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TESTIMONY
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HEARING ON BUILDING REGIONAL INNOVATION ECONOMIES
HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY
JUNE 9, 2021

Thank you Chairwoman Stevens, Ranking Member Waltz, and Members of the Subcommittee for convening this important hearing. I am a Professor in the Department of Engineering and Public Policy in the College of Engineering at Carnegie Mellon University, and a Research Associate with the National Bureau of Economic Research. My research focuses on the development, commercialization and global manufacturing of emerging technologies, and national policy in that context. My "research laboratory" is often the factory floor of manufacturing firms in regions across the U.S. and around the world.

Over the last half a century, the world and the U.S.'s position in that world has changed dramatically. The global geopolitical balance of scientific, economic, and production capabilities has shifted away from U.S. dominance. China is now the largest and most rapidly growing consumer and producer, and the U.S. is no longer in a singular position of scientific and technological leadership across domains (Branstetter, Glennon, and Jensen 2018; Segal 2019). At the same time, the U.S. faces equal or greater challenges on its home front. Domestic economic inequality has increased (Autor, Katz, and Kearney 2008; Autor 2014; Leonhardt 2017, Autor 2019), social mobility declined (Chetty et al 2017, Chetty et al 2020), and political polarization is on the rise (Autor, Dorn, Hanson, and Majlesi 2020). Center stage to both of these trends are trade and technology: research has documented negative impacts of import competition on employment and earnings in trade-exposed local labor markets (Autor, Dorn and Hanson, 2013; Acemoglu et al. 2016) and a rise in political extremism in locations hardest hit by trade (Autor, Dorn, Hanson and Majlesi, 2020).

Unfortunately, in this moment of dual internal and external crises, we lack the intellectual and institutional foundations to guide our nation on how to act. 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 2020) domestically; certain forms of technology change, such as automation, can reduce jobs without increasing productivity (Acemoglu et al 2020) and exacerbate inequality (Autor et al 2003). In light of these more recent findings, some intellectual leaders have suggested slowing the progress and adoption of technology (Piore 2018, Acemoglu et al 2020), and gradualism as a principle for trade policy (Autor et al 2016). Others are raising concerns about the U.S. losing global technology competitiveness, particularly to China (Augustine and Lane 2020). These experts are arguing for dramatically increasing funding of science and technology (Segal 2019, Johnson and Gruber 2019, Augustine and Lane 2020), and using regional distribution of funding of science and technology to reduce inequality and jobs (Johnson and Gruber 2019).

It is these very debates -- central to the sovereignty of our nation and well-being of our citizens -- that bring us together today. Unfortunately, these debates as they currently stand have two fundamental flaws: they confuse the complex relationship between innovation and jobs, and they overlook the heterogenous nature of technologies and thus the different effects of different technologies on a wide variety of outcomes. It is only by first rectifying these misunderstandings, that it begins to become clear that missing from these debates is that there may be win-win technology choices -- strategic technology investments that could meet multiple national objectives, such as improving national security and economic competitiveness, winning in global trade, and increasing the number of good jobs. I unpack these issues with four points:

First, science and technology can change the playing field and rules of the game. To efficiently and effectively realize the nation's multiple objectives -- national security, economic prosperity, and social welfare -- some portion of our science and technology investments should be approached as strategy on a chess board. In order to regain and maintain global economic dominance, our priority should not be reshoring existing commodity products. Rather, we should focus on making products that can only be made here, and that everyone in the world wants. In my research on advanced semiconductors for communications, we find that while offshoring reduces production costs in the short-term, it reduces incentives for and the possibility of firms undertaking innovations that may have significant implications for national security and in the longer term hold potential to enable those firms to access larger markets (Fuchs and Kirchain 2010). In addition, while the short-term incentive is for firms to produce older generation technologies offshore, the next generation products can only be produced in the United States and Europe (Fuchs and Kirchain 2010), and involve more skilled and innovative jobs for high school operators (Combemale, Ales, Whitefoot, Fuchs 2020; Combemale and Fuchs 2020). Our early research suggests a similar story is likely true in vehicle electrification and battery storage. Lithium-Ion batteries are currently the largest end use of cobalt (accounting for 50% of global cobalt demand.) Currently, more than 60% of all mined cobalt production comes from the Democratic Republic of the Congo (DRC), and cobalt mining in the DRC is expected to continue to be 62-70% of global production through 2030 (Fu et al 2020). With Lithium ion battery demand, particularly for electric vehicles, projected to increase by over 300% throughout the next decade, cobalt-dependent technologies face the risk of significant impact from supply concentration and mining limitations in the short term (Fu et al 2020). The country that leads in innovations in battery recycling and cobalt-free batteries has the potential to change the rules of the game, and have a better chance at winning given those rules. In addition, there is reason to believe aspects of electric vehicle production may be associated with better jobs (Combemale, Ales, Whitefoot, Fuchs 2020; Combemale and Fuchs 2020; Cotterman, Whitefoot, Small, Fuchs research in progress.)

To be clear, growing science and technology funding is important, and not all of it (perhaps even not most of it) should be focused on strategic aims. Government-funded research increasingly and disproportionately fuels innovation (Fleming, Greene, Li, Marx, and Yao 2019), U.S. science and technology funding as a percent of GDP is close to its lowest levels since WWII (Johnson and Gruber 2019, Segal 2019) and has fallen below other developed nations (Augustine and Lane 2020). However, increases in science and technology funding alone will be insufficient to ensure U.S. technology competitiveness without a strategy for how to ensure that those investments realize legislators' national objectives. Here lists can be helpful, but alone are insufficient.

Take, for example, the context of semiconductors. Orders of magnitude greater science and technology funding is sorely needed to address domain specific-challenges such as the end of Moore's Law in advanced semiconductors (c.f. Khan, Hounshell, and Fuchs 2018), with economic prosperity, national security, and social welfare at stake.[1] However, it would be easy to misallocate funding in an attempt to address this problem, and indeed to misunderstand the challenge itself. The microprocessors being produced today are commodity devices, or recombinations of commodity devices. While today's microprocessors are ubiquitous and essential to national security, there are multiple methods to improve the security of these devices even if in part or in full produced at a foreign fab (c.f. Sweeney et al 2019; Vaidyanathan et al 2014; Imeson et al 2013; Jarvis et al 2004.) However, the country that discovers the next computational device holds the opportunity to lead not only in economic prosperity but also in military competency and

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[1] During the 1990s 50% of growth in GDP in the U.S. and worldwide have been traced back to Moore's Law, and 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 (Jorsensen). 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).

AI. Scientific limits have in recent years brought the four-decade long cadence of Moore's Law to a halt. While advances in software and reconfiguration of existing hardware technology is allowing us to continue to make computational advances, a new Beyond-CMOS computational device will be required within the next decade to continue not only advances in computational hardware but also planned advances in AI (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. Commercializing this next device will require 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 discover the best-suited device or devices to various applications. Here, I am not promoting choosing technology winners. I am emphasizing the importance of spending our limited national dollars on the *right problem*. In my original work on DARPA (Fuchs 2010), I emphasize that DARPA program managers neither leave everything up to the market nor choose technology winners. Rather, they connect disconnected actors across our innovation ecosystem to build technical solutions (sometimes two teams working on the same technical solution and a third team working on a competing solution) to national problems. On the executive side, DARPA Program Managers are able to fulfill this role due to being technologists deeply embedded in the fields and communities they fund who come to government service from industry and academia for three to five year stints, often as strategic steps in climbing their career ladder (Fuchs 2010).

We also need more even nationwide distribution of science and technology education, funding, and commercialization (c.f. Johnson and Gruber 2019, Atkinson, Muro, and Whiton 2019). More even distribution of science and technology funding holds promise to accelerate innovation: For example, Bell et al find that there are many "lost Einsteins" – individuals who would have had highly impactful inventions had they been exposed to highly impactful innovating individuals (and in the case of girls, innovating women) in their communities in childhood – especially women, minorities, and children from low-income families. More even distribution of science and technology funding holds the potential for societal benefits in terms of increasing scientific knowledge in the general population as well as for increasing broad-based political support for science (for related thoughts see Holdren in Powell 2020, Schrank 2021). Strategic training for new jobs and placement of new industries in areas most hard-hit by those transitions may also hold promise to grow political support for technology transitions, such as vehicle electrification (see discussions by Rodrik and Sabel 2019; Hart 2019; Hart 2020; Walter et al 2020; Karplus, V. 2021).

Finally, IF production can be kept locally, more even distribution of science and technology can also improve economic prosperity in that local region. While five of the top 10 metropolitan statistical area earnings were in Michigan in 1980, by 2016 nine of the top ten were on the east or west coast (Johnson and Gruber 2019). Without intervention, these trends are likely to continue. This challenge brings me to my second point:

Second, investment in regional technology, innovation, and education will not necessarily succeed at accelerating regional job growth and economic prosperity unless we in parallel invest in transition pathways that ensure those regions have the local physical and human capital necessary to keep the economic benefits of those investments locally.

While the social and economic gains from novel scientific findings and technology inventions can be tremendous, they are a long-run game: it can take 10 to 30 years to go from a novel idea to commercialization, particularly in advanced manufactured products (in contrast to software). Even as new technologies move into development and the early phases of commercialization, for those novel inventions to be manufactured or commercialized locally where they were invented one or more forces would be necessary to keep them local: incentives to remain close to the inventor (for example, challenges separating research from manufacturing such as described in Fuchs and Kirchain 2010 or Combemale and Fuchs 2020), a strong local workforce in relevant domains (engineers, trainers and technicians, shop-floor operators), and there being economic geographic advantages to produce locally (from the perspective of factor input costs, economies of scale and transportation costs for that particular product and its supplies and end market c.f. Krugman 1995.) (Fuchs 2014.) I will tell a story to illustrate each.

Several years ago I traveled to a university in the Midwest as part of conducting research on the Semiconductor Research Corporation (SRC). SRC is a semiconductor-industry-led public private partnership which leverages a combination of government and industry investments to fund academics and universities to conduct research on three to seven year out challenges facing industry to continue advancing computational hardware capabilities. The particular program I was studying (which was funding multiple centers across the country) brought NIST, DARPA, NSF, and state-level funding together with industry to find a next computing device given the end of Moore's Law. It was an important, if dramatically underfunded (see Khan, Hounshell, Fuchs 2018) effort, funding centers with competing technology solutions. Brilliantly, the centers brought together physicists advancing basic research, semiconductor device experts, and industry representatives who might commercialize that technology in an attempt to discover and accelerate commercialization of the next technology revolution (Khan, Hounshell, Fuchs 2015). While too small, the program is an important step toward ensuring ongoing national leadership in computation and therethrough AI, and thus national security and economic prosperity, in winning at "technology strategy." A government official happened to be visiting at the same time, and as part of my trip, I was invited to join him on their tour of the university's corresponding new local economic development technology incubator facility. While there were some exciting companies in the largely empty incubator facility, there were no new computational devices being manufactured or commercialized from the SRC program. With fundamental physics advances needed, they would be lucky to have something that could even be manufactured, no less would be commercialized, within 10 years. In addition there were many centers with competing device alternatives, and not all devices would "make it." Indeed, NSF's part of the program was called "Let a Thousand Flowers Bloom" to represent the importance of keeping the search for the next device broad in these early stages. (Khan, Hounshell, Fuchs 2015.)

Even once one or more of those devices was ready to be piloted or even commercialized, the midwestern city where the research was funded -- even with its world-class university - may not have been the place to do it. With a thousand new ideas underway, ideally, a single national foundry would be built to further pilot those devices and advance not only the necessary understanding of the ideal design and production of the device but also allow device architects and software engineers begin to experiment with innovations necessary for their own roles in these new computational inventions. From there, a likely final outcome might be for that technology to be produced either in the location of the new foundry, or other places where there was existing physical and human capital (including knowledgeable operators and technicians) -- such as at an Intel facility in Santa Clara, CA, Texas, Arizona, or at an IBM facility in upstate New York.

This story should not lead us to despair about the value of science and technology investments -- rather to emphasize that while we need funding of science and technology to win at the long-term game of national security, economic competitiveness, and jobs for hardworking Americans, alone those investments will not lead to a diverse and equitable distribution in jobs. Unfortunately, my research experiences suggest that the U.S. manufacturing ecosystem is sufficiently dilapidated, that keeping innovations domestically can be a challenge, even when inventors want to do so. To make sure the best science and technology advancements and the high-end operator and technician jobs that go with them happen domestically (since co-location with manufacturing is in certain contexts, particularly materials and process innovations at the technical frontier, necessary for innovation -- c.f. Fuchs and Kirchain 2010), in parallel to investing in science we need to rebuild our domestic physical and human capital across a broader swath of our country.

Let me provide an example of how, unless we in parallel revitalize our manufacturing ecosystem, funding research and development alone will be insufficient to keep manufacturing domestically. My former Ph.D. student, Hassan Khan, after receiving his undergraduate degree in Chemical Engineering from Berkeley, moved to Mississippi to help launch the manufacturing facility of a Silicon Valley headquartered solar photovoltaic startup. Although the photovoltaic cell was invented at Bell Labs, by 2010 US capabilities in the manufacturing ecosystem had atrophied. My student found himself flying multiple times with wafers to Canada, because they didn't have locally the fabrication capabilities they needed. The firm struggled to find operators they needed in Mississippi, despite receiving thousands of applications and hired Chinese-trained operators instead. The start-up was also reliant entirely on foreign suppliers of process tools, including from Italy, Germany, and Japan. Eventually the start-up failed, unable to compete against Chinese manufacturers that captured the majority of the market. The firm's IP was sold, investors and the state of Mississippi took a loss and Hassan came to Carnegie Mellon to start his Ph.D., doing research on the SRC program. (Fuchs 2020 Testimony)

The dilapidation of our domestic manufacturing ecosystem and the loss of human capital needed for that ecosystem was highlighted by the COVID-19 pandemic. In the context of mask production, small and medium sized companies struggled with lack of easily accessible information on how to make medical-grade masks, access to machines which were predominantly manufactured in China, shipping delays related to the machines and the components required for their repair, high qualification and certification costs, and challenges breaking into mainstream hospital distributor markets. (Kalathil, Fuchs, Morgan, Karplus research in progress.) In one case, lack of elastic supply not on a spool or an automated despooler, and the inability to build or adjust the equipment, led one company for a period of time to have a worker hand unspooling the elastic, with the expected productivity slow-down (Fuchs 2020).

That said, while U.S. companies, particularly small and medium sized ones struggled to pivot into and ramp-up domestic production of masks, in our research (ongoing with Kalathil, Morgan, and Karplus) on companies that pivoted, I have been struck by how much what was left of our domestic manufacturing ecosystem was central to us being able to pivot in the cases where we successfully did so. One large American manufacturer was able to leverage its intellectual property and aerospace sourcing and production expertise to establish and ramp-up domestic manufacturing of masks within just a few weeks. General Motors was similarly able to leverage its automotive sourcing and production expertise to rapidly ramp-up domestic manufacturing of masks and ventilators. In Indiana, America Meltblown and Filtration was able, with support from the Indiana government, to leverage its expertise in filtration materials and oil absorbent products to pivot first into making meltblown polymer for masks and later to create a subsidiary for also making the N95 masks themselves Another company leveraged technical macgyvers to pivot from experience in waste management and construction to mask manufacturing. These observations during COVID have strengthened my belief in the importance of domestic core competencies in critical technologies and a strong domestic manufacturing ecosystem to responding and pivoting during crises. Some pivoting companies' previous experience in waste management, construction, and water or oil infrastructure products has also strengthened my belief that the greatest promise for rebuilding our manufacturing ecosystems may be equitable country-wide investments in building the infrastructure of the future. (Kalathil, Fuchs, Morgan, Karplus research in progress.)

As I discussed in my 2020 testimony before the Ways and Means Subcommittee on trade, I have come to believe *strategic infrastructure investments hold the greatest promise to revitalizing U.S. worker skills and firm necessary for vibrant U.S. manufacturing ecosystems.*[2,3] By infrastructure I mean not just roads, bridges, transit networks, water systems, and dams; but also energy, communications, manufacturing, and data infrastructure necessary for all of those. In the same way that we need to build domestically the products that global markets want and only we can make, our infrastructure investments need to be for *the infrastructure of the future*. The U.S. generally lags behind other peer industrialized nations in infrastructure. The American Society of Civil Engineers (ASCE)'s 2017 report finds that the nation's infrastructure conditions are "mostly below standard," exhibiting "significant deterioration," with a "strong risk of failure." Much of our infrastructure was constructed for the climate of the 20th century, rather than for the climate of the 21st century (Chester et al. 2020), leading to additional issues of safety and reliability (Olsen et al., 2015). Transportation, transit, and urban infrastructure should be designed to enable the safe and equitable introduction of driverless vehicles and smart city systems, and the matching large-scale interconnected data infrastructure for security, privacy, resilience and machine learning on that data (Anderson et al. 2016; Berges and Samaras 2019.) Electric grids should be restructured to ensure a clean and resilient power system that can accommodate a wide range of new designs and services (NASEM 2010, Lueken 2012, NASEM 2017).[4] Foundries should be built to lead the world in the invention and commercialization of next generation semiconductors and synthetic biology. (Fuchs 2020 testimony)

Traditionally in economics, the government has an important role in investing in infrastructure because it generates positive externalities including health benefits, enhancement externalities, nation-building (historically increases land value, firms benefiting from cheaper inputs, and contributing to a sense of unity by increasing economic interdependence between regions), and counter-recessionary spending

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[2] My focus on strategic infrastructure investments is due to the potential novelty of that approach. Manufacturing Extension Program and Manufacturing USA innovation institutes already play and will need to play an important role in reviving our manufacturing ecosystem. On the Manufacturing Extension Program's effectiveness in upgrading and the acquisition of competitive capabilities (c.f. Various pieces by Whitford, J.; Shapiro; McEvily, B.). On the Manufacturing USA innovation institutes, their original goals, and evaluation thereof (c.f. Recent studies by GAO, NASEM).

[3] The U.S. generally lags behind other peer industrialized nations in infrastructure: The American Society of Civil Engineers (ASCE)'s 2017 report finds that the nation's infrastructure averages a "D," meaning that conditions are "mostly below standard," exhibiting "significant deterioration," with a "strong risk of failure." This lag which can largely be traced back to funding: On average, European countries spend the equivalent of 5 percent of GDP on building and maintaining their infrastructure, while the United States spends 2.4 percent. The United States also differs from most other industrialized countries in the extent to which it relies on local and state spending to meet its infrastructure needs -- only 25 percent of U.S. public infrastructure funding comes from the federal government.

[4] Among other issues, much of our infrastructure was constructed for the climate of the 20th century, rather than for the climate of the 21st century (Chester et al. 2020). Rebuilding and reinvesting in our infrastructure to be resilient to extreme weather is essential for the safety of our communities and the resilience of our economy (Olsen et al., 2015).

(Glaeser and Poterba 2019). While entities like the U.S. Council of Economic advisors continue to link infrastructure investments to jobs, more recently, economists have begun to question the short-term benefits of infrastructure expenditures (Ramey 2019, Garin 2019). Missing from these debates has been thinking about infrastructure investments as strategic investments in technology and knowledge capabilities, equity, national security, as well as platforms not just that could enhance productivity but also innovation. Infrastructure has the interesting property not only of creating demand, but also of solving a problem and creating the physical and human capital platform upon which to build future technology investments and innovations.

Investments such as those described above address national needs for resilience, energy and internet access, and technology leadership within and beyond manufacturing. Infrastructure investments also build national capabilities for building things -- not just in the form of firms responding to the demand, but also in the form of operators and engineers. These workers will learn by doing. Indeed, as we think about these investments strategically, it is critical to recognize the interconnectedness of the knowledge and skills across these infrastructure domains. The physical and human capital relevant to deploying and managing sensors for sustainable and smart infrastructure -- from the concrete layer to forman to the engineer to the data infrastructure developer to the machine learning software -- have corollaries in resilient grid infrastructure, privacy-preserving health infrastructure, and intelligent manufacturing. We should be strategic about those complementarities, in where and how we invest, in creating demand in the complementary areas, as well as about facilitating those transitions across sectors through targeted training.[5,6] (Fuchs 2020 testimony)

Third, with parallel investments to rebuild U.S. manufacturing ecosystems, technology advance does not need to lead to fewer good jobs for hard-working high school graduates. While prominent economists have been focused on the relationship between innovation and inequality -- specifically, wage and skill polarization -- this research has focused on capital expenditures, robotics, and digitization, and lacked measures to distinguish how different technologies may lead to different labor outcomes.

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[5] More work on skill transition mapping is needed. A recent OECD report has looked at current worker skills, how demand for those skills is expected to change with automation, and the training required to support "reasonable" transitions (OECD 2019). In our own research, we have been mapping skill requirements to jobs at a individual operator task level (Combemale, Ales, Whitefoot, Fuchs 2020a), and we are extending that task-level skill mapping now beyond the shop floor to technicians, engineers, and managers (Combemale, Whitefoot, Fuchs 2020). Whether at the OECD level or our own more granular one (or another method yet to emerge), we need to be mapping and broadcasting to training entities that may not have the necessary knowledge the skill transitions required from current construction and manufacturing for any of the above to the construction and manufacturing for the transportation, energy, health and manufacturing infrastructure of the future, as well as the skill transitions necessary in each skill domain to apply skills from one to the other across sectors.

[6] In facilitating these transitions, we should not underestimate the power of on-the-job learning and learning by doing (building). This is not to suggest that training isn't necessary, rather that that training may not happen "out of work", per se. Here, where large firms exist, industry in each sector should lead the training that is needed, where relevant in partnership with unions, with government facilitating assessment and dissemination of best practices and the mapping of the cross-sector transitions. Where small companies are involved, the government will play an essential role, in conjunction with larger companies, in mapping and funding necessary workforce transition training.

Our research demonstrates that some of our more important emerging technologies -- particularly those in advanced materials and processes - may be win-wins in terms of national security, the economy, *and jobs, including for hardworking high-school graduates*. As an initial example, we focused on parts consolidation -- a technically challenging objective well-known to the public for example in Intel's ability to fabricate more and more components on a single chip (Moore's Law), and General Electric's ability to additively manufacture what was formerly a 455 piece engine in just 12 parts. It's also a capability being pursued in at least 4 of our ManufacturingUSA institutes.[7] Our research shows that whereas automation leads to more low-end and more high-end skills being required of high-school educated manufacturing shop floor operators with some of the high-skill tasks moving outside the jurisdiction of the operator, parts consolidation leads to more middle skills being required of high-school educated shop floor operators (Combemale, Ales, Whitefoot, Fuchs 2020).[8] In addition, in their early days the consolidated design production processes require more "sorcery" from the operators and more back-and-forth between operators and engineers, the latter who are skill working to stabilize and understand the relationship between material, process, and geometry design decisions and production outcomes (Combemale and Fuchs 2020).[9] (Fuchs 2020 testimony)

Fourth, currently, the U.S. lacks the intellectual foundations, data infrastructure, and analytic tools to ensure that the nation's investments realize legislator's multiple objectives for them.

Technology decisions sit at the center of issues as broad-ranging as national security, economic prosperity -- including good jobs for all Americans, and social welfare -- including health, environment, and equity. While U.S. agencies are mission driven, technology investment and associated policy decisions affect multiple national objectives. Technology and investment decisions -- let's take the example of the electric grid -- can simultaneously influence national security (what if a foreign adversary brought down a large proportion of the grid?), economic prosperity (an entire month of semiconductor chips had to be thrown out due to the recent power outages in Texas), health (if more power is shifted to the grid people located near electric generation sites -

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[7] The U.S. government has funded 15 manufacturing innovation institutes. One of those 15 is focused on robotics (ARM) and another one on digitization (MxD). A third has a digitization component (CESMII). At least four (AIM, America Makes, IACMI, and NextFlex) of the 15 manufacturing institutes involve advanced material and process innovations that lead to design and parts consolidation, and another three (biofabusa, lift, and poweramerica) likely involve parts consolidation or part integration through innovations in materials and processes as part of their broader projects and mission.

[8] We expect the convergence of skills we see with consolidation to generalize across contexts - from advanced materials and processes to software (Combemale, Ales, Whitefoot, Fuchs 2020b).

[9] Research suggests the complex relationship between design and production (and thus engineers and operators working together to bring new science to reality on the production floor) generalizes to immature materials and process technologies at the technical frontier. Due to technologists still being in the process of figuring out the underlying science, it is common for advanced materials and process technologies in their early stages to have non standardized production processes where the operator and engineer's joint role is more of an art and also thus difficulty separating design from manufacturing (Fuchs 2010, Fuchs 2014.) Historical examples include the early days of electronic semiconductors; and emerging technologies in chemical processes such as electronic and photonic semiconductors, pharmaceuticals, batteries, additive manufacturing, and many others yet today (Bohn 1995, Pisano 1997, Holbrook 2000, Bassett 2002, Bohn 2005, Lecuyer 2005, Bonnin-Roca et al 2017).

who are also more likely to be below poverty - will experience more pollution), environment (what mix of fossil fuels versus renewables is generating energy for the grid, how does that mix change the geographic location of jobs, and how might policy influence those outcomes), and equity (who has regular affordable energy access and who does not). As a consequence, even if each agency (the department of energy, the department of defense, the department of transportation, the department of labor, the department of the interior, and others) perfectly achieved its mission, we might achieve suboptimal outcomes when considering our multiple national objectives as a whole.

There is reason to believe that the U.S. government's experience with and capacity (institutional as well as data and analytic) to make large-scale decisions related to technology not only is limited but also has atrophied over the past 50 years. Today, on average, the U.S. spends half of European countries on infrastructure (as a percent of GDP), and only 25 percent of U.S. public infrastructure funding comes from the federal government. The last large-scale infrastructure investment by the federal government was in the 1930s. Over the last 50 years, R&D spending shifted from being dominated by government to being dominated by industry (the crossover was in 1980, Congressional Research Service 2020) and government R&D spending as a proportion of GDP has declined (Perils of Complacency). At the same time firms increasingly reduced or disbanded famous R&D laboratories like Bell Labs and shifted their focus away from more basic research (Arora, Belenzon, and Patacconi 2015.) Further, in a variety of defense-critical industries such as computing, consumers increasingly became the largest source of demand for frontier technologies, rather than government.

Between 1972 and 1995 Congress relied on the Office of Technology Assessment to provide in-depth analytics on technology decisions (Princeton OTA Legacy). From 1989 to 1999, the federal government identified critical technologies through a biennial National Critical Technologies Report (NCTR) to Congress, with feeds from multiple agencies. Various departments and agencies of the Federal government also published their own critical technology assessments between 1989 and 1999, including the Department of Defense (Militarily Critical Technologies List, US DOD, 1989, 1990, 1991), the Department of Commerce (US DOC, 1990), the Department of Energy (US DOE, 1995), and the National Aeronautics and Space Administration. Between 1991 and 2003 the Critical Technology Institute (renamed in 1998 the Science and Technology Policy Institute) provided research and analytic insights to address science and technology embedded issues related to national security out of RAND. Unfortunately, even when these critical technology analytic efforts existed they lacked i) a systematic approach for assessing relative competitiveness as well as strategic opportunities and weaknesses in critical technologies, and ii) a link between identification of critical technologies and policy actions, such as by federal research agencies, CIFIUS, the International Trade Commission, and the Intelligence Communities was weak and uncoordinated at best. (See also Mogee, Mary Ellen 1991

National Academies Press; Knezo, Genevieve J. 1993, Congressional Research Service, Bimber RAND 1994, Popper and Wagner 2003.) While the Department of Defense (and in particular the Defense Logistics Agency) used to pay for defense-critical domestic industries to be tracked in greater detail by the U.S. Census, in the last decade those funds and activities have also been discontinued.

In recent years, the need for the intellectual foundations, data infrastructure, and analytics to support technology decision-making if anything has grown. The opportunities to leverage technology combined with new institutional innovations to address those challenges has also grown. So far, however, the government stands ill-prepared to leverage those new technologies: research by ourselves and others show that inadequate data and analytic capability is weakening government decision-making regarding critical technologies, supply chains, and infrastructure. U.S. Defense agencies and policymakers lack mechanisms to assess their strategic weaknesses and opportunities versus other nations in technologies critical to national security (NASEM 2019).[10] The U.S. government lacks data on the long chain of intermediate suppliers supporting the production of final goods, and thus the resilience of our supply chains and reliance on other nations for products. Meanwhile, intra- and inter- governmental actions and knowledge pertaining to critical supply chains are siloed and uncoordinated (Nissen et al 2018). The challenges this creates have been underscored by COVID-19: While existing surveys such as the Annual Survey of Manufactures and the Economic Census provide snapshots of U.S. capabilities, these data do not capture the rapidly evolving supply status during a crisis such as the COVID-19 pandemic (the last data collected on all domestic manufacturers was 2017). Such real-time information is essential to guide decisions to coordinate and mobilize additional capacity whether during a global pandemic, other natural disasters, or war.

Novel combination of existing public and government data, natural language processing, and active machine learning hold promise to map the evolution of innovative capabilities in critical technologies and manufacturing ecosystems across countries, time, firms, technological domains, and human capital including shop floor workers and teams of leading inventors. At CMU, my colleagues Branstetter and Hovy have begun pioneering work in this direction which combines natural language processing of patents with US census data to assess capabilities in AI (Branstetter and Hovy 2020). My own work with colleagues Kalathil, Karplus, and Morgan has demonstrated the possibility of using text processing of public information to substantially improve the government's real-time situational awareness of critical supply chains (Fuchs, Karplus, Kalathil, Morgan, 2020). In other work with colleagues we are leveraging new tools to quantify the skills required for emerging technologies before large-scale investments are made (Combemale, Whitefoot, Ales, and Fuchs; Cotterman,

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[10] In the inaugural session of the National Academies' study on U.S. Science and Innovation Leadership for the 21st Century, DARPA and the DOD Strategic Technology Protection Office's representatives both articulated a lack of mechanisms to assess their strategic weaknesses and opportunities versus other nations in technologies critical to national security. (NASEM 2019)

Whitefoot, Small, and Fuchs ongoing research), and to better understand skill cross-walks that enable firm pivots (Kalthil, Fuchs, Morgan, Karplus ongoing research) and skill transitions (Cotterman, Whitefoot, Small, and Fuchs ongoing research).

During the pandemic, our rapidly spun-up research using language processing to scrape and categorize text from Thomasnet, one of the largest business-to-business websites for North American Manufacturers, quickly found existing and potential domestic manufacturers. Our results suggest substantial overlooked capacity in current White House estimates, and that small and medium sized enterprises were playing an important and poorly-documented role. The US Census Bureau and International Trade Commission need access to these types of capabilities, as, likely, do other organizations, like FEMA, the Department of Homeland Security, and others. (Fuchs, Karplus, Kalathil, Morgan 2020)

More work on skill transition mapping is needed. A recent OECD report looked at current worker skills, how demand for those skills is expected to change with automation, and the training required to support “reasonable” transitions (OECD 2019). Much, however, remains to be learned about regional revitalization, manufacturing ecosystem reinvigoration, and skill transitions. Our work interviewing firms that pivoted during the COVID-19 pandemic, there are amazing anecdotes about firms originally in waste management and construction that leveraged skills therefrom to pivot into manufacturing masks. In our research on technology transitions in advanced semiconductors for communications and powertrains for vehicle electrification, we have been developing novel data collection and analytic tools for mapping technology transitions to skill requirements and jobs at the individual operator task level prior to large-scale investment (Combemale, Ales, Whitefoot, Fuchs 2020a), and we are extending that task-level skill mapping now beyond the shop floor to technicians, engineers, and managers (Combemale, Whitefoot, Fuchs 2020). Relatedly, colleagues Brynolfsen and Mitchell have been using novel methods to identify what tasks are likely to be automated in the future, and the implications for future skills (Brynolfsen and Mitchell). These types of leading data and analytic tools need to be supporting decisions by legislators, the agencies that fund technology transitions, and regions facing major technology transitions supporting that funding so as to ensure that economic development efforts match the transitions facing those regions. Such tools also hold promise to inform how strategic investments in the transportation, energy, and communications infrastructure of the future could prepare a region’s workforce to have the physical and human capital and manufacturing ecosystem necessary to keep locally the commercial outputs of critical science and technology investments.

In summary, when making technology investments, it is impossible to separate national security, economic competitiveness, and social welfare (including health, environment, and equity) considerations. To design policies that realize their objectives, policy-makers need transparency into how different technology and technology policy choices may influence different objectives. Win-win solutions can exist: As our research shows, certain technology transitions in areas critical to national security offer better jobs for hard working high school graduates (Combemale and Fuchs 2020). That said, realism is needed in the time between investment in science and technology research and commercialization of those ideas. Likewise, realism is needed on the dilapidation of the current manufacturing ecosystem, and the significant investments necessary to keep manufacturing of that technology local with local jobs. Nation-wide investments in the infrastructure of the future hold promise not only to improve security, productivity, and equity, but also as pathways to revitalizing U.S. worker skills and manufacturing ecosystems throughout the country -- a critical step toward keeping more of the commercialization outputs of science and technology locally.

Getting these investments right is non-trivial. Some portion of science and technology investments must be focused on national technology strategy. I argue in my 2020 Ways and Means Testimony that this would be best done in a set a nimble science and technology agency with that explicit mission. With jobs and equity as central to our sovereignty as weapons, and technology investments as likely to reduce both as raise them, but done right holding the promise to strengthen both, that agency must be backed by the star-studded data and analytic team necessary to get those decisions right. While the current proposals for changes in NSF and EDA have promising components, if regional investments in research and development, in infrastructure of the future, and local economic development activities remain uncoordinated and lack the necessary data and analytic support these efforts are likely to fail to realize legislators' multiple objectives for those investments. Equally importantly, whether the new technology strategy agency I propose or whatever entity undertakes this mission will need incentives to work with and leverage the expertise across the excellent mission-oriented agencies in our government.

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). To successfully execute, a small, nimble agency focused on national technology strategy, and its analytic arm, will need to be able to work across, coordinate with, and catalyze initiatives within the existing mission-driven agencies.

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