THE HAMILTON PROJECT

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Building the Analytic Capacity to Support Critical Technology Strategy

Erica R.H. Fuchs

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THE HAMILTON PROJECT MISSION STATEMENT

The Hamilton Project seeks to advance America's promise of opportunity, prosperity, and growth.

We believe that today's increasingly competitive global economy demands public policy ideas commensurate with the challenges of the 21st Century. The Project's economic strategy reflects a judgment that long-term prosperity is best achieved by fostering economic growth and broad participation in that growth, by enhancing individual economic security, and by embracing a role for effective government in making needed public investments.

Our strategy calls for combining public investment, a secure social safety net, and fiscal discipline. In that framework, the Project puts forward innovative proposals from leading economic thinkers—based on credible evidence and experience, not ideology or doctrine—to introduce new and effective policy options into the national debate.

The Project is named after Alexander Hamilton, the nation's first Treasury Secretary, who laid the foundation for the modern American economy. Hamilton stood for sound fiscal policy, believed that broad-based opportunity for advancement would drive American economic growth, and recognized that "prudent aids and encouragements on the part of government" are necessary to enhance and guide market forces. The guiding principles of the Project remain consistent with these views.

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Building the Analytic Capacity to Support Critical Technology Strategy

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Carnegie Mellon University and the National Bureau of Economic Research

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This policy proposal is a proposal from the author. As emphasized in The Hamilton Project's original strategy paper, the Project was designed in part to provide a forum for leading thinkers across the nation to put forward innovative and potentially important economic policy ideas that share the Project's broad goals of promoting economic growth, broad-based participation in growth, and economic security. Authors are invited to express their own ideas in policy proposal, whether or not the Project's staff or advisory council agrees with the specific proposals. This policy proposal is offered in that spirit.

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Abstract

Fuchs proposes the creation of a national capability for cross-mission critical technology analytics to build the intellectual foundations, data, and analytics needed to inform national technology strategy. Fuchs's proposal would create a critical technology analytics (CTA) federal program focused on informing technology policy decisions that are cross-mission in nature—for example, spanning national security, economic prosperity, and social welfare—and thus beyond the purview of any one federal agency or private firm. The program would have a highly flexible, distributed structure capable of rapidly mobilizing experts from academia, industry, government laboratories, and government departments.

Contents

Introduction

Over the last half a century, the world and the United States of America's position in the world has changed dramatically as the global geopolitical balance of scientific, economic, and production capabilities has shifted away from US dominance. The US is no longer in a singular position of scientific and technological leadership, and China is now the largest producer and second largest market in the world (Branstetter, Glennon, and Jensen 2018; Segal 2019). At the same time, the US faces challenges at home. Domestic economic inequality has increased (Autor, Katz, and Kearney 2008; Autor 2014; Leonhardt 2017; Autor 2019), social mobility has declined (Chetty et al. 2017; Chetty et al. 2020), and political polarization is on the rise (Autor et al. 2020a).

Central to both of these trends are trade and technology. While earlier research highlighted the benefits of global trade (Ricardo 1817) and technology change (Solow 1957), empirical evidence has increasingly pointed to how these benefits can be uneven: globalization can decrease some wages (Samuelson 2004; Autor et al. 2016) and innovation (Fuchs and Kirchain 2010; Fuchs 2014; Autor et al. 2020b) domestically. Import competition, on average, has a negative impact on employment and earnings in trade-exposed local labor markets (Autor, Dorn and Hanson 2013; Acemoglu et al. 2016), and there has been a rise in political extremism in locations hardest hit by trade (Autor et al. 2020a). Further, certain forms of technology change, such as automation, can reduce jobs (Acemoglu, Lelarge, and Restrepo 2020) and exacerbate inequality (Autor et al. 2003).

Given this evidence, some intellectual leaders have suggested slowing the progress and adoption of technology (Piore 2018; Acemoglu, Lelarge, and Restrepo 2020) and gradualism as a principle for trade policy (Autor et al. 2016). Others have raised concerns about the US losing global technology competitiveness, particularly to China (Augustine and Lane 2020). These experts argue for dramatically increasing the funding of science and technology, particularly in "critical" technologies (Segal 2019; Johnson and Gruber 2019; Augustine and Lane 2020)—that is, technologies "essential for the United States to develop to further the long-term national security or economic prosperity of the United States" (National Defense Authorization Act of 1990, PL 101–189). Some of these experts further argue that through improved geographic distribution of science and technology funding, these investments would also reduce inequality and increase jobs domestically (Johnson and Gruber 2019).[1,2]

Missing from these debates are win-win technology choices—strategic technology investments that could meet multiple national objectives: improving national security and economic resiliency, expanding export opportunities, and supporting good jobs.

There are recent examples of win-win technology choices. Combemale et al. (2020) show that not all technology leads to wage and skill polarization; indeed many of the technologies on today's critical technology lists may lead to better jobs for high school graduates (Combemale et al. 2020; Combemale and Fuchs 2020).[3] Likewise, Fuchs (2020) argues that building the infrastructure of the future not only increases equity in access to energy and communications, resiliency, and security, but it could also be leveraged to expand domestic manufacturing, grow capabilities in critical technologies, and increase the number of good jobs. Here, the skills relevant to deploying and managing sustainable and smart infrastructure—from the concrete layer to the foreman to the engineer to the data infrastructure and machine learning software developer to the cybersecurity expert—have corollaries in resilient grid infrastructure, privacy-preserving health infrastructure, and intelligent manufacturing (Fuchs 2020).

The above examples are in manufacturing and not by coincidence. US manufacturing is one of the areas that has been most negatively impacted by trade and import competition. Recent experiences during COVID and beyond have highlighted the significance of product access, the domestic manufacturing of certain critical products and intermediate inputs, and a broad array of manufacturing capabilities for national security, economic prosperity, and social well-being. At the same time, manufacturing has disproportionately low venture capital funding (compared to software), comparatively higher R&D expenditures and innovation outputs, and higher wages for high-school-educated workers, and overseas manufacturing has a negative impact on domestic innovation (Fuchs and Kirchain 2010; Fuchs 2014; Fuchs et al. 2019; Autor et al. 2020b). These facts together make a clear case for government intervention.

Yet, neither funding all technologies domestically nor manufacturing all products domestically is feasible. Policymakers need data and analytics to inform the value of various potential investments for different national missions, and where strategic win-wins exist across missions, so that limited funds are spent in ways that realize legislator and agency goals. This requires investing in the interdisciplinary scholarship necessary to build the intellectual foundations and data and analytic tools to drive new paradigms of how to govern in the decades ahead. Acting upon these insights may require new government institutions, particularly in cases where individual agencies (e.g., the Department of Commerce, the Department of Defense, the Department of Energy, the Department of Labor, or the Department of Transportation) optimizing investments to achieve their specific mission may lead to suboptimal outcomes.

I propose a federal program to increase the national capacity to both rapidly spin up and pre-emptively perform the cross-mission data and analytics needed to inform critical technology strategy. In this proposal, I first provide background on the concept of critical technologies, how past approaches to critical technologies have failed to make their way into policy, and why a cross-mission approach is needed.

I then argue that the analytic tools exist to identify win-win pathways across national objectives, but the federal government today lacks access to these tools, and private companies and academia lack incentives to put together the integrated interdisciplinary teams to build these tools and identify these win-win pathways. I unpack three cases—personal protective equipment (PPE) shortages, semiconductor shortages, and shortages associated with ramp-up of energy storage for electric vehicles (EVs)—that illustrate how government could have in the recent past (PPE), could now (semiconductors), and could in the future (energy storage) preemptively and in real-time build analytic tools to improve the security, prosperity, and well-being of all citizens.

I next argue that the US government needs to create a distributed, critical technology analytics capability focused on win-win solutions across missions. The proposed capability is neither a top-down program to coordinate science and technology investment nor is it a dramatic shift in the excellent existing science and technology innovation system; rather, it is a small but important tweak (and addition). I argue that to meet today's challenges, such an institutional capability needs to 1) be strategic and forward-looking, 2) work on inter-agency projects, 3) leverage interdisciplinary-integrated teams, and 4) be implemented in a highly flexible distributed model capable of rapidly mobilizing and reconfiguring star private sector and academic talent, data, and resources.

Finally, I respond to questions and concerns that often arise when discussing a critical technology analytics program, including political challenges, department and agency infighting challenges, the challenge of cultivating and maintaining a strategic rather than a statistical approach, and the infamous question of "isn't this industrial policy?" I conclude by summarizing how all citizens and policymakers would benefit should this type of national cross-mission critical technology analytic capability be implemented.

The Challenge: Is Technology the Answer or the Problem?

Defining Critical Technologies

From World War II to the present day, US security and prosperity in a global economy has relied on US leadership in technology. In the 1990 National Defense Authorization Act (PL 101–189), Congress defined "critical technologies" as those that are "essential for the United States to develop to further the long-term national security or economic prosperity of the United States." Recent crises have highlighted the limitations of this definition. The COVID pandemic highlighted the criticality of technological leadership not only for security and prosperity, but also for measures of social well-being like human health. Consider, for example, how US leadership in mRNA manufacturing and proline stabilization techniques helped the US ensure its own access to the best vaccines during the pandemic. The last two years also highlighted that access to certain products (e.g., masks) and their intermediate inputs (e.g., melt-blown polymer for the mask material and elastic for ear loops) can be critical to national security, the economy, and well-being, independent of technological leadership. Figure 1 provides a summary of how the concepts of social well-being and access might be integrated with the notion of critical technologies.

Technology and supply chain strategy have cross-cutting implications for national security, prosperity, and social well-being, including equity:

- When there were medical supply shortages, small hospitals, rural doctors, essential workers, minorities, and those in the lowest income classes were hardest hit.
- Energy outages and environmental damage to infrastructure had significant costs for national security and private companies (consider the semiconductor losses after power outages in Texas), and also often disproportionately affect minorities and those in lower income brackets.
- When there were semiconductor shortages, jobs were lost (particularly of manufacturing operators) and fewer cars were produced.

Strategies regarding technology development (or innovation) and access are also inextricably linked. Innovation can be key in re-architecting supply chains and overcoming supply chain bottlenecks. Short-term redesign (e.g., shifting to cobalt-free batteries or reconfiguring semiconductor designs to circumnavigate shortages) can shift and overcome supply chain bottlenecks. In the longer term, innovation (e.g., skin patch delivery of vaccines reducing the quantity of vaccine required and removing the need for the cold chain) can fundamentally change international competition.

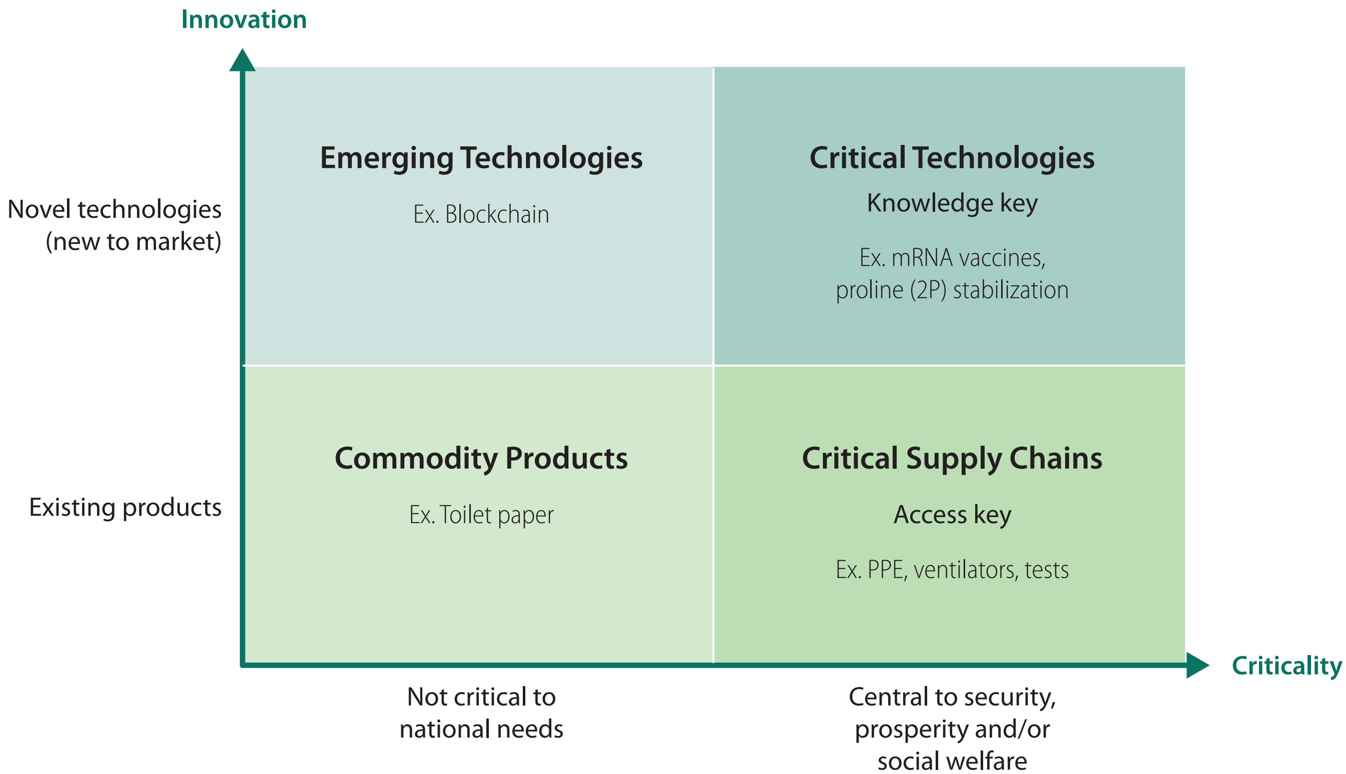
(A Lack of) Scholarship on Critical Technology Strategy

The intellectual underpinnings to inform technology strategy at the national level are limited. For decades, the field of economics placed significant focus on developing models and empirical studies on the benefits of global trade (Ricardo 1817) and technology change (Solow 1957). In the field of management, the need for technology strategy for firms only first emerged in the late 1970s (for a historic overview, see Kantrow 1980). Likewise, while scholars such as Gene Shkolnikov produced generations of political science scholars focused on technology and industrial expertise, the field of political science has increasingly moved toward a focus on theory and away from phenomenologically driven research. Across these fields, the closest existing body of scholarship is that on national innovation systems (c.f. Nelson 1993). Leading scholarship today in this space can be found in Industry Studies (which remains as an association but for which the original Sloan Foundation funding was discontinued), and in papers published in journals such as *Industrial and Corporate Change* and *Research Policy*.

Unfortunately, the extant research provides little guidance on how a nation should make strategic technical decisions across domains while looking simultaneously across multiple national objectives. Where this work exists, there is still a pressing need to translate scholarship on national competitiveness into organizational and strategic guidance for action. Important translation to policy implications can often be found in *Issues in Science and Technology*, in

FIGURE 1

Dimensions of Criticality: Adding Access and Social Well-being



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interdisciplinary field journals focused on energy and the environment, and in the policy, perspectives, or comments sections of the *Proceedings of the National Academy of Sciences*, *Science*, and *Nature*. Relatedly, while extensive operations research has sought to understand supply chain resilience and associated investments from the perspective of the firm (Simchi-Levi et al. 2015) or in specialized domains (Alderson et al. 2015; Brown, Carlyle, and Wood 2008; Çelik et al. 2012; Craft, Wein, and Wilkins 2005; Ergun et al. 2011; Golany et al. 2009; King and Muckstadt 2009; Lee et al. 2006; Simchi-Levi et al. 2015; Wein et al. 2003), less has been done to instead assess supply chain resilience and associated investments in terms of a national strategy.

Technology and investments therein can be designed to realize more than one objective, but only if the right incentives are in place to do so. In mission-oriented programs, it is rare for science and technology investments to explicitly be focused on achieving multiple missions. Similarly, while increasingly scholars have worked to quantify synergies and trade-offs—for example, between energy security, the environment, and jobs (c.f. Hart 2019; Sabel and Rodrik 2019; and in particular Baker and Nock 2019)—I am aware of no research to date (including my own) that seeks to quantify trade-offs and win-wins across a broader range of national objectives.

Current Government Efforts to Support Critical Technologies

Given the above, while there is bipartisan interest in investing in "critical technologies," the US lacks the data, intellectual foundations, and policy roadmap for how to act. There is no agreement on what makes a technology critical, much less measures to inform the extent of criticality. For example, while the 1990 National Defense Authorization Act (PL 101–189) defines "critical technologies" as "essential for the United States to develop to further the long-term national security or economic prosperity of the United States," what makes a technology "essential to develop" for long-term national security? Should this essentiality be a function of the technology's current and future applicability to warfare or the potential to create technological surprise? How would one determine if a technology is important to develop for economic prosperity, and how would one define if its contribution to economic prosperity is sufficient to count as critical? Should all general purpose technologies (c.f. Bresnahan and Trajtenberg 1992) be considered critical? How "general" do they need to be? What about technologies that disrupt existing businesses (c.f. Bloom et al. 2021)? Creating conceptual frameworks and dimensions and quantitative measures of a technology's criticality will be important steps.

Even if a critical technology could be identified, more work is then necessary to connect a technology's criticality to appropriate and effective policy actions. Prior efforts around critical technologies have focused on naming or listing which technologies are "critical" in reports and lists that have struggled to find their way into policy (c.f. Mogee 1991; Congressional Research Service 1993; Bimber 1994; Popper and Wagner 2003). With such reports, lack of action should not be surprising: there is a long path from, for example, listing a technology such as "energy storage" as critical to prescribing a specific policy action like "fund innovation in cobalt-free batteries and novel techniques for lithium extraction while increasing access to capital for companies commercializing these technologies." In addition, while government funded, these reports lacked a way to ensure that the reports had demand from and were acted on by policymakers.

There are a myriad of other questions that are difficult to tackle without better supporting analytics; for example, when, for whom, and for how long should a technology be kept secret? During World War II, compulsory secrecy was effective at keeping sensitive technology out of public view, but it had a cost in that it caused firms to shift their patenting away from areas with compulsory secrecy, with effects persisting through at least 1960 (Gross 2022). Secrecy also restricted commercialization and impeded follow-on innovation. Knowing which countries already have knowledge of and the capability to implement a technology would be essential information in informing whether and how a technology should be kept secret and for how long given potential downstream costs.

Other difficult questions involve the context of production. When is it necessary for a technology to be manufactured onshore or with allied nations? Is having national firms with international presence enough or is onshore production necessary? Does that onshore production need to be done by national firms or is foreign direct investment sufficient? Is there a possibility for innovation to transform geopolitical dynamics or supply chain constraints? In other words, do we need to change the location of production in the existing supply chain or the technology or design and thus the supply chain itself?

Developing the (Missing) Data and Data Strategy to Inform Critical Technology Strategy

Rigorous analysis and eventual answers for many of these policy questions will require improved timely awareness of both US and global capabilities. Currently, the US government lacks systematic mechanisms to assess its relative global strengths, weaknesses, and opportunities in technology (National Academies of Sciences, Engineering, and Medicine 2019). It also lacks awareness of the long chain of suppliers involved in producing products critical to national missions.

It will be a challenge to develop capabilities for timely awareness in a way that is strategic, problem focused, and anticipatory without falling into the trap of exhaustive data collection or solving today's problems rather than investing to transform tomorrow's bottlenecks. With modern data and analytic tools, this timely situational awareness is increasingly attainable, although comprehensive monitoring of global capabilities in production and human capital is likely to require substantial investments in institutional and research capabilities and advancements. This is one of the needs that this proposal addresses.

Multiple entities are currently actively working on building capacity to improve the US's timely awareness of technology and production capabilities. These entities include the National Science Foundation's (NSF's) National Center for Science and Engineering Statistics; the NSF's Technology, Innovation, and Partnerships (TIP) Directorate; the Department of Defense and specifically the National Security Agency; and the Department of Commerce through the Economic Census and International Trade Commission. For example, the Defense Advanced Research Projects Agency (DARPA) is pushing the possibility frontier in terms of scraping public data for enhanced supply chain transparency because timely awareness of production capabilities is one of the hardest of these problems analytically. Despite the interest in building these capabilities, little strategic thought is being put into how and where policy can best leverage continuous government data collection—spinning up data collection using modern algorithms—versus other tools (e.g., public-private partnerships). Again, this is one of the needs that this proposal addresses.

Successfully developing the intellectual foundations and analytics to inform critical technology policy also presents unique organizational challenges. Critical technology and supply chain decisions have implications for multiple, if not all, of a nation's missions, including national security, economic prosperity (including jobs), and social welfare (including health, environment, and equity). In contrast, government departments are generally focused on a single mission. This proposal does not seek to make changes to how the Executive Branch and its agencies are organized. Indeed, scholars have long emphasized the importance of the diversity and redundancy of the US innovation system, where agencies have different missions and can take differing—at times complementary and at times opposing—funding roles (c.f. Nelson and Winter 1977; National Research Council 1999). At the same time, the current system leaves a hole whereby each agency perfectly fulfilling its mission could lead to suboptimal outcomes compared to if all national missions were taken into consideration.

There are also practical issues at hand. For example, a central problem for the US government is which department keeps what data, how departments can access non-public data held by other departments, and how those data sets link to each other. As these efforts proceed, each department will need to continue to build and retain its expertise (e.g., NSF covering the National Center for Science and Engineering

Indicators, the International Trade Commission continuing to cover trade data).

In contrast to the activities of the individual departments, the national capability for critical technology analytics would be focused on forging a strategy for how emerging capabilities could enhance, disrupt, and transform existing departmental capabilities; where linking between the data sets may be particularly needed; and in what context continuous data collection versus question- or crisis-specific institutional or algorithmic approaches should be leveraged. By working through pressing cases and questions, the national program on critical technology analytics should focus on what dimensions of data and data infrastructure may be important for solving different types of problems and learn to avoid getting mired in infrastructure or cross-department politics. Here, drawing broader lessons from solving individual problems and maintaining a problem-focused and multi-mission perspective may be particularly important in charting a unique and valued path across existing programs and departments.

The Proposal: Building a National Capability for Cross-Mission Critical Technology Analytics

To effectively advance US policy in technologies critical to national security, economic security, and social well-being will require establishing a new government program that can bring expert knowledge from government, industry, and academia together in integrated interdisciplinary teams to inform critical technology policy.

This program would develop cross-mission synergies in government science and technology decision-making, effectively complementing and coordinating relevant activities in existing government departments. By creating a national capability in critical technology analytics, the program would find solutions that work toward multiple missions. That outcome would improve on current approaches, where each department can perfectly fulfill its own mission and yet end up with sub-optimal outcomes for critical technologies once all missions are considered.

The critical technology analytics program (henceforth "CTA program") should focus on 1) translating into government how modern data and analytic tools and innovative new approaches to public-private partnerships can be leveraged to build timely situational awareness as those capabilities and options continue to evolve, 2) identifying opportunities for innovation to improve US economic and political strength and stability, and 3) demonstrating early on how work on specific critical technology problems can generate broader lessons, including what data to collect, what technology to monitor, how to set priorities, and more generalizable frameworks for critical technology policy.

An institutionalized CTA program would build the intellectual foundations, data strategy, and analytic methods to inform critical technology policy. In doing so, it would need to build the analytical foundations for what makes a technology critical and how much data are valuable in what situations. Further, it would need to build tools (institutional and algorithmic) to spin-up timely situational awareness and to assess the contexts where the moving frontier of institutional and algorithmic options have greatest value. These problems require talent not easily attracted by or recruited to individual agencies, from disciplines that normally are unlikely to work together, no less on government problems. Further, these problems are uniquely cross-mission in nature as they span multiple departments. While all-of-government efforts exist, cross-departmental efforts are known to be rare and challenging in the US government.

Guiding Principles for a CTA Program

To meet these challenges, my proposed CTA program would

- *be strategic and forward-looking*, for example, work would be conducted on timelines on the order of six months to two years rather than days or weeks (and think about problems on two- to 50-year timelines);
- *have integrated interdisciplinary expert teams* that leverage leading technical expertise in engineering and the physical sciences, modern data analytics (machine learning, operations research, natural language processing), and the social sciences (economics, political science, sociology, history);
- *operate through a highly flexible, distributed model* capable of rapidly mobilizing and reconfiguring star private sector and academic talent, data, and resources; and,
- *work on interagency projects*, including being able to receive work from multiple agencies on a single topic.

I unpack the importance of each of these dimensions below.

Be Strategic

There are two pitfalls that would diminish the program's ability to be strategic: focusing on short-term problems and functioning as a data monitor. Avoiding becoming the permanent place to do particular tasks for government supports not only maintaining this strategic focus but also being able to maintain positive relationships with other agencies.

A national cross-mission capability that is strategic and forward-looking would need to avoid getting dragged into solving the short-term problems of the day or week and instead leverage the urgency of those challenges to inform how to prospectively avoid them.

To maintain a strategic focus, the program should also avoid becoming the permanent place to maintain certain types of work. For example, the CTA program should not become the place that monitors technology and supply chains. Instead, it should leverage external talent and neutral third parties to demonstrate what is possible with modern data and analytic tools or innovative public-private collaborations. Thus, the CTA program would not focus on building data infrastructure long-term but rather on strategic and quantitative guidance on how to think about building such capabilities including what data to collect and demonstrating what capabilities are possible.

Have Integrated and Interdisciplinary Teams

Effectively bringing relevant data and analytic insights to critical technology policy will require being problem oriented rather than being data or tool oriented. Problem orientation will require bringing together integrated teams where those with technical and sectoral knowledge can identify the core problems and what data and analytic information should inform solutions. Given the current foci of academic programs, staffing the program is a central concern. Here, the CTA program's focus on bringing together integrated teams to solve real-world technology policy problems would also serve to incentivize the building of new capabilities in academia. Currently, academia is primarily organized around building new theory in siloed disciplines or developing new methods or tools. Instead, a cross-mission CTA program would fund and thus incentivize research focused on real world policy problems, undertaken by integrated teams across engineering, data science, policy programs, and other fields.

Operate through a Highly Flexible Distributed Model

While the CTA program would need internal capability to identify the highest priority problems to address and organize the work, it should not build a substantial capacity of government employees. Rather, the work of a cross-mission CTA program would require knowledge, talent, and infrastructure distributed across the private sector, government agencies, and academia. Further, different challenges would require a different distribution of skills and experience. Indeed, for the same challenge, that distribution can change over time. The CTA program should be organized to flexibly tap different experts to work on challenges, constituting and re-constituting public-private partnership made up of problem-specific thought leaders from industry, government, and academia from across the country.

Work on Inter-Agency Projects

To maintain its cross-mission focus, the CTA program would need to work across multiple government departments and agencies and receive broad buy-in. To achieve this relevance and buy-in, the work of the program will be organized in particular ways. First, it would have an advisory board with leaders from government departments as well as from academia and industry (perhaps selected out of the National Academies of Science, Engineering, and Medicine). Participation by government department leaders would help ensure the CTA program stays connected to department-specific challenges and maintains policy relevance.

Second, each project undertaken by the CTA program should have a project-specific advisory board from the relevant agencies, industry, and academia. Some projects would be proposed by the program, and agency advisors would be recruited. Over time, as the program becomes more established, government agencies would increasingly suggest areas where they see the program's cross-mission approach and analytics as being needed. Ideally, the externally proposed projects that the CTA program would take up would have interest from multiple agencies, and those agencies should provide significant funding.

Third, to enhance buy-in and the efficient transfer of outcomes, government departments should have people on rotation at the program. These rotational members or "liaisons" could sit with academic or industry teams addressing specific problems or could join the internal CTA program staff.

Fourth, to ensure that new reports do not fail to have policy action, CTA advisory board members and government advisors on project advisory boards for specific studies should be required to write a public-facing document on how they will act upon the program's recommendations.

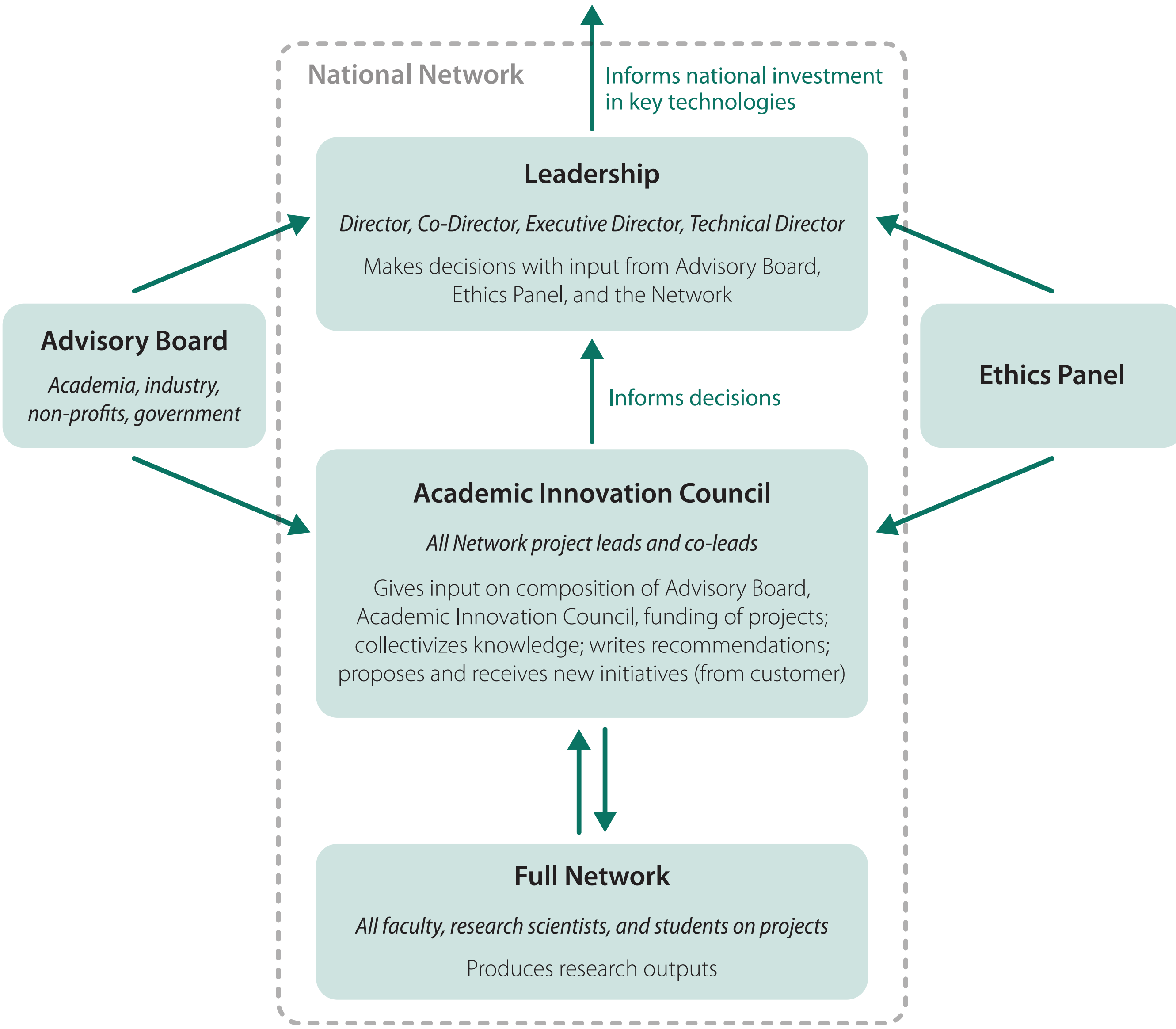
Finally, to ensure the capabilities developed have uptake within agencies, government departments would, in parallel, have or develop internal competencies into which they would merge the strategic cross-mission insights or new analytic capabilities they contracted from the CTA program. These competencies may be particularly well developed by government liaisons on rotation at the program, both during their rotation and when they return to the relevant agency. While the expertise of the CTA staff would be primarily around its capacity to stand up and operate these teams, a small number of staff would be experts in intragovernmental affairs, working with the advisory council and advising the analytic team on potential landing spots, stakeholders, and opportunities in this space.

The Critical Technologies Analytics (CTA) Program

The CTA program should start as a small pilot program and become larger over time. It would focus on building capabilities across the country through a flexible distributed structure (hereafter referred to as "the Network") to determine best practices. In its first year, the Network would have an annual budget of $4 to $5 million, which would then grow to $10 million over the next four years. During that time,

FIGURE 2

Organization of a National Network on Critical Technology Analytics



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the Network would focus on building the intellectual foundations, academic, industry and government partnerships, and overall national capacity. While the Network should be funded by government (such as is being done for the pilot year by the National Science Foundation's TIPs Directorate), the building of the broader national capacity should ideally be enhanced by additional private and public sources, such as foundations and industry. The Network would, in parallel, need to build close relationships and encourage internal investments in data expertise and infrastructure by national statistical agencies, including the US Census Bureau, the Bureau of Labor Statistics, and the National Center for Science and Engineering Indicators.

Figure 2 describes the pilot program structure. The program would be directed by a leadership team. The Advisory Board, as described above, would have members from relevant government agencies who would help to identify areas of research and other scoping issues. However, the Director would ultimately determine the program's agenda. The Review Panel would offer ongoing feedback on the distributional implications of the program's work and other issues around equity, fairness, and impartiality. The Academic Innovation Council would facilitate the execution of the analysis itself, with all project leads being members of the council for the duration of their projects. The full set of experts working on CTA projects would make up the full Network

FIGURE 3

Flow of Work for an Eventual Critical Technology Analytics Program

Advisory Board of Thought-Leaders

From Academia and Industry, plus OSTP Director and Department Heads

Critical Technology Analytics Program

Program Director

Deputy Director

Administrative staff

10–15 Rotating program managers

- 7–10 with domain-specific expertise: AI, cybersecurity, semiconductors, energy technologies, biotechnology
- 3–5 with expertise in the social sciences: economics, history, sociology, psychology, political science but focused on technology policy (e.g., science communication, the political economy of technology transitions)

5–8 Department rotational positions

- DoD, NIH, DOE, DOT, DOL, etc.

Flow of work

Scans for national challenges across missions and potential solutions

- With input from the Advisory Board
- Has conversations with government departments, executive, and legislative branches
- Has conversations with experts from academia and industry across the country

Broadcasts the identified problem and searches for teams

- Sets up an external advisory board for each project consisting of relevant national thought leaders and agency representatives
- Supports external learning for academic, government, and industry players
- Decides on any matching funding from agencies to be offered

Funds one or more integrated teams to solve the real-world problem

- Funding is through 1–5 year contracts at combinations of universities, industry, and government laboratories; average contract is 1–2 years; 5-year contracts have annual milestones
- Recruits agencies to complement and expand program funding, and thus impact
- Agencies may send additional rotational positions to work directly with the integrated team

Integrated teams produce data, models, analytic results, and reports on next steps and lessons learned

Program managers produce a report on lessons

- Reports on immediate lessons, generalizable lessons for national strategy, and key next steps for the nation including for the critical technology analytics program and subsequent projects to be funded

Relevant department rotational positions produce a joint report on recommended next steps

- Recommends future work to be done through the cross mission critical technology analytic program (individually and jointly by departments); capabilities to be built internally; and existing transition and ongoing transition plan (ramp-up of personnel for model transfer, internal data collection, etc.)

Government department heads release a public statement on a strategic plan

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and would be distributed across academia, government, and industry.

Over time, the CTA program would become a formal government program with an annual budget that ramps up to roughly $50 million (in 2022 dollars) and with an increasing capacity to focus on cross-mission problems. About 60 percent of the budget would be expected to come from funding from other government agencies, when the projects that those agencies propose are taken up by the CTA program. Figure 3 offers a diagram of the flow of work for the CTA program. The shaded box at the top of the figure shows that an Advisory Board would continue to inform the work, and the next shaded box shows how the CTA program would be organized. The leadership team and a small rotating group of experts would work for a government agency or independent government entity like a university-affiliated research center or a federally funded research and development center. But, like the pilot program, the bulk of the work would be done by a distributed network of experts across the country.

To maintain a focus on drawing upon "best in class" across the country, this cross-mission CTA program should start small, with a Director, Deputy Director, and initially approximately 10 expert staff from the physical or biological sciences, engineering, social sciences, or history who rotated into their positions from academia, industry, or government laboratories; and approximately 5–10 experts on rotation from government departments. The initial staff should focus on the transition of capabilities to government in order to keep the focus on building and leveraging the external capacity across the nation. Eventually, the staff might grow as large as 50 rotational staff, with 30 expert staff in three- to five-year positions from industry or government and 20 experts on one- to five-year rotational positions from government. Contract authorities that might serve well to mobilize academic talent and industry capabilities from across the nation (and flexibly configure and reconfigure teams) and facilitate private sector data sharing include an Other Transaction Authority or a subcontract within an agency or a federally funded research and development center.

Between one-half and two-thirds of the CTA program's funds would be spent on contracting out work done by the distributed network. Funding would increase over time. After the pilot phase, the formal CTA program should be initially funded with an annual budget of $15 million (in 2022 dollars, with $10 million of that funding external projects); by year 5, $25 million (with $15 million funding external projects); and by year 10, $50 million (with $25 million funding external projects). That slow expansion will help the program increase internal government capacity while leveraging star talent across the country and maintaining high standards. Annual funding of $50 million in 2022 dollars would be of equivalent scale to the Office of Technology Assessment's budget when it closed in 1995.

The success of the CTA program would rely on the leadership having the necessary independence to set priorities. That team would oversee a process that scanned for global technology and supply chain capabilities, engage with scientific and technological experts, and consult with department agencies to understand their existing approaches to problems. The CTA program should be flexible enough to form teams of academics and industry experts as well as public-private partnerships; such partnerships can sometimes serve as a neutral third party between industry and government. After the CTA program releases proposals, other government agencies would be required to issue public-facing documents with strategic responses to the proposal. Lessons on how to provide the CTA program with the necessary independence should be taken from approaches to the work done by the Congressional Budget Office, the Government Accountability Office, and the Office of Technology Assessment.

Where the program is situated promises to have significant implications for the identification of problems and for the program's ability to serve multiple agencies. An extended conversation of the pros and cons of different agency placements and how problems are identified would be a valuable outcome of the initial National Network pilot. To maintain a cross-mission focus, the program's home must not be in a department (e.g., the Department of Defense, the Department of Energy, or the National Institute of Health) focused on a single mission. Obvious potential placements would include reporting to the Office of Science and Technology Policy (perhaps as a subcontract out of the Science and Technology Policy Institute), the NSF's new TIP Directorate, or the Department of Commerce.[4] Notably the first two are not mutually exclusive; for example, the program could eventually be funded by NSF TIP, with the program funded as expanded capacity at, or a subcontract through, the Science and Technology Policy Institute's federally-funded research and development center, and the director of the Office of Science and Technology Policy on the Advisory Board. Indeed, NSF TIP is a particularly promising agency owner, as it is directed in the Innovation Bill to support the quadrennial science and technology review and to annually update the US's list of key technologies.

Early Tasks for the CTA Program: Case Studies

Early tasks for the CTA program should include 1) developing metrics to quantify what makes an emerging technology capability or access to a particular product critical to multiple national missions (security, economic growth, health, equity) and 2) building a framework for thinking about what type of data are needed for timely situational awareness in these technology and supply chain areas critical to national missions.

However, the program would be ill-served to immediately attempt a holistic effort at developing such metrics or such a framework. To start, the program should undertake deep dives into select technology areas, relate how the specific problems they are facing inform broader long-term strategic insights, and determine how approaches may or may not generalize across sectors. These deep dives should focus on solving those specific problems, seeing what data are needed to solve those problems and how differences across those technologies and sectors may or may not generalize to other problems.

Drawing upon work conducted with colleagues at Carnegie Mellon University, I provide three examples of situations where a cross-mission critical technology analytics capability could have in the past or could still have the potential to transform outcomes. All three examples emerge out of a moonshot initiative that I launched together with 14 faculty across Carnegie Mellon's School of Engineering, School of Computer Science, and the Heinz College of Information Systems and Public Policy. The purpose was to begin to build the capability to address the lack of intellectual foundations, data, and analytics tools to inform critical technology policy outlined in this paper. The moonshot won a competition in Carnegie Mellon University's College of Engineering for two years of seed funding to try to demonstrate the importance of a "crazy world-changing idea."

The three examples that follow—the need for timely situational awareness to address PPE shortages during the start of the pandemic, the need for common design platforms to overcome overspecialization and brittle supply chains in safety-critical robust semiconductor applications, and the identification of win-win pathways to facilitate a feasible, robust, and equitable transition to electric vehicles—demonstrate the importance of what I argue are the four components necessary for a critical technology capability: strategic, integrated teams, activated through a flexible distributed model, who are working on problems at the intersection of agency missions. These examples also demonstrate why a "one-size-fits-all approach" to critical technology analytics doesn't work while highlighting different dimensions of critical technology policy problems and the different analytic methods that might be relevant for addressing them.

Given that it is my own area of expertise, I focus all three examples on physical products that are manufactured goods. US manufactured goods have been among the hardest hit by trade (Fuchs et al. 2022) and have a disproportionate impact on innovation, labor, and equity (Fuchs et al. 2022) and simultaneously have the potential to offer win-wins on all of these issues (Fuchs 2020). Furthermore, at times the US's lack of access to certain manufactured goods is a pressing and immediate threat to national security, the economy, and social well-being (CFR 2019; Fuchs 2020). This focus is also particularly relevant in the context of multi-mission approaches to critical technologies.

Timely Situational Awareness: The Case of Medical Shortages during COVID-19

The US government lacks timely, easy-to-navigate, product-level data on the long chain of intermediate suppliers supporting the production of final goods. While existing surveys such as the Annual Survey of Manufactures and the Economic Census provide snapshots of US capabilities, these data do not capture the rapidly evolving supply status during a crisis such as the COVID-19 pandemic. The US Census collects data on all domestic businesses once every five years. At the time of the pandemic outbreak, the last data collected on all domestic manufacturers was in 2017. The most severe supply shortages of the pandemic were between January 2020 and May 2020. During this early period, the government went by the traditional pandemic crisis handbook and brought together the five largest firms. However, timely information is essential to guide decisions to coordinate and mobilize additional capacity during crises, whether a pandemic, other natural disasters, or war.

With modern data and analytic tools, timely situational awareness is also increasingly attainable. Leveraging automated text analysis of public data, our team at Carnegie Mellon University was able to gain timely awareness of US domestic manufacturers entering, pivoting into, and scaling up in response to the COVID-19 crisis, particularly small- and medium-sized businesses. Within two weeks, we revealed significantly greater domestic mask and respirator manufacturing capacity than was known by the government at that time (Fuchs et al. 2020).

Once we had identified firms responding to the crisis—information the government did not have—we were able to collect data on what barriers those companies were facing, such as black-listing low-quality machine suppliers, having funds to cover Food and Drug Administration (FDA) certification costs, and breaking into mainstream hospital markets. We also identified companies across the country that were good candidates for expanding capacity because they had relevant capabilities, like the manufacturing of melt-blown polymers for other applications, having prior experience selling to medical markets, or getting certified by the FDA.

Our research did not reach the federal government in time to change outcomes during the most severe shortages (Kalathil et al. 2022). While it only took two weeks to spin up the initial data, we did not start collecting the data until May 2020. In a world with a national capability for critical technology analytics, the analysis could have been done in a timelier manner. The types of algorithms we used would be already part of the suite of tools inside government. If the tools needed were at the technical frontier, awareness of those capabilities across the country and a mechanism to tap into them would have existed such that the executive branch could rapidly contract with and spin up an external team to collect these data and solve this problem.

Overall, our work on masks and respirator producers during the pandemic highlights the value of working on specific challenges when seeking to build more generalizable insights both for analytic tools and methods and strategy with respect to critical technology policy. We produced novel insights that could be applied in other situations like supply chain shortages and crises. Our work demonstrated that the US government (through the Economic Census) lacks timely awareness of select critical products and their supply chains; these data are insufficient to inform reactive policy, much less proactive.

Traditional government tools for crisis preparation are stockpiling and relying on established firms to expand production (e.g., through the Defense Production Act). With weekly data on firm emergence in response to mask shortages, we can ask questions about how the government might add economic dynamism to its arsenal of policy responses to crises. If small- and medium-sized enterprises are able to rapidly enter and add to production capacity, then stockpiles need not be as large. In which products essential to national interests, however, could small- and- medium sized firms rapidly pivot, and which less so? Is there a certain minimum number of manufacturing firms that the country needs to support economic dynamism? Where should the number of firms with certain suites of capabilities be tracked?

Furthermore, should firms that entered to support national needs subsequently be supported in ways that favor national firms (e.g., through regulation that ensures access and demand, paired with a requirement of procurement) and for how long? Should they be supported in transitioning to a new area post-crisis? Where might it be important for firms with certain suites of capabilities to have standing agreements with government promising they will enter in times of need? In our research we find that state responses and the number of firms that entered by state also varied dramatically (Kalathil et al. 2022). Were certain state responses more effective than others in encouraging economic dynamism, or was the variation in response about the existing capabilities in each state? A national capability in critical technology analytics should have in its portfolio the capability to develop answers to these types of questions so government can learn.

At the time of the crisis, the government's traditional tools (convening large companies and conducting extra real-time business surveys) were inadequate. For a small set of critical products of high enough national importance, extensive supply chain data should likely be collected regularly and vulnerabilities should be regularly assessed. However, such data collection is costly. Analyses must be done (and reviewed regularly) to assess which products have sufficiently high national value—whether for national security, the economy, or health. The ability for modern data and analytics to rapidly spin-up timely situational awareness means that 1) domestic capabilities and responses can be assessed as crises emerge; 2) surveys on barriers can be targeted to firms that would have incentives to respond to the survey in order to get government support, and 3) firms with relevant capabilities to the specific crisis can be identified and targeted in calls for help.

Our work on masks and respirator shortages led to insights into important technology and sector-specific dimensions when thinking both about timely situational awareness and the potential for economic dynamism during crises. Importantly, the initial data we collected was useful but imperfect: it included many companies listed as North American or US manufacturers that were listed as manufacturers but in fact were primarily distributors, and it included firms that did not specifically have mask or respirator production facilities in the United States. In our first iteration, it took many weeks to subsequently revise the data, and weeks beyond that to survey the companies on the challenges they were facing in ramping up mask and respirator production. As we learned through our initial project, we were able to begin to brainstorm multiple ways to accelerate future iterations, including crowdsourcing information on listing accuracy. Likewise, as we begun to be approached by government to apply the same methods to other contexts, we began to learn how one source (Thomasnet's business-to-business website listing of North American manufacturers) might be excellent in certain contexts (e.g., existing capabilities and small- and medium-sized entry into mask and respirator production during the pandemic), but much less useful in other contexts. For example, in COVID PCR tests there were initially only two producers of a particular intermediate input in the world. These follow-on lessons were as important of an outcome of the initial study as the original results.

A CTA program must maintain a strategic focus, both in finding challenges to demonstrate what is possible and to generate lessons learned. The search for those broader lessons should begin initially, when a project is embarked upon, and continue through to the project's end when the lessons are likely clearer. A CTA program would, in all the analytics it undertakes, start with and return to the broader question of how modern data and analytic capabilities and the insights from those analytics should be changing the way government approaches policy—for example, whether in the data it regularly collects, the firms it approaches during crisis, or stockpiling.

If a CTA program had existed before the pandemic, it might have already created the necessary infrastructure to avoid mask and respirator shortages. In addition, the program might have taken on the problem not just because of the urgent national need but also with the goal of demonstrating the value of modern data analytic capabilities, transferring those demonstrated capabilities into relevant government agencies and identifying longer-term policy questions that critical technology analytics and the failed government response raise.

A CTA program might spin-up multiple such short-term demonstrations to learn about where those analytics do and do not have value and to inform decisions about when to collect data and what data to collect. As in all the projects a CTA program would undertake, those demonstrations would grapple with the broader question of how modern data and analytic capabilities, and the insights from those capabilities, should change the way government approaches policy. To be sure, those goals go well beyond the work we did to solve the mask and respirator shortages.

Finally, the mask and respirator case highlights how data collection, the support of domestic manufacturing, or any policy intervention will inevitably have implications for multiple missions—here defense and health most directly but also commerce (including jobs, small businesses, and economic competitiveness) and equity. Different decisions might be made if optimizing a response to only one of those missions. A national capability in critical technology analytics should go beyond the research we did on masks and respirators, to explore whether the optimal solution for one department (e.g., the Department of Defense) might be different than that of another (e.g., the crisis response coordinator optimizing national health at the Department of Health and Human Services).

Innovation to Transform US Competitiveness: The Case of Semiconductors

While new scientific concepts can take over 30 years from idea to commercialization, in other cases innovative solutions can be implemented in months or years. Semiconductors, which are a general purpose technology (c.f. Bresnahan and Trajtenberg 1992) found in applications throughout the economy, illustrate the different ways innovation can transform geopolitical dependencies and competitiveness. Efforts to ensure access, security, and leadership in this technology also highlight the importance of integrated, interdisciplinary teams with deep technical and sectoral knowledge. Deep sector and technical knowledge is needed to understand these differences, and where private incentives may cause underinvestment in incentivizing short- and long-term innovation in technologies critical to across multiple missions.

I discuss two issues facing semiconductors. The first issue is the opportunity, building on existing knowledge, for chip redesign. This redesign could be achieved by the government funding of common design rules to reduce market overspecialization and attendant supply chain risk. The second is the need for government funding of capital-intensive public infrastructure: one or more fabrication facilities for experimentation in new semiconductor designs. That public infrastructure would enable coordination in innovation among firms, including smaller enterprises and entrepreneurs, for the next generation of semiconductors.

I start with the opportunity for chip redesign and government funding of common design rules to reduce market overspecialization and thus supply chain risk. The ongoing shortage in safety-critical, robust semiconductors for applications in aerospace, defense systems, and automobiles is threatening national security and preventing cars from being produced. However, increasing supply chain resiliency to avoid this problem in the future is not as easy as increasing domestic or international production capacity or moving semiconductors away from concentrated foreign and potentially geopolitically risky locations.

Despite the importance of these capabilities for national and economic security, the economy, power, and health, sectors demanding safety-critical robust semiconductor chips (including transportation, defense, utilities, and medical devices) can have less market power during shortages. These nationally strategic applications are small percentages of the total semiconductor market compared to cell phones and computers, and also have lower profit margins for producers. Indeed, safety, reliability, and robustness to environmental conditions like high temperatures and vibrations make older, more reliable semiconductor process "nodes" more attractive for production; that is, these chips don't require the latest in semiconductor production technology.

Market incentives have led to specialization in the semiconductor industry, and in particular, in safety-critical robust applications. Semiconductor chip producers design chips to single lines in single fabrications, creating high switching costs. Switching a chip to be produced elsewhere would require, at minimum, six months to a year and costs to redesign the chip to a different fabrication facility and line. Although high switching costs give customized chips manufacturers confidence that returns will cover their high investment costs, the high switching costs also give semiconductor producers temporary monopoly power.

Public funding for the development of common design rules or platforms holds the potential to address these challenges and to move the industry out of a sub-optimal, and supply-risky situation. From the chip purchaser perspective, common design platforms would aggregate and enhance their market power and reduce the manufacturers' switching costs between fabrication facilities (the latter of which enhances supply chain resiliency), potentially at the cost of some customized performance features. Such aggregation would particularly benefit defense-related manufacturing, where the use of semiconductors is sufficiently low that supply can be unreliable.

Without government intervention, purchasers would never come to common design rules because they do not know enough about semiconductors (they produce cars or medical devices or defense systems) or the demand of other firms with similar needs. From the semiconductor producer perspective, too much heterogeneity at too low a volume increases production costs and reduces supply chain resiliency, even if customization can increase revenues and lock-in consumers. Thus, government funding of a common platform would support overcoming information asymmetries and a collective action problem to the benefit of national security, the economy, and social well-being.

Identifying the actual problem and proposing a functional solution—and in a way that maintains competition and leverages market forces—requires a combination of in-depth technical expertise in semiconductors and sophisticated data and analytic capabilities. Absent this approach, it would be all too easy for the government to simply give money to the semiconductor industry and fail to make any progress on the underlying structural failings. Identifying the design platform that optimizes commonality will require sophisticated understanding of the technical implications of defense and commercial interests and likely some amount of cross-sector data sharing in public-private partnerships and funding of common design platforms. Identifying the ideal path will also require understanding and valuing of the systemic implications of semiconductor shortages across the economy for businesses (including start-ups pushing the technical frontier), economic prosperity, and jobs. Finally, the effective development of design platforms must anticipate potential large shifts in semiconductor chip demand—for example, as production of electrified and autonomous vehicles ramps up.

To make progress on these issues, we formed an integrated team of electrical engineers, machine learning and natural language processing experts, supply chain experts, and economists at Carnegie Mellon. With this broad range of skills, we were able to understand and correctly identify the problem (design commonality), chart a potential solution, and convene the private sector and government around that solution. We have subsequently begun to independently develop a consortium with industry around the problem and the need for analytic pathways forward.

However, the effort lacks the participation of a government agency with a cross-mission function such as the proposed CTA program. As a result, there is no entity to organize the many stakeholders with their various incentives, no entity to bring the government departments to the table on equal footing, and no established source of funding for the effort. If a capability for critical technology analytics had been in place in advance of the current semiconductor shortage, we may have been able to act more quickly in response to the shortage (nearly a year has been lost) and would be able to be set up the industry to have fewer market frictions and unexpected shortages in the future.

A different challenge facing the semiconductor industry is a series of market failures that have curtailed experimentation, coordination, and innovation in the technologies needed to continue to advance computing beyond the industry's current technology trajectory, defined historically by Moore's Law. The government needs to fund capital-intensive public infrastructure to enable experimentation, coordination, and the engagement of smaller enterprises and entrepreneurs in the discovery and creation of complementary innovations around entirely new knowledge and technology trajectories for the next generation of semiconductors. Importantly, both types of semiconductors (the safety-critical robust ones in need of standardization and the next generation of semiconductors for the future of computing) will be essential parts of our national infrastructure for decades to come.

Orders of magnitude greater than current science and technology funding is desperately needed to find a solution that will continue to advance computing performance (c.f. Khan, Hounshell, and Fuchs 2018), with economic prosperity, national security, and social welfare at stake.[5] Scientific limits have in recent years brought the four-decade-long cadence of Moore's Law to a halt. The country that discovers the next computational device will benefit not just economically but also through greater national security. While advances in software and reconfiguration of existing hardware technology is enabling computational advances, a new beyond-CMOS computational device will be required within the next decade to continue advances in computational hardware and also planned advances in artificial intelligence (Khan, Hounshell, and Fuchs 2018).

For the vast majority of applications, that decade-out solution for advances in computing will not be quantum. Inventing this next device will require advances in basic science including physics. It will also require coordination of innovation across the computing stack, since a new computing device will require, at minimum, new manufacturing equipment, new chip architecture, new software, and new programming languages. Enabling this cross-stack coordination—that is, to scale-up and commercialize a new computer device—will require investment in a national foundry to experiment across the computing stack (e.g., with the device design and production process itself as well as with the chip architecture and software to program that device) and to discover the best-suited device or devices to various applications. Again, deep knowledge of the semiconductor industry paired with analytic expertise will be necessary to identify the right solution. The team will need to value different potential directions offered by different devices for commercial and military aims. In addition, it will need to optimize how many and which devices are supported at the facility, with more devices risking cross-material contamination and thus slower commercialization.

Quantifying Cross-Mission Win-Wins: The Case of Energy Storage for Vehicle Electrification

Motivated by the substantial impact of internal combustion vehicles on carbon emissions and air quality, personal transportation is undergoing the largest transition in over a century. Global sales of electrified vehicles (EVs) are projected to outpace conventional internal combustion engine vehicles (ICEVs) by as early as 2030. In addition to personal vehicles, other transportation systems are also increasingly looking into, and shifting to, electric propulsion. The shift away from oil and gasoline not only benefits the climate but also energy security goals. Despite these benefits, it remains an open question whether the transition from ICEVs to EVs can be achieved in a way that is economically, socially, as well as environmentally sustainable.

The ecosystem around the shift to EVs creates new requirements: for manufacturing workers and for workers in fueling, repair, and maintenance. While past work suggested that the shift from ICEV to EV powertrains would lead to a loss in labor demand and, in particular, a loss in demand for low-skilled labor (Hart 2019), our recent work leveraging shop-floor-level data finds the opposite. In fact, EV powertrains require more labor content and more middle to higher-end skills than ICEV powertrains, with the majority of labor content being in battery production (Cotterman et al. 2022). Our findings demonstrate that from the perspective of labor, economic resiliency, and national security, it matters where the battery components are produced *and* where the battery is assembled (which is the focus of most of the US battery manufacturing announcements). These results suggest that policymakers should be considering the full supply chain in batteries to prevent breakdowns similar to those recently experienced in masks, respirators, and semiconductors.

As demand increases, the global supply chain for lithium ion batteries is constrained in several ways that could be catastrophically disruptive to the economy, jobs, and national security interests. In this context, innovations in the synthetic production of battery materials as well as in the recycling of battery materials and novel battery chemistries could be transformative: if production were to occur in the

US, those changes represent little to no supply chain risk in terms of cost, transport, working conditions, and geopolitical strife (Burke and Whitacre 2020; Sovacool et al. 2020).

Lithium extraction from land or innovations to implement lithium extraction from oceans take time and capital to implement. These investments did not look attractive several years ago (Ciez and Whitacre 2019), but at today's prices, they would be competitive. However, small firms have difficulty accessing funds for capital investments, and extraction investments would need years to ramp up.

Synthetic processes to produce battery components that employ well-understood and common methods and can be scaled with low cost could help circumvent a tenuous supply chain in favor of locally sourced materials, recycled materials, and cost-optimizing processes (Ciez and Whitacre 2019). Recycling improves supply chain constraints and the environmental sustainability of the transition. Finally, innovations in cobalt-free batteries exist today. And there are other less geopolitically risky battery chemistries that, with investment, could transform the above-described dynamics.

All of these hardware innovations hold potential for new entrepreneurial opportunities that could fundamentally change the existing industry. Unfortunately, data is lacking on how the government should think of the value and trade-offs associated with of each of these potential investments (lithium extraction, synthetic processes, different battery chemistries) given limited funds. A CTA program would have significant value in charting a transition pathway that is a win-win across missions as well as in quantifying the value and trade-offs of different forms of investment.

A CTA program should fund research addressing what outcomes would make US-based lithium extraction cost effective, under what conditions (given the scale-up of EVs) those outcomes are likely to occur, and how delays in ramp-up (e.g., need for innovation, time to stand-up an extraction facility) inform the speed of government action to be of greatest value. For example, Ciez and Whitacre (2019) showed several years ago how high lithium prices would need to get to make domestic extraction cost-competitive—a price that lithium has now reached. However, currently there is not substantial domestic production of lithium due to the high capital costs and long lead times to stand up facilities as well as the need for further innovation to increase the cost effectiveness of novel lithium production and extraction techniques. Here again, a clear policy action would be to invest in novel production and extraction techniques for supply-constrained raw materials and to increase access to capital for companies attempting to invest in existing and novel extraction facilities.

Whether a policymaker's interest in vehicle electrification is for energy security, economic security (and reduced reliance on the pricing of oil and gasoline), or sustainability, understanding the effects of electrification is essential. To do that, researchers must quantify transition pathways for different regions. Our work on the labor impacts of vehicle electrification identifies clear skill shifts required during both the manufacturing and the use phases as well as how different regions would be affected. With additional work, recommendations could be made regarding the type and location of training programs and where production activities should optimally be located. Without something like the proposed CTA program, these highly quantitative and actionable insights are less likely to be worked out or, if worked out, are less likely to influence policy.

We have begun to quantify the expected value of different battery chemistries, given the probability of various potential global supply chain disruptions like natural disasters (an earthquake in Asia), political upheaval (disrupted access to raw cobalt from the Democratic Republic of the Congo), or trade and tariff disputes (a unilateral cut-off of refined lithium from China) in addition to our work on domestic capabilities and labor market implications. A CTA program could do this work faster at greater scale and *pre-emptively*.

Questions and Concerns

A CTA program faces significant challenges, including maintaining a strategic focus and agility while proving its value to stakeholders and policymakers that are in a position to act on its analysis. I focus below on risks to the program implementation and maintenance along the four dimensions of my policy proposal and that are exemplified in the three cases.

What If the CTA Program Is Not Created?

If a national capability for a cross-mission CTA program is not funded within an agency in government or as a federally funded national network, one could build and demonstrate the importance of such a capacity outside government that is philanthropically funded. However, a lesson of the cases shown above is that analytic timeliness and implementation did not follow. Without the federal government, it will also be much more challenging to attract star talent from industry and academia to work on these problems and to incentivize and reward the necessary capabilities in academia. Moreover, leadership from the federal government helps to ensure that incentives are properly aligned for all stakeholders, including those of individual government agencies. Given those stakes, the federal government should drive the building of the data and analytics to inform its critical technology funding decisions and to ensure its own access to mission-critical products.

What If the CTA Program Is Pulled into Short-Term Problems or into Collecting Data Rather than Solving Problems and Fails to Maintain a Strategic Focus?

Visionary leadership would create the initial tone, culture, and priorities for the CTA program, including its national mission-driven strategic focus. In particular, leadership would be necessary to walk the careful balance of maintaining a strategic focus and choosing work that will lead to broader insights on how to think about critical technology policy writ large while still having immediate value to a sufficient number of stakeholders. Leadership will also be necessary to understand and use the capabilities and different academic incentives in different fields across the nation, so as to be able to leverage those capabilities and incentivize integrated teams focused on real-world challenges.

Given the significant role of leadership in setting the tone and choosing initial projects, a CTA program could suffer significantly with changes in leadership. Here, DARPA offers important lessons. At DARPA, directors change, on average, every two years, and program managers change every three to five years, but the culture of what a DARPA program managers does is institutionalized and remains (Fuchs 2010). Contractors at DARPA who stay despite this turn-over may also play an important role in consistency (Piore, Colatat, and Reynolds 2019). Thus, for a CTA program, initial leader and contractor selection may be most important to institutionalizing a culture and creating a strategy for decades to come.

What if the Analysis is Good but Implementation Fails?

Program leadership will play an important role in engaging multiple government agencies and achieving cross-department neutrality. In particular, boundary-spanning leadership will be essential to be able to describe the problem in the language of different departments' interests, and thus bring to the table and engage those departments around a single problem. In avoiding capture by an individual agency, having a dominant, relatively neutral source of funding, such as NSF (in contrast to being entirely reliant on raising funds from departments) may be particularly valuable to avoid funding by multiple agencies creating an incentive to appease those agencies. Instead, agencies will need to see the CTA program as a resource to leverage (and complement its contracts with their own funding), for cross-department issues involving technologies of high value to multiple missions, and for building and transferring novel capabilities and insights.

What If the CTA Program Fails to Maintain Stakeholder Support?

To protect the office from politically motivated interference, the program will need to focus on providing data and analytics that support government agencies' and legislators' decision-making, making win-wins and trade-offs for different missions transparent, while leaving the decisions about what to do with the analysis to elected officials and departmental leadership.

What Are the Pros and Cons of Having the Budget Allocation Entirely within a Single "Neutral" Agency versus Split across Agencies?

The CTA program simultaneously needs a "customer" who wants and will implement the analysis and protection from politically motivated interference (e.g., objectivity and independence). One potential solution to meet these needs would be for the CTA program to be created through legislation and be directly funded by and report directly out to Congress—similar to the Office of Management and Budget, the Government Accountability Office, and the former Office of Technology Assessment (OTA). Another potential solution would be for the CTA program to receive funding from multiple agencies, where the agencies came together around topics of common interest —similar to the National Academies or the former World Technology Evaluation Center, which was funded by the National Science Foundation.

Both approaches have potential benefits but also challenges. The Office of Technology Assessment was discontinued due to being perceived as being overly biased toward one political party. Likewise, the National Academies struggle against the sources of funding (including individual agencies) biasing the studies undertaken and their outputs. I propose a merged approach—a self-sustaining amount of funding coming to a single neutral entity, and complementary funding coming from agencies and other external sources as a way to thread this needle and balance the potential pros and cons of either approach on its own.

What Would an "Early Win" Look Like for CTA?

Early wins could demonstrate a change in how things are done. I propose here some examples of early wins from the three cases described in this proposal. For example, in the medical supply chain case described above, the Economic Census has recently hired two new employees based on the timely situational awareness that the effort showed was possible. Based on CTA-like analysis, a government agency changed its approach to data collection.

Another example of an early win from the cases described above might be a standing public-private partnership to conduct analytics on common semiconductor platforms across commercial and defense applications that require safety-critical robust semiconductors. Current efforts to create such a partnership are constrained by a lack of funding and significant bureaucratic challenges.

Finally, an early win could include identifying supply chain bottlenecks that might emerge if vehicles electrify at different rates, and how high-probability natural disasters and geopolitical tensions could further exacerbate those vulnerabilities. The CTA program could also identify actions that the government could take to lessen those risks, such as incentivizing more resilient battery chemistries, incentivizing innovation, and providing capital to support the commercialization of domestic raw material extraction facilities. Identified actions could also include mitigating the negative effects of potential bottlenecks or the shift to electrification more generally, such as building up training programs and encouraging more investment in regions at risk of negative consequences.

Conclusion

To the extent that private firms will under-invest compared to what is optimal for social well-being, governments need to act to ensure the technology leadership and product access that will protect people's security, prosperity, and social welfare, including health. Unfortunately, the federal government lacks the data, intellectual foundations, and analytic tools to satisfactorily inform decisions that advance the government's multiple missions, particularly in contexts where each department acting on its own may lead to suboptimal decisions. For the recently passed CHIPs and Science Bill and other critical technology policy to realize legislators' goals for those investments, the US government must in parallel invest in a cross-mission critical technology analytic capability that can flexibly bring together expertise from academia and the private sector to inform critical technology policy. Without such a program, we will lack the data and analytic tools necessary to inform government action.

A national capacity in critical technology analytics is an essential step to enable the US to move beyond lists of critical technologies with no link to specific policy actions and beyond reactive supply chain policies toward a national technology strategy that is strategic, pre-emptive, and during unexpected crises, informed by timely data. While the vision I put forward for a CTA program is ambitious, there are right now important, concrete opportunities for first projects and early wins to advance government capabilities to inform national technology strategy.

Effectively implemented, a CTA program holds the potential to shift US policymaking.

- Government action could be informed by the value to government missions of different technology capabilities and different types of product access. Supply chain vulnerabilities in products essential to multiple national missions could be identified in advance of them failing, assessed for the probability of future failures, and analyzed for the value of multiple possible solutions (such as investing in multiple sources or incentivizing innovations that could reduce those vulnerabilities).
- Government investments and regulations could be informed by the possibility to change the US's technology capabilities or product access. A CTA program could identify high-value actions to develop and commercialize technologies critical to multiple missions.
- The value of different solutions to different government missions would be quantified and made more transparent, along with any win-wins pathways across sectors and missions. Analytics would draw upon timely data of global capabilities in terms of knowledge, production, and human capital, and the US's standing therein.

Founded in the aftermath of Sputnik with the goal of preventing technological surprises, DARPA was set up to cut through the rivalry between the military services (Fuchs 2010). For the United States to meet the domestic and international challenges it faces, the country needs a national capacity in cross-mission critical technology analytics to work across, coordinate with, and catalyze initiatives between the existing mission-driven agencies. Successfully implemented, a CTA program will mobilize talent from across academia, the private sector, and existing government departments to inform strategic, data-grounded critical technology policy that supports the security, prosperity, and well-being of all citizens.

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Endnotes

1. These first two paragraphs are taken directly from my congressional testimony (Fuchs 2021).
2. Unfortunately, despite the relatively small total number of jobs in the production of science and technology research, the long gap between science funding and broader positive economic outcomes, and the additional local investments required for the commercialization of science to remain local, leave little likelihood that the positive externalities of just 15 regional hubs (particularly in their proposed locations) will reach the majority of impoverished areas—and particularly not rural areas—in the next decade if ever (c.f. Fuchs 2021).
3. Indeed, work by Combemale et al. (2020) shows that technologies with different labor outcomes compete as perfect substitutes (with the same performance and production costs) in the marketplace.
4. Over the past four years, several entities have begun initiatives to build aspects of such a capability, including all of the entities named above. For example, while it didn't make it into the final CHIPS and Science Act, following my 2021 testimony before the House Science Committee Subcommittee on Research and Technology, the Critical Technology and Innovation Analytics Program Act was added to COMPETES with bipartisan support to authorize such a capability and grant an Other Transaction Authority in the Department of Commerce. More recently, the NSF's TIP Directorate has been tasked with closely collaborating with the stakeholders in the nation's research, innovation, and education enterprise to advance innovation that will lead to breakthrough technologies that can address national and societal challenges, enhance US competitiveness on a global stage, and create pathways for every American to pursue new, high-wage jobs. According to the FY2022 budget, "TIP will open up new possibilities for research and education by catalyzing strategic partnerships linking academia, industry, government, philanthropy, investors, and civil society to cultivate 21st-century local, regional, and national innovation ecosystems, ensuring US leadership in critical technologies as well as national and societal challenges." As part of this mission, NSF TIP's goal is to accelerate the translation of fundamental discoveries from lab to market by scaling investments in technology, innovation, and partnerships (NSF 2022). In the CHIPs and Science Act, NSF TIP is explicitly mandated to undertake Critical Technology Assessment directly aligned with the goals described here for a cross-mission CTA activity, and which it would be imperative to have a cross-mission critical technology analytics capability to support. Specifically, NSF TIP is mandated to annually identify not more than 5 national, societal or geostrategic challenges, not more than 10 key technology focus areas (with the initial list of 10 mandated by Congress), and the relationship between the national, societal, and geopolitical challenges and the key focus areas.
5. During the 1990s 50 percent of growth in GDP in the US and worldwide have been traced back to Moore's Law and to, more specifically, biannual advances in microprocessors and the complementary product and process innovations that made and used those microprocessors up and down the supply chain (Jorgensen 2001). Through Moore's Law, chips have become so cheap, small, fast, powerful and abundant in such numerous applications that their social benefits increase quality of life in ways that transcend economic quantification (Khan, Hounshell, and Fuchs 2018). However, in the last decade physical limits have impeded this progress. The microprocessors being produced today are commodity devices, or recombinations of commodity devices. While small advances in performance continue to be made through existing processes, recombinations of existing chips, and software, without finding a way to continue to advance computing performance beyond Moore's Law, economic growth, jobs, and technological advances in national-security critical areas such as artificial intelligence will be constrained in their advances within the next few years.

THE HAMILTON PROJECT

ADVISORY COUNCIL

Existing federal agencies relevant to the science and technology enterprise are appropriately focused on their missions, but the US lacks the intellectual foundations, data infrastructure, and analytics to identify opportunities where the value of investment across missions (e.g., national security, economic prosperity, social well-being) is greater than the sum of its parts. In a Hamilton Project proposal, author Erica R.H. Fuchs of Carnegie Mellon University and the National Bureau of Economic Research proposes the creation of a national capability for cross-mission critical technology analytics. The critical technology analytics (CTA) would identify 1) how emerging technologies and institutional innovations could potentially transform timely situational awareness of US and global technology capabilities, 2) opportunities for innovation to transform U.S. domestic and international challenges, and 3) win-win opportunities across national missions. The program would be strategic and forward-looking, conducting work on a timeline of months and years rather than days and weeks, and would seek to generalize lessons from individual cases to inform the data and analytics capabilities that the government needs to build to support cross-mission critical technology policy.

Dimensions of Criticality: Adding Access and Social Well-being