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TESTIMONY
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HEARING ON TRADE, MANUFACTURING, AND CRITICAL SUPPLY CHAINS: LESSONS FROM COVID-19
HOUSE WAYS & MEANS COMMITTEE
SUBCOMMITTEE ON TRADE
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Thank you Chairman Blumenauer, Ranking Member Buchanan, and Members of the Subcommittee for convening this important hearing. I am honored to be here and to be joined by colleagues who are leading manufacturing technology, industry, and labor organizations in the service of the United States and the global economy. 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. In my research I work on problems at the intersection of science, technology, and public policy. My “research laboratory” is often the factory floor of manufacturing firms here in the U.S. and around the world.

Times of adversity draw out the best in a nation and also shine new light on our structural challenges. The COVID-19 global pandemic has shone light into darker corners of the U.S. economy: deep global interdependencies in health and manufacturing as well as national challenges in racial, geographic, and income inequality and job safety. The good news is that crises offer rare moments in policy for true change (Hart 1998).

I will start with a story.

As part of the current global pandemic, I had the opportunity to briefly interact with a medium-sized U.S. medical supply company. Shortly before the pandemic the company had imported equipment from China capable of manufacturing 9 Million ASTM Level 2 masks per month. They planned to provide the masks at-cost for the duration of the pandemic. With the pandemic in full swing, their colleagues in China kindly supported them in getting the equipment up and running. However, inability to gain access to a number of material inputs prevented them from running at capacity. Surprisingly, their most challenging bottleneck was not the highly-publicized and technically challenging melt-blown polymer, critical for the mask itself and its filtration quality, but the elastic for the ear loops. That elastic needed to have no latex, be a precise width and elasticity (stretchiness), and come in a bag to work in the automated machines. They eventually found a domestic supplier for a small fraction of the necessary elastic, but that firm wasn't able to supply the elastic at sufficient scale for 9 million masks. Further, that firm's elastic came on a spool, so the company for a period of time had a worker hand unspooling the elastic, with the productivity slow-down one would expect. The reality of this company's challenges are bolstered by our data on domestic manufacturing of final products and intermediate inputs for COVID-19 medical supplies: While 118 U.S. companies report on ThomasNet manufacturing non-woven fabrics, only 6 U.S. companies report manufacturing no-latex elastic. Of those 6 manufacturers, only 3 of them report serving medical markets (Kalathil and Fuchs 2020).[1,2,3]

When we talk in D.C. about potato chips versus microchips, we wouldn't classically think we needed to produce elastic. And yet, in this story, that lack of elastic cost our country millions of masks *a week*. The lesson from this story is *not* that we need to produce elastic in the U.S. per se. What's missing is the capability to pivot: In the best of situations, the owner of that medical supply company would have been helped to connect with non-woven fabric and elastic manufacturers within and outside the United States. That medical supply company would have had the technicians and operators with the know-how to change the automated machine to take other ear loop materials. And perhaps inventors might in parallel pursue a product innovation which

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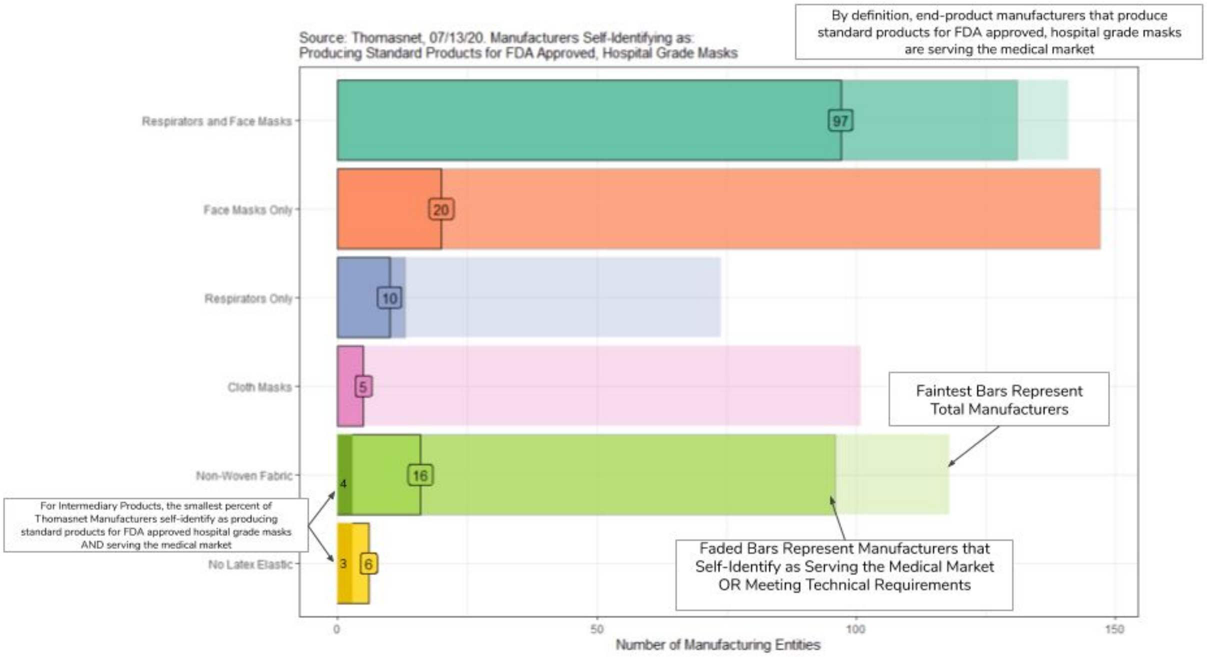
[1] Thomasnet is an imperfect datasource, in that we can only see what companies self-report, and we are not able to distinguish between whether their reported locations are their headquarters and/or also their production facilities. At the same time, the Thomasnet data has the benefits during a fast-moving pandemic over something like the U.S. Census Bureau's Annual Survey of Manufacturers (last year available is 2016) or the Economic Census (done every 5 years, with the last year available being 2017) in that we are able to follow individual companies and see (and reflect in our data) changes as new companies emerge in the data and/or companies report them. As I discuss later, the U.S. should be advancing its analyst capabilities to understand, develop new data and methods around, and leverage such analyses.

[2] The Annual Survey of Manufacturers (ASM) sample is skewed towards the largest manufacturing plants. Smaller plants are sampled, but not with certainty (as opposed to the largest). The last year available of the ASM is from 2016, with the 2018 ASM probably going to be available in late 2021. To capture the SME firms, the Economic Census (which is done every 5 years) is best. The 2017 EC of manufacturing plants is scheduled to be released in Fall 2020) and captures ALL manufacturing plants in the economy (250,000+ plants versus the ~45,000 plants in the ASM). A COVID-reponse survey that might also have important insights is the Small Business Pulse survey (https://www.census.gov/data/experimental-data-products/small-business-pulse-survey.html) which was executed between April 26 and June 27, 2020. While it doesn't specifically target manufacturing plants (or domestic capacity), it does ask about how and whether firms have pivoted since COVID. This survey samples representative of each MSA geographic area by NAICS 3-digit industry sector once out of the 9 weeks. The survey is voluntary and there are reasons it may have selection bias; however, its weekly execution during COVID is unique, and it may offer important insights when triangulated with Thomasnet and other data sources.

[3] For example, alone between May 30 and July 15 more than 60 new respirator or surgical mask manufacturer postings emerge on Thomasnet. Likewise, in that same half-month period 18 respirator and/or surgical mask manufacturers and two non-woven fabric manufacturers add language to Thomasnet alone suggesting pivoting or scaling-up in response to COVID.

uses adhesive to stick to the face, and doesn't need elastic at all. That inability to pivot is the tip of the iceberg for how dilapidated the U.S. manufacturing ecosystem is. Figure 1 below is suggestive of the potential scale of the domestic pivoting opportunity for COVID-19, alone within manufacturers of masks, respirators, and their intermediate inputs.[4,5]


Source: Thomasnet, 07/13/20. Manufacturers Self-Identifying as: Producing Standard Products for FDA Approved, Hospital Grade Masks

By definition, end-product manufacturers that produce standard products for FDA approved, hospital grade masks are serving the medical market

Faintest Bars Represent Total Manufacturers

Faded Bars Represent Manufacturers that Self-Identify as Serving the Medical Market OR Meeting Technical Requirements

For Intermediary Products, the smallest percent of Thomasnet Manufacturers self-identify as producing standard products for FDA approved hospital grade masks AND serving the medical market

Figure 1: Thomasnet-Listed Manufacturers of Masks and Respirators and Intermediate Inputs Self-Identify as Producing Standard Products for FDA Approved, Hospital Grade Masks. The "Number of Manufacturing Entities" on the x-axis represents the number of unique locations listed in Thomasnet, where the company self-identifies on ThomasNet as a manufacturer.[6] The faintest bar in

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[4] Our data from Thomasnet suggests a significant role for small and medium sized manufacturers in responding to the mask supply shortage. Self-reported monthly production capacity of respirators reported on July 13, 2020 by just 30.4% of Thomasnet Manufacturers of Standard FDA Hospital Grade Respirators with confirmed U.S. manufacturing of respirators or respirators and face masks adds approximately 10% to the monthly domestic production capacity reported in June to the White House by 3M, Owens and Minor, Honeywell, Moldex, and Prestige America. Likewise, self-reported monthly production capacity of surgical masks from just 15.4% of Thomasnet Manufacturers of Standard FDA Hospital Grade Surgical Masks with confirmed U.S. manufacturing of masks or respirators and face masks adds approximately 20% to the monthly domestic production capacity reported in June to the White House by 3M, Owens and Minor, Honeywell, Moldex, and Prestige America. These results suggest that small and medium sized manufacturers may already be contributing a significant portion of our country's domestic manufacturing capacity in masks. Our data also suggests that there may be many additional small and medium sized companies well-positioned to pivot into domestic manufacturing of masks.

[5] In 2014, I became intrigued by the flexibility of high-quality medium sized electronics contract manufacturers in China. These were not the Foxconns of the world manufacturing billions, rather companies manufacturing smaller production lots (that were too small for Foxconn to take interest), including prototypes for high-tech foreign start-up companies and subsequent scale-up thereof. Fascinating was the adaptability of these companies to produce so many different products - thus leveraging economies of scope rather than economies of scale (Nahm and Steinfeld 2013, Treado and Fuchs 2015). These companies managed their high product mix in part through repeatable and robust routines applied in supplier relationships which they referred to as "strategic alliances" and through the codification of labor routines that enabled shop floor flexibility despite labor turnover. Intriguingly, we observed related techniques for low-volume high product mix flexibility being used by military contractors in the United States.

[6] There are only two companies in the data that list multiple locations: 3M and The Louis Gerson Co, Inc.. 3M lists that it is producing respirators and/or facemasks in both its Valley, Nebraska and Aberdeen, South Dakota manufacturing facilities. In our figure, 3M counts as two "Manufacturing Entities" in our "Respirator and Face Masks" bar in Figure 1. The Louis M. Gerson Co., Inc. currently operates two facilities, both located in Middleboro, MA. The Louis M. Gerson Co, Inc counts as two "Manufacturing Entities in our

Figure 1 is the total number of Thomasnet listed manufacturing entities for our target products. The faded bar is the number of those listed manufacturing entities that self-identify on Thomasnet as serving the medical market or meeting technical requirements for hospital grade masks. The section of each bar outlined in black with a corresponding number shows the manufacturing entities self-identifying as producing standard products for FDA approved, hospital grade masks. (See figure definitions below.) The data in Figure 1 is a snapshot of Thomasnet data on July 13, 2020. We are collecting the data weekly. Note: Company locations listed in Thomasnet may not be their manufacturing plant locations in general, or for our target product. In our preliminary data cleaning we are triangulating the Thomasnet data against the information on the companies' own websites and with direct interviews with the companies to identify whether the companies are producing our targeted product in the U.S. Of the "Manufacturers of Masks and Respirators and Intermediate Inputs Self-Identifying as Producing Standard Products for FDA Approved, Hospital Grade Masks" listed on Thomasnet, so far we have been able to confirm i) of the 97 companies listing themselves as producing both respirator and face masks, 19 (20%) are producing them in the U.S., 46 (47%) are not producing them in the U.S., and 32 (33%) we don't yet know; ii) of the 20 companies producing just face-masks, seven (35%) are producing the masks in the U.S., five (25%) are not producing the masks in the U.S., and eight (40%) we do not yet know; iii) of the 10 companies producing just respirators, four (40%) are producing the respirators in the U.S. (although only one of those four companies is manufacturing n95s, the other three are manufacturing PAPR or other full-face respirators), two (20%) are not producing the respirators in the U.S., and four (40%) we do not yet know; iv) of the 16 non-woven fabric companies 11 (69%) are producing the non-woven fabric in the U.S., three (19%) are not producing the non-woven fabric in the U.S., and two (13%) we do not yet know; and v) all six (100%) of the six no-latex elastic companies indeed have their manufacturing locations in the US. Further data cleaning will be required to figure out the headquarters and ownership of each company. We expect the majority but not all of the companies to be U.S.-headquartered.[7] We are in the process of further tracking down the manufacturing locations of the remaining mask, respirator, and non-woven fabric companies in the Thomasnet data through their websites, interviews, and other means.

Figure Definitions -- **For End Products:** Producing Standard Products for FDA Approved, Hospital Grade Masks Defined As: Self-identifying as producing an N95, KN95, 801, NIOSH, FDA, ASTM, ANSI, or AAMI product. **For Non-Woven Fabrics:** Producing Standard Products for FDA Approved, Hospital Grade Masks Defined As: Self-identifying as producing a meltblown or spunbonded fabric. **Other Definitions:** Supplying the Medical Market Defined As: Self-identifying as producing a "medical", "surgical", "dental", "veterinary" product, or "PPE". Producing Products that Meet Technical Requirements for Hospital Grade Masks Defined As: Self-identifying as producing a "medical", "surgical", "dental", "veterinary" product, a "dust mask", a mask made in an ISO certified facility, a mask or respirator for cleanroom environments, a "3-ply" or "non-woven" product, or "PPE". Producing Products that Meet Technical Requirements for Hospital Grade Masks Defined As: Self-identifying as producing "spunlace", "hydroentangle", or "electrospun" fabric; or a fabric with metal (silver, nickel, or copper) coatings; For No Latex Elastic: By definition, no-latex elastic meets the technical requirements for hospital grade masks. Source: Kalathil, N. and Fuchs, E.R.H. 2020.

Respirators and Face mask bar in Figure 1. Together, 3M and The Louis M Gerson Co, Inc. add up to 4 of our 19 "Manufacturers of Masks and Respirators and Intermediate Inputs Self-Identifying as Producing Standard Products for FDA Approved, Hospital Grade Masks" for whom we have been able to confirm that they are manufacturing either the respirators or face masks in the U.S. Both companies are producing n95s in the U.S. as part of their overall production activities domestically.

[7] To-date, we have found a few of the companies in Figure 1 have a foreign entity as the parent company: Specifically, so far we have found 6 (17%) of the 97 respirator and face mask companies are foreign (5 Canada, 1 Switzerland), and 1 (1%) of the 20 face-mask only companies are foreign (Canada).

In my comments that follow, I will make three points: 1) making more advanced products here in the U.S. in a way that expands good middle-class jobs, 2) revolutionizing the nation's infrastructure as a pathway to developing the capabilities and ecosystem necessary to lead in manufacturing, and 3) developing the ability as a nation to make informed, far-sighted decisions about technology competitiveness.

1. **For the U.S. to compete, we must make innovative products here in the U.S., that only can be made here (or that at least that can be made here best), and that are demanded by the world.** Doing so can be a win-win for the economy and jobs (as well as for technology leadership, national security, and access to critical supply). Importantly, making advanced products domestically need not equal automation and fewer "good" jobs.

I want to start by debunking the assumption that manufacturing advanced technologies needs to equal fewer jobs, or more low-skill (often low-wage) and high-skill (often high-wage) jobs and fewer jobs in "the middle." Some time ago, I began to feel troubled by the focus on automation, robotics, and IT in the discussions on technology and the future of work. While these technologies are important, they are only one set of the vast innovations in the world and the world economy.

Our research demonstrates that some of our more important emerging technologies -- particularly those in advanced materials and processes - industry-wide 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.[8] 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 2020a).[9] 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

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[8] 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.

[9] 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).

relationship between material, process, and geometry design decisions and production outcomes (Combemale and Fuchs 2020).[10]

In the future, materials and process innovations behind parts consolidation may let you manufacture your i-Phone as a single flexible electronic device, or an optoelectronic transceiver so small that it can fit on your contact lens. Imagine if your iPhone, were a single flexible electronic bracelet like my daughter's slap bracelet…which you wore as a watch, but could take off and then unfold on your desktop and use as a computer. What if instead of having its components produced around the world (primarily in Asia) and assembled in China as it is currently, it were produced and manufactured here in the U.S., with middle-skill operator jobs. The goal of the U.S. cannot be to produce today's iPhone in the U.S. in the same way it is currently made in developing Asia. We want to produce the flexible electronic slap-bracelet watch/phone/computer of the future, that everyone in the world wants, and that only U.S. technologists and operators can together make. The win-win, is that that futuristic technology might also have more fulfilling jobs, not just for engineers, but also for high-school educated operators.

How do we get to that technology being manufactured in the United States? We need to take immediate steps to support start-ups pursuing advanced materials and process technologies for longer, and to rebuild our manufacturing ecosystem.

The U.S. currently still leads the technical frontier in multiple of the above-described technologies (if barely);[11] however, my research shows that *globalization means that the valley of death is getting larger for certain advanced material and process technologies:* when firms move manufacturing overseas to developing countries, such as China, Singapore, Malaysia, and otherwise, it can become unprofitable for those firms to pursue innovative new products and technologies. Lower wages and better assembly overseas reduce the costs of incumbent technologies, making emerging technologies have to achieve more[12] before they are able to successfully enter and complete against incumbent technologies on the market. (Fuchs and Kirchain 2010; Fuchs, Field, Roth, Kirchain 2011; Fuchs 2014)

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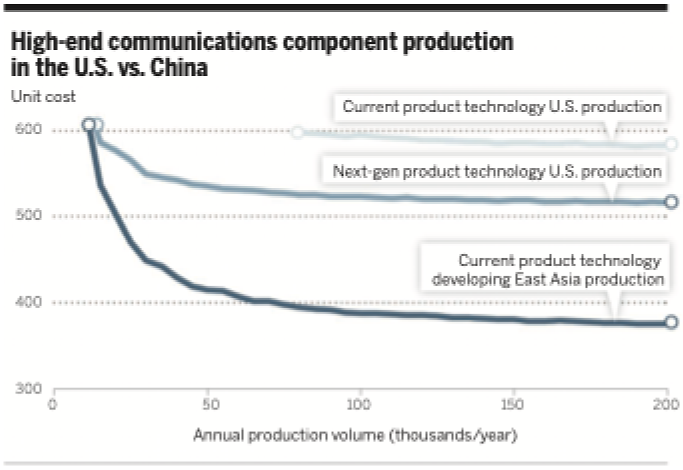
[10] Research suggests the complex relationship between design and production (and thus engineers and operators working together to bring new science to reality on the production floor) generalizes to immature materials and process technologies at the technical frontier. Due to technologists still being 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).

[11] While the U.S. currently still leads the technical frontier in multiple of the above-described technologies, we do not clearly have leadership in the operator skills to manufacture that technology domestically, and if we don't manufacture that technology locally, we will be unable to maintain our marginal technological leadership.

[12] Here "more" could be achieving lower production costs or achieving more in terms of improved performance and thus consumer demand despite higher prices.



Lines shown represent average capabilities across firms in the industry. [Adapted from (9)]

Figure 2: Globalization means that the valley of death is getting larger for certain advanced material and process technologies - when firms move manufacturing overseas to developing countries, such as China, Singapore, Malaysia, and otherwise, it can become unprofitable for firms to pursue innovative new products and technologies. Source: Fuchs 2014, adapted from Fuchs and Kirchain 2010.

Small Business Innovative Research (SBIR) funding is one important tool. (Lerner 1999, Fuchs 2014). Given the traditionally high capital expenditures required, long concept to development timeline, and dearth of venture capital funds in advanced manufacturing (c.f. Combemale, Glennon, Whitefoot, Fuchs 2020), *SBIR funding may also need to be more and longer just for advanced materials and processes*, given their different nature.

Materials-tailored SBIR funding and changing corporate incentives to invest in longer-term goals including manufacture domestically,[13] *however, alone is not enough.* We need to rebuild a U.S. domestic manufacturing ecosystem both to keep companies here and to innovate.

To rebuild a domestic manufacturing ecosystem, R&D funding, supply-side (e.g. R&D tax credit and tax incentives for domestic manufacturing) and traditional

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[13] Given the greater proportion of large firms in manufacturing versus non-manufacturing sectors, it is important to also address large firms in manufacturing policy. 66% of industrial R&D spending comes from manufacturing firms, with the five leading subsector spenders being pharmaceuticals and medicine, semiconductors and electronic components, communications equipment, automobile and light duty motor vehicles, and aerospace products and parts. Due in large part to significant offshoring during the last decade by these and other manufacturing subsectors, manufacturing contributes only 12% to domestic value added, as measured. (Combemale, Glennon, Whitefoot Fuchs 2020) The erosion of U.S. semiconductor manufacturing capabilities suggests the need for alternative incentives to support longer-term goals and to keep less profitable business lines (Fuchs, Mai, Blanton, Morgan proposal). More research is needed on this front. Part of the challenge may be increasingly short-term pressures on firm leadership leading to decision-making that maximizes short-term profits rather than undertaking more risky directions that confer long-term advantage (c.f. Fuchs and Kirchain 2010 on short-termism in offshoring, Lazonik 2014 on stockholder buy-backs). Government R&D funding has historically played an important role in seeding and launching new industries, as well as seeding non-mainstream projects within companies that would otherwise have been cut internally (c.f. NRC Funding a Revolution, Fuchs 2010). Companies have also themselves organized public-private partnerships (Khan, Hounshell, Fuchs 2015) and used venture funding and other mechanisms (c.f. Gawer and Cusumano 2002) to advance research and development in technologies critical to their industrial roadmap 3-7 years out.

demand-side (domestic procurement) policy instruments need to be aligned with strategic investments in the broader manufacturing and innovation ecosystem.

Let me provide an example of how, given the dilapidated state of our manufacturing ecosystem, funding research and development alone is insufficient (even if that funding were spread around the country.) 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.

2. **Strategic infrastructure investment as the pathway to rebuilding our manufacturing ecosystems (and a lot more)**

To rebuild domestic manufacturing, we need to use *strategic infrastructure investments as pathways to revitalizing U.S. worker skills and manufacturing ecosystems.*[14,15] By infrastructure I mean not just to 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*. 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

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[14] 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).

[15] 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.

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).[16] Foundries should be built to lead the world in the invention and commercialization of next generation semiconductors and synthetic biology.

Infrastructure has the interesting property not only of creating demand, but also of solving a problem. 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 skills 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.[17,18]

Finally, to fully benefit from what economists refer to as infrastructure's "multiplier effect" (a multiplier effect I've arguably defined much more broadly here), as much as possible, not only the final product but also the intermediate inputs should be largely sourced domestically. Further, influence in standards for those technologies should be aggressively pursued internationally.

3. T**he U.S. must act to develop strategic decision-making capabilities to inform critical technology investments.**

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[16] 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).

[17] 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.

[18] 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.

Reports with lists of (critical) technologies cannot be the central foundation of a robust U.S. technology strategy.[19,20,21,22] One of the many assets of the U.S. innovation system is its diversity, nimbleness and flexibility to respond to changing times. One mission-oriented agency that has been a hallmark of this nimbleness, and which I have researched is the Defense Advanced Research Projects Agency, or DARPA (Fuchs 2010).

A successful U.S. approach to technology strategy for U.S. competitiveness will require an analyst arm, an executive arm, and an external expert advisory board housed within a single entity for which strategic investments for national technology competitiveness is its mission. I believe that that entity needs enough money for its investments to be influential, but a sufficient lack of money such that it is required to engage and influence efforts in other agencies to have a larger effect: I recommend $3 billion for external seed funding (same as DARPA), plus an operating budget to employ 100 program managers[23] and ~100 analyst staff.[24]

Similar to DARPA, the executionary arm, should have a staff of rotating program managers brought in from academia, industry and government who are the best-and-the brightest across a variety of relevant contexts, and use the position as a stepping stone to subsequent leadership positions in their career.[25]

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[19] Between 1989 and 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.

[20] While publication of the National Critical Technologies Report ceased after 1999, with the rise of China, the concept of critical technologies has seen a revival in recent years. See for example NRC report on Critical Technology Accessibility 2006, Variety of GAO reports from 2015-2018, National Law Review 2018, Hearings by the House Science, Space, & Technology Committee.

[21] Even during past efforts, however, 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. 1993Congressional Research Service, Bimber RAND 1994, Popper and Wagner 2003.

[22] Problems remain: 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. US Science and Innovation Leadership for the 21st Century: Challenges and Prospects. National Academies Consensus Study. Co-Chairs Erica Fuchs and Eric Lander. https://www8.nationalacademies.org/pa/projectview.aspx?key=51225

[23] At any one moment in time, DARPA has approximately 100 program managers.

[24] The best example for the analyst arm would be the Office of Technology Assessment (OTA). (c.f. (Morgan, M.G. 1995), Princeton's Website on the OTA Legacy https://www.princeton.edu/~ota/) The OTA had at any one time a professional staff of about 140, over half of whom hold doctorate degrees in a variety of fields that include science, engineering and various areas of social science. In addition, to assure balance and completeness, each study was assisted by an advisory board of outsiders who were selected to represent a wide range of knowledge, perspectives and interests. Topics of OTA studies have ranged widely from nuclear proliferation to pollution control, industrial competitiveness, computer security and privacy, and medical technology. For comparison, the Institute of defense analysis today has 1500 analysts, approximately 25 of whom are part of the Science and Technology Policy Institute (STPI).

[25] The dominant PM training would likely be in academia and industry for specific technologies and capabilities such as advanced materials, batteries, manufacturing, or infrastructure - however depending on the perceived bottlenecks for technology competitiveness, relevant expertise might also come from areas as diverse as venture capitalists to education to inequality.

An analyst arm will be essential for a multitude of reasons:[26],[27] The analyst arm needs to provide transparency for policy-makers in the trade-offs of various technical investments in meeting potential national objectives (the value of those objectives which different individuals groups will weigh differently).[28] It needs to leverage existing and new data and methods to systematically assess our and other nations technological capabilities: In the inaugural session of the National Academies' study on U.S. Science and Innovation Leadership for the 21st Century which I co-chaired, representatives from DARPA and the DOD Strategic Technology Protection office both articulated a lack of sufficient mechanisms to assess strategic weaknesses and opportunities versus other nations in technologies critical to national security.

Even if we did have perfect information on our relative competitiveness, where and how to invest remains extremely challenging. Identifying how to effectively support data infrastructure for leadership in machine learning or foundries for experimentation in synthetic biology or next generation semiconductor devices alone is challenging, despite being technical areas where it is broadly agreed we will need such investments to lead. Systemic investments in educational (including training) or manufacturing ecosystems may be even harder. The domestic mask shortage during the current global pandemic illustrates just how tricky these decisions can get in the context of manufacturing ecosystems. Getting these decisions right, is going to require interdisciplinary teams with technical depth that bring together our best and brightest --

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[26] Similar to the Joint Research Center for the European Union, the U.S.'s former Office of Technology Assessment (OTA), or the current U.S. Science and Technology Policy Institute and Institute for Defense Analysis, the analyst arm will need to be staffed by a dynamic, deeply interdisciplinary group of experts (both Ph.D.s and practitioners), dominated by technologists, but including economists, historians, political scientists, and others.

[27] In the 1990 Defense Authorization Act (PL 101–189 signed into law on 29 November 1989), Congress defined "critical technologies" as "essential for the United States to develop to further the long-term national security or economic prosperity of the United States." As the nation reflects on global technology capabilities and our relative position globally today, is this still the right definition? Are critical technologies technologies we need for national security? Economic security? Health security? Where technology leadership may be necessary to uphold values and norms related to human rights and privacy? These potential dimensions of criticality need fleshing out. Finally, even if the 1990 definition is a good one, what does it mean in terms of concrete technologies and associated policy actions?

[28] Not only will we as a nation never have unilateral agreement on the appropriate definition of a critical technology, we never should. What we need is transparency for policy-makers in the trade-offs of various technical investments in meeting potential national objectives (the value of those objectives which different individuals groups will weigh differently). There are methods to map technologies to potential outcomes for national objectives, such as those undertaken by the RAND Critical Technology Institutes in the 1990s and by academics such as my departmental colleague Destine Nock (c.f. Nock and Baker 2019, Nock, Levin, and Baker, 2020). I would argue, however, that these methods are still in their infancy and require significant national focus and investment. We also lack a systemic way to assess our and other nations technological capabilities. In the inaugural session of the National Academies' study on U.S. Science and Innovation Leadership for the 21st Century which I co-chaired,# representatives from DARPA and the DOD Strategic Technology Protection office both articulated a lack of sufficient mechanisms to assess strategic weaknesses and opportunities versus other nations in technologies critical to national security. There are a number of existing measures (national portfolios of patents, publications, R&D funding, venture funding, products, and trade statistics in specific technology areas) combined with highly-sophisticated techniques commonly used by economists that could be repurposed instead to offer strategic insights (c.f. (Branstetter, Glennon, and Jensen 2018) for a birdseye perspective of relative national competitiveness in specific technologies by patents; (HAI 2019), the global AI Index published by Stanford University for an integrated assessment of technology capabilities in one specific technology, AI; and (Alderucci, Branstetter, Hovy, Runge, and Zolas. 2020) for research using natural language processing of U.S. patents.) In addition, novel metrics and analytical techniques are needed. For example, additional insights may be able to be gleaned using expert elicitation (c.f. Morgan, M.G. 2014), natural language processing, and the predictive value of machine learning seeded by the expert-elicited knowledge.

both the executing PMs and the analysts to support them and legislators in making their decisions.

As the U.S. goes forward, we must make sure we have the infrastructure necessary to invent and make the next generation of beyond-CMOS microchip (Khan, Hounshell, Fuchs 2018), and other technologies already identified by multiple parties -- such as the Council on Foreign Relations -- as critical to our future (c.f. Council on Foreign Relations 2019). We need to leverage building the infrastructure of the future to rebuild our manufacturing ecosystem -- both in terms of domestic firms and domestic workforce -- into one that can make the above advanced technologies and and nimbly pivot into and out of making everything else. But most importantly, we need to invest in the strategic decision-making capacity to nimbly and continuously identify where and how to invest in the technology and infrastructure necessary to collaborate, compete, and lead world-wide.

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