Program management Compare different datasets held by different performers to overcome sample and data limitations

Methods Large language models, machine learning, surveys, descriptive statistics, econometrics (causal analyses)

Data Publications, patents, Bureau of Labor Statistics Survey, US Census data

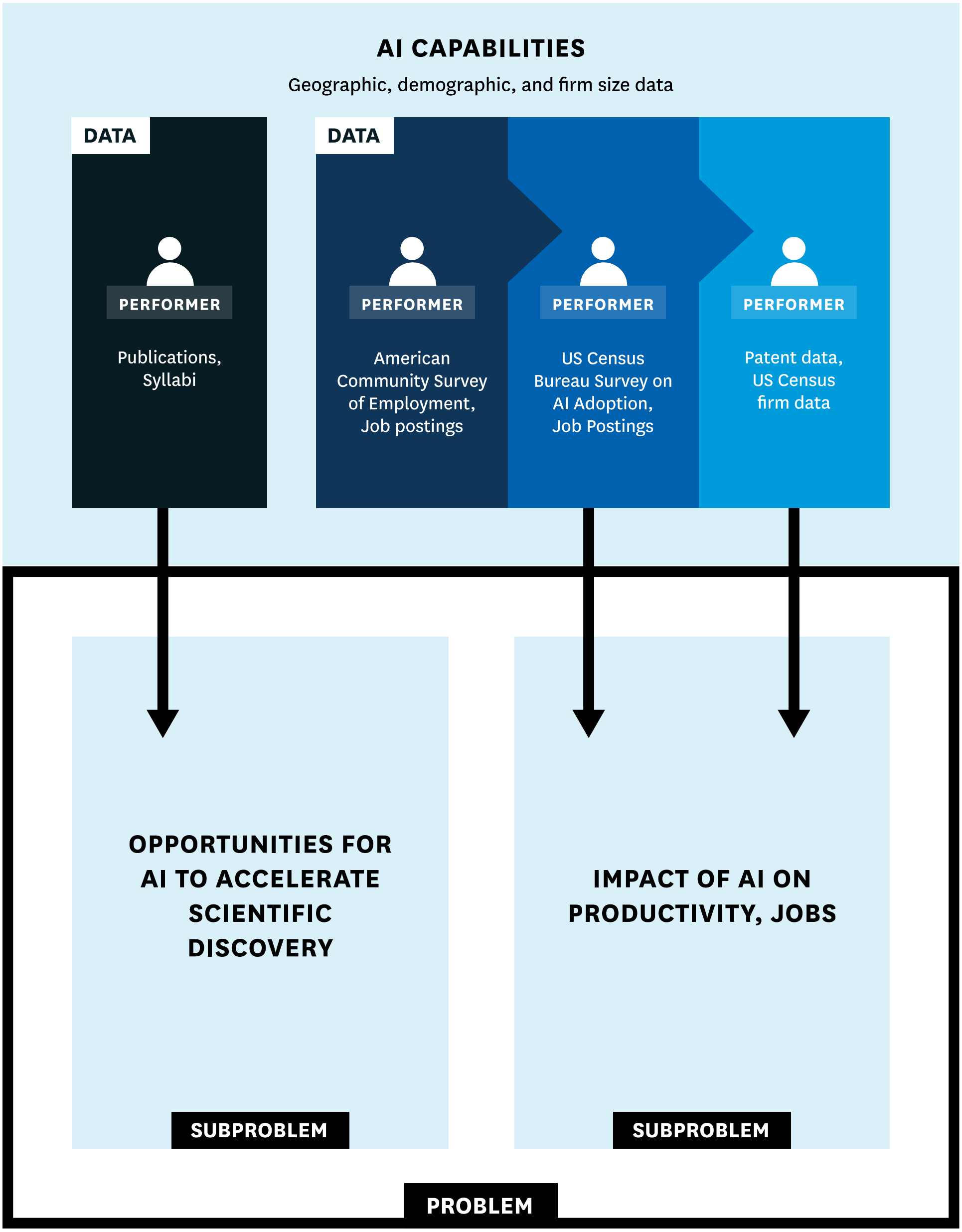
Criticality dimensions measured Economic well-being (S&T competitiveness, productivity, jobs), societal well-being (participation)

Challenges for future critical technology assessment Inadequate availability of and access to timely data—including from private sources—available to top analysts, given the rapid rate of change of the technology; sharing of data and algorithms; broader geographic and demographic participation; demographic impacts of algorithm bias

Additional contributors: Hwijeen Ahn, Catherine Aiken, Sarah Bana, Sagar Baviskar, Krisztina Eleki, Jacob Feldgoise, Jian Gao, Bishu Giri, Emma Herrerra, Eduard Hovy, Christie Ko, Luke Koslosky, J. Frank Li, Nestor Maslej, Tanvi Murke, Maria Ryskina, Shubham Shastri, Sebastian Steffen, Nikolas Zolas

ARTIFICIAL INTELLIGENCE

Different data point in *same direction*
(complementing weaknesses)



ARTIFICIAL INTELLIGENCE

FINDING: New large-sample survey data indicate that AI adoption is limited to larger, more technologically sophisticated firms and concentrated in a handful of "superstar" cities.

RECOMMENDATIONS: Improve measurement by examining indirect AI adoption through digital services. Expand the ranks of AI workers with the skills needed to work at the disciplinary frontier in AI, through both immigration and support of advanced education of domestic students, to reduce one of the major constraints to AI adoption by smaller enterprises.

FINDING: New firm-level data suggest that AI inventions lead to substantially more rapid growth in the inventing firm's productivity, output, and employment.

RECOMMENDATION: Support basic research and graduate education in AI-related fields while improving methods for measuring AI innovation at the firm level. Create a National AI Research Resource (NAIRR) to provide greater access to the computational resources and datasets for academics, nonprofit researchers, and startups from diverse backgrounds.

FINDINGS: Analysis of US employment and job posting data finds that occupations with AI-relevant knowledge, skills, and abilities represented about 9% of US employment in 2019 and are projected to grow twice as fast as all US occupations. AI occupation supply and demand are also geographically concentrated in several metropolitan areas, including some that are located outside of known "tech hubs."

RECOMMENDATIONS: Authorize funding to staff AI office and workforce support initiatives, such as by increasing staffing at the National Artificial Intelligence Initiative Office for Education and Training; develop a federal framework of technical and nontechnical AI work roles and competencies; and establish federal grant programs for AI industry-academia partnerships, AI-related degree and nondegree programs at community colleges and minority-serving institutions, and equipment at AI labs and related facilities.

FINDING: AI is impacting scientific research, but not all fields and scholars are benefiting from this shift, and the teaching of AI is lagging behind.

RECOMMENDATIONS: Expand the AI-related professoriate immediately by broadening opportunities for foreign graduates of related US PhD programs to remain in the United States; redesign university curriculum to teach more AI skills and facilitate cross-department collaborations with AI experts; and increase funding for female and underrepresented groups to pursue graduate study in AI-related fields.

FINDING: Underinvested and underrepresented segments of the US population are not being engaged in AI in ways that would maximize innovation or national interests, and they experience more stress when pursuing STEM fields.

RECOMMENDATIONS: Targeted programs are needed to increase representation in STEM of diverse identities not only to more fully leverage talent but also to mitigate harms perpetuated by biased AI systems. To uncover inequalities related to AI-powered technology, future work will need to study who is producing algorithms, in what kinds of organizations, for whom, and what data are used in the algorithms.

Research Questions

What are the most effective ways to measure the implications of innovations in artificial intelligence for prosperity, jobs, and equity? What is the potential for AI to drive advances in scientific research? Which firms adopt AI-related technologies and what are the effects of adoption? What does the US AI workforce look like and how can it be leveraged and expanded?

Motivation/Framing

After decades of incremental progress, artificial intelligence (AI) has made impressive strides over the past 15 years, prompting talk of a 4th industrial revolution. However, US aggregate productivity growth remains stuck at historically low levels, holding down growth in living standards, geopolitical power, and fiscal sustainability. Will AI live up to its promise, generating an industrial revolution that raises productivity growth?

Impacts on aggregate productivity of past technological revolutions have taken decades to emerge because of the slow processes of complementary innovation and technology adoption required for a new "general purpose technology" to work its way into the entire economy. A definitive assessment of the impacts of AI is years away, but preliminary evidence can be obtained by exploring the impacts of AI invention and adoption on the inventing and adopting firms, which are likely to be in the vanguard of any AI revolution. To this end, our research has developed new methods for identifying and measuring AI invention and adoption at the firm level—something official government datasets have historically not captured. We have also developed new methods for identifying AI-related scientific publications.

Methods and Sources of Data

We developed new methods for measuring AI invention and adoption at the firm level; for analyzing their impacts on firm output, employment, and productivity; and for identifying AI impacts on scientific research.

Our CMU team developed machine learning algorithms that parse the text of US Patent and Trademark Office patents to identify those that are AI-related. These algorithms also provide a univariate measure of the AI-intensiveness of each patent, allowing us to experiment with various thresholds of "AI-ness." Through a partnership with the US Census Bureau,[1] we link these patents to US firms that create the inventions these patents protect, using the bureau's carefully developed "crosswalk" that links patent owners to US firms. Because both patent data and Census surveys are regularly updated, they can be used to track the impact of AI invention on inventing firms in future years.

Our Stanford team worked with the Census Bureau over several years to create, implement, and refine a survey of AI use and adoption by US enterprises. This provides badly needed visibility into the degree to which, and the processes by which, American firms have adopted AI technologies created by other firms. The labor-intensive nature and expense of these surveys mean they cannot be conducted often, and data access is limited. Nevertheless, the data on adoption provide a useful window through which to observe the impacts of AI on output, employment, and productivity, and one that complements the window provided by our data on AI invention. Over time, the Census Bureau will conduct further surveys, generating a rich panel dimension to the data that will enable continuing statistical analysis of the impacts of AI adoption on firm-level outcomes.

Wang's team used natural language processing techniques and comprehensive data from Microsoft Academic Graph, the Open Syllabus Project, and the Survey of Doctorate Recipients to estimate AI effects on the nature, composition, and impact of scientific research.

1 Any opinions and conclusions expressed herein are those of the authors and do not necessarily represent the views of the US Census Bureau. All results have been reviewed to ensure that no confidential information is disclosed. The DRB codes for this project are DRB-B0027-CED-20190205, CBDRB-FY19-414, CBDRB-FY20-105, CBDRB-FY22-182, and CBDRB-FY22-CES007-004.

Georgetown University's Center for Security and Emerging Technology (CSET) created a series of maps that compares its measure of AI employment, Stanford's measure of AI job postings, and CMU's measure of AI invention (Gehlhaus and Rahkovsky 2021). The CSET team defined the AI workforce by linking the skills and competencies necessary to design, develop, and deploy AI systems to 54 occupations as defined by the Department of Labor. Both technical and nontechnical occupations are needed to develop safe and effective AI systems. The team analyzed data from the Census Bureau's American Community Survey, occupational employment projections from the Bureau of Labor Statistics, and job posting data from Burning Glass (now Lightcast) and LinkedIn Insights (**box 4-2**).

Integrative Findings

AI INVENTION RAISES OUTPUT, PRODUCTIVITY, AND EMPLOYMENT

The CMU team's algorithms identified significant numbers of AI patents since the 1990s, although the early numbers are dwarfed by the scale of AI invention in the 2010s. This long panel dimension to our data makes it possible to compare the productivity growth of AI-inventing firms to that of other firms—a dimension of comparison that economists refer to as the extensive margin. We can also observe how the same firm's output and productivity vary as it invents additional AI-related technologies, a dimension of comparison we refer to as the intensive margin. We see evidence that AI invention boosts firm output per employee by 15–27%, value added by 10–23%, and total factor productivity by 6–8%. These are economically large effects, and they are all statistically significant. While it is not possible to confirm that these effects are causal, tracking firms over time provides a degree of leverage around the possibility that both AI invention and productivity increases are driven by some omitted third variable. Despite concern that AI adoption might lead to significant declines in employment, our results suggest that AI invention leads to growth in employment, although our data do not identify gains or losses for particular types of jobs.

BOX 4-2

Combining Data Sources for a Whole Greater than the Parts

Lee Branstetter

The AI team found that the synergistic combination of multiple datasets can make up for significant flaws in any one dataset. AI-related patents matched to firms and assigned the date of application provide rich, detailed data on AI invention, but all patent data are subject to the problem that not all patents result in real inventions and not all real inventions are patented. Thus patents alone may or may not correspond to economically meaningful innovation. By matching patent data to census firm-level input and output data, one can observe statistically significant and economically meaningful changes in output, employment, and productivity that could be statistically associated with AI-related patenting (invention) in both the intensive and the extensive margin. By bringing in Annual Business Survey data on firm-reported AI adoption and matching these data to the same firms, researchers can simultaneously observe the firms' AI invention and adoption. But these survey data are costly to obtain, and it will be many years before they acquire a time series dimension sufficient for the econometric techniques that are used to make causal inferences from observational data, although patents have a deep time series dimension that offsets this shortcoming in adoption data. Finally, Lightcast/Burning Glass data on AI hiring could be linked to the same census firms, providing yet another dimension to indicate which firms are investing in AI capability. In this way the "holes" or shortcomings in any one data series are partially compensated for by the others, and the combined complementary pictures of AI adoption, use, hiring, and innovation sketched out by different datasets yield a much richer, and likely more accurate, picture of the phenomenon.

In addition to these regression-based results, data on AI-related patenting enable us to examine the distribution of AI invention across geographic boundaries, time, firms, and industries (**figure 4-7**). These results complement the Stanford team's findings that AI adoption also is correlated with growth and increased employment.

AI ADOPTION IN THE UNITED STATES IS CORRELATED WITH SUBSEQUENT GROWTH, BUT ITS INCIDENCE IS HIGHLY UNEVEN ACROSS FIRMS AND GEOGRAPHY

The Stanford team analyzed data from the Census Bureau's 2018 Annual Business Survey of over 850,000 firms to establish a number of stylized facts about early AI adoption in the United States. While less than 6% of firms use any of the AI technologies we measure, adoption is prevalent in firms with the following characteristics: over 5,000 employees; owners who are more educated and experienced with AI, younger, and motivated by aspirations such as bringing new ideas to market or helping the community; early markers of high-growth entrepreneurship, innovation, and growth-oriented strategies; and location in a handful of "superstar" cities. AI use is conditionally correlated with significant later-stage firm growth. In addition, AI job postings are correlated with increases in job postings outside AI. The concentration and growth potential of AI's leading edge portend economic and social impacts far beyond this limited early diffusion, along with a potential "AI divide" if early patterns persist.

We characterize AI adoption patterns at the core-based statistical area (CBSA) level and find significant geographic disparity. We focus on single unit firms to pinpoint the exact location of AI use, then calculate the number of those firms in the CBSA (weighted by employment) and the percentile rank of the CBSA in terms of AI usage rate (lighter colors correspond to higher rankings). We look separately at all single unit firms and young startups. Regions that are well known for pioneering technologies, such as Silicon Valley and the Research Triangle, stand out with high AI intensity. Areas in the Northeast and Midwest have lower AI intensity as a share of the number of firms, as indicated by the size of bubbles. Further discussion of our results is in our working paper, "AI Adoption in America: Who, What, and Where" (McElheran et al. 2021).

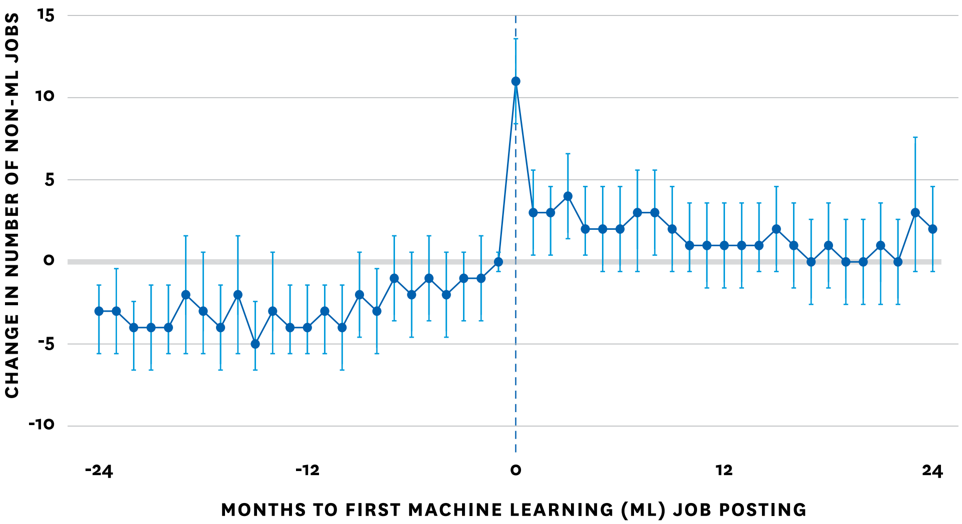


FIGURE 4-7. The Stanford team's work shows that more AI job postings correlate with more non-AI job postings at firms.

AI BENEFITS SCIENTIFIC RESEARCH, BUT BENEFITS ARE UNEVEN ACROSS FIELDS AND CATEGORIES OF RESEARCHERS

The direct and potential impacts of AI on scientific research are analyzed using semantic analysis of AI papers and patents, and scientific papers across fields. Direct impact is measured using the frequency with which words and phrases from AI papers and patents appear in papers in other fields. Potential impact is measured by extracting verb-noun pairs from the titles of AI papers and patents (i.e., what AI can do) and comparing these to verb-noun pairs in the titles of papers across fields (what the field does).

First, the use of AI appears widespread throughout the sciences, growing especially rapidly since 2015, and papers that use AI exhibit a citation impact premium. Second, despite heterogeneity in AI's impact across research areas, almost every discipline has some subfields that benefit substantially from AI innovations. Third, analysis of university course syllabi across 17 disciplines reveals a systematic misalignment between the teaching of AI in higher education and its impact on scientific research (**figure 4-8a**), suggesting that the preparation and supply of AI talent in scientific disciplines is not commensurate with AI research demand. Fourth, rapid advances pose growing knowledge demands on individual scientists, who increasingly rely on collaborators with AI expertise instead of working to push AI applications forward in their disciplines (**figure 4-8b**). Fifth, women and underrepresented minority scientists benefit substantially less from AI advances, which may exacerbate existing inequalities in science.

Options and Tradeoffs for the US Government

AI OFFERS A PROMISING POTENTIAL ROUTE TO FASTER PRODUCTIVITY GROWTH

The most important determinant of growth in future US living standards, economic size, and global power is arguably the country's rate of productivity growth, which has been stuck at low levels since the mid-2000s.

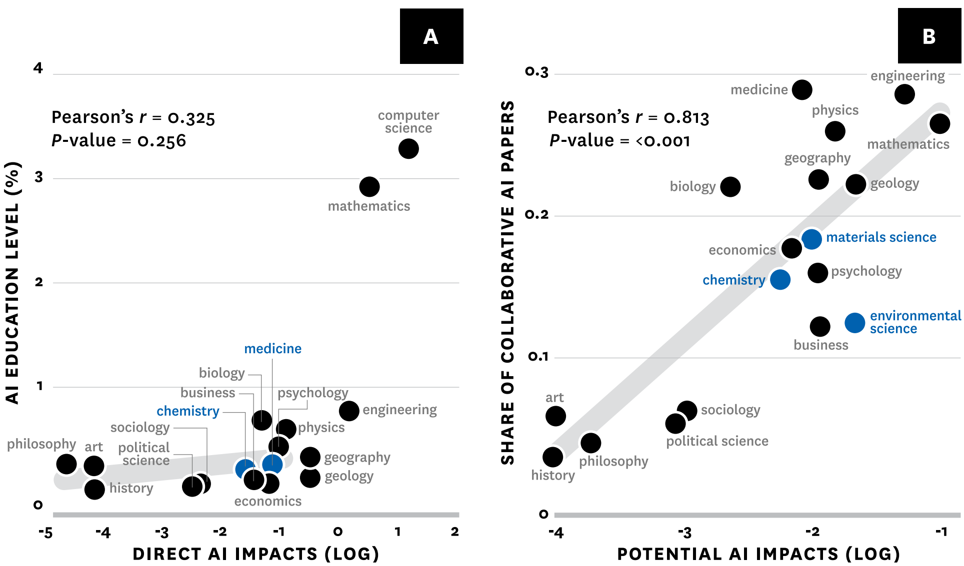


FIGURE 4-8. Estimating the benefits of AI in science. (a) Correlation between AI impact score and AI education levels. (b) Correlation between the share of collaborative AI papers and potential AI impact.

Our results provide grounds for optimism that continued innovation in AI and firm adoption of AI inventions could help spur significant and lasting acceleration in productivity growth. The federal government should seek to support this by (i) continuing to invest in AI-related basic research, (ii) expanding the domestic pipeline for AI talent by supporting graduate education in AI-related disciplines, (iii) taking meaningful steps to increase the number of foreign graduates of US AI-related programs who receive permission to work in the United States, especially in teaching positions at US universities, and (iv) investing in continued efforts to measure the invention and adoption of AI at the firm level. Realizing the potential productivity benefits of AI will also require continued societal attention to issues related to how AI changes the nature of jobs, increasing some kinds of employment while decreasing other opportunities.

AI IS HAVING PROFOUND — BUT UNEQUAL — IMPACTS ON SCIENTIFIC RESEARCH

The pervasive impact of AI across disciplines and its rapid advances pose growing AI knowledge demands on scientists. In particular, the misalignment between AI education and AI's impact on science indicates a critical need to redesign university curricula for teaching more AI skills and/or to facilitate cross-department collaborations with AI experts. Both AI education and collaboration will upskill scientists, and this has implications for preparing next-generation scientists to take full advantage of cutting-edge AI advances in their research. It is also important to recognize that, as AI becomes increasingly capable of performing research tasks, it may create unequal impacts on the research workforce. Our analysis reveals inequalities in AI's benefits for science, with implications for building a diverse, equitable, and inclusive research workforce.

THE US AI WORKFORCE AND PATENTS ARE GEOGRAPHICALLY CONCENTRATED

Figure 4-9 compares CSET's measure of AI employment, Stanford's measure of AI job postings, and CMU's measure of AI invention (patents). There is geographic concentration in AI occupations and skills demand, primarily in Los Angeles, San Francisco, Chicago, New York, and Seattle.

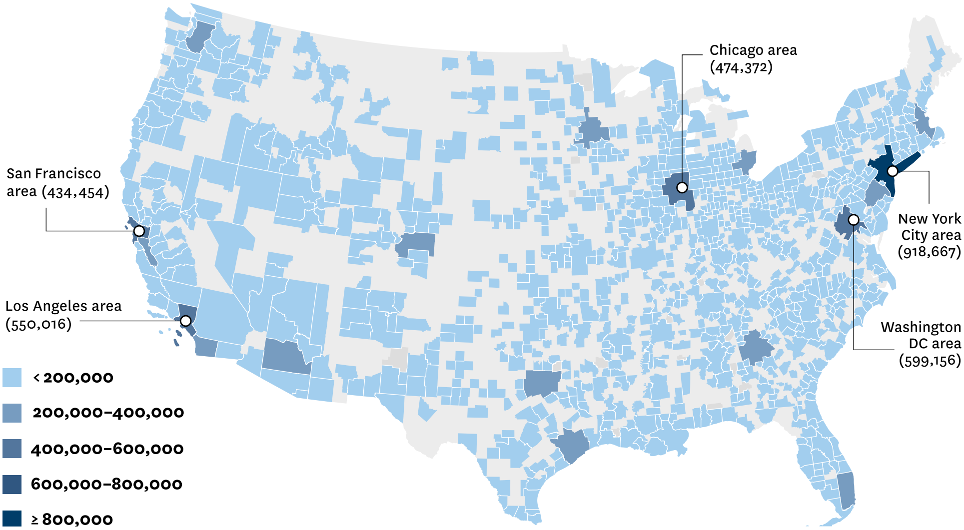
Vision for Future Analytic Work

Not all AI inventions are patented. How do we measure AI invention when patents are not generated? Firms seeking to use AI to either introduce or substantially reengineer products or services need to hire AI experts trained up to the technology frontier. The CMU team is using publication data to identify star AI scientists and the doctoral students and postdocs with whom they coauthor. We then use a mix of publication and social media data to trace the movement of these experts from the academy where they are trained and into firms. Using our link to Census data, we can test the hypothesis that firms acquiring a critical mass of PhD-level AI experts trained by star scientists experience large productivity gains. The CSET team is identifying other subsets of AI talent and mapping their education and career histories. The team is also drawing on novel data to explore trends in the Chinese AI workforce, which can provide important insight and help inform US policy actions.

A better understanding of AI's impact on science may not only help guide AI development, bridging AI advances more closely with scientific research, but also have implications for science and innovation policy. The work by Wang's team takes an initial step in assessing how AI might impact scientific research. As AI research evolves rapidly, there is a critical need for continuous monitoring and updates to estimates of AI's benefits for scientific research.

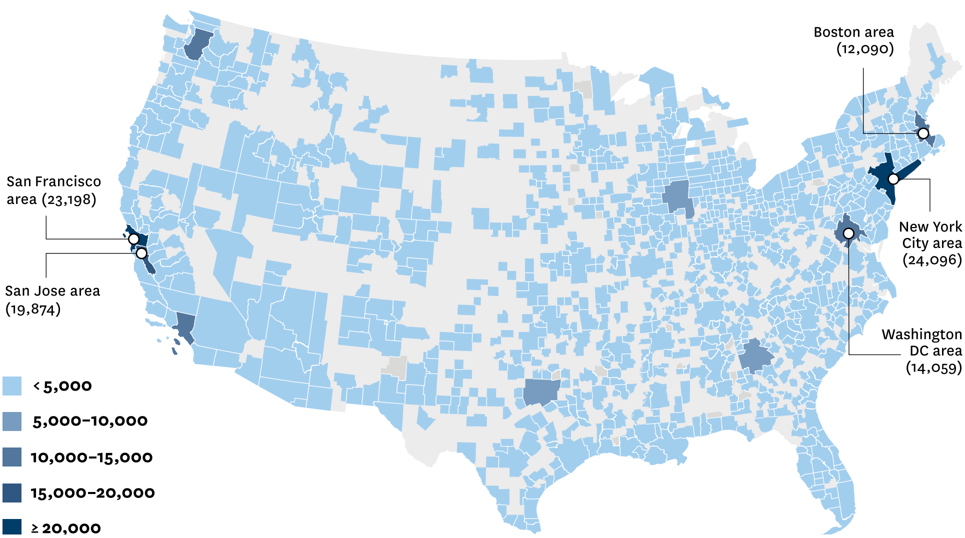
The team is using large-scale datasets covering about 6 million research grants and resulting publications to study whether funding support for AI research is commensurate with AI's scientific impacts. This analysis may inform funding allocation strategies to better support AI research that may benefit the development of many research fields.

AI EMPLOYMENT IN 2019 BY US CORE-BASED STATISTICAL AREA (CBSA)



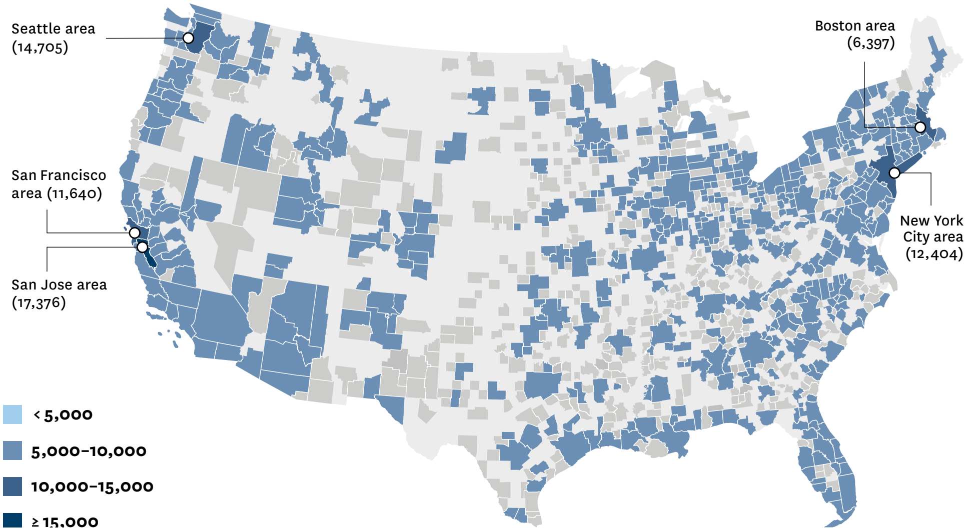
Note: 357, 188 AI employment records did not have location data.
Map: Center for Security and Engineering Technology. Source: American Community Survey

AI-RELATED JOB POSTINGS IN 2019 BY US CORE-BASED STATISTICAL AREA (CBSA)



Map: Center for Security and Engineering Technology
Source: Lightcast, Stanford University NNCTA Team

CUMULATIVE AI PATENTS THROUGH 2018 BY US CORE-BASED STATISTICAL AREA (CBSA)



Map: Center for Security and Engineering Technology
Source: USPTO, Carnegie Mellon University NNCTA Team

FIGURE 4-9. Comparison of US core-based statistical area capabilities in AI according to different NNCTA teams' measures: employment, job postings, and cumulative patents.

Going forward, important questions about AI, equity, and labor need to be addressed. AI-powered technologies may affect different communities differently; in particular, racial, educational, and immigration status disparities in paid work may be exacerbated with AI and automation. Evidence also suggests that the United States is failing to leverage substantial STEM and AI talent (e.g., Black, Indigenous, Latinx, rural communities, and women of all races). Addressing these issues will require systematic development and collection of metrics that capture how AI impacts different types of jobs and different types of workers.

Increased representation in STEM of diverse intersectional identities (e.g., race, gender, among others) is necessary to mitigate harms perpetuated by biased AI systems. To understand how inequalities relate to AI-powered technology, research on AI should consider who is developing AI, based on what knowledge, in what kinds of organizations, and for whom and what uses.

To that end, Hoffman et al. (2022) articulate five critical questions: (1) What do data mean? Problems occur when AI system designers and users fail to see that neutral-seeming data (e.g., criminal record, ZIP codes, location of hospitals) also reveal socially significant inequalities (e.g., class, gender, race, segregation, racist policing practices). (2) What are myths about AI? A myth that AI accomplishes human-level tasks without human intervention can make it more difficult to observe how social actors are shaping where, why, and by what means AI is used in practice. (3) How do interlocking structures of inequality influence AI systems? Intersectional analyses can show which human actors and values drive AI development and identify harms from AI systems across age, race, ethnicity, gender, sexuality, and class. An intersectional approach can also help everyone imagine new futures in which benefits (and harms) are distributed more equally. (4) Where is labor to support AI going unnoticed? Firms that provide seemingly futuristic AI capabilities often outsource or offshore the necessary work of contract laborers who engage in a range of small tasks that help ensure automated systems' accuracy and efficiency, labor hidden behind platform interfaces. (5) What more just AI futures can be imagined? Problems in AI development are not inevitable. Research must be used to create more equitable knowledge production contexts for this critical technology.

Potential Broader Lessons for Critical Technology Assessment

In principle, the methods applied to measure AI innovation and adoption and their effects on inventing firms could be adapted to other critical technologies. Machine learning algorithms could be used to parse patent documents and identify those associated with other critical technologies, showing the distribution of inventive activity across geography, time, and firms. Then the Census Bureau's patent-assignee-to-enterprise crosswalk could be used to connect the patents to the inventing firms. This would enable researchers to (i) estimate the impact of the critical technology on inventing firm output, productivity, and employment; and (ii) place invention in the targeted critical technology, and its effects, in the larger context of US aggregate innovation and productivity growth. Expanding and regularly conducting Census Bureau surveys to examine adoption of other critical technologies would enable the government to assess the impact of adoption on firm outcomes such as output, employment, and productivity.

INTEGRATED SUMMARY:

SEMICONDUCTORS

Regaining US competitiveness in semiconductors requires a multi-pronged approach. First, targeted investments in worker training will be necessary to overcome challenging labor and skill gaps in certain regions identified for new leading-edge domestic semiconductor facilities. Second, the US is behind competitor nations in enabling researcher access to commercial production technologies. Firms should be required to increase such access if receiving subsidies for US-based facilities. Last, given the stakes for the economy and security, advances by competitor nations, and funding being insufficient for a broad enough portfolio given uncertainties, the US should increase funding for next-generation (beyond-CMOS) semiconductor devices beyond that in the CHIPS and Science Act.

Type of critical technology assessment Evolving technology with high economic/security impacts; vulnerable supply chain for existing technology

Lead performers Yong-Yeol (YY) Ahn, Christophe Combemale, Hassan Khan, M. Granger Morgan, Neil C. Thompson

Program management Identify the most important problem and problem subcomponents, identify and leverage performers with different methods and disciplines on different components of the problem; midway workshop to elicit stakeholder input and feedback from academia, industry, and government

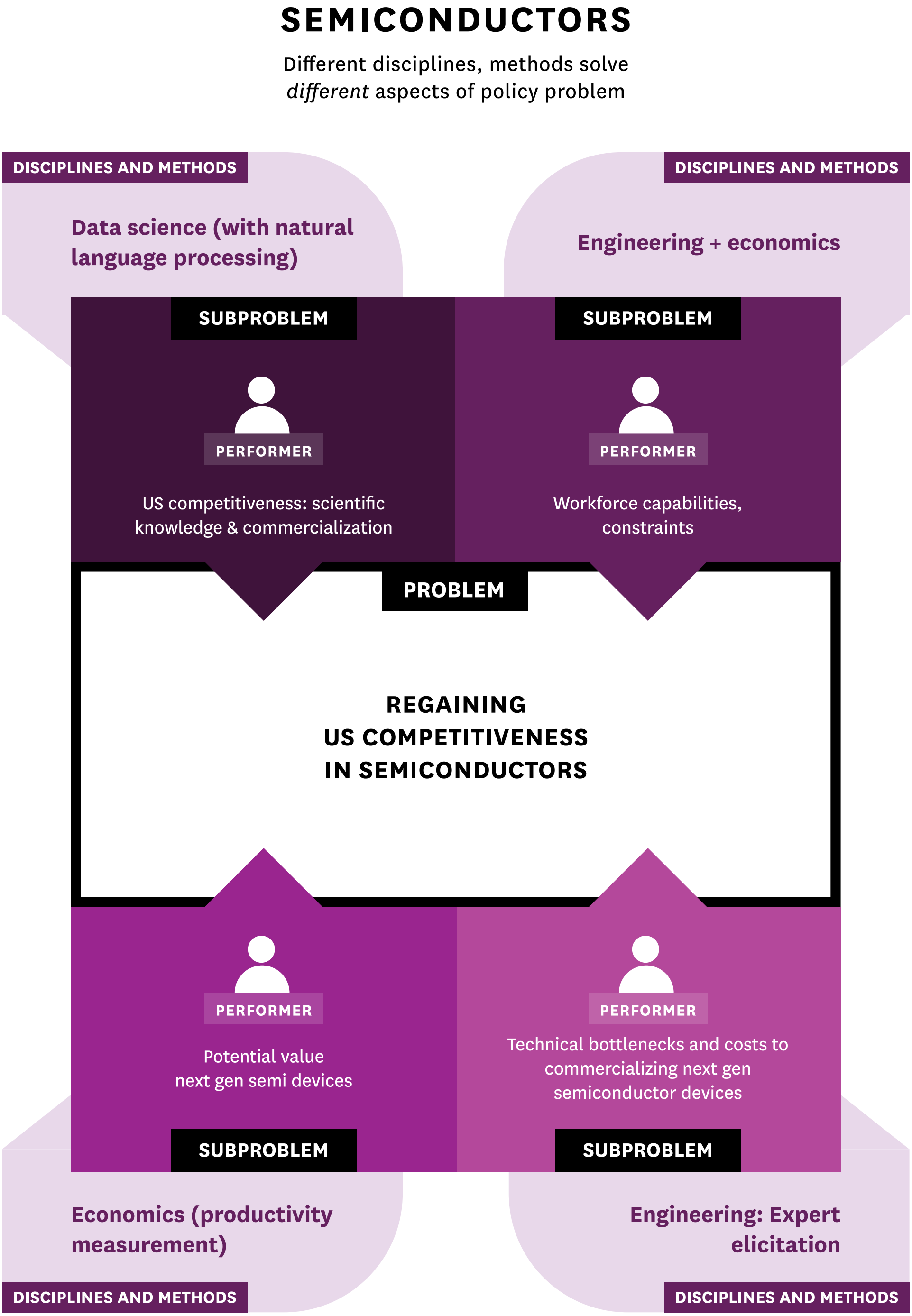
Methods Expert elicitation, local labor skill gap modeling, productivity measurement, LLMs, engineering-economic models

Data Expert survey results, publications, O*NET data, productivity data from the US Bureau of Labor Statistics, USPTO patent data, the International Technology Roadmap for Semiconductors, and data on CPU and GPU characteristics

Criticality dimensions measured Economic well-being (S&T competitiveness, productivity, jobs)

Challenges for future critical technology assessment Few analysts who can (i) conduct labor constraint analysis, or (ii) pair advanced analytics with deep (non stakeholder) technical and industrial knowledge

Additional contributors: Michael Affare, Tamay Besiroglu, Soojung (Crystal) Chun, Nicholas Emery, Elizaveta Gonchar, Ian Helfrich, Eunji (Emily) Kim, Harrison Leon, Jayson Lynch, Katy Yu


SEMICONDUCTORS
Different disciplines, methods solve *different* aspects of policy problem
DISCIPLINES AND METHODS
Data science (with natural language processing)
DISCIPLINES AND METHODS
Engineering + economics
SUBPROBLEM
PERFORMER
US competitiveness: scientific knowledge & commercialization
SUBPROBLEM
PERFORMER
Workforce capabilities, constraints
PROBLEM
REGAINING US COMPETITIVENESS IN SEMICONDUCTORS
PERFORMER
Potential value next gen semi devices
SUBPROBLEM
PERFORMER
Technical bottlenecks and costs to commercializing next gen semiconductor devices
SUBPROBLEM
Economics (productivity measurement)
DISCIPLINES AND METHODS
Engineering: Expert elicitation
DISCIPLINES AND METHODS

SEMICONDUCTORS

Mature and Leading-Edge Semiconductor Devices

FINDING: International academic researchers are increasingly able to access advanced commercial production technologies more than US researchers. This access is necessary for device commercialization.

RECOMMENDATION: The United States should require that companies provide a certain amount of researcher access to commercial facilities in order to receive the currently offered subsidies for investing in US-located leading-edge semiconductor facilities.

FINDING: The gap between workforce supply with relevant skills and those needed for semiconductor fabrication facilities is large in many regions, including in some metropolitan areas that have been earmarked for large scale capability development, causing risks to the investments.

RECOMMENDATIONS: Employers and policymakers should assess the supply of relevant skills as part of the location selection process for large-scale capacity investments. Depending on the specific mismatch between skill demand and supply in a region, targeted skill-specific training programs and incentives to attract new workers to the region should be supported through public-private partnerships.

Next-Generation (Beyond-CMOS) Semiconductor Devices

FINDING: Historically, the gains from improved semiconductors have been large, yielding between $600 billion and $1 trillion in net present value benefits to the US economy per year. As Moore's law ends, these benefits will fade. Beyond-CMOS technologies offer a way to continue improving semiconductors. Potential gains from successful development of these technologies can easily yield trillions of dollars in economic benefits to the US economy, with estimated costs of $100 million to demonstrate and $1 billion to scale up such devices.

RECOMMENDATION: A large portfolio of early- and late-stage post-CMOS technologies should be funded for development at a scale larger than currently allocated in the CHIPS and Science legislation to ensure that the United States develops post-CMOS technologies quickly and before competitors.

Research Questions

What is the optimal implementation of CHIPS funding in semiconductors to achieve the legislation's stated objectives, given financial, technical, and human capital constraints? What is the potential value of investments in next-generation (beyond Moore's law) semiconductor technologies and what investments are needed to overcome bottlenecks to commercialization and scale-up of these technologies?

Motivation/Framing

Improvements to computing are central to American innovation, generating perhaps a third of national productivity growth and underpinning national security. Historically, the United States led the development and deployment of computing, providing military and economic advantage. But technical challenges mean that computing improvement has slowed, so being years ahead of China in computing no longer amounts to as much of a competitive advantage as it once did.

TABLE 4-2. Connection between semiconductor process nodes technology and policy goals

Technology maturity	Mature nodes	Leading edge	Future of compute
Policy goals	Resilient manufacturing supply chains	Competitive US ecosystems	Catalyze and capture emerging tech
Technology	Silicon CMOS		[TBD, "post-CMOS"]
Policy approach	Domestic facility subsidies; international partnerships	Domestic facility subsidies; advanced packaging	CHIPS R&D infrastructure (NSTC, DOD Lab to Fab)
Pilot year demonstration	Assessment and options for addressing labor shortages for regional semiconductor facility build-out		Emerging technology competitiveness; investment portfolio; commercialization and scale-up

China's enormous investments also mean that it has largely closed the advanced computing gap with the United States and is now outpacing US publications on future computing devices that use post-CMOS[1] technologies. If competitive advantage arises from these technologies, it may be China rather than the United States that benefits. Faced with these realities, it is crucial that computing improvement be reaccelerated and that the United States be a leader in developing these technologies.[2]

The CHIPS and Science Act heralds a new era for American semiconductor policy. Policymakers have allocated $76 billion in support for the industry through a combination of manufacturing subsidies ($39B), R&D funding ($13B), and investment tax incentives ($24B). In its allocation of funding and in recognition of the critical role of semiconductors, Congress enumerated a range of desired outcomes, including improving US competitiveness in existing and emerging technologies, strengthening supply resilience for critical industries, and creating jobs. However, Congress was relatively light-handed regarding questions of program design and implementation.

Our pilot year demonstration focuses on how best to implement CHIPS funding in semiconductors to maximize the legislation's stated objectives for security, resilience, jobs, and the economy, given financial, technical, and labor constraints. A variety of semiconductors serve different markets. Semiconductors produced on more mature process nodes often serve safety-critical and robust automotive, aerospace, medical, and military applications; semiconductors on leading-edge nodes tend to applications requiring faster processing and higher performance, like communications and computing. Finally, with the end of Moore's law (the doubling of the number of transistors on a chip about every 2 years), new computing devices are needed to continue progress in a number of applications critical to national and economic security, including AI. As shown in **table 4-2**, in seeking to inform implementation of CHIPS and science legislation, our analyses address the different issues in different types of semiconductors.

1 CMOS = complementary metal-oxide semiconductor

2 See, for example, Armbrust et al. (2023).

Methods and Sources of Data

The pilot year demonstrations in semiconductors bring together insights from different disciplines and data sources.

SECURING ACCESS TO CURRENT MATURE AND LEADING-EDGE ADVANCED SEMICONDUCTOR PRODUCTS: HUMAN CAPITAL CONSTRAINTS FACING DOMESTIC SEMICONDUCTOR FACILITIES

We develop and deploy a novel capability to assess human capital constraints facing planned domestic semiconductor facilities. We leverage the US Current Population Survey, American Community Survey, and Occupational Employment and Wage Survey to characterize the skill, wage, and occupational distributions for all US metropolitan statistical areas as well as occupation-specific labor mobility. We then assess the gap between the existing skills in each area and the skills required for semiconductor facilities.

ENSURING ACCESS AND LEADERSHIP IN THE FUTURE OF COMPUTE: COMPETITIVENESS IN KNOWLEDGE, COMMERCIALIZATION, AND SCALE-UP

We analyze the US economic benefits of improved semiconductor performance by estimating the share of innovation and hence productivity gains attributable to semiconductors. We then connect these historical gains to improvements in chip-level characteristics, to extrapolate the economic gains from post-CMOS technologies. These estimates can be used to generate optimal portfolios for investment.

We draw on technically detailed interviews with subject matter experts to understand technical bottlenecks and emerging technology capabilities beyond CMOS. The interview questions allowed open-ended responses. An example of our interview protocol and a longer discussion of the method are available under the semiconductors tab on the NNCTA website (nncta.org).

To evaluate country-specific knowledge, commercialization, and scale-up capabilities we used data analytics on a corpus of scientific publications. Our dataset on R&D access to commercial facilities covers 3,500 papers published in the *Journal of Solid State Circuits* from 2012 through 2022. For each paper we manually coded institution type, technology used, and type of collaboration to enable more granular analysis. The data yield a quantitative view of scientific knowledge in specific subfields as well as country-specific access to commercial production facilities for scale-up.

Integrative Findings

SECURING ACCESS TO CURRENT MATURE AND LEADING-EDGE ADVANCED SEMICONDUCTOR PRODUCTS: HUMAN CAPITAL CONSTRAINTS FACING DOMESTIC SEMICONDUCTOR FACILITIES

Depending on the region, the successful realization of public and private investments in building out new domestic semiconductor facilities may face significant human capital constraints. Conversely, where proposed sites have strong labor markets for the relevant manufacturing skills, the new facilities may erode the skill supply for incumbent industries, potentially creating labor constraints and corresponding supply chain risks. As shown in **figure 4-10**, these human capital constraints might be resolved through broader-based talent recruitment and training, including targeting nontraditional industry sources from occupations with less similar skill sets (Columbus, Ohio). However, even relaxing the skill similarity may not solve the skill deficit in some regions (e.g., Sherman-Denison, Texas).

ENSURING ACCESS AND LEADERSHIP IN THE FUTURE OF COMPUTE: COMPETITIVENESS IN KNOWLEDGE, COMMERCIALIZATION, AND SCALE-UP

There is great economic value in investing in demonstrating, commercializing, and scaling up post-CMOS technologies as soon as possible because improved semiconductors will yield innovations that permanently improve productivity.

Each year of delay in developing post-CMOS technologies forgoes near-term benefits, costing the US economy hundreds of billions of dollars. Our economic analysis reveals that the costs of developing post-CMOS technologies (early results from expert interviews suggest about $100 million in dedicated funding for a novel post-CMOS technology to reach the demonstration stage [roughly equivalent to Technology Readiness Level 5-6]) are small compared to the prospective benefits, which could easily be many trillions of dollars in net present value terms.

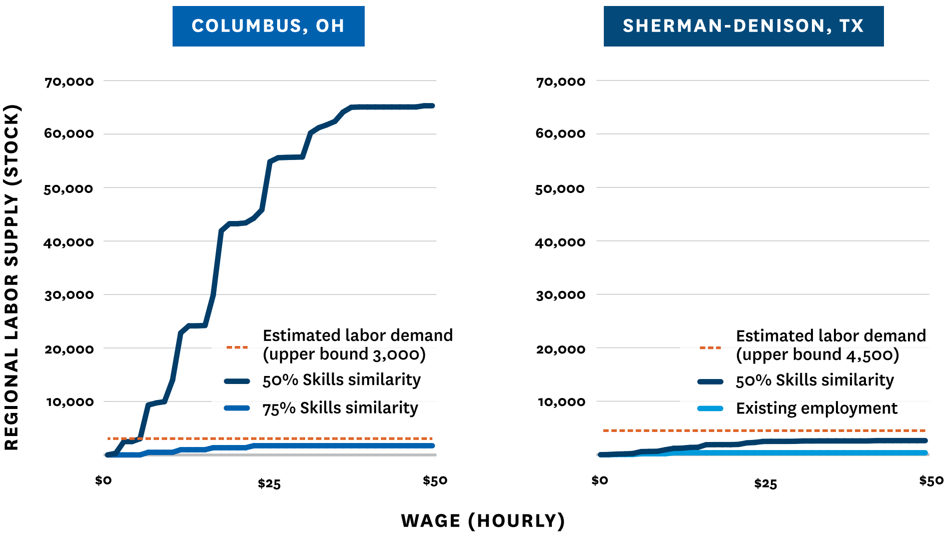


FIGURE 4-10. Availability of employees with skills similar to those needed for a proposed semiconductor manufacturing facility in Columbus, Ohio, and Sherman-Denison, Texas.

While today it is unknown which beyond-CMOS technologies will be successful, the potential economic benefit suggests that investing in a broad portfolio of early-stage technologies, even at costs of tens of millions of dollars each, holds high potential returns. Many later-stage technologies should also be funded, despite being more expensive, because the benefits of even a single success justify a portfolio of investments.

The share of US-based publications leveraging advanced production technologies declined significantly from 2017 to 2022 (**figure 4-11**). Our analysis of over 3,000 papers in the *Journal of Solid State Circuits* suggests that foreign researchers, in both industry and academia, are increasingly able to access the leading-edge commercial production technology needed to move from a demonstration to a commercially viable product.

Options and Tradeoffs for the US Government

US policymakers should assess workforce capabilities in regions targeted for semiconductor facility investment and coordinate with firms and local, state, and federal governments to assess skill and labor gaps and associated region-specific occupation-transition training opportunities. Region-specific public-private partnerships will likely be the best method to address those needs.

Two policy tradeoffs of note emerge from the findings of our pilot year demonstration. First, in the case of R&D infrastructure spending, policymakers will need to find a balance between funding prototyping facilities and investing in researcher access to the type of commercial production facilities necessary for scale-up. In the United States there is considerable focus on building prototyping capabilities with investments at university or nonprofit entities. But it is unlikely that these facilities will be able to support the full commercial production flows necessary to go from demonstration of a beyond-CMOS device to development for commercialization.

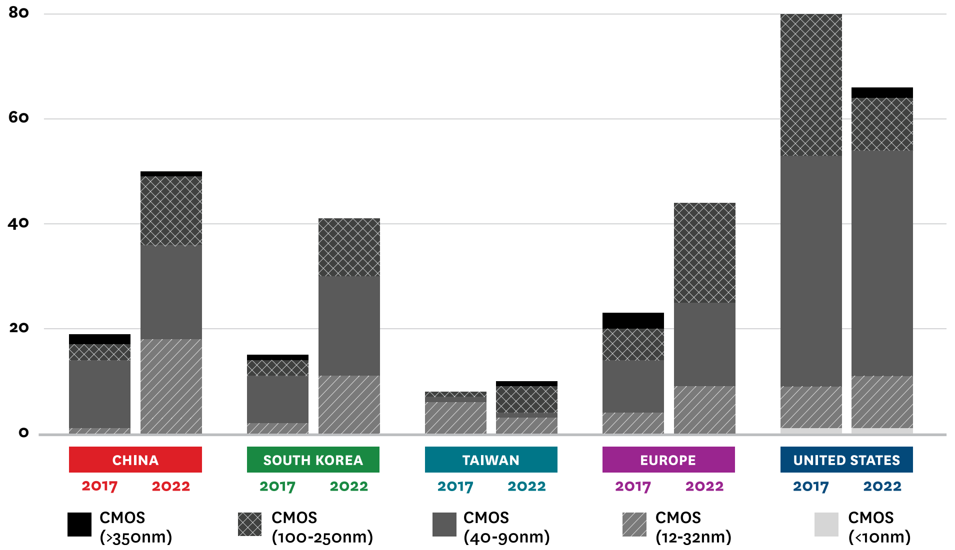


FIGURE 4-11. International economic competitors are increasingly better equipping academic researchers for commercial development.

That said, prototyping facilities have benefits: they are a lower-cost investment than later-stage technology development and so can be implemented at more locations and in different device material systems across the nation with a fixed amount of funds (instead of an investment in a more costly facility to continue development of a technology for commercialization). Limited funds thus allow a greater portfolio of devices to be demonstrated. In addition, prototyping facilities at multiple universities, each for different device materials systems—more numerous than a single later-stage emerging device scale-up facility—offer training opportunities for more students and skilled labor across more geographic regions. For commercial scale-up, the CHIPS office, in implementing the proposed National Semiconductor Technology Center (NSTC), might identify technology nodes and flows with a breadth of applications and look to secure design kits, test structure, and process design kits to enable those at a single closer-to-commercialization prototyping facility. An alternative, lower-cost option emerged from our findings: Instead of a single NSTC, the CHIPS office might focus prototyping funds on upgrading existing university facilities and incentivizing firms—as part of receiving subsidies for US-based semiconductor facilities—to dramatically improve their shuttle run and MPW offerings for US researchers. The specific program for improving shuttle run and MPW offerings could then be executed in coordination with the National Semiconductor Technology Center (NSTC). This option is particularly attractive since beyond-CMOS technologies will likely find their earliest commercialization opportunities in existing CMOS-centric designs (such as application-specific accelerators).

Second, our demonstrations highlight a tension between the spending allocated in the CHIPS and Science Act for semiconductors and the costs of pursuing emerging technologies with potentially massive societal benefits. Experts estimated the costs to bring an emerging beyond-CMOS technology to readiness stage 5 to be on the order of $1 billion. Even with the act's historic spending amounts, it would not be feasible to bring more than one or two technologies to that stage absent private funding or strong complementarities between the technologies. Because of the scale of the benefits from post-CMOS technologies, and the strategic importance of US leadership in cutting-edge computing, we recommend that funding for the development of novel computing technologies be made available.

Vision for Future Analytic Work

The NNCTA's semiconductor research and demonstrations in the pilot year focused on implementation of the stated goals and objectives of the semiconductors portion of the CHIPS and Science Act, given funds allocated and technical and human capital constraints. Continued NNCTA capability could help policymakers answer the question of "what policy responses can help America close the gap in leading-edge semiconductor production capabilities?"

Looking forward, our goal is to build a critical technology analytics capability that is strategic and forward looking. We hope to anticipate emerging challenges in semiconductor policy, enabling policymakers to be proactive. To that end we are working with the Network's situational awareness team on broader and deeper assessments of international research capabilities. This work will include evaluation of different institutional models and possible lessons for the design and operation of the NSTC.

It would also be important for the NSTC to promote a broader, more comprehensive survey of experts than is currently provided by the IEEE International Roadmap for Devices and Systems (IRDS), to generate more detailed and comparable assessments of the promise of each technology. For context, the IRDS covers 14 categories of post-CMOS technologies; of these, only 8 have quantitative estimates for their technical potentials. A full list, with better uncertainty quantification, is needed.

Enhanced understanding of the labor dimensions of critical technology challenges in semiconductors requires further estimates of the flow and elasticity of labor supply, to capture the timeline over which skills may become available. Our assessment currently relies on measures of similarity in occupational skill requirements; these measures need to be validated against empirically observed rates of transition. This approach will require further analysis of the costs of (i) training or other interventions to facilitate transitions across skill gaps between occupations and (ii) turning potential labor supply into a realized occupational transition.

Another potential area for future work is deeper supply chain analytics. However, data availability challenges must be overcome. The independent NNCTA may offer a solution to concerns about data sharing between industry competitors. But decades of outsourcing and offshoring have resulted in limited visibility into extensive and multilayered international supply chains, especially in complex products such as automobiles and defense systems. Assuming such data challenges can be overcome, analytics can help provide insight into what types of chips are most critical for reducing risky overreliance on foreign manufacturers. Today these questions are difficult for policymakers to answer at an industry level and impossible to answer at the economy level.

Potential Broader Lessons for Critical Technology Assessment

Economic analyses can provide order-of-magnitude estimates that are crucial for understanding the scale of investments and breadth of technology portfolio needed to maximize the benefits to the US economy. While manufacturing capabilities have been the focus of global comparisons in semiconductors there is evidence that international researchers are reducing the capability gap with US researchers, in part through better access to commercial production technologies, especially in China. This suggests that US investments in R&D infrastructure need to encompass both dedicated noncommercial facilities and access to industry facilities. This framing requires thinking about R&D and manufacturing capabilities in conjunction with each other and not as separate programs.

Substantial variability in US regional skill supply is a potentially binding constraint on the viable development of critical technology capabilities. Strategies that include diffusion of technology for greater economic inclusion will require place-based assessments of skill readiness and the development of corresponding approaches to address disparities. There may be tradeoffs between regions that are most ready to participate in technology capability building and those most in need of resources to enhance economic prosperity and equity.

INTEGRATED SUMMARY:
BIOPHARMACEUTICALS

In the short term, policies to adopt advanced manufacturing technologies are more likely than innovation to enhance generic pharmaceutical supply chain resilience. Public engagement strategies will need to address the public's lack of industry trust and pricing concerns.

Type of critical technology assessment Commodity product for which loss of access would have high social and security impacts

Lead performers Rena Conti, Baruch Fischhoff, Marta Wosińska

Program management Put side-by-side the results of performers with different disciplines, perspectives, and methods; workshop engaging leaders from academia, industry, and government to launch analytics

Methods Interviews, economics, descriptive statistics, expert elicitation, citizen elicitation for public awareness and early input

Data Expert interviews; IQVIA pharmaceutical market data; USP data on supplier locations and drug raw materials; FDA data on drugs that have had supply shortages; expert and citizen survey data

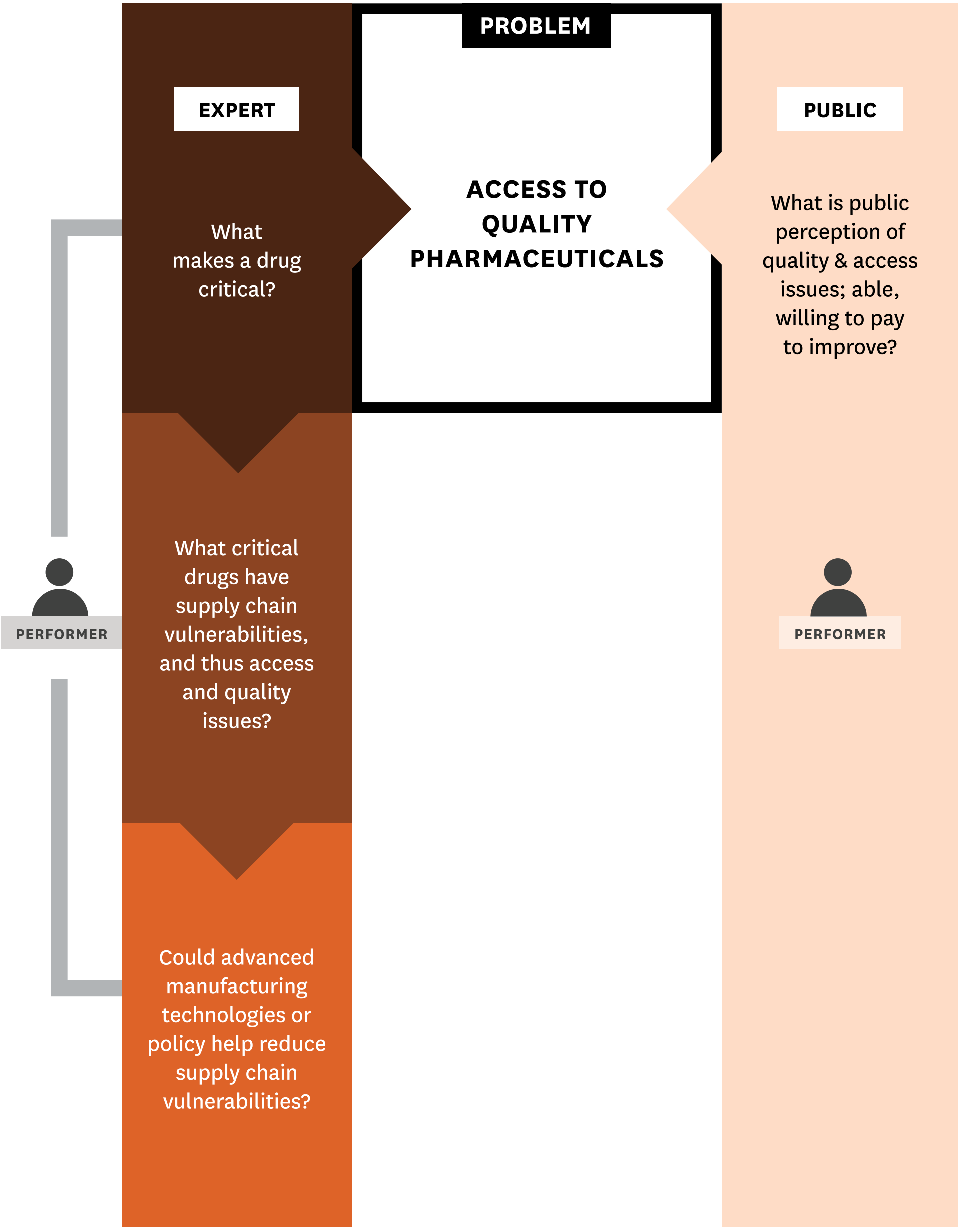
Criticality dimensions measured Social well-being (health, demographics of populations affected)

Challenges for future critical technology assessment Limited government and nonstakeholder analyst access to product-level supply chain data

Additional contributor: Emily Grayek

BIOPHARMACEUTICALS

Different disciplines, methods offer different perspectives on same problem



BIOPHARMACEUTICALS

FINDINGS: The United States is vulnerable to manufacturing supply chain resilience deficits, which result in shortages. Advanced manufacturing technologies (AMTs) such as continuous manufacturing, modular manufacturing, advanced batch processing, and digital twins offer advantages in ensuring product quality and reliability of the manufacturing process, yet the private sector does not adopt such technologies where they are needed most: generic off-patent drugs. This AMT adoption needs to be supported by financial incentives from the federal government.

We propose a framework for determining which drugs are critical, which supply chains are vulnerable, and which are best suited for AMT solutions. We identify priority use cases to test the benefits of AMT techniques to improve resilience and identify data and analytic needs necessary for future private sector efforts and federal policy.

RECOMMENDATION: To advance private sector efforts and federal policies, we suggest expanding surveillance efforts and developing an empirical evidence base to evaluate the benefits of AMT to improve resilience relative to other policies. We suggest that the development of empirical evidence should focus on what could improve individual and population health outcomes, ensure that citizens across all demographics benefit, and improve domestic manufacturing capacity.

FINDING: Public communication strategies for policies in this area are not developed or defined. Respondents to a general public survey had many, and often strong, feelings about policies' impact on generic drug prices and manufacturers' potential abuse of policies. The public is aware of, concerned about, and affected by access issues, but may not be aware of quality issues.

RECOMMENDATION: Policy implementation and communication in this area will need to address these concerns in order to achieve public acceptance. The mental models method applied by the public acceptance initiative in this demonstration area can identify similar gaps between expert and public understanding across the NNCTA's selected critical technologies.

Research Questions

Could the federal government leverage advanced manufacturing technologies (AMTs) to support greater generic drug supply chain resilience? What factors determine which drugs are critical for health outcomes? What products are "critical" and "vulnerable" from patient, provider, and public health perspectives and amenable to AMT intervention? What are the most effective strategies for communication with the public?

Motivation/Framing

Pharmaceuticals are the most used medical care in the United States, yet their supply chains are not resilient, resulting in quality deficits and shortages that pose risks for patients and the medical system. The risks of supply deficits are concentrated among generic (off-patent) drugs, which represent the majority of pharmaceutical prescriptions. AMTs such as continuous manufacturing, modular manufacturing, advanced batch processing, and digital twins have been suggested as possible investments to improve resilience, but there is inadequate evidence to assess their applications, priority use cases, economic barriers and costs, and benefits relative to alternatives.

Our work supports both Executive Order 14081: Advancing Biotechnology & Biomanufacturing Innovation for a Sustainable, Safe, & Secure American Bioeconomy and the CHIPS and Science Act by identifying (i) essential medicines whose supply resilience could be addressed through advanced manufacturing technologies, (ii) barriers to AMT adoption, and (iii) interventions to overcome the barriers.

Methods and Sources of Data

Analysis of pharmaceutical supply chain resilience involved interviews with multidisciplinary academic and industry experts in pharmaceutical manufacturing, regulation, medicine, pharmacy, distribution, regulation, procurement, and reimbursement about potential private sector market failures in the supply of pharmaceuticals, qualitative assessment of available AMTs and their amenability to support resilience, and a quantitative assessment of pharmaceutical criticality and supply chain vulnerability among priority technology use cases.

Relevant AMTs were identified based on research literature, government reports, and 60+ hours of iterative discussions with multidisciplinary academic and industry experts, culminating in a workshop of stakeholders in March 2023 hosted by MIT. Analysis of the discussions suggested (i) definitions of "critical" pharmaceuticals and "vulnerable" supply; (ii) potential matches between highly critical, highly vulnerable drugs and available AMT (we term these "priority AMT drugs"); (iii) market-driven failures in the private sector's investment in resilient supply, and economic rationales for public sector investment to improve the supply resilience of priority drugs; (iv) policies that may improve pharmaceutical resilience; and (v) data gaps that reduce situational awareness of existing and potential supply vulnerabilities and of private and public sector investments in resilient supply, including AMT. We augmented concepts ii–v with a literature review and additional analyses.

Quantitative assessment of the supply chain of priority AMT drugs identified through the expert interviews was based on IQVIA data on the sale, use, and characteristics of pharmaceuticals in the United States in 2022; US Pharmacopeia (USP) data on the location of all finished dosage form generic drug suppliers in 2022; USP data on 329 excipients (inactive base ingredients) of all finished generic drugs; and FDA data on the 231 drugs that were in short supply in 2020–22. We generated descriptive statistics on priority AMT drugs to further characterize their demand and supply and inform decision making.

The public acceptance perspective on this area adapted the mental models approach, a flexible risk communication method that has been applied to a variety of technologies and policies. It has been used to study and inform individuals' decisions about their lives (e.g., how much more will I pay for an assured drug supply?) and about public policies (e.g., how much do I support industry subsidies?). It facilitates two-way communication between experts and stakeholders and can be used to understand what the public (i) already knows about a problem and (ii) needs to know in order to make informed decisions. It recognizes that the public includes diverse groups, with differing backgrounds, preferences, and information needs.

The mental models approach has four interdependent steps. The first asks what factors are most important to address the problem at hand, based on the research literature and expert interviews. In this case, two expert models were created. One addresses the impacts of the technology and potential supporting policies, the other addresses interactions with the public that affect its trust and acceptance of the technologies and policies (see figures 1 and 2 in the supporting documentation at nncta.org). These models were refined based on the findings from seven open-ended interviews with experts from industry, academia, and government (recruited at NNCTA's March workshop on technology solutions for generic pharmaceutical shortages). The interviewees suggested that the public would be more likely to care about implemented policies than specific technologies used by innovator companies.

The second step involves semi-structured interviews with members of the general public, paralleling those with the experts, so that their mental models can be compared to the expert model. This step may be skipped in situations, like the present one, where there has been little public discussion of an issue. In that case, the structured survey offers background information. The developed survey explains several policy options, identified in the expert interviews as having particular potential. This survey was administered to a diverse but not representative sample of 100 US participants 18 or older, recruited through the Prolific platform.

In the third step, development and deployment of those interviews inform the development of structured surveys suited to large sample administration, identifying critical topics and appropriate language. The fourth step is to develop and deploy communications to address gaps in understanding between experts and the public identified in the third step. As with all research elements, that information is extensively pretested for comprehensibility and balance. For more detailed information about the public acceptance study please see the supporting documentation.

Integrative Findings

Pharmaceutical supply chain vulnerability concentrates in generic drugs, which constitute most units sold but the minority of revenues, as they are low priced relative to brand (on-patent) pharmaceuticals. Vulnerability can result from demand shocks (e.g., pandemics, CBRN [chemical, biological, radiological, or nuclear] threats, new uses) or supply shocks (e.g., manufacturing quality problems, geopolitical risks, natural disasters), any of which may disrupt supplies and adversely affect patient care. In 2020–22, 231 pharmaceuticals were in short supply, primarily due to supply shocks. The absolute number of shortages remained stable in comparison to the 2 years pre pandemic.

There is significant enthusiasm by experts interviewed for this project for the application of AMT to resolve or mitigate challenges in pharmaceutical supply quality and resilience. Main use cases of AMTs are in prescription drugs that need better and more consistent quality, more flexible supply that can scale up, and reduced lead times between identified need and production at scale. Workshop experts suggested prioritizing focus on prescription drugs that are amenable to AMT-based improvements in manufacturing and that are high volume, with sustained demand, and include generic drugs with complex manufacturing requirements, such as sterile injectables, antibacterials/antivirals, and drugs with a narrow therapeutic index (NTI) which require greater precision in formulation. These drugs comprise central therapy in inpatient settings, for children, and for other vulnerable populations, and they account for a minority of drugs sold by count and use measures; of approximately 4,600 pharmaceuticals, sterile injectables constitute 22% (992), antibacterials 7% (294), and NTIs <1% (11).

Market forces, specifically price pressures that keep margins low, do not support private sector investment in AMTs for generics because private sector actors (pharmaceutical firms, hospitals, pharmacies, among others) do not internalize the benefits of such investments in their work processes to justify the costs incurred. Experts at the March workshop suggested that AMT investments in generic drugs cost an individual firm at minimum \$3.5–\$5 million and take approximately 3 years from conception to production at scale. The small number of firms that supply priority drugs would not invest in applying AMT to their production today. This compels a role for the federal government in correcting market failures through incentives to adopt AMT. To guide such investments, it is important to quantify their benefits and costs, weighed against alternative policies to support resilience, and to assess pharmaceuticals' vulnerability and their criticality to patient health and medical care, bearing in mind that criticality goes beyond that defined by the FDA's essential medicines list.

Manufacturing of these products is concentrated in selected firms and locations, but data are limited. Market concentration data are available for AMT drugs at the finished dosage form level, but not for upstream supply chains making intermediate and base ingredients. Finished dosage form drugs were mostly supplied by two or more suppliers, although market share-based calculations suggest the dominance of one or two suppliers. Finished dosage form drugs in shortage were concentrated among sterile injectables (58%), low in price, and on average manufactured by two or fewer firms. The finished dosage form for most priority drugs (weighted by volume) is made in the United States (41%) and India (42%); the European Union (11%) and China (4%) account for smaller shares.

The FDA knows the location of active pharmaceutical ingredient (API) suppliers, but not their volume produced, sold, and linked to fill and finish drugs, and the agency has no insight into supply chains for key excipients and starting materials for APIs and excipients. We obtained data on 380 excipients linked to fill and finish drugs, but not the location of production. Experts interviewed suggest that many commonly used excipients have no substitutes or that substitution would require additional studies to support use. Experts suggested that concentration and opacity increase supply vulnerability to disruption. Conversely, improvements in supply resilience require increased transparency into the supply of and demand for pharmaceuticals.

Because private firms do not bear all of the social costs of supply chain failures, they have inadequate incentive to invest in resilience. Several pull and push mechanisms pursued by federal policies may be effective in generating private investment. But the intended and unintended consequences of these policies are unclear. For example, while private insurers are dominant payers of these pharmaceuticals, the public payers (Medicare and Medicaid) are responsible for a sizable share of priority AMT drug payment. This suggests the vulnerability of publicly insured populations to low-quality prescription drugs and vulnerable supply and the importance of federal efforts in identifying effective and cost-effective solutions to resilience challenges.

To shore up congressional support for government investment and industry support to match, better evidence is needed about AMT benefits, costs, risks, and uncertainties of public investment relative to alternative policies. For example, little is known about the effectiveness of government policies and private sector efforts in improving pharmaceutical supply chain resilience during the pandemic and other shocks, and empirical evidence of material impacts of supply vulnerabilities on patient health is limited. Improved data and additional efforts into situational awareness are needed to prospectively identify supply vulnerabilities and their amenability to policies to support improved resilience including but not limited to AMT.

PUBLIC ACCEPTANCE INSIGHTS

The survey results revealed that drug shortages are a widely experienced concern. All respondents to the physician and pharmacist surveys have dealt with them. Many noted that although shortages often have no consequences for patients, in some cases they lead to rationing or use of imperfect substitutes. Wrote one, “Many times, it doesn’t matter. Other times, it can have important adverse consequences, including increasing the risk of death.”

Survey respondents in both groups felt that manufacturers and the government were responsible for preventing the shortages they had experienced. “Ideally it would be the pharmaceutical companies themselves based on internal code of ethics. However, that seems largely unlikely in [the] pure capitalist society that we live in, so it is then left to the federal government to ensure that the health of the populace can be maintained….”

Among respondents to the general public survey, 42% had experienced, or knew someone who had, the shortage of a drug on the FDA or American Society of Health-System Pharmacists shortage list; another 10% reported shortages of other drugs. Most shortages were for ambulatory medications such as Adderall (17%) and insulin (5%). Many respondents gave detailed, and painful, descriptions of their struggles to find drugs, the health problems experienced when they failed to find them or used inferior substitutes, and stress even when they were successful. One respondent said “For me, one of my most prominent issues is lack of emotional stability. I am also Bipolar II and I was going through a manic episode at that time. Without my Adderall, I was even more unstable than usual.”

Respondents to the general public survey believed that life-saving drugs should be the top priority for investments in improved supply chain resilience. That preference is generally aligned with the FDA's definition of essential medicines, which emphasizes acute emergencies, CBRN threats, and pandemic response. But there may be important differences in definitions. One respondent, for example, ascribed life-saving status to a drug that might be classified for a chronic condition: "A shortage that would be a big problem for me personally would be…acid reflux medication. I take prescription reflux pills and without them, I cannot eat." Many respondents reported dire consequences for other drug shortages that would not be used for acute emergencies (as seen in table 1 in the supporting documentation).

The imperfect match between the reference categories for experts and nonexperts regarding "generic drug shortages" could lead to miscommunication about problems and policies. For example, the public could have unrealistic expectations about the scope of policies, expecting that drug shortages for chronic drugs are also addressed. Communication about the reasons for generic drug shortages and the health impacts of common shortages could create a shared understanding of policy objectives between experts and the public.

Respondents to the general public survey had many, and often strong, feelings about policies' impact on drug costs and manufacturers' potential abuse of policies, such as reporting false information about supply chain resilience. Common policy recommendations were caps on drug prices or government incentives and subsidies to offset an increased price. Policymakers should account for these concerns when designing policies and communicating about implemented policies to the public.

Respondents to the general public survey were not always optimistic that policymakers were interested in hearing them (e.g., "ultimately I don't think it changes the minds of policymakers as they are often in a more advantaged place, and can be out of touch"). Physicians and pharmacists expressed similar sentiments (e.g., "The voice of the healthcare professional has been severely muted, not to mention the relationship between those in the corporate world and our politicians.").

Pharmaceutical leaders feel that public acceptance is critical for the success of policies aimed at increasing supply chain resilience for generic pharmaceuticals. They also believe the public is likely unaware of the implications of supply chain issues not just for access but also for drug quality. They perceive that the public is unlikely to care about the specific technologies involved, but will care deeply about how policies affect their health and economics. As one expert put it, "I'm not sure people want to know, oh, this drug was made with artificial intelligence or this drug was made with continuous manufacturing.… I think they want confidence that when they go to the pharmacy, what they need is going to be there and then that it's going to be safe and effective."

While pharmaceutical leaders recognize the need for communication about the drug shortage problem, its potential impacts on drug quality, and potential policies, it is unclear who will lead this communication. For example, one expert felt that "physicians, pharmacists, hospitals, government, educators,…the whole shabang" should be responsible for communication. While this recognizes that communication is important, it leaves a gap in leadership for this effort. A strategic communication initiative will be needed to engage the public about policies, incorporate their concerns in decision making, communicate about decision making, and monitor public opinion.

Options and Tradeoffs for the US Government

How best to balance short-term resilience needs with other objectives such as minimizing drug costs is the key unanswered question. Our work supports the building of a comprehensive and contemporaneous data infrastructure and a research agenda to provide an empirical evidence base to answer this question.

Beyond data, no matter what policy options are chosen to address drug shortages, effective communication will be required to (i) address the public's current understanding and lack of trust in the healthcare system and pharmaceutical industry and (ii) realize benefits, including those for health, national security, manufacturing productivity, and the economy. Communication about oversight and monitoring will be important for policy acceptance, and addressing concerns about drug pricing and automation will be equally important. Communication strategies will need to be tested to make sure that adequate information is shared about the policymaking process and the public's concerns. Both experts and the public recognize that communication about the policymaking process is important, but from expert interviews it is unclear who will be responsible for this communication. A dedicated body should be tasked with communication when policies are developed and implemented, in this and other critical technology areas.

Vision for Future Analytic Work

We put forward a framework for identifying priority use cases in supporting adoption of AMT to enhance pharmaceutical supply resilience. Using available data, we identified a preliminary list of prescription drugs suited for AMT investments, characterized their supply vulnerability, identified benefits and costs of AMT investment to improve resilience, and determined how such a list could be refined with improved data infrastructure.

Moving forward, we plan to augment the existing data infrastructure to continue improving situational awareness and complete a series of empirical studies using modern causal inference methods to support future investments by the private and public sector to improve pharmaceutical quality and resilience. We plan to prioritize answering the following questions:

- Which pharmaceuticals create the largest negative impacts if their supply is disrupted?
- Who are the populations most impacted by nonresilient pharmaceutical supply chains? What are the patient health and payer impacts of current and past supply chain vulnerabilities?
- What are current and future climate-associated supply chain vulnerabilities and opportunities for investments in resilience?
- What are the benefits, costs, risks, and uncertainties entailed in supply chain resilience investments, including but not limited to those associated with AMT?
- What investments have US federal agencies made in pharmaceutical supply chain resilience and what has been their impact?
- How have other OECD countries addressed pharmaceutical supply chain resilience? Are there opportunities to improve resilience by leveraging existing capacities among trade partners?

Planned work will require additional complementary expertise to our current research team, including greater access to data related to base ingredients as well as international drug use and supply, and experts in trade and environmental economics, geospatial modeling, and ethics and equity.

COMMUNICATION AND PUBLIC ACCEPTANCE

Proactive reciprocal communication with the public could help shape policies and create the trusted channels that would secure and retain public acceptance. Absent that communication, opportunities might be missed (or worse). The next step in the process would be developing communications that elicit reactions to more fully developed policy proposals, drawing on analytical NNCTA research, focused on the specifics of those policies. That work would require additional iterations involving experts, representative samples of the public, and professionals, in consultation with policy and technology leaders cognizant of which policies are possible and interested in developing the most effective ones. In the case of the pharmaceuticals area, communication about policy development and outcomes could be tested for comprehension. In addition, communication addressing the public's top concerns (drug pricing and industry trust) could be tested for impacts on public acceptance of presented policies.

The mental models method demonstrated here integrates research knowledge (in the draft expert models), input from expert interviews, and survey research (with members of the public and front-line professionals). Although the application focuses on generic drug shortages, the issues revealed in this case study are present in some form in all emerging technologies and policies, of different prominence in each domain and perhaps with some additional concerns. The present methodology thus provides (i) a common analytical framework for addressing public acceptance of the critical technologies that define a future US national technology strategy, and (ii) economies of scope, in terms of the models, empirical research procedures, analyses, and, eventually, communications that all technologies will need. Future work should apply these methods to other critical technologies, such as energy storage, focusing their analytical research and developing their communication strategies.

Given that there are limited resources to assess public acceptance across all critical technologies, the Network would benefit from assessing in which technologies and policies public input would be most important. Predictive models could be used to analyze what topics the public is most likely to engage with and where policymakers should have communication strategies. It will also be important to study what communication avenues the public is most likely to interact with; social media, for example, presents challenges in terms of misinformation but can be useful with effective communication strategies. Data analysis across platforms and surveys could help determine where the public is most likely to seek certain types of information.

Potential Broader Lessons for Critical Technology Assessment

Opaque and complex supply chains, geopolitical risks, and climate change will continue to stress access to needed pharmaceuticals. The private sector is underinvesting in solutions to improve supply resilience for critical products because such resilience has lower value to private firms than to the health system as a whole. Prioritization is needed both for effective and cost-effective investments by the private sector and for the development of government policies that improve supply chain resilience for pharmaceuticals. But the opacity of supply chains and improper framing of the problem have limited the capacity to identify priorities. Additional data and analytics will improve situational awareness and support private efforts and government responses to support supply resilience of critical products and thus improve individual health, public health, equity, national security, domestic capacity to manufacture and innovate, workforce development, and economic growth.

The CHIPS and Science Act requires "educating researchers on engaging with end users and the public…regarding United States societal, national, and geostrategic challenges." Fulfilling that requirement requires proactive reciprocal communication among technology developers, policymakers, and the public. Technology leaders are often poorly informed about the public, limiting their ability to realize the potential of the technologies and making them vulnerable to misinformation and disinformation. Critical technology assessment must provide analytically and behaviorally informed guidance for securing public acceptance, in terms of what technologies and policies are created and how they are communicated.

INTEGRATED SUMMARY:

ENERGY AND CRITICAL MATERIALS

Battery material supply issues could have negative impacts on the same order of magnitude as the semiconductor shortage on US vehicle prices, consumers, and workers as early as 2030. Vulnerability to lithium and cobalt supply shocks can be avoided with supply chain diversification and increased adoption of cobalt-free batteries.

Type of critical technology assessment Emerging product for which loss of access would have high social and economic impacts (and possibly security impacts)

Lead performers Elsa Olivetti, Kate S. Whitefoot

Program management Team two previously unconnected performers

Methods Industrial organization modeling, scenario modeling, supply chain modeling, engineering-economic models

Data Global mine supply data from S&P; historic data on material demand, prices, mining production, and mining costs; design, process, production, and labor hour data collected from private firms and published by Argonne National Laboratory; data on the top firms in the automotive market from Ward's

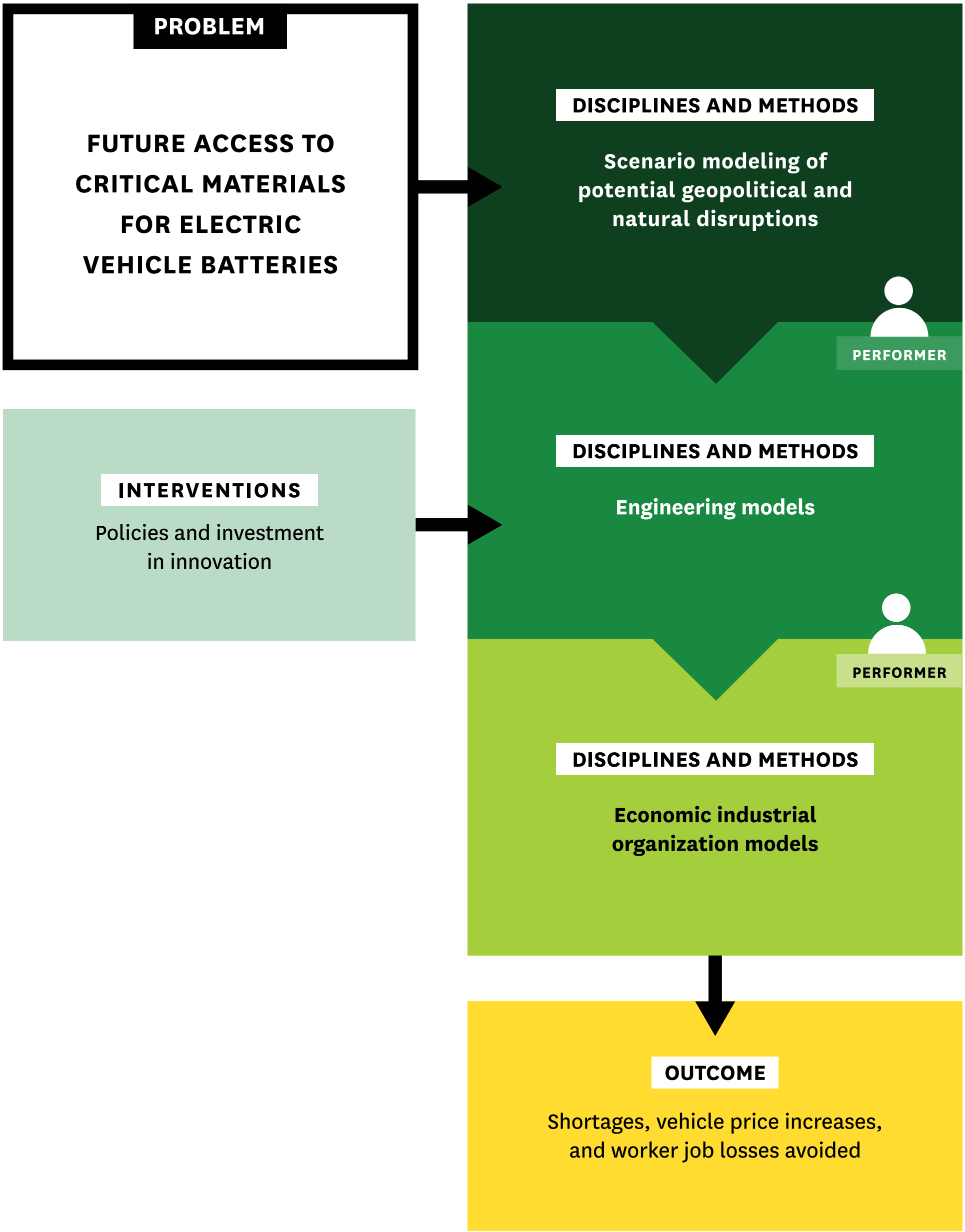
Criticality dimensions measured Economic well-being (consumer surplus losses, jobs)

Challenges for future critical technology assessment Need to bring together scholars with industrial organization and engineering analytic (technoeconomic) expertise, and make policymakers aware of the possibilities of such analysis and cobalt-free battery chemistries.

Additional contributors: Joe F. Bozeman III, Karan Bhuwalka, Sanya Carley, Connor Forsythe, Catharina Hollauer, Valerie Karplus, John D. Kim, Daniel C. Matisoff, Jeremy Michalek, Jason O'Connor, Abigail Marie Randall, Richard Roth, Venkat Viswanathan

ENERGY AND CRITICAL MATERIALS

Combination of disciplines, methods produce novel findings



ENERGY AND CRITICAL MATERIALS

FINDINGS: Battery material supply issues could substantially increase US vehicle prices, harm consumers, and reduce manufacturing labor hours as early as 2030. Simulations of 2030 scenarios show that shocks to either lithium or cobalt can lead to increases in average US new vehicle prices (both conventional and electric vehicles) by about $1,100–$2,700 (2023 USD); 500,000–900,000 US households unable to purchase a new vehicle; consumer surplus losses of approximately $24 billion; and 20,700–37,400 labor-months of lost wages for battery cell and pack production line workers.

Unlike lithium and cobalt, graphite shortages (e.g., due to trade disputes) can be more easily mitigated by substitution of synthetic graphite in anodes. We estimate that this substitution would double the price of the input material but, compared to the lithium and cobalt scenarios, have a relatively low impact on battery production and US consumers.

RECOMMENDATIONS: Vulnerabilities to lithium and cobalt supply shocks can be avoided with supply chain diversification and increased adoption of cobalt-free batteries. Simulations suggest that encouraging additional supply of lithium domestically or in locations with lower risk of trade restrictions will mitigate the negative impacts of the modeled trade dispute scenario. Increasing the use of cobalt-free batteries (such as lithium-iron-phosphate) in the large majority of battery electric vehicle sales significantly reduces the negative impacts of the modeled cobalt supply shock scenario. Immediate alternatives exist to increase supply of lithium and for cobalt-free batteries, and increases in lithium supply and cobalt-free batteries could be further accelerated through investments in innovations in novel lithium processing.

Research Questions

What would be the impact of future battery material supply issues on the US automotive industry, consumers, and manufacturing jobs? What potential actions could mitigate these supply issues?

Motivation/Framing

The necessary electrification of the automotive industry will require attention to battery material supply chains. The location and ownership of some of these supply chains are concentrated in a limited number of countries, increasing risk of exposure to trade or other political disputes, natural disasters, and labor strikes. US vulnerability to these risks can be avoided if efforts are taken to enhance the resilience of materials supply and of industry to shocks or delays in expanding supply. A better understanding of how to build this resilience requires quantifying the impacts of material supply shocks and delays on the US automotive industry, consumers, labor, and vehicle production. This analysis identifies future scenarios that would negatively impact battery material supply, quantifies the expected material price increase, and estimates the impact of the price increase on US consumers and automotive manufacturing. We also discuss measures that could reduce the impacts of these scenarios.

Methods and Sources of Data

The modeling combines (i) interviews and literature review to form scenarios grounded in current mining concerns and historical mineral supply disruptions, (ii) global material supply and demand curves constructed using estimates of projected mine capacities, and (iii) simulations of the US automotive market using an oligopolistic equilibrium model. Our materials supply and demand models build on work by the Olivetti Group (Ryter et al. 2022) and the Materials Systems Lab (Bhuwalka et al. 2022) at MIT that uses global mine supply data from S&P.[1] Using historic data on material demand, prices, mining production, and mining costs, we generate future demand and supply curves for each of the at-risk critical materials to determine their marginal price under supply reduction scenarios developed from historic context and interviews with automakers, material and mining companies, and mineral resource experts. The scenarios chosen were deemed of higher probability, compared to other potential scenarios suggested in the expert interviews, but the experts did not identify a quantified probability of likelihood for any specific scenario.

Under the baseline scenario without disruptions, the mining supply matches the projected demand. When supply disruptions occur, the supply curve is modified according to the defined scenario and a new price is estimated based on the supply-demand equilibrium after accounting for the short-run price elasticity of supply and demand. For each scenario that we model, the estimated mineral prices are translated to input battery material costs (e.g., for NMC, LFP, and NCA battery chemistries[2]) using established cost models (Hsieh et al. 2019, Wentker et al. 2019), and we use the BatPaC (version 5.0) model to determine the resulting battery electric vehicle (BEV) battery pack production costs. We calculate (from Cotterman et al. 2022) the labor hours required to produce each battery pack. The automotive market model estimates how increases in battery production costs in each of the material supply scenarios will affect vehicle prices and production quantities. Specifically, we use a partial-equilibrium model of the US vehicle market where the top 17 automakers set vehicle prices to maximize profit while facing production capacity constraints on how much they can increase production of internal combustion engine (ICE) vehicles to counteract rising BEV production costs. This approach represents the short-term (i.e., 1- to 2-year) impact of the material supply scenarios before suppliers and automakers are able to alter production plans or supply chains in response to the material price increases. Details are provided in the supporting information available on the NNCTA website (nncta.org).

Integrative Findings

BATTERY MATERIAL SUPPLY CHAIN SCENARIOS

Table 4-3 lists the scenarios identified in interviews as plausible future conditions (between 2030 and 2040) that would affect battery material supply. These scenarios focus on supply chains for chemicals in the active materials for batteries, including lithium, nickel, cobalt, and graphite. Manganese, another such constituent, was not included in our scenarios as experts did not express concern about supply challenges in manganese-derived compounds. While manganese does face geographic concentration in processing the electrolytic form needed in batteries, the element is relatively inexpensive and mining reserves are globally abundant. Phosphorus and iron are also common active battery constituents that do not face notable availability concerns, although phosphorus warrants brief comment because of its application in LFP chemistries. Global phosphate reserves are not going to be depleted, but there may be concern about the regional availability of phosphorus for fertilizer manufacture, which could lead to food security concerns, particularly in high-population countries (such as India and Brazil) that depend on a few phosphorus-rich producing countries (Cooper et al. 2011). In addition, harmful impacts associated with the release of phosphorus into the environment call for careful attention (Penuelas et al. 2020).

In terms of scope, our quantitative scenarios focused on negative disruptions to supply; we did not quantify the impacts of increased supply or quantify shifts in demand, instead we qualitatively discuss potential mitigation measures.

1 S&P Global Market Intelligence, https://www.spglobal.com/marketintelligence/en/campaigns/metals-mining#snl-metals-mining

2 NMC = nickel-manganese-cobalt; LFP = lithium-iron-phosphate; NCA = nickel-cobalt-aluminum

Scenario		Quantity	Estimated resulting median material price (2023 USD)	Estimated NMC811 battery production cost (2023 USD)
Lithium	Baseline	2.8 Mt	$20,000/t LCE	$99/kWh
	PRC lithium export *restriction* causes 15% refined supply reduction	2.58 Mt	$80,000/t LCE	$126/kWh
	US lithium mine *delay* causes 250 kt raw lithium supply *shortage*	2.7 Mt	$40,000/t LCE	$108/kWh
Nickel*	Baseline	3.2 Mt	$20,000/t	$99/kWh
	Declining ore grades cause 800 kt raw supply *reduction*	2.4 Mt	$88,457/t	$138/kWh
Cobalt	Baseline	302 kt	$49,280/t	$99/kWh
	Human rights abuses cause 14% raw cobalt supply *reduction* to US	274 kt	$199,360/t	$110/kWh
	Natural disasters in the DRC cause 65 kt global raw cobalt supply *reduction*	258 kt	$479,360/t	$126/kWh
Graphite	Baseline	-	$10/kg	$99/kWh
	PRC export *restrictions* create significant reduction in natural graphite supply	-	$20/kg	$109/kWh
*Nickel scenarios are in 2040 because the foreseen supply gap forms in the longer run.				

TABLE 4-3. Price and quantity impacts of electric vehicle battery material supply scenarios in 2030. DRC = Democratic Republic of the Congo; LCE = lithium carbonate equivalent; NMC = nickel-manganese-cobalt; PRC = People's Republic of China. To help contextualize the price impacts of these scenarios: S&P Market Intelligence monthly price data from 2010–23 show that cobalt has ranged from $22,000/t to $94,000/t, lithium has ranged from $5,000/t to $80,000/t, and nickel has ranged from $8,000/t to $32,000/t.

Each scenario is modeled individually. Due to the nonlinear nature of metal supply curves, we anticipate that multiple disruptions would increase the magnitude of impacts on the battery market, making the scenarios more dire. These impacts could be estimated in future work to understand how the nonlinearities would interact with each other under multiple scenarios.

These conditions are based on historical supply disruptions and current supply concerns, which provide bounds on the values proposed in the scenarios. We describe them below in the order of their estimated impact on the costs of a 100 kWh NMC-811 BEV cathode and anode as a reference. These scenarios represent those that are currently anticipated; unanticipated disruptions may also occur, and in those cases the scenarios are proxies for disruptions that would have a similar magnitude impact on the quantity of mineral supplies listed.

DECLINING ORE GRADES CAUSE 800 KT NICKEL SUPPLY SHORTAGE

Industry reports expect an 800 kt supply gap to form in the nickel market between the 2200 kt of nickel sulfate available and the 3000 kt demanded (Fraser et al. 2021). This gap is due to declining nickel ore grades and the energy-intensive and more expensive process required to refine battery-grade nickel from laterite mines. Since nickel sulfide (the historic source of battery-grade nickel) ore grades have been declining, nickel laterites will be the main source of battery-grade nickel sulfate in the future. However, the two processes to convert laterites to battery-grade "class 1" nickel, high-pressure acid leaching (HPAL) and conversion of nickel pig iron (NPI) to matte, are costly and have negative environmental impacts. The carbon emissions released in HPAL are double those of the current process of converting sulfides to class 1 nickel and HPAL also involves negative environmental impacts from tailings disposal (IEA 2021, pp. 70–71). Moreover, capital costs for HPAL projects are typically more than double those for conventional smelters for oxide ore. The NPI-to-matte route is very energy-intensive, which leads to high energy costs and carbon emissions over 5 times larger than those of sulfide refining. The higher economic and environmental costs of converting laterites to battery-grade nickel may lead to a shortage in the future. In Indonesia, which has been incentivizing growth in its nickel refining industry with raw nickel export bans, processing constitutes roughly 90% of the energy consumption of the full nickel production process (Wei et al. 2020). If refining technology advances do not lower the environmental impact of laterite nickel refining processes, then there may be increased risk associated with the development of battery-grade nickel supply by 2040, resulting in undersupply. In this scenario, we assume that demand for nickel in 2040 is 3000 kt, but there is undersupply with only 2200 kt of nickel sulfate supply available (as projected by Fraser et al. 2021). In response to this undersupply, prices increase in this scenario to reduce the demand such that the market is in equilibrium.

PRC EXPORT RESTRICTION ON REFINED LITHIUM CAUSES 15% REDUCTION IN GLOBAL SUPPLY

China has made a long-term and strategic shift toward leading in lithium refining, controlling more than 50% of the world's refined lithium supply (IEA 2022). The United States was a leader in lithium refining in the 1990s, but lost critical years for domestic expansion in 2018–21. It is now trying to bring more lithium refining online but will not be able to meet domestic demands in the short and medium term. In this scenario, which echoes the 2012–15 rare earth mineral trade dispute, refined lithium from China is subject to a 30% reduction in export quotas, which would result in a 15% reduction in supply for the rest of the world.

NATURAL DISASTERS IN DRC CAUSE 25% (65 KT) REDUCTION IN GLOBAL RAW COBALT SUPPLY

In 1990–94 the world's largest underground mine, the Kamoto mine, collapsed and the world's largest open pit cobalt mine flooded, both of them in the Democratic Republic of the Congo (DRC). The disasters were due to underinvestment in mining infrastructure. Other DRC mines during this period were inoperable because of worker strikes due to economic instability, so the country went from producing over 60% of the world's cobalt to less than 10% (Gulley 2022). As a result cobalt prices jumped from $17/kg to over $40/kg (Gulley 2022). The DRC now supplies more than 70% (120 kt) of the global 170 kt cobalt supply (USGS 2022). If similar disasters occur and the top three cobalt-producing mines in the DRC become inoperable, then 65 kt of cobalt would not be available globally, according to S&P mine data, causing a more than 20% reduction from the estimated 300 kt of supply in 2030.

HUMAN RIGHTS ABUSES IN ARTISANAL MINES CAUSE 14% RAW COBALT SUPPLY REDUCTION

The DRC produces 71% of global cobalt supply, 20% of which is produced in informal and unregulated (artisanal) mines (Banza Lubaba Nkulu et al. 2018), which present human rights abuse risks, particularly for women and children. The United States prevents imports of solar panels from China's Xinjiang region because of suspected human rights abuses in their manufacture (Groom 2022). A similar restriction on imports of artisanal mined cobalt would result in a 14% supply reduction for the United States.

US LITHIUM MINE DELAY CAUSES 9% (250 KT) RAW LITHIUM SUPPLY SHORTAGE

The United States is starting the process to open domestic mines, but the permitting process can be lengthy. It is expected that 250 kt of global lithium supply will be sourced from US mines in 2030, in comparison to 2.7 Mt globally in 2030, according to S&P data. If this supply does not come online by then, there will be a 250 kt global shortage of raw lithium supply, although this shortage may be mitigated by supplies from other countries, like Australia or Chile.

PRC EXPORT RESTRICTIONS SIGNIFICANTLY REDUCE NATURAL GRAPHITE SUPPLY

Graphite used in battery anodes may be natural or synthetic. Internationally produced anodes contain more natural graphite, whereas US-produced anodes contain roughly 70% synthetic graphite, whose price has historically been double the price of natural graphite (Wessel and Greenberg 2016). China controls 80% of global natural graphite mining (IEA 2022). The United States produces synthetic graphite but relies on imported natural graphite from China. In this scenario, China's natural graphite is subject to a 30% reduction in export quotas. This scenario mimics the rare earth mineral trade dispute of 2012–15, when China leveraged its market power over rare earth mineral supply to drive up global prices. If China repeated this behavior with natural graphite, the United States could substitute synthetic graphite—and anode material costs would double.

IMPACTS ON THE AUTOMOTIVE MARKET, CONSUMERS, AND MANUFACTURING WORKERS

In our baseline scenario, approximately 50% of new car purchases and 30% of new SUV purchases in the United States are BEVs. This is a projection of BEV availability in 2030 with no battery material supply chain shocks or delays (details are provided in the supporting information). The baseline BEV shares are the result of the equilibrium model simulation using projected battery pack manufacturing costs, vehicle characteristics, and estimated consumer preferences (for details, see the supporting information). The simulated shares are in line with BEV market projections from the BNEF Electric Vehicle Outlook 2023. Out of the set of identified scenarios for 2030, we model (in the following sections) three scenarios that are expected to have the largest effects on vehicle prices, consumers, and manufacturing workers based on the estimated effects on mineral prices discussed above.

PRC Lithium Export Restriction Causes 15% Reduction in Refined Lithium Supply Globally

Under this scenario, the per kilowatt-hour cost of battery manufacturing increases by approximately 25%, driving up the price of BEVs and increasing consumer demand for ICE vehicles. As a result, in the short-run (1- to 2-year) market equilibrium, the average price of both BEVs and ICE vehicles increases by $1,620 ($1,140–$2,100) for cars and

$2,120 ($1,500–$2,730) for SUVs.[1] Calculations of consumer surplus show that, on average, every car buyer is worse off by $348 ($250–$440) and every SUV buyer is worse off by $720 ($520–$920). These figures imply an annual total loss across all consumers of $24 billion ($17.3–$30.5) while vehicle manufacturer operating profits decrease or increase by less than 2%.

In this scenario, 500,000–900,000 US households are unable to purchase a new vehicle for each year that the price hike continues. This represents a contraction of new vehicle sales in the United States of 5.3% (3.8–6.8%), including a drop in BEV sales of 14% (10.0–17.9%). This drop in production could cause 29,300 (20,900–37,400) labor-months of lost wages for battery cell and pack production-line workers alone.

As shown in **figure 4-12**, the estimated impact of this scenario on the US automotive market is similar in magnitude to that of the semiconductor shortage that began in 2021. The price increase and drop in production of new vehicles that occurred with the semiconductor shortage also created large increases in used vehicle prices that persisted for more than a year.

Natural Disasters in DRC Cause 25% (65 kt) Global Raw Cobalt Supply Reduction

If natural disasters reduce DRC cobalt production by 65 kt, the average price of US new cars will increase by $1,535 ($1,083–$1,985) and SUVs by $2,145 ($1,519–$2,764), battery workers will lose 29,000 (20,700–37,000) months of wages, every car buyer will be worse off by $335 ($240–$430), and every SUV buyer will be worse off by $720 ($520–$920).

Lithium Delay Causes 250 kt Raw Lithium Supply Shortage

This scenario has a smaller impact on the automotive market. Production costs for 300-mile battery packs increase by $740 and the average new car price increases by $530. Over 100,000 US households are unable to purchase a new vehicle for each year the price hike persists.

IMPACTS OF OTHER IDENTIFIED SCENARIOS

As the results show, scenarios where the global price of refined lithium is significantly increased because of trade (or other political) disputes or the DRC supply of cobalt is significantly reduced have substantial impacts on automotive manufacturing and the average price of new vehicles, comparable to those of the semiconductor shortage that began in 2021. We anticipate that the scenarios affecting battery-grade nickel supply by 2040 would cause comparable or larger estimated increases in new vehicle prices and automotive production, considering their high impact on battery pack production costs. In contrast, the delay of US lithium mine openings and trade or political disputes affecting natural graphite have smaller impacts.

POTENTIAL MEASURES TO MITIGATE IMPACTS

The estimated impacts of future supply chain shocks and delays could be mitigated by shifting battery production toward cobalt-free chemistries, investing in less energy-intensive nickel refining, and reducing the market power of concentrated material supply at risk of trade or other political disputes.

Shift Batteries to Cobalt-Free Chemistries and Increase Energy Density of All Chemistries

Shifting US BEV production to cobalt-free battery (e.g., LFP and next-generation) chemistries would mitigate the vulnerability of US new vehicle prices and automotive manufacturing to cobalt price hikes. This shift has already partially begun, with many automakers using LFP batteries in their entry-level BEVs. LFP is typically less expensive thanks to lower costs in battery manufacturing and less price volatility in its critical minerals (IEA 2023). However, because LFP has lower energy density, some automakers prefer to use

[1] The lower and upper bounds represent the effects of the 95% confidence interval of material prices that result from the scenario. Details of these calculations are provided in the Critical Minerals demonstration summary (nncta.org).

cobalt-containing batteries in their longer-range BEVs. Developing LFP and next-generation chemistries to increase performance at the battery pack level could reduce US reliance on cobalt.

Reduce Environmental Impacts and Costs of Nickel Refining

Investing in supply-side technologies that can refine nickel laterite to battery grades at lower costs and with better environmental impacts than current processing technologies can provide battery manufacturers with the necessary nickel supply. Reducing reliance on coal-based energy for refining and improving tailings management can help mitigate environmental impacts of laterite refining, but can add to already high costs. Technological improvements that reduce refining costs will be key to ensuring that laterites can be used as a sustainable long-term source of battery-grade nickel.

Reduce Market Power of Concentrated Material Supply at Risk of Trade or Other Political Disputes

As the results show, large price increases in batteries are possible because of the geographic concentration of refined lithium in China, and similarly large price increases may result if cobalt supply is restricted because of natural disasters or a leveraging of market power and if BEV batteries do not shift to cobalt-free chemistries. Diversification of supply sources for these materials can enhance resilience to disruptions and mitigate impacts on new vehicle prices, US consumers, and manufacturing workers. The Inflation Reduction Act and subsequent guidance proposed by the IRS and Treasury Department[2] are expected to incentivize supply chains in this direction by limiting BEV tax credits for vehicles with batteries containing critical minerals extracted or processed by a non–free trade agreement country. R&D efforts that improve supply-side technologies, such as direct lithium extraction, may also expand domestic supply.

[2] Section 30D New Clean Vehicle Credit, https://www.federalregister.gov/documents/2023/04/17/2023-06822/section-30d-new-clean-vehicle-credit

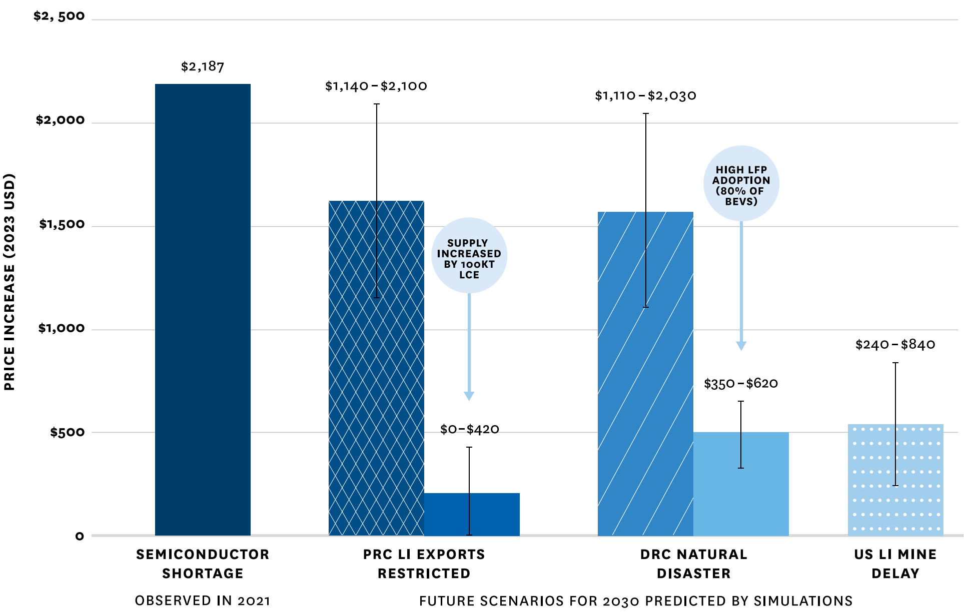


FIGURE 4-12. Average US new car price increases in future scenarios compared with those associated with the semiconductor shortage that began in 2021. BEV = battery electric vehicle; DRC = Democratic Republic of the Congo; LCE = lithium carbonate equivalent; LFP = lithium-iron-phosphate; Li = lithium; PRC = People's Republic of China

Continue Investment in Best Technologies and Practices for Extraction and Recovery

Continued access to secondary supply through recovery and recycling would also mitigate the impact of primary supply restriction. Under ideal conditions, retired batteries could supply more than half of global demand for cobalt, lithium, and nickel in 2040 (Dunn et al. 2021). However, with dramatically increasing demand for EVs, secondary supply from end-of-life batteries is not expected to be a significant source of supply before 2040. Industry learning and domestic capability development to manage and process manufacturing scrap could provide another source of recycled supply. Support of existing and emergent domestic resources and circular pathways for materials through programs such as NSF TIP's Regional Innovations Engines and ARPA-E's MINER, hold the potential to improve these capabilities and increase supply resilience in the future.

When considering incentives to expand production domestically and in other countries, it is essential to consider impacts on the communities surrounding mining and refining sites. For example, 90% of graphite, 87% of lithium, 76% of nickel, and 72% of cobalt resources globally are located on or near Indigenous and peasant lands (Owen et al. 2022). To foster an equitable energy transition, the United States should encourage engagement of affected communities before, during, and after the permitting process to ensure that they receive benefits from mining and manufacturing developments. Local community and environmental impacts of extraction and processing are not included in the current modeling approach; future work could incorporate metrics of these impacts.

Vision for Future Analytical Work

In analyzing scenarios of battery material supply shocks and delays, this project sought to identify the sources of vulnerability in BEV battery material supply chains and impacts on the US automotive market, consumers, and manufacturing workers. Future work will examine the influence of potential actions that would buffer the impacts of the identified scenarios, including existing measures (e.g., through the Inflation Reduction Act) as well as potential government and industry investments to increase supply chain resilience (e.g., to expand domestic extraction and processing or strategic reserves of materials). The model could be enhanced by incorporating possible industry shifts in anticipation of the material supply shocks or delays, such as novel mineral extraction and processing technologies, integrated recovery architectures, and the battery materials and automotive industries' responses to anticipated future materials prices, such as changes in the mix of battery chemistries and improvements in vehicle energy efficiency to reduce material requirements. Future analysis will evaluate technological developments and investments that would help to achieve these resilience measures.

Some gaps in data could be addressed by future research and modeling. Our model represents a global market for battery materials, but vertical integration and independent contracts between battery manufacturers and miners affect supply chain vulnerabilities. Research is needed to understand the impacts of vertical integration and long-term contracts on the battery material markets. There are also nuances in the natural and synthetic graphite markets; detailed graphite supply data would help to further develop the model to accommodate these separate markets.

Finally, preliminary research suggests that LFP is more robust to high-speed charging than some other chemistries currently used in EVs. This early finding, if true, has equity implications for low-income vehicle owners who tend to buy second-hand vehicles and are more likely to lack home charging and thus be more dependent on high-speed public charging infrastructure.

CHAPTER 5: CROSS-CUTTING LESSONS FROM THE FIVE PILOT AREAS

DIMENSIONS OF CRITICAL TECHNOLOGY ASSESSMENT

The four area-specific demonstration cases illustrate emerging scientific discoveries, technological disruptions, and vulnerabilities, all with the potential to significantly impact the United States' national security, economy, job market, and public well-being. Together the cases provide a snapshot of selected capabilities and opportunities to advance the country's abilities to assess critical technologies across a range of industries and stages of technological discovery, development, production, and use.

The area cases offer representative examples of general classes of critical technologies and demonstrate relevant methods to assess their national impact, vulnerabilities, challenges, and opportunities for policy intervention and investment. The areas represent different stages of technology discovery, development, production, and use; different positions of US versus global competitiveness; and different stages of policy development. **Table 5-1** shows these dimensions relevant to the critical technology assessment (CTA) activities. Across the selected areas, the specific technological details and (when in stages of production and use) the industrial structure shape the questions, methods, data needed, and policy solutions. Where each area demonstration sits on this spectrum and the implications for relevant CTA methods are discussed in **appendix 5A**.

The four area demonstrations also represent different types of national impact, or criticality: (i) a future evolution of a general purpose technology (semiconductors) anticipated to have significant impacts on economic growth and S&T capabilities (beyond CMOS); (ii) the current status of a general purpose technology (AI) in early stages of adoption with high impacts on economic growth, jobs, and S&T capabilities; (iii) an emerging technology (electric vehicle battery technologies) poised for rapid adoption but with anticipated vulnerabilities in supply chains; and (iv) a mature technology (the application of biotechnology for generic drugs) that is widely used but has supply chain vulnerabilities (**figure 5-1**). These different forms of criticality also require different types of assessment. We focus on these differences in types of criticality, a technology's maturity (e.g., stage of discovery, adoption, and diffusion on the S-curve), and their implications for assessment.

<table>
<tr><td>LOCATION ON THE S-CURVE</td><td>Scientific discovery</td><td>Invention</td><td>Commercialization
Development | Scale-up</td><td>Diffusion + adoption</td><td>Commoditization</td></tr>
<tr><td rowspan="2">US COMPETITIVENESS</td><td colspan="2">Knowledge</td><td colspan="2">Production</td><td>Use</td></tr>
<tr><td colspan="5">Human capital</td></tr>
<tr><td>STAGE OF POLICYMAKING PROCESS</td><td colspan="2">Not on policy radar</td><td>Policy debate</td><td>Policy implementation</td><td>Policy impact assessable</td></tr>
</table>

TABLE 5-1. Factors, identified from the pilot demonstrations, that shape technology assessments.

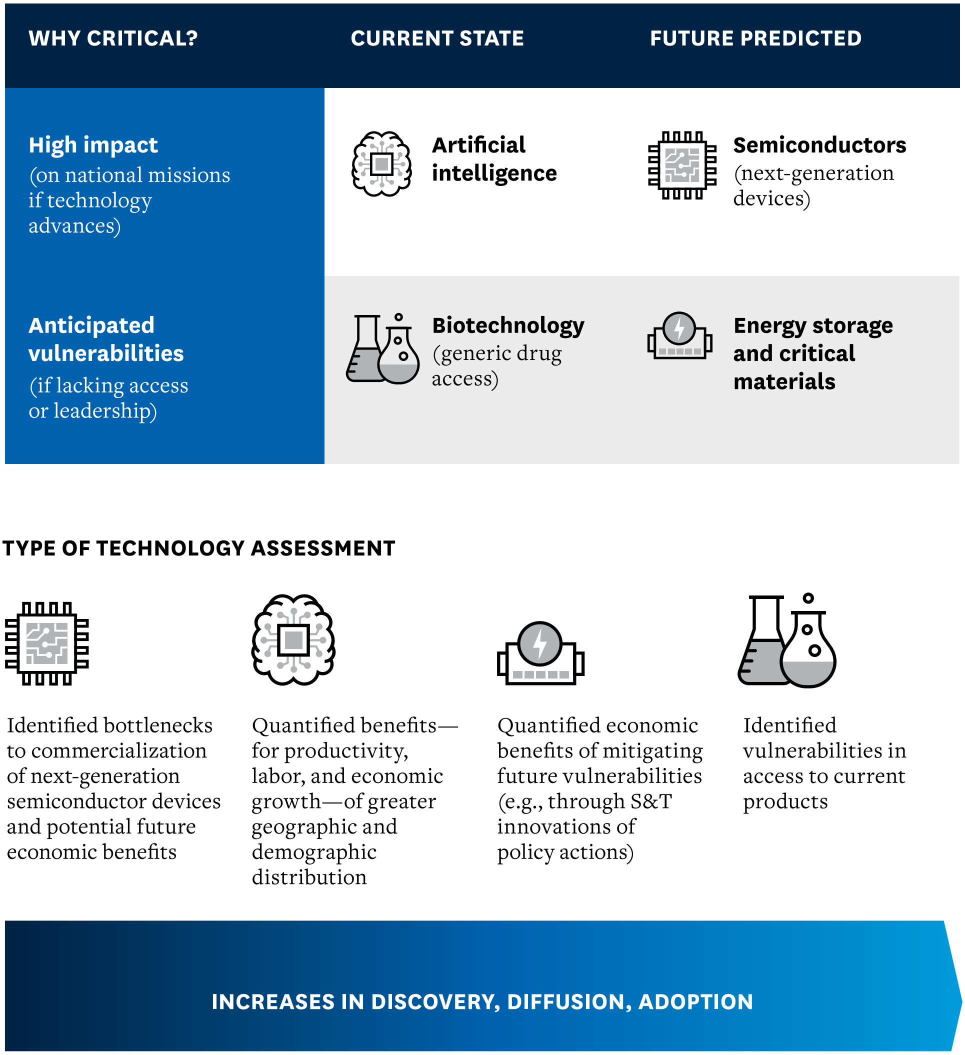


FIGURE 5-1. Implications of types of criticality and stage of technology maturity and adoption (along the S-curve) for the relevant approach to technology assessment.

High-Impact and General Purpose Technologies (GPTs)

The demonstrations provide quantitative insights into the benefits of high-impact technologies, including emerging and future general purpose technologies (GPTs), in terms of productivity, GDP growth, and the geographic and demographic distribution of benefits. Additionally, the assessments identify bottlenecks to commercialization and thus US economic growth and societal well-being. The quantified benefits can inform policymakers about the value of science, technology, and policy solutions in fostering the development and diffusion of these technologies.

For instance, AI patenting leads to a 23–27% increase in labor productivity and an 8% increase in total factor productivity. The potential gains from improved semiconductors (using post-CMOS technologies) are similarly large, with the potential, if a path to commercialization is found, to yield more than $1 trillion in net present value benefits to the US economy. Each year of delay in getting these technologies forfeits hundreds of billions of dollars. In the case of post-CMOS technology, the United States lags in research output and commercialization compared to other countries. Policy interventions are needed to ensure US competitiveness in this critical area.

Technologies with Current or Anticipated Vulnerabilities

Depending on the stage of a technology's development and US capabilities compared to those of other nations, the United States may face different types of vulnerabilities. For technology areas in later stages of maturity, development, and diffusion, vulnerabilities can affect access, such as through global supply chains. The demonstrations related to later-stage technologies (energy storage for electric vehicles, generic drugs) identify priority areas and quantify the impacts of mitigating their vulnerabilities for the benefit of public well-being, including health, economic surplus, and equity considerations. In the case of energy storage technologies, the demonstration reveals that a priority area is the vulnerability of global lithium supply chains to trade disputes; addressing this vulnerability would avoid losses on the same order of magnitude as those that occurred in the automotive industry during the semiconductor shortage. For technologies with substantial national security implications (e.g., those involved in defense, economic, or health security), vulnerability may emerge from a lack of scientific or technology leadership, such as an inability to ensure privacy or failure to address ethical concerns associated with AI or synthetic biology. Such activities and vulnerabilities due to leadership were not a focus in this pilot year's demonstrations, but are very important to include in future assessments.

Quantification of potential impacts of vulnerabilities for national interests and of the potential value of interventions in mitigating such vulnerabilities can help policymakers understand the comparative value of specific science, technology, and policy solutions for mitigating potential risks.

S&T Investment and Policy Insights

Through its area demonstration analyses this report begins to contribute to a taxonomy of CTA capabilities essential for effective national decision making. The pilot year findings demonstrate that it is possible to inform targeted investments and policy interventions that promote technological progress, economic growth, job creation, and resilience in the face of a rapidly evolving technological landscape.

Among other lessons learned, the Network members recognized important synergies between the selected technical areas; for example, the recent lack of improvements in computing hardware may hamper new directions in AI, advances in AI may contribute to scientific discovery and commercialization, and investments in AI infrastructure can accelerate scientific discovery and commercial development while supporting education and training for discovery, production, and use. The members also understood that there were limitations in attempting (or appearing) to compare "apples to oranges" in identifying whether one area was more "worthy" in the US investment portfolio, given the extraordinarily different dimensions of impact of each. This dichotomy led some members to conclude that annual lists of technologies with supporting information on their implications for national objectives might be easier for a national CTA activity to create and communicate politically (but see **box 3-1**). Such lists, to be credible and useful, would be based on quantitative and qualitative implications for national objectives, and presented with specific policy actions to advance US competitiveness in those technologies.

Finally, the Network activities highlight the importance of learning across technology and industrial contexts—from different measures of criticality to expert input to identify technology bottlenecks, public input to identify social obstacles to policy acceptance, awareness of the implications of investments for geographic and demographic participation and distribution of benefits, and the combination of scenario models with models of their impacts on industrial structure, consumers, and the economy to quantify the economic and societal implications of vulnerabilities, to name just a few. Indeed, one of the more significant outcomes of the pilot may be the start to a dynamic framework for critical technology assessment, demonstrating the types of analytic efforts that are most helpful to different types of technologies and challenges and what questions can be answered for each.

The pilot year's area demonstrations showcase the potential of the NNCTA in providing insights on US technological capabilities and vulnerabilities at different stages of the policymaking and funding allocation process: agenda setting, formulation (generic drugs), adoption (AI), implementation (semiconductors), and evaluation (energy). In some cases, policymakers are aware of vulnerabilities and policies are being implemented to address them; in these cases, the analyses identify priority areas to guide implementation. In other cases, policies have not been formulated to address the vulnerabilities, and the analyses highlight their importance.

DATA NEEDS AND TRADEOFFS

The types of data that are relevant depend on the characteristics of the selected technology, the technology's stage of the S-curve, the research question being asked, and where that question lies in the critical technology assessment framework. Data on the inputs (e.g., human capital, funding) and outputs (publications) of scientific discovery are more likely to be publicly available, although they may require sophisticated analysis to extract and interpret correctly. Scientific publications are perhaps the easiest form of data to access publicly, given their very nature of making knowledge public. But access to granular data on who and what is funded (e.g., the full portfolio of funding and associated outcomes of individual researchers) and on funding sources (e.g., foundations) can be challenging. In contrast to the generally public nature of scientific discovery, data on technology development, commercialization, production, and use are more likely to be privately held and difficult to access unless required by government (although government may be limited in its ability to compel firms to provide data or to validate the accuracy of data reported) or negotiated by individual researchers.

Because firms and governments have different objectives (firms to maximize profit, governments to ensure security, the economy, and societal well-being), they may need different data to inform their decision making. Moreover, government decision making is diffuse and disjointed, spanning federal and state levels and agencies with different missions. The data collected to support that decision making are similarly diffuse and unlinked, complicating assessments across federal and state or agency datasets.

As a consequence of these challenges, many Network members expressed a desire for more accurate, frequent, complete, granular, and timely data in their demonstration projects and expertise area. That said, data collection, sharing, and storage have costs, and thus face tradeoffs in their design and use.

We identify the following dimensions of data: *timeliness and frequency, accuracy and completeness, granularity, privacy requirements,* and *ease of access and cost of collection, storage, and validation* (these are described in **appendix 5A**). **Appendix table 5A-1** shows the intersection of data types and dimensions for the four pilot year demonstration areas (semiconductors, AI, energy storage and critical materials, and biopharmaceuticals). Below we consider potential tradeoffs between these dimensions; why, given these tradeoffs, more of one dimension is not always better; and how procedures and incentives for data disclosure can influence all six dimensions.

Tradeoffs in Dimensions of Data

There are often tradeoffs between the different dimensions of data. For example, publicly available data may be timely but unvalidated and thus less accurate or complete. Other data (e.g., from the US Census Bureau) may be highly accurate and complete but more costly (in terms of both time and money) and less frequently updated or timely. Differential privacy protections can also impair data access or quality. For example, companies may be unwilling (and indeed unable without compromising their competitiveness and security) to share supplier data openly, but willing to share the data with a neutral third party to provide insights into supply chain vulnerabilities that would not be identifiable from single-firm data.

These examples emphasize the importance of tailoring data collection to the context and the question of interest. This necessary tailoring raises questions about the contexts and problems for which data collection should be institutionalized, and with what frequency the data should be collected.

Matching Data Solutions to the Question Posed

Network members discussed the suitability of a variety of solutions to different types of questions and data challenges. They distinguished between (i) cases that may need a high-quality data collection process (e.g., for a data science observatory or critical product supply chain), associated infrastructure (such as that of NCSES or the US Census Bureau), and/or high-frequency collection (e.g., for rapidly changing technologies or industries or on production capacity for essential products during a crisis); and (ii) cases for which data are best collected in time to answer a particular pressing question (e.g., for technology commercialization pathways, early public input, or institutional or worker response) (**table 5-2**).

There was general agreement among the Network members that the United States requires better infrastructure for data on the scientific enterprise globally and on the relationship between scientific inputs and outputs. Some scholars have called for an improved and people-centered federal science policy data infrastructure to measure scientific inputs and outputs and enhance the effectiveness of investments (Hausen et al. 2023). Erik Brynjolfsson (**box 5-1**) explains, in the context of rapidly advancing technologies and technology capabilities, why data collection may need to be more frequent to be relevant to policy decisions, and how improving researchers' access to these data will improve the quantity and quality of the insights available to policymakers. Recognition of certain data as a public good and their accessibility to academics can also expand the geographic and demographic population of researchers looking at and asking questions of the data. And data accessibility to the general public may enhance public awareness and inform public opinion.

Farther out the S-curve, it can be very challenging to track technology development and production activities and capabilities, human capital requirements, and at times use; aspects of these challenges are illustrated by Rena Conti in the context of the pharmaceutical industry (box 5-2). A technology in the commercialization, scale-up, and production phase is typically housed in private enterprises, where such data are often proprietary. Data that can be particularly difficult to access (e.g., on capabilities in China or supply chains) can also be costly to obtain—and confer a competitive advantage, whether for a nation or for an individual researcher or organization in the context of analytic enterprise.

For contexts where data may be highly proprietary, Dewey Murdick cites the need for a robust data infrastructure and suggests a data trust (box 5-3). For supply chain data, Valerie Karplus and Erica Fuchs make the case for a strategic roadmap to (i) determine what technologies are sufficiently critical to monitor regularly and (ii) establish institutional capabilities with public-private partnerships for near-real-time knowledge sharing during crises (**box 5-4**). With expert or public surveys (e.g., to identify commercialization bottlenecks), individual confidentiality can be protected while ensuring the value and public availability of anonymized data in an interactive format.

Stage of S-curve	Data availability	Data solution
Earlier	More public data	Observatory
Later	Less public data	Trusted 3rd parties, public-private partnerships, data trust

TABLE 5-2. Different types of data solutions can be needed for scientific discovery—which tends to happen in the public domain—and for technology commercialization, adoption, and use (including production and supply chains)—which often involve private and confidential information.

BOX 5-1

Timely Access to High-Frequency Data for Academic Researchers

Erik Brynjolfsson

Academia plays a critical role in furnishing nuanced and comprehensive analyses to fortify data-driven decision making. However, rapid technological advances, as in AI, pose significant challenges for academics, policymakers, and the general public. The pace of change requires academics to be more time-sensitive in their work, which requires access to high-frequency data on the economy, workforce, and AI technology. Publicly available datasets are often several years old by the time of academic publication. Private datasets offer valuable insights into real-time developments in skills, innovation, and the workforce, but their accessibility often comes at a high cost. Therefore, it is crucial to take measures that promote access to high-quality, high-frequency data for academic researchers.

In other contexts, such as identifying commercialization pathways, private firm design or production or worker task data may be useful to inform simulations. Public access to both the modeling tools and the collected aggregate or generic industry data has precedent both in academia and the national labs, and can be of high value for use by other academics, firms, and government agencies. Such access typically does not require a complicated data infrastructure. In addition, retaining the raw data (and the right, when possible, for aspects of the data to eventually be incorporated in a data trust or the public domain) could be valuable in retrospective evaluation of these activities, to (i) improve efforts to assess and predict technology commercialization pathways and (ii) expand knowledge of potential relevant policy interventions. That said, given the sensitivity of much design and process data to firms' core competitiveness, such data are typically shared with a single trusted party under strict confidentiality agreements. Making the model public with aggregate data is an essential negotiation in such agreements for the public good.

Regardless of a technology's state of diffusion and adoption, interpretation of data to inform critical technology assessment frequently requires deep knowledge of specific scientific, technology, and industrial contexts to determine meaningful and tractable policy options. How different types of data were used in the demonstrations for different research questions is described in the appendix and captured in **appendix table 5A-1**. The dimensions of data across the pilot year topic areas—situational awareness, semiconductors, AI, energy storage, and biopharmaceuticals—are explored in **appendix table 5A-2**.

BOX 5-2

Data Needs in Pharmaceutical Products

Rena Conti

To be sold in the US market, prescription drugs must meet or exceed stringent regulatory standards for safety, purity, and efficacy set by the Food and Drug Administration (FDA). But international trade disruptions, military actions, or global outbreaks of disease may threaten US drug quality or supply without anyone realizing it until it's too late. The federal government's knowledge of the complex and often foreign-based supply chain of prescription drugs is limited. Pharmaceutical companies may manufacture their own active pharmaceutical ingredients (APIs) or final dosage forms (FDFs, also called drug products; e.g., tablets, capsules, ointments), or they may choose to transfer the manufacturing process to a company affiliate or outsource it to domestic or foreign facility contractors. Statistics on the relative importance of domestic compared to foreign manufacturing are limited. Several reports indicate that increasingly the manufacture of excipients, APIs, and generic FDFs intended for US consumption is done abroad and is highly concentrated among a handful of companies. In 2017 almost 90% of sites manufacturing API for generic drugs and about 60% of FDF manufacturing sites were located outside the United States (Berndt et al. 2017a,b). The United States is the largest source of FDF production (41% in 2019), India is second (21%), and China is third (8%). But from 2013 to 2019 the number of US API sites declined by about 10%, with dwindling supply largely located in regions vulnerable to interruptions from severe weather and in the Rust Belt states.

The required labeling of prescription drugs sold in the US does not disclose the name or location of the FDF, API, or excipient manufacturer, and contract manufacturing of prescription drugs and base ingredients remains completely hidden from public view. Nonpublic data provided by the FDA do not indicate the formulation types (e.g., oral, injectable/infusible, or other) manufactured at a site. No information is available about the volumes of a drug manufactured in a specific time frame nor the capacity of a site to manufacture that product. And the FDA does not systematically collect the identity, use, or potential deployment of new technology related to the production of new products or the manufacturing of base active and inactive ingredients. Knowing the identity of manufacturers, and their capacity and volume of prescription drug production, is increasingly valuable to stakeholders interested in maintaining competition in the prescription drug market, for assessing vulnerabilities to climate change–related events and potential geopolitical conflicts and their consequences for supply adequacy and affordability. More information is needed to determine which factors are amenable to change based on potential investments in new technology and domestic production, and their tradeoffs and alternatives.

BOX 5-3

A Data Trust: Shared Core Data Infrastructure for Critical Technology Analysis

Dewey Murdick

In critical technology analysis, experts tackle a wide range of analytic tasks. They aim to optimize R&D portfolios, pinpoint vital innovation partners, manage risks from "bad actors," prevent undesired tech transfers, evaluate supply chain vulnerabilities, monitor skilled talent movement, assess the economic outcomes of different scenarios, and gauge the disruptive potential of emerging technologies. A robust data infrastructure, built and continuously refined, is crucial for these analytical explorations. Often, new analytic initiatives miss the chance to capitalize on previous projects, especially in terms of enhancing and connecting the underlying data. Governmental and other users of this analysis should support the creation of a shared infrastructure that is updated and improved over time. Such an approach would integrate AI and advanced analytical tools, prioritizing data security, privacy, and accessibility across teams. It's essential to tailor this resource to address foundational research questions common to a broad range of critical technology analysis challenges. One way to address this need could be to build a "data trust," envisioned as a collaborative platform.[1] Organizations would merge their data assets, fostering both innovation and shared advantages. Appointed "trustees" would play a pivotal role, navigating data collection, licensing intricacies, and data management and ensuring ethical data use. A data trust would anticipate and proactively manage the vulnerabilities associated with data use through a commitment to professional data stewardship. The trustees would advocate for the interests of the trust's members as well as individuals from society whose information is captured in the data.

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1 Consider, for example, the 2022 report by the Global Partnership on AI, *Enabling Data Sharing for Social Benefit Through Data Trusts*, https://gpai.ai/projects/data-governance/data-trusts/.

BOX 5-4

A Strategic Approach to Data Collection and Management

Erica R.H. Fuchs and Valerie Karplus

When the COVID-19 pandemic hit the United States in March 2020, decision makers lacked information on the ability of domestic manufacturers to provide critical medical supplies on short time frames with high confidence. The US Economic Census collects information on all businesses only every 5 years, and annual surveys (such as the US Census Survey of Manufactures [now the Annual Integrated Economic Survey]) are tied to this sample. Moreover, firms were neither prepared nor incentivized to respond to such a low-probability (e.g., in the case of COVID, once per 100 years), high-risk event. Although a number of domestic manufacturers from nonmedical product industries entered or pivoted into medical products and were able to expand US domestic capacity in critical products, many new entrants noted that their efforts were slowed by barriers in knowledge, shipping, and regulatory approvals.

Network research identified two gaps that if closed could provide the framework and incentives for appropriately ramping up domestic production to meet national need in a crisis: (1) a roadmap that defines the roles of the White House and various federal and state stakeholders in data collection and information flows both in normal and crisis conditions, and (2), for the most essential "critical" products, US Census collection of business and production capacity data with greater depth and frequency.

To implement (1), the Department of Commerce could identify critical products and intermediate inputs for which these costly but important efforts have sufficient expected value, based on the probability of various future crises, and at what scale and frequency. To implement (2), the Department of Commerce could work with relevant agencies (e.g., in the case of the pandemic, FEMA, HHS, CDC) to conduct cost-benefit analyses to quantify the value of tracking different products and their intermediate inputs and with what frequency, again bearing in mind that data collection is costly.

To augment this capability as needed, the White House should develop mechanisms for the US Census to (i) share business data with government crisis response teams and (ii) integrate data on domestic manufacturers and their capacity with data from the Bureau of Industry and Security on US international trade to support analysis of geopolitical dependencies, as there may be concerns about intermediate input availability from different parts of the world. Also in support of (2), the United States should invest in an integrated, secure, near-real-time public-private data architecture to maintain high-frequency production capacity data for firms that produce (or demonstrate the willingness or potential to produce) some critical products. During crises, these products would be prioritized for collection and analysis, with a focus on both domestic production and the international footprint of their upstream supply chain. The administrators of this architecture should also consider maintaining a council whose members represent selected critical producing industries and can provide expert guidance on appropriate equity metrics for White House supply chain officials to use when evaluating potential crisis response policies and sourcing strategies.

This discussion is drawn from Fuchs and Karplus (2021).

CHAPTER 6: A VISION FOR THE FUTURE

NETWORK SUSTAINABILITY

As explained in the preceding chapters, a nongovernmental body for science and technology (S&T) analysis, such as this year's pilot National Network for Critical Technology Assessment, could help Congress and agencies sift through and evaluate information bearing on numerous national issues. To survive any length of time the program will have to identify unfilled policymaking needs, satisfy them, and continue to do so while building and maintaining trusted relationships. It will have to determine whether and how it can provide policy-relevant findings for what are inevitably political decisions. And it will have to establish both credibility and usefulness among policymakers, stakeholders, and the public.

A number of analytical groups in the federal government (e.g., the Census Bureau, NSF, Energy Information Administration, Bureau of Economic Analysis, and Bureau of Labor Statistics) have established and sustained reputations for reliable data gathering and presentation. In addition, the Congressional Budget Office, Congressional Research Service, and Government Accountability Office are valued sources of digestible information for Congress.

As discussed in chapter 2, the Office of Technology Assessment (OTA) was specifically established to provide objective S&T analysis to Congress, but was closed in 1995 after little more than 2 decades.[1] Despite the perceived quality and usefulness of its reports, OTA did not have a sufficiently broad and deep support structure among congressmembers, committees, and their staffs to be sustained. OTA studies generally sought to address the socioeconomic implications of emerging technologies; although questions about critical technologies were discussed in several OTA studies, no OTA studies focused on them. Practically all of its studies were requested by members of Congress and approved by its Congressional Board, but, unlike CBO and GAO, its work was not grounded in federal spending and what taxpayers get for their money, an abiding consideration for congressmembers.

A reputation for reliable information and analysis requires nonpartisan independence and transparency, including acknowledgment of uncertainties. Usefulness for policymakers who must make difficult decisions comes in part from clear communication, relevance, and consistency in approach over time. During its pilot year, the Network demonstrated these qualities as well as technical depth and breadth, and resourcefulness and innovation in its use of available data and tools to yield clear, substantiated insights. These qualities are evidenced by the number of demonstrations that attracted agency and industry attention and influenced outcomes therein (situational awareness—DARPA; semiconductors—DARPA, DOD, and Commerce as well as industry and universities; generic drugs—the White House; and energy—DOE and OMB).

But by many indications, more and more US residents now reject the findings of competent scientists, engineers, and physicians, who were once but no longer are widely accepted as experts. Experiences and behaviors during the COVID-19 pandemic as well as the 2020 election and its aftermath revealed the impacts of widespread misinformation, mistrust, and manipulation. In addition, many Americans simply adopted different views of the pandemic and associated choices: dollars vs. deaths, PPE vs. personal autonomy, inoculation vs. individualism, one risk vs. another.... The skeptics and their values were often confounding to the scientists and technocrats who staffed and advised government agencies. Beyond COVID, Americans are similarly divided over climate change, alternative energy, public education, and much else. This

[1] A good deal has been written about OTA since its closure. See, for example, *Technology in Society* 42(2-3) (1997), "Special Issue: Technology Assessment: The End of OTA"; Sadowski (2015), Graves and Schuman (2020), and Blair (2013).

suggests that whatever analytical findings emerge from a CTA effort might come under attack. An effective CTA program will have to anticipate such reactions and seek to counter them as best it can by recognizing when potential policy options would implicitly be based on values that may not be universally held and by establishing its political neutrality, openness to evidence, thorough analysis, and evenhandedness. To avoid backlash, the CTA program should incorporate a diverse set of representatives of civil society organizations (e.g., consumer advocates, environmentalists, trade unionists, chambers of commerce, professional associations, civil rights groups), much as OTA did with its advisory panels, to listen to their concerns and suggestions, enlist their support, and defuse charges of elitism. In addition, to earn both agency and public trust it will be essential to elicit public perceptions and early public input, document the geographic and demographic distribution of impacts, and engage experts in science communication to make as much data as possible publicly available in an interactive, easily digestible form.

Coordination of this sort may be more difficult in a decentralized network, where participants have distinct roles, identities, and organizational homes, than in a single agency. But to the extent that the coalitions that emerge from a more inclusive planning process are likely to be broader than their predecessors, the results are likely to be more sustainable as well. If the CTA program is going to prove viable and make the most of its resources and political capital, it needs to build bridges not only among the so-called experts of different disciplines but also with policymakers and the broader US population.

LONG-TERM OPERATIONS MODEL AND ORGANIZATIONAL FORM: LESSONS FROM THE PILOT YEAR

Building a national capability in critical technology assessment involves formidable challenges: the analytical tools are not clearly defined, the cross-disciplinary work involved is not academically recognized, the problems require interdisciplinary talent not easily attracted by individual agencies, and the problems are both interdependent and cross-mission in nature, spanning multiple departments and agencies (cf. Fuchs 2020, 2021a,b, 2022). The ideal analytic capability to inform national technology strategy would

- **Be strategic and forward-looking,** conducting work on timelines of 6 months to 2 years, while thinking about problems on the 1- to 50-year timeline. For example, the critical technology analytics program would focus not on building long-term data infrastructure but on providing strategic and quantitative guidance for building such capabilities and on demonstrating what capabilities are possible.
- **Integrate insights across disciplines and institutions,** bringing together technical expertise in engineering, the physical sciences, modern data analytics (e.g., machine learning, operations research, natural language processing), and the social sciences (e.g., economics, political science, sociology, history) as well as practitioners with experience in policy implementation.
- **Work on interagency projects,** including work from multiple agencies on one topic. Such work might reflect, for example, national security objectives per the Department of Defense; economic objectives per the Departments of Commerce or Treasury; and labor, health, and equity objectives per the Departments of Labor or Health and Human Services.
- **Be a neutral third party across stakeholder, agency, or political interests,** or have the capability to spin off public-private partnerships to serve as neutral third parties.
- **Operate through a highly flexible, distributed model** capable of rapidly mobilizing and reconfiguring outstanding private sector, government, and academic talent, data, and resources (e.g., through contracts or other mechanisms as necessary).

This year-long pilot was an exceptional opportunity for the nation to begin to operationalize this vision, with lessons about next steps necessary to more fully develop and realize it.

Organizational Form and Investment

PROGRAM MANAGEMENT: DIMENSIONS OF INTEGRATION

Operating in a Flexible, Distributed Model That Orchestrates Integrated Interdisciplinary Insight from Top Talent Nationwide

Submitting to NSF Technology Innovation and Partnerships' Broad Area Announcement meant that the NNCTA pilot year consisted of demonstrations *proposed by academics* of the potential for analytics to inform investments in science and innovation. With just 4 weeks to submit, the individuals engaged were leading academics in science and innovation policy of which the director was aware, and others enlisted by those individuals or suggested to the director during the 1- to 2-week search period. Given the limited search and organization period, the director and the small operational support team helped define the demonstration areas, sought and paired multidisciplinary talent for the demonstration areas, and managed and facilitated the interactions between performers. The scanning, orchestration, and management were similar to the collaboration and community orchestration done by DARPA program managers (Fuchs 2010).

To scale the above activities in future years, the ideal would be for program managers with expertise in the individual area demonstrations to assume responsibility for the relevant scanning (of government needs), orchestration (e.g., identification and funding of university faculty), and project management, all of which were done in the first year by the director and executive technical director. This scale-up will have benefits: Topic experts will do a better job of scanning in their area of expertise and will be focused specifically on critical technology assessment and what's needed to inform national investment.

In the long term it would be ideal for analytical talent to be drawn not just from academia but also from industry, nonprofits (e.g., RAND, MITRE), and government (especially government labs). That said, the pilot year's orchestration of academic talent from multiple disciplines offered important insights into management approaches to yield a whole that is greater than the sum of its parts (**box 6-1**).

Facilitating "Co-Optition" across Complementary Analytic Outcomes and Data

In the context of AI, three Network groups undertook analytics with similar or complementary objectives, using data sources that were different (surveys, job postings, patents, publications, depending on the group) and in some cases highly complementary (e.g., due to different foci, for US and Chinese data). Management involved facilitating engagements and interactions across the groups and identifying opportunities for collaboration. In the longer term, potentially important managerial roles might include offering neutral third parties or contexts to manage data or algorithm comparison or sharing, or bringing external incentives for cross-team engagement and collaboration. In the pilot year the groups compared outcomes across data sources, each with different limitations, and benefited from seeing where they pointed in the same direction. Future efforts will benefit from further staffing for facilitation, extramural fund raising, and the engagement of a neutral third party for data or analytic comparisons to bring about, for example, the sharing of US and China labor data held by different parties.

Orchestrating Analytics by a Nonacademic Leader with Technical, Industry, and Analytic Expertise

Unlike the other pilot year topic areas, the semiconductor lead was not a professor. Instead, he had experience working at a semiconductor startup and at a firm consulting to the semiconductor industry and in the introduction of new microelectronics products. For this project he orchestrated analytic research led by professors in four areas: economic analyses of the potential market value of emerging technologies and the optimal investment portfolio, expert interviews about technical bottlenecks to the commercialization and scale-up of emerging technologies, situational awareness of global semiconductor capabilities, and analytics of labor and skill requirements for and gaps in new semiconductor facility investments.

BOX 6-1

Consideration of an Alternative Organizational Form

An alternative organizational form discussed by Network members was a less top-down but gated membership organization that was organizationally more similar to a "network" like the Jasons and the Santa Fe Institute, both of which vote in new members. Concerns included lack of flexibility to call on whoever might be most suited to a particular problem and lack of dedicated staff to build the field of critical technology assessment. To build in flexibility, Network members discussed funds for emergent issues to be allocated by the director, with approval by the academic research council; and project reallocation by a board and the academic research council at the end of each year. This organizational model was eventually not favored because of the cited limitations and concerns about "involution," "group think," and incentives for existing members to sustain their funding and exclusive position.

He also oversaw his own project that led to an "early win" in terms of identifying an immediate gap in US access to what was needed for emerging technology commercialization, not yet addressed in the CHIPS and Science legislation. He was hired by the Department of Commerce to implement insights derived from the analyses he led. For this group the Network director was able to have less of a managerial role as the research topic identification, orchestration, and management were handled by the nonacademic lead.

Orchestrating Separate Analytic Perspectives in Parallel

The pharmaceuticals and public awareness teams each had important research insights in this area: what pharmaceuticals (especially generics) were most vulnerable to shortages, and what interventions may be most effective for public communication, understanding, and acceptance of policies to address the shortages. Close collaboration was not necessary for the two research activities; indeed, there was value in their being undertaken separately, resulting in independent analysis of criticality from the perspective of data, and rigorous academic analysis of expert and public perceptions of medicine criticality and potential solutions. From a managerial perspective, the most important function was to guide the two teams in parallel and to engage a neutral third party in writing the final integrated summary of the topic area. This function is not that different from a DARPA program manager funding complementary or competing technical solutions to a problem facing the Department of Defense.

Facilitating Teaming and Analytic Collaboration across Complementary Expertise

The energy storage and critical minerals PIs together proposed the most interconnected collective analysis, and required the least management of any team. The primary orchestration and management role of the director was in introducing the PIs to each other and asking them to work together in the pilot year. From there, the teams managed the project on their own. The director's only additional management involvement was in facilitating integration of the equity team's work, by identifying a broker across the highly integrated group and the equity team, which was conducting an energy equity survey.

Being Strategic and Forward-Looking

Because the academics were invited to propose the analytics, the projects were by definition on a longer time horizon than, for example, White House timelines. Given the normal multiyear timelines for many academics in S&T research and the focus of academic work on pushing the knowledge frontier, it was particularly impressive that the initial demonstrations were completed in just 6 months and integration across demonstrations in 9 months. The open multilateral conversations with government decision makers about academic work in progress, at the midway and third-quarter meetings, is also uncommon but was welcomed by the government and academics alike. The full benefits of drawing these two groups closer, including throughout the analytic process, may yet emerge.

Some aspects of the original vision were more challenging than others to realize. First, a national technology strategy must by definition span multiple government departments, each with specific, singular national objectives (e.g., defense, commerce, labor). The pilot year activities focused on demonstrating the potential for analytics to inform national technology strategy writ large (e.g., across departmental missions); because mission optimization is the job of each agency, and given the lack of coordination of activities across agencies, analytics that identify win-wins and tradeoffs across national objectives will continue to be an important focus for future CTA activities.

Second, the focus on how analytics could inform national technology strategy meant less research on what is a critical technology and how to measure a technology's criticality. While workshops and surveys elicited structured responses from the PIs and Advisory Council on these questions, in the longer term the Network would benefit from a small number of integrational research scientists dedicated to these types of research activities.

Finally, in the future the ideal approach to launch to new projects might be some combination of dedicated program managers whose job it is to scan government needs and academic, industry, and nonprofit capabilities, and the pilot year workshop that convened academia, industry, and government to launch the biopharmaceutical activity. Building on the concept behind our own advisory board, which had experts in each topic area pursued this year, program managers should also have area-specific expert advisory groups, which engage in these launch and stakeholder feedback workshops and serve as advisors on important topics. These advisory groups and workshops might serve a similar function in launching new projects to the Information Science and Technology (ISAT) advisory group for DARPA.

EXCHANGE: LESSONS ON INFORMING ANALYTIC PROJECTS THROUGH MULTILATERAL DIALOGUE BETWEEN ACADEMIA, INDUSTRY, AND GOVERNMENT

NSF TIP's 1-year $4M pilot award for a National Network for Critical Technology Assessment enabled the first step of bringing together top *academics* from across the country to define a vision for critical technology assessment, considering current capabilities, gaps, and the national investment and organizational form needed to realize that vision. But to be successful, a CTA vision must also involve practitioners from industry, government, and nonprofits. Industry and government stakeholders are essential contributors who need to inform not only the data and analytics but also the questions asked. Moreover, in multiple cases industry has essential data or analytic capabilities not available in government or academia.

Network leads sought and received an award from the Alfred P. Sloan Foundation for a series of workshops or other mechanisms to convene and engage in a multilateral dialogue with practitioners in industry, government, and nonprofits. The workshops provided a forum to discuss the proposed demonstrations and an opportunity for the practitioners to comment on the associated data, analytics, questions, and policy problems, to potentially team up with the academics in solving challenges, and to inform the vision for the future of critical technology assessment. In total we held eight workshops: one workshop for each area demonstration, one cross-cutting workshop for labor and equity, and two workshops where we engaged in multilateral dialogue on the analytic results with industry and government leaders as well as building a cross-area vision of critical technology assessment with performers.

The area workshops yielded important insights into long-term operations of a national network. By coincidence, the area leaders ended up experimenting with the timing of the workshops, which were held at three different stages of the analytic enterprise: during problem formulation before the use of substantial analytics (the biopharmaceuticals team led this workshop), roughly midway through the proposed analytic endeavor when stakeholder response had high value (the semiconductor team), and toward the end of the 1-year demonstration when red teaming of the results helped inform interpretation and future work (the situational awareness team). We propose that the three prototyped workshop functions would be valuable for future network projects to ensure robust dialogue between academia, industry, and government.

Problem Formulation (Biopharmaceuticals)

This workshop served as a prototype for convening industry, government, and academic leaders (both those doing the analytics and those conducting research in pharmaceutical science and technology, S&T) early in the analytic process. When the workshop took place data had arrived for one PI team and before analyses had begun for the other two PI teams. For two of the pharmaceuticals analytic experts, the workshop discussions provided qualitative data on technologies that could be used to overcome supply chain bottlenecks. For the other two teams, the discussions framed their research process. A main takeaway of this workshop was the value of convening government, industry, and academia to launch the analytic process. Similar to how Information Science and Technology (ISAT) workshops can launch ARPA programs, project funding would ideally follow (rather than, as this year, precede) these launch workshops.

Midway Stakeholder Feedback (Semiconductors)

The semiconductor workshop was held roughly midway through the analytic process. Once again, it convened leaders from industry, government, and academia (the latter were leaders in both analytics and relevant semiconductor S&T). Having read many public papers on what the government should do in this area, the lead PI had an early insight and recommendation for policy action—and also preliminary results on a second analysis that was different from the published positions. The PIs didn't know how stakeholders would respond, and expected potential opposition from industry on one recommendation and from university stakeholders on another. Surprising to the PIs, the workshop's industry participants were in favor of the early recommendation for policy action and among the academic stakeholders there was greater consensus (than in public statements) about the technical and human capital constraints to optimal capital investment to support R&D activities in this area. Last, a new direction of research emerged at the workshop related to workforce constraints, which the analytic team added to the analyses over the next 3 months.

Red Teaming (Situational Awareness)

A red-teaming workshop on situational awareness was held toward the end of the pilot year's analyses to deepen understanding of the results and build on them to inform the focus of future research. Again, leaders from industry, government, and academia were assembled, but instead of the workshop being run by the PI, the Network supported the event by assembling the experts and enlisting an outside contractor deeply engaged in relevant topics to identify additional experts and run the workshop. Area experts from NSF, ONR, DARPA, and a defense contractor took area demonstrations into the results that China was more disruptive than the United States in specific topics, to begin to unpack the source and validity of the results. For example, the experts agreed that the publication-based finding that Chinese researchers appear to be outpacing their US counterparts in selected beyond-CMOS technologies, specifically insulators, could be valid. At the same time, experts felt that the most important next steps for this research would be to do more analysis, specifically comparing independent expert assessments with the publication-based indicators or measures, in terms of (i) what were the most disruptive, prescient, and emergent publication (and nonpublication) scientific discoveries over the past 2–3 decades, and (ii) where China was and was not leading the United States in scientific discovery.

Cross-Area Workshops (Labor and Equity)

The labor and equity workshop highlighted the value of bringing together scholars with common interests across areas and methods, and should be replicated in the future on this topic as well as other cross-area themes to build both community and intellectual foundations. The workshops that created structured, multilateral interactions between industry, government, and the academic performers were particularly valuable in understanding stakeholder interests, needs, and support or lack thereof.

Overall Workshop Takeaways

As one Network PI said, "The demonstrations and workshops should by definition be different. This whole undertaking is a grand experiment. If we all did the same thing, we wouldn't be learning anything." The multiple workshop formats experimented with in the pilot year should continue in future years, and be run by the CTA program, both to standardize format and to learn lessons across them.

The area workshops were similar to those typically run by White House entities to convene industry leaders, academic experts, and government representatives across agencies, except with the goal of building analytics to inform the policy actions considered by those stakeholders. If all four types of workshops—launch, midway feedback, end-of-project red teaming, and cross-area community building—were run for all projects, this approach would have significant analogues to existing workshops associated with programs at DARPA: ISAT workshops, which likewise have multiple stages (for ISAT often three sequential workshops) and which often lead to program managers' decisions about funding directions for research. The cross-area workshops had community-building and direction consensus characteristics similar to DARPA workshops (such as the Electronics Resurgence Initiative annual meetings). While perhaps slightly different from the NNCTA midway or red-teaming workshops, DARPA program managers' multiple workshops also bring together performers to share information and influence the direction of their projects as they evolve. The diverse leadership of some of our most successful area workshops — by an Advisory Council member (who had previously been in the White House), the semiconductor lead (who had previous multi-institutional experience including in industry and consulting), and an external contractor (who had previous experience at WTEC and the NNCO) — speak to the large advantages for a CTA program creating a standard format for and facilitating future workshops.

Toward a Rapid Critical Technology Assessment Program

The pilot year activities highlight that there is both an art and a science to effective critical technology assessment, and that such assessment is essential to ensure that the country smartly invests and enacts the necessary policy to achieve short- and long-term security, prosperity, and broad-based social well-being. This effective assessment is not top-down coordination or optimization of investments that copies competitor nations' style and approach, nor can it be solely a curiosity- (for science) or market- (for technology) driven approach that fails to acknowledge the nation and its people as stakeholders in outcomes (such as access to semiconductors, whether for national security or for societal well-being). As Congress recognized in the creation of TIP, something disruptive is needed. However, to be effective in fulfilling its charge, TIP as a funding agency and more broadly the federal government will need to intentionally design a rapid CTA function for Congress and the executive branch alike. This program must embrace the pace of innovation today, draw on the nation's variety of institutions, disciplines, and agencies (which, with different missions, don't all easily talk to one another), and exploit the analytic power and technical expertise of institutions across the nation. Such work will be best led by program managers trained in the art of critical technology assessment to select the most important problems, match methods to problems, and coordinate the distributed national capability.

STAFFING

We recommend that a program manager orchestrate talent from across the nation to perform analytics to inform critical technology strategy in each key technology area (**figure 6-1**). The core CTA function would be conducted by the program manager.

Topic area program managers, as at (D)ARPA (Fuchs 2010), would scan for global and domestic challenges and the state of government response to them. They would coordinate national talent to address the challenges, on contracts that would typically last 6 months to 2 years but could extend to 4 years for undertakings requiring sustained effort.

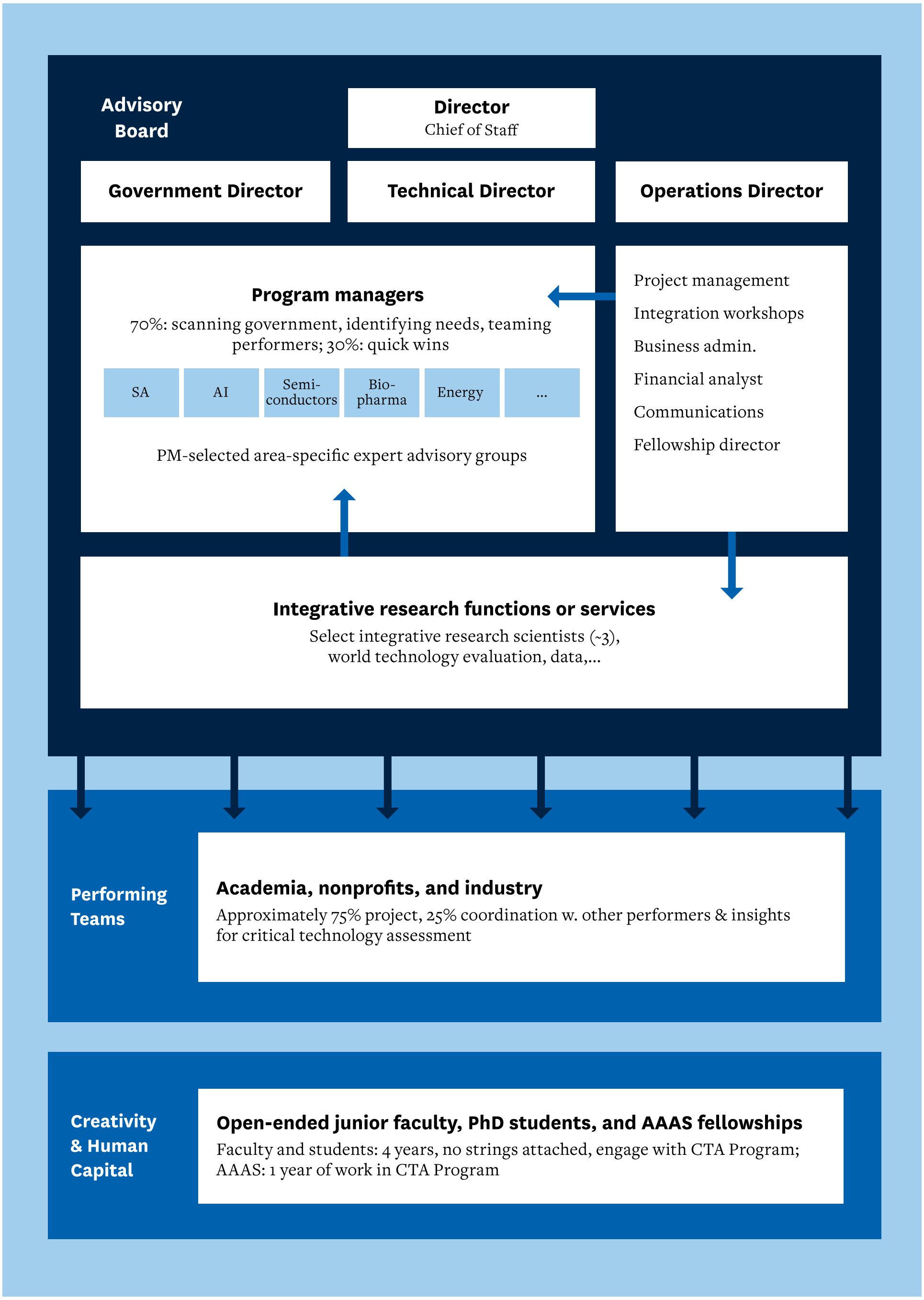

FIGURE 6-1. Proposed organization of a national Critical Technology Assessment Program. PM = program manager

The area program managers would focus on pushing the frontier of analytics to inform CTA and on transitioning the recommendations and findings to government stakeholders and supporting select government agencies in moving closer to the analytic frontier by transitioning select relevant data infrastructure or modeling capabilities. Since the objective would be to inform government technology strategy, funds would not be well spent on a high-risk portfolio of potential failures or on long-term data infrastructure, which would be better housed in established government entities. Funding would instead support efforts to transform the possibility frontier in terms of data and analytics (and data infrastructure) and to assist governmental adoption of those capabilities.

As outlined in this chapter's appendices (particularly, **appendix 6A-1**), the CTA program manager would identify not only important national problems needing to be solved but also the dimensions of integration to address those problems. Critical qualities to successfully execute these responsibilities are sufficient depth in a technology area complemented by "multilingual" ability across disciplinary and institutional contexts to bring together performers across disciplines and institutions to serve national needs.

The area program managers would also have responsibilities in the synthesis, interpretation, integration, and translation of project findings into recommendations for government. This synthesis within and across areas was led in the pilot by the leadership team. With a smaller amount of funding, synthesis and integration would be the primary function of the program managers, with smaller-scale contracts for academics and others to inform their work. With more funding, the integration might be done by supporting integrational research scientists or staff comparable to ARPA's science and engineering technical advisors.

Finally, in their translation role, similar to the semiconductor policy lead's activities in the pilot year, the area program managers would look for "quick wins" with immediate implications for policy, drawing from either existing academic and industry knowledge or funded projects (possibly even before project completion). As in our semiconductors case, the program manager might put staff directly on these topics, identify needed policy actions, and/or rotate into government to help implement the activity findings. The program managers would split their time between scanning for policy challenges in need of analytic capabilities, scanning for national knowledge and talent to address those challenges, managing and orchestrating the distributed talent, and synthesizing lessons for government, including quick wins for immediate policy implementation. It would be appropriate and expected for the particular allocation of effort to vary by topic area and program manager.

The program managers would, as at DARPA, have limited terms: given the timeline of the project contracts, we recommend 1- to 3-year terms, instead of the more typical 3- to 5-year terms of DARPA program managers. These limited terms would both help keep the organization nimble and up-to-date and facilitate the positions as a stepping stone to leadership positions.

The program managers would ideally have diverse institutional experience—in academia, industry, and government—along with experience in analytics to inform science and innovation policy (in the pilot year this diversity of experience was uniquely, and beneficially, held by the semiconductor project lead). Such multi-institutional background harkens to the Japanese model (Fransman 1999) and is quite important because of the multiple perspectives it affords, associated adaptability, and increased likelihood that the program manager will be able to serve as a broker between institutional forms.

Overseeing the program managers, in a way similar to DARPA office directors' integrational role, would be a government director and a technical director. The government director would identify relevant government challenges across departments where there may be particular value in analytics, including in quantifying tradeoffs or win-wins across missions. The technical director would identify opportunities for collaboration or integration across the topic areas. Both the government and technical director, along with the Network director, would be responsible for identifying the topic areas for program managers, reducing or eliminating funding of lower-priority topic areas in favor of higher-priority ones, and bringing on new program managers and raising funding in newly needed topic areas.

In addition to the program managers, a small number (at first, perhaps only 3–5) of integrational research scientists should be housed at the hub. They would focus on the big picture of what is a critical technology, build the intellectual foundations across areas, and continually push the frontier of the data and analytic tools possible to inform critical technology strategy. They may fund, in consultation with the directors, a few grants to build the emerging field of critical technology assessment as the academic community grows. The integrational research scientists would also play a lead role, in coordination with the program managers, in writing the annual report of the state of critical technology assessment.

FUNDING STRUCTURE

Effectively mobilizing, synthesizing, and integrating capabilities distributed across the country's rich variety of researchers, disciplines, and institutions will require that a rapid CTA program spend the majority of its funds on external contracts. When functioning at a smaller scale (e.g., potentially in the early days of a staged ramp-up), no less than 50% and as much as 80% of funds should go to external contracts, with the remaining funds focused on the operations of the program itself (director, technical director, government director, program managers, integrational research scientists, and the necessary operations functions). In this early phase, the internal operations will focus on synthesis of distributed capabilities and smaller-scale external contracts. Once established, 80–90% of funding should go to external contracts.

The CTA program's funds should not be assigned to specific projects or technologies; rather, the most important technologies and problems on which to focus should be the explicit task of the director, government director, technical director, and program managers, in consultation with OSTP, NSF TIP leadership, and the interagency working group. The director, along with the government and technical directors, will maintain the focus and balance of the overall activity portfolio, ensuring that new areas grow and less vibrant areas are discontinued. Similar to DARPA, the director and deputy directors will determine (i) how the unassigned funds should be distributed across the program managers and integrational research scientists and (ii) the projects most important for funds to address.

Given the all-of-government, cross-mission nature of identifying a national technology strategy and the legislation's charge to identify key US challenges and technologies to address them "in consultation with the interagency working group," an interagency advisory mechanism should be set up for the CTA program. Without a direct sponsor (as Congress was for OTA), it will be essential to have other departments and arms of government (the executive and legislative branches) as, in essence, "clients" of the CTA program's activities that are relevant to them. A sign of the CTA program's success would be government entities' recognition of value in the analytic functions offered. Such recognition could be embodied in liaisons or personnel assigned to the rapid CTA program from other labs or agencies, requests through the interagency advisory mechanism for analytics on challenges particularly cross-mission in nature (such as, for example, the relevance of access and leadership in semiconductors to DOD, DOC, DOE, and DOT missions), or possibly even the cofunding of project topics central to their specific mission but spanning multiple agency missions.

OPERATIONS: STANDING SUPPORT FUNCTIONS

In association with the program management, the CTA program should support not only administrative and other business activities but also workshops to convene PIs on related topics (as done by DARPA PMs) and other representatives from academia, industry, and government for multilateral dialogue on the analytics at various stages (launch, middle, and close to the end) of the analytic process (**appendix 6A-2**). Separate from the Advisory Council, program managers would likely keep formal or informal topic-specific expert panels spanning industry, academia, and government to support these activities.

CTA CAPACITY BUILDING

Given the relative short-term problem orientation of a CTA program, it will be important to fund activities that encourage creativity and big-picture thinking, as well as high-risk work that may be impossible for the CTA program itself to undertake. In our engagement with policymakers and even venture capitalists, they commented on the rarity of the analytic capability offered and advanced by the NNCTA, and the need to build the human capital with this capability. The technical breadth, matched with disciplinary and institutional breadth, required for program managers was noted by multiple Network members as even rarer. This capacity may best be developed in industry or other private sector positions, in the AAAS S&T policy and similar fellowship programs, and in a handful of S&T policy, computer science or telecom policy, or engineering and public policy programs across the country. Building human capital in critical technology assessment will benefit not only staffing of the CTA program but also decision making in government, industry, and across the country.

We believe this human capital development is best undertaken through three types of foundation-funded fellowships: AAAS fellowships to work with the CTA program (which has precedent from the days of the OTA), no-strings-attached 4-year fellowships (similar to Howard Hughes Medical Institute Fellowships or the MacArthur Genius Grants) for junior faculty, and no-strings-attached 4-year fellowships for PhD students (similar to NSF's graduate research fellowships). All would involve doing professionally daring, interdisciplinary, policy-problem-oriented research on critical technology strategy, with the AAAS fellowships being more applied than the other two. These fellowships will be particularly valuable given the lack of an academic field associated with critical technology assessment or national technology strategy and the corresponding career risks and lack of academic incentives to undertake the associated interdisciplinary, phenomenologically driven research on real-world technology policy problems. Recipients, ideally selected by a rotating independent fellowship committee convened by the CTA program, would be invited to participate in CTA program activities and benefit from associated community-building activities and resources.

CHAPTER 7: CONCLUSIONS AND FUTURE NEEDS, GAPS, AND CHALLENGES

The pilot activities highlight that there is both an art and a science to effective critical technology assessment, and that such assessment is essential to ensure that the country smartly invests and enacts necessary policies to achieve short- and long-term security, prosperity, and broad-based social well-being. Effective assessment is not top-down coordination or optimization of investments that copies competitor nations' style and approach, nor can it be solely a curiosity- (for science) or market- (for technology) driven approach that fails to acknowledge the stakes and the outcomes for the nation and its people.

As Congress recognized in the creation of TIP, something disruptive is needed in how we fund the pathway from translational discovery to commercialization. In addition, for TIP to be effective in fulfilling its charge, something novel and organizationally disruptive is also needed in how the nation conducts critical technology assessment (CTA): the federal government will need to intentionally design a rapid CTA function for Congress and the executive branch alike. This program must embrace the accelerating pace of innovation, draw on the nation's rich variety of institutions, disciplines, and agencies, and exploit their analytic power and technical expertise. Such work will be best led by a single organizational unit charged to think across national objectives and technology interdependencies, engaging topic-specific program managers trained in the art of critical technology assessment to identify the most important problems, match methods to problems, and mobilize and orchestrate the distributed national capabilities both within and outside government.

The NNCTA pilot year activities demonstrate that data and analytics can meaningfully inform national technology strategy, but the necessary capabilities do not sit with one discipline, investigator, or type of organization. The novel pairings and cross-disciplinary collaborations that were effective in this pilot year had to be orchestrated (a hallmark of the efforts undertaken by DARPA program managers). This orchestration is an "art" that, if done well, yields a whole greater than the sum of the parts: creating a dynamic exchange between a 30,000-foot machine-driven and a bottom-up expert-driven perspective to benefit from both; combining data across scholarly areas and institutions to transcend gaps; marshaling different disciplines and methods to solve different aspects of a policy problem; setting up different perspectives on the same policy problem to enhance understanding through complementary or contradictory insights; creating teams to combine disciplines and models in a way that produces otherwise unavailable novel findings; identifying transition partners; and transparently engaging throughout and communicating the final findings across the variety of relevant stakeholders. The analytic methods leveraged in specific fields are the frontiers of science—whether economics, computer science, sociology, political science, psychology and decision science, or engineering.

The pilot year investigations also revealed that the most appropriate methods and data are not static but closely linked with (i) the status of a technology's discovery, diffusion, and adoption; (ii) US global competitiveness in the knowledge, production, and use relevant to the technology; and (iii) the state of the policy process with respect to the technology. Understanding the most important problems to tackle in a particular area, and how to match methods across disciplines to those problems, requires deep knowledge of the industrial, technological, and policy contexts. Program managers with the talent to identify and understand national challenges as well as top researchers' activities across disciplines, and to provide the orchestration needed to address those challenges, are rare. The nation should cultivate them by investing in nontraditional educational programs and professional fellowships to build human capital with problem-oriented policy skills that leverage analytic rigor, interdisciplinary methods, and contextual and phenomenological depth—in short, to develop a community of practice in (rapid) critical technology assessment.

A number of cross-cutting insights for critical technology assessment can be drawn from the area demonstrations:

Advanced analytics today can be used to inform

- US global competitiveness in scientific funding and its collaboration networks
- US domestic funding biases that are failing to leverage the full bench of talent
- Technology commercialization pathways, including policy, investment, and other interventions—technical, human capital, infrastructure, regulatory, and citizen awareness and participation—to overcome bottlenecks. Following are examples of options identified this year to overcome technology commercialization bottlenecks:
  - Identify infrastructure gaps and increase access to that infrastructure to boost innovation;
  - Identify skill gaps in specific regions and training or worker mobility interventions to overcome these gaps;
  - Identify public, technical, and regulatory bottlenecks to the introduction of new technologies in commodity products, and opportunities to overcome those bottlenecks.
- Investment and policy interventions that could reduce supply chain vulnerabilities, and the value of that reduced vulnerability for national objectives in security, the economy, and social well-being.

US CTA capability is hampered by the following gaps:

- Building situational awareness of global technology and production capabilities is much more challenging than analyzing scientific and inventive capabilities through publications and patents: the data currently don't exist, and therefore few scholars or practitioners are rigorously addressing these problems. A CTA function must invest in these capabilities and develop a framework to determine where and how frequently they should be applied.
- The data needed for analytics to inform policy and investment in a timely fashion for rapidly moving critical technologies such as AI are lacking. Public-private partnerships must be established to create these datasets to inform critical questions in national technology strategy. There are analogous needs to coordinate data across the private sector and government in a timely fashion in certain critical technology supply chains.
- The inclusion of equity in each analysis requires resources. Equity is not a single field of study, and experts with complex analytic, technical, and phenomenological knowledge are needed to address issues in algorithmic bias, energy equity, health equity, and equity and discrimination in labor and training (e.g., conscious and unconscious recruiting bias, macro- and microaggressions in STEM fields), among others. CTA leadership (the director, government director, and technical director) will also need to ensure that program managers maintain a cross-mission focus involving all three dimensions of criticality (security, the economy, social well-being) and that all analyses include the geographic and demographic implications of policies and investments.

US CTA capability will require the following institutional innovations:

- Leveraging the best of the nation's analytic capabilities to address the full portfolio of CTA challenges, opportunities, and needs will require integration of capabilities across a range of performers from academia, industry, and nonprofits such as FFRDCs.
- To scale this year's project and performer selection and orchestration activities, area-specific program managers should have deep contextual (technical and industrial) expertise in their topic area, experience in a diversity of institutions (academia, industry, and government), and an ability to understand leading analytic capabilities. There is a shortage of this type of human capital.

- To ensure policy relevance and impact of selected projects, program managers should be charged with (i) scanning globally and domestically for US challenges and gaps and (ii) scanning the nation's top talent for analytics to address those challenges, identifying multiple stakeholder agencies to partner with on specific analytic projects, and ensuring government transition partners for the outcomes.
- To simultaneously maintain relevance to policy and develop buy-in from relevant government stakeholders in the legislative and executive branches, members of Congress, the executive branch, and government agencies should be allowed to cofund analytic undertakings.
- The lack of a field of critical technology assessment means there is also a lack of human capital with the skills necessary both to perform the analytics needed for national technology strategy development and to serve as program managers of the work conducted across the country in each area. New education programs and professional fellowships are needed to invest in building this human capital.

Across demonstration areas, many scholars, government labs, and nonprofits (including FFRDCs) have a deep bench of data and models. The US government must develop a disruptive new program to tap into and integrate this expertise.

Based on these observations and our pilot year demonstrations, we recommend that the United States invest in a rapid critical technology assessment entity to provide the executive and legislative branches with the tools needed to inform national technology strategy. This CTA program would, as part of its primary functions, support NSF TIP in its annual roadmapping and OSTP in its Quadrennial National Technology Strategy, serve Congress and the executive branch with analytics to inform critical technology strategy across national (and agency-specific) missions writ large, and serve as a trusted source of technology assessment capability to government, industry, nonprofits, and the public. The program should focus on problems that span national missions, taking account of technology and policy interdependencies and of win-wins or tradeoffs across national objectives (or individual agency missions).

The CTA program would in many ways serve as an "analytic ARPA" to orchestrate the analytics necessary to inform national technology strategy. The program should draw heavily from the DARPA model in terms of its dynamism, and the independence and discretion of talented program managers to choose problems and orchestrate top performers to address those problems. It should also, like DARPA, push the frontier of analytic capabilities, then transfer those capabilities eventually into the executive and legislative branches. Unlike DARPA, however, the program should not undertake high-risk analyses but be grounded in a simultaneously disciplined and innovative analysis process, pushing the frontier of scientific and analytic capabilities.

The core CTA function would be conducted by a program manager with both area-specific expertise (e.g., technical depth, such as in AI or semiconductors) and institutional and disciplinary breadth. Program managers would, as at DARPA, have limited terms to help keep the organization nimble and up-to-date and also to facilitate these positions as a stepping stone to follow-up leadership positions. The CTA entity would involve and draw on agency and organizational expertise across the government. It would fund problem-oriented research and also serve a business development role in supplementing nonspecific funds with matching contracts from relevant executive or legislative branches (e.g., for issues that cross departmental missions in semiconductors, involving the Departments of Commerce, Defense, and Energy; or, in the case of novel data infrastructure, NCSES, the International Trade Commission, and/or the US Census Bureau). In addition to the CTA entity's advisory board, which should include leaders from government agencies as well as from academia and industry, each program manager should have an area-specific advisory committee, and run workshops that bring together relevant thought leaders and stakeholders from academia, industry, government, and nonprofits to launch and inform analytic programs.

Overseeing the program managers, in a way similar to DARPA office directors' integrational role, would be a government director and a technical director. The government director would identify relevant national challenges across departments for which there likely is particular value in analytics, including in quantifying tradeoffs or win-wins across missions. The technical director would identify opportunities for collaboration or integration across the topic areas. The government and technical directors, along with the CTA program director, would together be responsible for one of the most challenging and important functions: where to focus the limited analytic resources—identifying the topic areas for program managers, reducing or eliminating funding of some areas as appropriate, and bringing on new program managers and funding in newly needed topics.

The CHIPS and Science Act calls for a new federal capacity to fortify the nation's leadership and ability to determine policies and investments that will ensure national security, global competitiveness, economic prosperity, and social well-being. To effectively operationalize this mandate will require something truly disruptive. This report of the pilot National Network for Critical Technology Assessment provides evidence of what analytics can accomplish, and the critical components for a path forward as effective and disruptive as legislators envisioned.

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APPENDICES

Appendix Table 1A-1. Contributors to Vision Chapters

Note: Network members and independent contractors below contributed to the mentioned chapters in the form of written content, a grey box, or oral or written feedback.

Contributor	Chapter 2: Current And Historical US Capabilities In Critical Technology Assessment	Chapter 3: National Objectives, Technology Criticality, and Technology Assessment
Yong-Yeol (YY) Ahn	X	
John A. Alic	Written Content	Written Content, Grey Box
Lee Branstetter		X
Erik Brynjolfsson		
Rena Conti		
Robert Cook-Deegan	X	X
Baruch Fischhoff	X	X
Erica Fuchs	X	X
Geoff Holdridge	Written Content	X
Valerie Karplus		
Christie Ko		
M. Granger Morgan		Written Content, Grey Box
Tom Mitchell		Grey Box
Dewey Murdick	X	X
Jason O'Connor		
Elsa Olivetti		
Andrew Reamer	Written Content	X
Elisabeth Reynolds		
Andrew Schrank	X	X
Cassidy R. Sugimoto		
Kate S. Whitefoot	X	X

Contributor	Chapter 5: Dimensions of Critical Technology Assessment: Lessons from the Pilot Year Demonstrations	Chapter 5: Data Needs and Tradeoffs	Chapter 6: Long-Term Operations Model and Organizational Form: Lessons from the Pilot Year
Yong-Yeol (YY) Ahn			
John A. Alic		X	Written Content
Lee Branstetter		X	
Erik Brynjolfsson		Grey Box	
Rena Conti		Grey Box	X
Robert Cook-Deegan			X
Baruch Fischhoff	X	X	X
Erica Fuchs	X	X	Written Content
Geoff Holdridge			
Valerie Karplus		Grey Box	
Christie Ko		X	
M. Granger Morgan			
Tom Mitchell			
Dewey Murdick	X	Grey Box	Written Content
Jason O'Connor	Written Content		
Elsa Olivetti	Written Content		
Andrew Reamer	X	X	X
Elisabeth Reynolds	Written Content		
Andrew Schrank	X		Written Content
Cassidy R. Sugimoto	X	X	X
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Appendix 3A

The mission of the security of our nation and that of our allies: Critical technologies in this domain are those that can make a large present or future contribution to the effectiveness of offensive and defensive weapon systems, and improve situational awareness, communication, coordination, and intelligence. While some of these technologies are unique to national security applications, many are "dual use." For years this has given rise to export controls, under which international sales of technologies that have both civilian and military applications are forbidden or restricted. Balancing the conflicting objectives of protecting access to technology that is critical for national security but also for economic well-being has been a long-standing policy challenge. For example, over a decade ago, export controls prevented US firms from exporting financial and banking IT systems that contained high-quality encryption. This resulted in European firms, which had access to similar dual use technology, gaining a substantial comparative advantage over US domestic firms.

The mission of US economic well-being: Critical technologies in this domain are those that play the most central role in producing and sustaining a strong GDP, contributing to high labor productivity, and assuring a strong present and future US comparative advantage in global markets. Also critical is making sure that the supply chains that enable such technologies are robust. For example, today it is apparent that microelectronics (chips) are central to economic prosperity. However, assessing in advance which technologies are, or will be, critical to future economic prosperity and comparative advantage can be very challenging. For example, office automation and computer-based word processing existed for several decades before their contributions to productivity became apparent in economic assessments.[1]

The mission of US social well-being: Obviously a strong and growing economy, with high levels of employment, is important to social well-being. However, that alone is not sufficient to assure a high level of social well-being. Also important are technologies that are critical to assuring social equity and opportunity, wide and affordable access to quality education, and high levels of public health. One of the most compelling recent examples of a critical technology in the domain of social well-being is the advanced understanding in biotechnology that made it possible to rapidly develop mRNA-based vaccines to combat the SARS-CoV-2 pandemic.

[1] As Robert Solow (1987) memorably highlighted in his statement that one could "see the computer age everywhere, except the productivity statistics."

APPENDIX TABLE 3A-1. Examples of outcomes and metrics that may yield short- and longer-term insights about the impact of policies designed to address critical technologies in the three domains of criticality.

Domain of criticality	Cross-cutting short-term impact indicators	Technology-specific short-term impact indicators	Synoptic/ long-term impact metrics
US national security and that of our allies	Adequate/diverse raw material supplies; adequate/diverse intermediate product supplies	Defense budget as % of GDP; force ratios; wargame outcomes; DHS border security metrics	Years w/o major conflict; cumulative metrics of battlefield performance; effective arms control agreements
US economic well-being		For specific technology innovations: impact on US competitive position; change in employment levels; change in wage levels; other impacts on people	GDP; TFP; % employed; median household disposable income; GINI coefficient
US social well-being		For specific technology innovations: short-term equity impacts; results from focused survey research	Life expectancy; mean and variance in quality-adjusted life years; US and global environmental and ecological quality

APPENDIX TABLE 3A-2. Indication of quantitative and qualitative discussions of impacts across the three domains of criticality in the four areas of technology. "Discussed" refers to projects that qualitatively discuss a given national objective without making it their core metric of performance. Direction of arrow corresponds to strategic planning vs. impact-assessing metrics: left-facing arrows indicate historical assessment metrics and right-facing arrows indicate future strategic planning metrics. Numbers in the arrows correspond to the note numbers below.

National objective	Security	Prosperity			Social well-being		
Project topic area		**Economy**	**Productivity**	**Labor**	**Health**	**Climate**	**Equity**
AI			← 1	← 2			← 3
Semi-conductors	discussed	discussed	← 4, 5 →	6 →			discussed
Biopharma	discussed	discussed			← 7		
Energy and critical materials		8 →		9 →		discussed	discussed

- ← 1 Firm-level productivity increase following receipt of an AI-related patent
- ← 2 Change in quantity of job postings by a firm following its first machine learning (ML)-related job posting, both ML- and non-ML-related
- ← 3 Geographic concentration of AI-adopting firms
- ← 4 Historical economywide productivity increase derived from improved semiconductor performance
- 5 → Modeled economywide productivity gains from advanced "beyond-CMOS" semiconductor technologies and estimated commercialization costs of these technologies
- 6 → Geographically mapped semiconductor technician skill supply and identified clusters with potentially transferable skills
- ← 7 Essential medicine domestic supply chain resilience and barriers to advanced manufacturing adoption
- 8 → Electric vehicle pass-through cost sensitivity to a battery material price increase
- 9 → Battery manufacturing and supply chain labor demand and skill supply mapping

APPENDIX TABLE 3A-3. Evaluative metrics of projects focused on situational awareness as well as any technology-specific projects that addressed the innovation ecosystem. Direction of arrow corresponds to strategic planning vs. impact-assessing metrics: left-facing arrows indicate historical assessment metrics, right-facing arrows indicate future strategic planning metrics. Numbers in the arrows correspond to the note numbers below.

National objective	Science and technology (S&T) ecosystem			
Project topic area	Inputs		Outputs	
	Research funding	Research labor force	Scientific discovery	Technology commercialization
Situational awareness	← 1	← 2, 3 →	← 4	5 →
AI		← 6	7 →	
Semiconductors				8 →
Biopharmaceuticals				9 →
Energy and critical materials	10 →			11 →

1. Compared national research funding sources and international scientific funding streams
2. Inventoried science and engineering labor capitalization rate and identity characteristics
3. Scaled research productivity penalty incurred by scientists who pivot between topic areas
4. Analyzed national-level research productivity and disciplinary clustering in both established and emerging fields
5. Identified "on the shelf" research with high commercialization potential and characterized barriers and frictions in the technology transfer process
6. Measured level of AI-related skill development in the education of scientific disciplines
7. Quantitative assessment of potential applicability of AI to a variety of scientific fields
8. Identified technical bottlenecks of advanced ("beyond-CMOS") semiconductor technologies, estimated the cost to commercialize these technologies, and characterized the facilities used in published research on these designs
9. Assessed public perception of emerging biopharmaceutical and advanced manufacturing technologies, access and quality of generic drugs, and the mismatch between public and expert perceptions
10. Identified that additional supply of lithium domestically or in locations with lower risk of trade restrictions and increased use of cobalt-free batteries (such as lithium-iron-phosphate) will mitigate current supply chain vulnerabilities and their negative impacts and that increases in lithium supply and cobalt-free batteries could be accelerated through investments in innovations in novel lithium processing and cobalt-free battery chemistries
11. Identified that additional supply of lithium domestically or in locations with lower risk of trade restrictions and increased use of cobalt-free batteries (such as lithium-iron-phosphate) will mitigate current supply chain vulnerabilities and their negative impacts and that advancing the commercialization and adoption of existing cobalt-free battery technologies would help address these issues

Appendix 4A-1. Two-Page Area Summaries by Individual Investigators

For each area demonstration, two-page summaries from each investigator and supplemental information are available on the NNCTA website (nncta.org).

Appendix table 4A-2. Selected examples of emerging areas based on keyword search of publications, 2012–18

Year	Keywords	Representative papers
2012	['robust estimation,' 'optical waveguides,' 'batteries,' 'finite difference,' 'li4ti5o12,' 'wettability,' 'optical absorption,' 'cavitation erosion,' 'biomimetic,' 'seismic hazard,' 'superhydrophobicity,' 'chlorophyll a fluorescence']	Biodegradable black phosphorus-based nanospheres for in vivo photothermal cancer therapy
2016	['organic semiconductor,' 'organic field-effect transistor,' 'public interest,' 'autolysis,' 'surfaces and interfaces']	Borophene: a promising anode material offering high specific capacity and high rate capability for lithium-ion batteries
2016	['high speed,' 'organic semiconductors,' 'thermal radiation,' 'charge transport,' 'organic light-emitting diode,' 'copper nanoparticles']	Functional gradients and heterogeneities in biological materials: Design principles, functions, and bioinspired applications
2018	['image recognition,' 'image restoration,' 'matrix factorization,' 'manifold learning,' 'image denoising,' 'semi-supervised learning']	Parameter-free auto-weighted multiple graph learning: A framework for multiview clustering and semi-supervised classification
2018	['dos,' 'excitons,' 'organic photovoltaics,' 'boron nitride,' 'nanocatalyst,' 'electrochemical properties,' 'tin dioxide,' 'macrocycles,' 'photonic crystals,' 'capacitance,' 'transition metal,' 'clusters,' 'dye-sensitized solar cell,' 'optical absorption,' 'microwave synthesis,' 'mof,' 'spectroelectrochemistry,' 'li-ion batteries,' 'ferrocene,' 'organic light-emitting diodes,' 'oled,' 'metal oxide']	Zirconium nitride catalysts surpass platinum for oxygen reduction

Appendix 5A

DIMENSIONS OF DATA CHALLENGES

Timeliness and frequency of data collection. These will vary with context. For example, during the COVID-19 pandemic, new small and medium-sized firms were emerging daily in response to mask and respirator shortages. High-frequency data collection was important to determine whether US production capacity for these items could meet demand. In contrast, daily data collection for semiconductor manufacturing is unlikely to be of similar value since it takes 3 years and $10 billion to build a greenfield semiconductor facility, and 6 months to a year to redesign a chip to be produced in a different fabrication facility.

Accuracy and completeness of data collected. Is the sample complete or reflective of the total population? Can the data be trusted? For example, during the pandemic companies reported on business-to-business sites whether they sold masks and in some cases listed themselves as manufacturers although their manufacturing was not domestic. And patents may represent a limited sample of inventions (research shows that only 42% of new-to-market products are patented). Finally, data can be deceptive, depending on how they are presented. For example, news and policy outlets have reported an exponential rise in China's patenting, but researchers have shown that this rise is due to coinvention by Chinese employees at multinational firms with non-Chinese inventors as leads on the invention. The two reports may lead to different conclusions and policy actions, and by themselves are likely too little to effectively inform clear policy action.

Granularity. Data often lack the granularity necessary to answer important questions. For example, trade data don't provide product-level information or volumes, making it difficult to map critical supply chains. Paper or patent keywords or human-selected classifications may not capture the evolution of an emerging technology for which the most relevant terms may be evolving.

Privacy protections. Depending on the type of data, it may be important to maintain individual or firm privacy. In some cases (e.g., the US Census Bureau or Bureau of Labor Statistics), individual or firm privacy is maintained by the government; in others, it's by a nongovernmental third party such as an FFRDC or trusted university partner. For example, private firms prefer that supply chain data and data on composite materials used in emerging technology standards not be held by government.

Ease of access and the cost of collecting, storing, and validating data. Technology assessment is particularly challenging when data do not exist or are not in an easily accessible form. Researchers may need to collect data themselves (e.g., workers' knowledge and skills on a particular machine in a selected fabrication location), data may not be easily accessible if they are maintained by private entities (e.g., private firms' manufacturing or supplier data, or Amazon's supply chain data), or data may be geographically or institutionally distributed (e.g., efforts to understand national access to critical products may require collecting data from multiple private firms). Sometimes data are available but costly or slow to access, such as Census data. Data may be differentially available to different individuals, depending on their status, affiliation, cultural norms, or other factors. A final dimension of data collection, storage, and validation is the cost—in time or money—of those activities. For example, the collection and accurate interpretation of undocumented firm- or community-level data may require being on-site for weeks at a firm or in a community. Data validation may require contacting individual firms to confirm publicly posted information or crowd-sourcing information from locals. Storage costs depend on the data size.

INTERSECTION OF DATA TYPES AND DIMENSIONS

Appendix table 5A-1 shows the range of data used by different Network projects to answer different types of questions.

The technology's stage of the S-curve to some extent determines what data are available and their prevalence (in the case of measures of the economy or societal effects). Data used to assess technologies at an early stage of the S-curve generally focus on discovery and invention activity; data on inputs to the innovation process may include human capital, investment, and grants, often combined with bibliometric data, which are predominant at these stages (and generally publicly available). For technologies further up the S-curve, data related to commercialization and diffusion may include patent licenses and company products, but can be more challenging to collect because they are often proprietary. Data needs on the outputs of innovative activity include standard bibliometrics (patents and papers), products and services developed, measures of technology adoption, and productivity and labor market effects of technology use. As adoption increases, data on the development of supply chains, interactions between the technology and economic and social systems, and dependencies around the technology become critical for assessment. Common types of data here include product designs and attributes; user preferences; prices, production process inputs, tasks, and organization; labor requirements including skills, wages, and hours worked; and production, consumption, and trade quantities. Also needed are qualitative data (e.g., from ethnography, interviews, and surveys) from scientific and technical experts; organizations including firms, governments, and nonprofits; their (potential) customers, communities, and the public on technology commercialization and adoption bottlenecks; processes by which outcomes are achieved; on-the-ground realities of new technologies; organizational behavior; and implementation of rules and legislation.

APPENDIX TABLE 5A-1. Pilot demonstration methods. Overview of the various quantitative data used by NNCTA projects, organized by method type and critical technology. Direction of arrow corresponds to strategic planning vs. impact-assessing methods: left-facing arrows indicate historical assessment, right-facing arrows indicate future strategic planning or modeling. Number in the arrow corresponds to the note number immediately below, which provides detail on the specific methodological approach. When multiple methods are integrated their note number is duplicated.

	Early-stage technologies		Integrated technologies	
	Semiconductors	Artificial intelligence	Energy storage and critical materials	Biopharmaceuticals
QUALITATIVE METHODS				
Expert elicitation	1 ▶		2 ▶	3 ▶
Public elicitation			◀ 4	◀ 5
Survey methods		◀ 6	7 ▶	
Interviews	1 ▶		◀ 4, 2 ▶	◀ 5
QUALITATIVE METHODS				
Bibliometrics		8 ▶		
Econometrics		◀ 9		
AI, natural language processing	◀ 10	◀ 11, 8 ▶		
Techno-economic modeling	12 ▶		13 ▶	14 ▶
Scenario modeling			15 ▶	16 ▶
Structural economic modeling			17 ▶	

1. Expert elicitation and semi-structured interviews about technical bottlenecks to commercialization of the "beyond-CMOS" semiconductor technology with which subjects were most familiar

2. Expert elicitation and semi-structured interviews to characterize the expert mental model of the impact of energy storage technologies and supply chains, their supportive policies, and expert perception of public trust and acceptance of these technologies and policies

3. Expert elicitation and semi-structured interviews to characterize expert mental model of the impact of biopharmaceutical supply chains and generic drugs, their supportive policies, and expert perception of public trust and acceptance of these technologies and policies

4. Public survey elicitation and semi-structured interviews to characterize the public mental model of the impact of energy storage technologies and supply chains, their supportive policies, public trust and acceptance of these technologies and policies, and comparison of this model to the analogous expert model to identify discrepancies

5. Public survey elicitation and semi-structured interviews to characterize the public mental model of the impact of biopharmaceutical supply chains and generic drugs, their supportive policies, public trust and acceptance of these technologies and policies, and comparison of this model to the analogous expert model to identify discrepancies

6. Characterization of the size, age, and geographic distribution of AI-adopting firms using matched ABS and LBD weighted by macroeconomic statistics, and identification of organizational factors complimentary or integral to AI adoption

7. Characterization of the supply of battery manufacturing–relevant skills across regions, occupations, and industries and identification of potential labor mobility into high-demand skills from industries and occupations outside of critical technology applications using data from the US Current Population Survey, American Community Survey, and Occupational Employment and Wage Survey

8. Extraction of verb-noun pairs of AI-related research with natural language processing AI to create a semantic proxy of AI-related activities, and then analyze academic disciplines for the density of these pairings to determine applicability of AI to scientific fields

9 Analysis of firm-level output, productivity, and employment changes associated with AI-related patent awards and employment of AI-related researchers, their coauthors, or students using firm fixed effects models and event study approaches

10 Analysis of *Journal of Solid State Circuits* article titles and abstracts to characterize the proportion of publications on "beyond-CMOS" technologies that had access to a commercial fab

11 Analysis using a large language model (LLM) in conjunction with a variational autoencoder (VAE) to learn efficient encodings of unlabeled firm-level job posting data to analyze the effects of AI/ML-related hiring on firm-level demand for both ML- and non-ML-related labor

12 Technoeconomic model of the economic value and cost effectiveness of "beyond-CMOS" technology investment based on the technologies' performance characteristics, and the historical economic productivity gains of improvements in those characteristics

13 Technoeconomic model of the economic value of critical material supply resilience investments and policies by comparing the effects of critical material supply chain disruptions on the price and output of battery electric vehicles against a no-disruption baseline

14 Technoeconomic model of the applicability of advanced biopharmaceutical manufacturing techniques to significant drugs

15 Scenario modeling of future price impacts of supply disruptions on critical battery materials and resulting battery pack production costs

16 Scenario modeling of the impact of loss of access to a geographically concentrated supplier country on "essential" generic drug supply

17 Oligopolistic equilibrium model of the US automotive market to estimate how manufacturers would respond to changes in critical battery material supply by calculating a new partial-equilibrium outcome for the US vehicle market

APPENDIX TABLE 5A-2. Quantitative data used in the pilot year demonstrations. The various quantitative data used by NNCTA projects are organized by type and critical technology. Arrow direction corresponds to data used for strategic planning (right facing) vs. impact assessment (left facing). Numbers in the arrows correspond to the notes below, detailing the data source and, when relevant, collection process.

	Semiconductors	Artificial intelligence	Energy storage and critical materials	Biopharmaceuticals
Patents (e.g., USPTO)	1	2		
Publications (e.g., Dimensions/ Open Alex, Web of Science, SCOPUS, Dimensions)	3	4		
Technology roadmaps (e.g., IRDD)	5			
Government census data (e.g., ABS, ACS, APS)		6	7	
Government labor data (e.g., BLS, state-level labor and education data)	8	9		
Online job and skill data (e.g., O*NET)			10	11
Job postings (e.g., Burning Glass)		12		
Private firm data	13	14	15	16

1. US patent specifications from Harvard USPTO Patent Dataset (HUPD)
2. 7.6 million patents granted by the US Patent & Trademark Office (1960–2019) and Open Syllabus dataset
3. All titles and abstracts of articles published in the IEEE *Journal of Solid State Circuits* since 2012
4. 87.6 million publications from the Microsoft Academic Graph (1960–2019), spanning 19 disciplines and 292 fields
5. IRDS 2022 CMOS technology maps
6. Nationally representative survey, the 2018 Annual Business Survey (ABS), which since 2017 has data on firm-level adoption of advanced technologies, including AI, for more than 850,000 private sector firms matched to the US Census Bureau's Longitudinal Business Database (LBD) to obtain data on firm employment, revenue, and founder characteristics
7. US Current Population Survey, American Community Survey, and Occupational Employment and Wage Survey data
8. Sector-level productivity data from US Bureau of Labor Statistics
9. LBD data on firm employment and revenue
10. Labor and skill demand for battery-related manufacturing characterized using the O*NET survey instrument from BLS
11. Labor and skill demand for advanced pharmaceuticals-related manufacturing characterized using the O*NET survey instrument from BLS
12. Detailed job posting data from Lightcast (formerly known as EMSI Burning Glass), a high-quality data source with comprehensive coverage of over 40,000 online job portals since 2010
13. Firm and organizational data on CPU and GPU characteristics (desktop, mobile, and server and high-performance computing)
14. Firm-level size, geographic data, job postings, and production statistics
15. Firm-level historical data on critical material demand, prices, mining production, and mining costs
16. Private firm data relating to advanced pharmaceutical techniques, supply chains, and investment activities

APPENDIX TABLE 5A-3. Dimensions of data challenges in the pilot year's five topic areas.

	Situational awareness	AI
Type of data	Patents/publications/documents/citations/funding/production facilities/supply chains	Use of AI in firms/progress of AI/patents/citations/employment data
Ease of access	Relatively easy access to publicly available publications/patents, etc., but requires extensive curation and can require expensive licensing. Skewed toward Western and English-speaking countries. Less access to funding data at a granular level. Not possible to identify data that can be compiled in an intersectional way. Patents not representative of full body of inventive activities, because of trade secrets. Limited or no access to product, production, and supply chain data, which are mostly held by private firms	Unclear what to track/standards of measurement
Accuracy/ completeness	Limited to scope of data sources and languages of publication or countries of patenting. May be missing researchers and institutions, lacking comparability of documents or technology descriptions, unpublished work, and work in other languages	Different datasets have different limitations. Job postings are limited to those that post on that site. Patents only cover a percentage of activities. Surveys limited by response quality, rate, and population. Census surveys can be mandatory.
Timeliness/ frequency	Publication speed, some ability to see in real-time with preprints, technical reports, or venues like the Social Science Research Network	Surveys take a longer time but are more accurate. Patents take 2–3 years to come out. Job postings are immediate.
Cost of validating	Low cost: peer-reviewed papers Higher cost: preprints, technical reports, or venues like the Social Science Research Network	High
Data suppression	Corporate control of publications; governmental control of publications; privacy concerns with sociodemographic data	Incentives not to patent. Depending on the company, some incentives not to publish. Top-caliber individuals may not be recruited through sites.

	Semiconductors	Biopharmaceuticals	Energy and critical materials
Type of data	Production data/trade data	Production data/clinical trials/trade data/ FDA	Production data/trade data
Ease of access	Difficult to access from different firms, linkages aren't available/ accessible, treated as parts of other products (aggregation issues)	FDA data publicly available (easy to access), granular production in other countries difficult	Expensive to access production data from aggregators (e.g., Bloomberg)
Accuracy/ completeness	Lack of linkages, unclear production sites (what is produced), missing data, aggregated at high level; treated as parts of other things (aggregation issues)	Unclear production sites, differences in different types of data (e.g., devices vs. pharma), level of aggregation (especially for inputs)	Missing trade and production data, aggregation of different chemical products, uncertainty around types of intermediary inputs used
Timeliness/ frequency	Production data: firm-level (yearly) Trade data: country-level (monthly)	Production data: firm-level (yearly) Trade data: country-level (monthly)	Production data: firm-level (yearly) Trade data: country-level (monthly)
Cost of validating	Extremely high cost/potentially impossible to validate (production data) Trade data easier to validate but potential issues around noise; difficulty of auditing foreign manufacturers	Lower cost for FDA-approved devices/ institutions; difficulty of auditing foreign manufacturers	Extremely high cost, potentially impossible to validate at individual level (production data); possible to validate by end product sales. Trade data easier to validate but potential issues around noise and missing trade; difficulty of auditing foreign manufacturers
Data suppression	Incomplete disclosure for competitiveness reasons		Incentives exist for foreign/illicit entities to hide/reroute trade to avoid tariffs/sanctions/ embargoes

"Solutions to many of the challenges confronting our nation—from the environment to health care, from national security to the economy—require technology advances. Herein is a pathway to such advances."

NORMAN AUGUSTINE, Former Chair and CEO, Lockheed Martin; Former Under Secretary of the Army

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"This insightful report makes a compelling and well-documented case for a national office that spans agency missions, capable of deep analysis of critical technologies, the US position in these technologies, and the risks to continued US leadership and access. The country's economic and national security are dependent on a number of key technologies, and a better and earlier understanding of these dependencies and the risks to them has become mandatory."

JOHN HENNESSY, Professor and President Emeritus, Stanford University

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"US leadership in the critical technology areas that will be required for our global competitiveness can no longer be taken for granted. Using examples in several key technology areas, this must-read report shows how analytics can help inform our citizens, Congress, and federal agency leaders on where investments are needed to secure our future."

WILLIE E. MAY, AAAS President-Elect; Vice President of Research, Morgan State University; Former Director, National Institute of Standards and Technology

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"NNCTA's pilot year has demonstrated that we can—and must—develop and deploy analytical tools, processes, and human expertise to make decisions about our investments in the critical technologies that underpin our economic competitiveness, national security, and the equitable translation of the benefits of technology to all of society. The science of technology management is as important as any specific technology."

J. MICHAEL MCQUADE, Former Senior Vice President S&T, United Technologies Corporation; Former Vice President of Research, Carnegie Mellon University

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"NNCTA's report highlights the urgent need to restructure how we deploy national funds to support the commercialization of technologies critical to US advantage."

KATIE RAE, CEO and Managing Partner, The Engine