Crisis Innovation Policy from World War II to COVID-19*

Daniel P. Gross†
Duke University and NBER

Bhaven N. Sampat‡
Columbia University and NBER

April 12, 2021

Prepared for the 2021 NBER EIPE Workshop

*We thank Josh Lerner, Scott Stern, and Ken Shadlen for helpful comments. We also thank Harvard Business School and the NBER Innovation Policy grant (2016) for financial support. This material is based upon work supported by the National Science Foundation under Grant No. 1951470. All errors are our own.
†Address: Duke University Fuqua School of Business, Durham, NC 27708, USA; email: daniel.gross@duke.edu.
‡Address: Columbia University, New York, NY, USA; email: bns3@cumc.columbia.edu.

The COVID-19 pandemic has illustrated that innovation and innovation policy can be crucial components of governments' responses to crises. It has also brought into focus that crisis innovation problems raise different questions for science and technology (S&T) policy, and may require different tools, than non-crisis times. Though crisis innovation policy was not a major feature of the U.S. innovation policy dialogue immediately before COVID, it has been a prevailing theme of the past year. It also a long and storied history: the most famous earlier response—indeed one appealed to by many in the COVID-19 pandemic—was the U.S. World War II research effort. Led by the Office of Scientific Research and Development (OSRD), under the direction of Vannevar Bush, the wartime effort helped develop, test, and get into practice numerous technologies and medical treatments that were essential to the Allied victory, including radar, mass-produced penicillin, the proximity fuze, malaria treatment, and the atomic bomb. The wartime R&D experience also led to long-run changes in the U.S. innovation system and postwar innovation policy.

In this paper, we survey the efforts undertaken in World War II and the COVID-19 pandemic and consider implications for innovation policy in crisis and regular times. We begin with the premise that crises can put unique demands on the innovation system which may require a distinct response (Gross and Sampat 2021). The responses to these two crises can in turn offer lessons in method and contrast. Our goal for this chapter is to summarize what each of these efforts comprised, draw comparisons, identify key policy tradeoffs, and provide insight on the short- and long-run effects of crisis innovation.

We begin in Section 1 by examining the World War II response to distill the main elements of the wartime model of crisis innovation policy and the high-level questions it needed to consider. The OSRD model, while specific to its time, was also by most accounts successful, and the experience is cited as precedent for a wide range of crisis innovation activities. In Section 2, we then discuss the evolution of the postwar innovation system and how policy was shaped by World War II, traversing and summarizing 75 years of science policy from the end of the war to the dawn of the pandemic. This evolution would in turn mean that the COVID-19 crisis confronted a very different innovation system than existed in 1940.

As of the time of this writing, it is challenging to fully evaluate the COVID-19 model, as we are still in midst of the crisis and the crisis response. Moreover, we lack for COVID-19 the types of data, correspondence, and other records available to study the World War II period. In Section 3 we nevertheless attempt to describe the COVID-19 innovation response based on currently available information, anticipating that more will be written when the full story can be told. We then discuss how the COVID response seems similar to and different from the World War II model, and how that may reflect broader differences in today's innovation system and the different nature of the central innovation policy problem.

In Section 4, we use the two episodes to identify key tradeoffs in crisis innovation policy, discuss how they manifested in each crisis, and suggest what factors may influence policy choices. We focus on four tensions: top-down vs. bottom-up priority setting, concentrated vs. distributed funding, patent policy, and managing disruptions to the innovation system. Though several of these tensions are endemic to S&T policy even in ordinary times, we argue they can be particularly acute in a crisis.

In Section 5 we then use the World War II experience to survey the short- and long-run effects of crisis

innovation. Beyond impacts on the crisis at hand, these include effects on the rate and direction of innovation, effects on R&D-intensive firms and industries, effects on scientific careers, and effects on science policy. In Section 6 we put the collective evidence into perspective and consider some ways in which the COVID-19 R&D effort might also have long-lived impacts on U.S. innovation and innovation policy. While we will have to wait for the post-pandemic future to unfold, if the past is any guide, more changes may yet be in store for the U.S. and global innovation system in the years ahead.

1 The World War II Research Effort

1.1 Historical background

World War II began in September 1939 when Germany invaded Poland; the United Kingdom, France, and several other countries declared war on Germany; and Russia counter-invaded Poland two weeks later. Two months later Russia invaded Finland, and four months after that Germany controlled Denmark and Norway. In early May 1940, Germany invaded Belgium, the Netherlands, Luxembourg, and France, and on June 14, Paris fell to Germany, with France formally surrendering on June 22.

Americans could observe this conflagration from a distance, as the U.S. was not at immediate risk of being invaded. But the fall of France broke the general sense of complacency and made clear to many U.S. leaders that the country would be drawn in: for the U.S., the war in Europe was a crisis in the making. It was also on June 14 that a small group of scientists and science administrators, led by Vannevar Bush (President of the Carnegie Institute of Washington and former Vice President and Dean of Engineering at MIT), met with President Franklin D. Roosevelt to express concerns that the U.S. was "unprepared to fight a modern war" (Stewart 1948) and propose that he put civilian scientists to work on developing military technology. On June 27, 1940, Roosevelt formally created the National Defense Research Committee (NDRC) for this end. The U.S. would not formally enter the war until December 8, 1941.

The NDRC was led by Bush as its Chair, supported by Karl Compton (President of MIT), James Conant (President of Harvard), and Frank Jewett (President of the National Academy of Sciences and of Bell Labs), Richard Tolman (CalTech physicist), Conway Coe (the U.S. Patent Commissioner), and one representative from each of the Army and the Navy, who together comprised "the Committee". Funded by the President's discretionary budget, NDRC's mandate was to "coordinate, supervise, and conduct scientific research on the problems underlying the development, production, and use of mechanisms and devices of warfare." To do so, it was authorized to perform research directly as well as to contract for extramural research. NDRC's work was to supplement that of other agencies, including the military.

NDRC began with an ambitious mission but only eight staff (the members themselves) and no precedent to follow. At its first meeting, the committee organized into five divisions by subject (Table 1) and concurrently began recruiting other top scientists to fill the new agency's ranks. It also decided that it would contract out research rather than perform it directly—a radical move for its time.

Table 1: NDRC Divisions (1940-1941)

NDRC Division	Director
A – Armor and Ordnance	Tolman
B – Bombs, Fuels, Gases, Chemical Problems	Conant
C – Communications and Transportation	Jewett
D – Detection, Controls, Instruments	Compton
E – Patents and Inventions	Coe
Committee on Uranium	Briggs*

*Lyman Briggs, Director of the National Bureau of Standards.

Impressed by a string of early accomplishments, on June 28, 1941 President Roosevelt issued Executive Order 8807 creating OSRD. The new organization, to be led by Bush, addressed several deficiencies in the original structure (including expanding its scope to medical research), and would be the principal agency organizing civilian science and technology for war. Now funded by Congressional appropriations, OSRD subsumed NDRC (now chaired by Conant) and added a Committee on Medical Research (CMR) (chaired by A. N. Richards, a pharmacologist at the University of Pennsylvania). The scope of crisis activities that OSRD engaged in was broader than research alone. In addition to NDRC and CMR, the OSRD included an Advisory Council, which coordinated research activities across the government. It later added an Office of Field Service (to deploy scientists to the field, where they would study field problems and aid in training and use of OSRD devices in combat operations), a Liaison office (for sharing and coordinating research with Allied countries, including via foreign branches), a Scientific Personnel office (to manage personnel shared by the OSRD and other agencies, and to handle draft deferments for technical staff at OSRD and its contractors), and an Administrative office (for contract management).

Both NDRC and CMR were organized into divisions by subject matter led by scientific experts. NDRC's structure expanded significantly as the scope of its work grew, and by the end of the war it had grown to 26 divisions (Table 2). The largest were Radar and Rocket Ordnance, which primarily funded large, central labs (the MIT Radiation Laboratory ("Rad Lab") and the CalTech Jet Propulsion Lab, which were created or significantly expanded to meet the needs of the war effort).

Despite having just one-tenth of NDRC's budget, CMR was also essential to the wartime effort. Its mandate was to mobilize medical researchers and identify "the need for and character of contracts to be entered into with universities, hospitals, and other agencies conducting medical research activities." Funding of extramural medical research was also new: one of the leaders of the effort (Chester Keefer, the "penicillin czar") later characterized CMR as "a novel experiment in American medicine" noting "planned and coordinated medical research had never been essayed on such a scale" (Keefer 1969).

OSRD's annual budget grew from $6.2 million in 1940-1 to $160-170 million in 1944 and 1945. By the end of the war, OSRD had spent over $536 million on R&D, across over 2,500 contracts, including 1,500 contracts by NDRC, 570 by CMR, and about 100 for research on atomic fission, before this work was spun out into the Manhattan Project, as we describe below. It also grew to be a large organization, at its peak employing nearly 1,500 personnel across multiple locations (Stewart 1948).

Table 2: OSRD Divisions, Panels, and Special Sections (1941-1947)

National Defense Research Committee (NDRC) Division/Section	Name/Description	Contract Authorizations ($, '000s) (1943-1947)	
1	Ballistics	5,327.2	
2	Effects of Impact and Explosion	2,701.4	
3	Rocket Ordnance	85,196.5	
4	Ordnance Accessories	20,014.3	
5	New Missiles	12,881.2	
6	Subsurface Warfare	33,883.5	
7	Fire Control	7,711.7	
8	Explosives	11079.9	
9	Chemistry	4,698.2	
10	Absorbents and Aerosols	3,524.2	
11	Chemical Engineering	9,216.2	
12	Transportation Development	2,199.4	
13	Electrical Communication	2,073.9	
14	Radar	104,533.4	
15	Radio Coordination	26,343.0	
16	Optics	5,923.9	
17	Physics	7,655.3	
18	War Metallurgy	3,794.4	
19	Miscellaneous Weapons	2,416.1	*
AMP	Advanced Mathematics Panel	2,522.9	
APP	Applied Psychology Panel	1,542.5	*
COP	Committee on Propagation	453.0	*
TD	Tropical Deterioration	232.4	*
SD	Sensory Devices	272.5	*
S-1	Atomic Fission	18,138.2	*
T	Proximity Fuzes	26,400.0	*
Total		400,735.1	

Committee on Medical Research (CMR) Division	Name/Description	Contract Authorizations ($, '000s) (1941-1947)
1	Medicine	3,873.3
2	Surgery	2,847.6
3	Aviation Medicine	2,466.5
4	Physiology	3,981.5
5	Chemistry	2,383.9
6	Malaria	5,501.9
–	Miscellaneous	3,635.3
Total		24,689.9

Notes: NDRC authorizations from January 1, 1943 onwards, except where noted below. *Authorizations for Division 19 from April 1, 1943; APP, from September 18, 1943; COP, from January 22, 1944; TD, from May 18, 1944; SD, from November 1, 1945. Authorizations for Sections S-1 and T are from June 27, 1940 onwards, with Section S-1 terminating in September 1943.

Table 3: OSRD expenditures, by fiscal year, 1941-1946

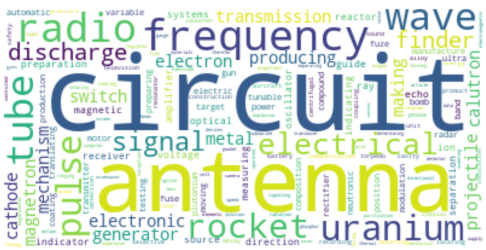
Fiscal year	FY1941	FY1942	FY1943	FY1944	FY1945	FY1946	Total
Obligations ($, MMs)	6.2	39.6	142.5	162.5	167.5	17.9	536.1

Notes: Government fiscal years at this time ran from July 1 to June 30. Data from Stewart (1948).

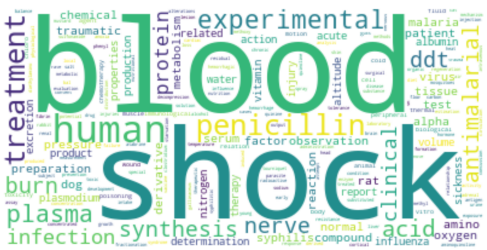
In the space of five years, this effort produced major developments in a wide range of technologies. Figure 1 illustrates the focus of OSRD's work, using words in the titles of OSRD patents and publications. NDRC was responsible for many of the most notable technological developments of the war, including radar, electronic communication (including early computing), underwater detection (sonar), rockets and jet propulsion, and atomic fission, among others. CMR's work helped support the mass production of penicillin; influenza and other vaccines; new malaria treatments; new approaches to managing wartime hardships such as sleep and oxygen deprivation, cold temperatures, nutrient deficiencies, and psychological stress; and techniques for treating injuries and wounds. Beyond its immediate impacts on the war and on science, the OSRD also created the template for federal R&D procurement, laid the foundation for postwar S&T policy, and reshaped the postwar innovation system, as we will discuss below.

Figure 1: Common words in OSRD patent and publication titles

Panel (A): Words in patent titles



Panel (B): Words in publication titles



Notes: Figure illustrates the most common words appearing in the title of OSRD-supported patents and academic publications. Font size is proportional to number of occurrences, with larger words being more common. Patents primarily resulted from NDRC-supported technological R&D, and academic publications from CMR-supported medical research.

1.2 The wartime model for crisis innovation policy

The war posed a challenge to the budding U.S. innovation system: develop a range of new technologies, produce them at scale, and get them deployed quickly enough to deliver an Allied victory. As Conant wrote, "The basic problem of mobilizing science during World War II was [one] of setting up *rapidly* an organization or organizations which would connect effectively the laboratory, the pilot plant, and the factory with each other and with the battlefront" (Conant 1947). Bush likewise wrote, "It was the function of [OSRD] to channelize and focus an amazing array of variegated activities, to co-ordinate them both with the military necessities which they were designed to help to meet and with the requirements of the powerful industrial structure on which their effective application relied" (Bush 1970).

How did OSRD meet this challenge? In recent work (Gross and Sampat 2020b) we examine the OSRD model in detail, focusing on six features: (1) priority setting, (2) engaging researchers, (3) the contract mechanism, (4) incentives, (5) coordination, and (6) downstream production and diffusion.

Applied focus, top-down priority setting

OSRD led a primarily applied research effort.[1] Executive Order 8807 explicitly tasked it with the following duties, which leave no ambiguity about the purpose of its work (emphasis added):

- *Advise the President with regard to ... scientific and medical research relating to* national defense.
- *Serve as the center for mobilization of the scientific personnel and resources ... to* defense purposes.
- *Co-ordinate, aid, and, where desirable, supplement ... research activities relating to* national defense *carried on by the Departments of War and Navy and other ... agencies of the Federal Government.*
- *Develop broad and co-ordinated plans for the conduct of scientific research in the* defense program.
- *Initiate and support scientific research on [instruments] of warfare ... required for* national defense.
- *Initiate and support scientific research on medical problems affecting the* national defense.
- *Initiate and support such scientific and medical research as may be requested by the government of any country whose defense the President deems vital to the* defense of the United States.

Its priorities were thus defined by military need, and the urgency of the crisis meant that it mostly had to take basic science as given. As we explain below, this approach is a contrast to many postwar R&D funding institutions, where research is investigator-initiated, often fundamental, and scientists have a larger role in shaping the agenda. At NDRC it was ultimately divisions, and within them individual study sections, which identified research priorities, organized proposals, and made arrangements with contractors. CMR, on the other hand, partnered with the National Research Council's Division of Medical Sciences (DMS) in setting priorities and solicited proposals.

Engaging top R&D performers

A second feature of the wartime effort was its focus on funding top institutions and researchers. To support this activity, one of NDRC's first undertakings in 1940 was to build a roster of potential contractors by subject area, which became a standard reference for placing contracts. It prioritized getting results quickly over distributional concerns, favoring contractors "with the facilities and the manpower which promised the best results in the shortest possible time" (Stewart 1948).

Incentives and the contract mechanism

The decision to outsource research, rather than perform it directly, was novel. To do so, OSRD invented the federal R&D contract, which balanced specificity with flexibility to explore. The language was standardized but negotiable, and contractors "almost invariably started work under letters of intent which preceded the signing of contracts by weeks or months" (Stewart 1948), so as to not delay progress. Though contracts were written for short (e.g., 6-month) periods, there was an "informal understanding that they would be extended if the progress of the work warranted." In the end, OSRD effectively procured research services rather than specific outputs, making its contracts grant-like in nature.

Because results from this work were often patentable, it also developed a novel, contractual patent policy that balanced private incentives with the public interest. OSRD contracts bore either a "short form" or

[1] Conant (1947) wrote, "Time set a limit on what could be done: the basic knowledge at hand had to be turned to good account" and "For the duration of the war further advances in pure science for the most part were suspended."

"long form" patent clause, specifying which party retained title to inventions produced under patent (the government and the contractor, respectively), while ensuring that the U.S. government retained a royalty-free license for military use. These terms were standardized but adapted for specific contracts as needed, with the government generally relinquishing patent rights to industrial contractors but retaining them with academic ones and in especially sensitive subject matter like nuclear energy.

Coordinating research efforts

As the principal agency mobilizing research for war, the OSRD was also responsible for coordinating research with the military, other U.S. scientific agencies, and the broader Allied research effort. This was achieved in part through cross-appointments, as members of other agencies were appointed to OSRD's Advisory Council, and Bush was concurrently Chairman of the Joint Committee on New Weapons and Equipment at the Joint Chiefs of Staff, which ensured that the scientific perspective would remain close to military strategy. Day-to-day coordination on individual research projects was performed by division-specific military liaisons. In some cases, research programs begun by one division or agency were transferred to another, most notable being the NDRC's atomic fission project being transferred to the U.S. Army Corps of Engineers as the Manhattan Project when it advanced to a weapons development project.

International coordination was also a feature of the OSRD model. American-British collaboration began in the fall of 1940, shortly after NDRC was created, when the British Tizard mission to the U.S. ended in an exchange of data, plans, and prototypes of a wide range of technologies being developed in each country (most notably the British cavity magnetron, the key input to the U.S. radar program). OSRD later opened a field office in London, which was a conduit for information to flow between American and British researchers, and the British similarly opened an office in Washington, DC. In some cases, individual OSRD research programs also ran foreign branch laboratories near their British counterparts.

Investment in production and diffusion

Though it was foremost a research funding and R&D management organization, OSRD also took a role in production and diffusion. The philosophy behind this choice was that fulfilling its mission required, in the previously-quoted words of Conant (1947), "connect[ing] effectively the laboratory, the pilot plant, and the factory with each other and with the battlefront." This meant that OSRD's work needed to be advanced from laboratory prototypes to reliable, mass-produced units in the field. Because time was of the essence, OSRD was at times aggressive in building capacity at risk. This was particularly true for the atomic fission project, in which it scaled up multiple enrichment sites and methods before knowing which approach would be able to produce enough fissionable uranium to manufacture a bomb.

OSRD also had specific offices focused on getting technology from bench to battlefield, supporting initial production runs, clinical trials and field tests, manufacturing at scale, and deployment. Tight links between researchers and military users facilitated rapid feedback and tweaking. That the military was the main user may have also made it easier to adapt established practices than it would have been otherwise, circumventing common organizational frictions to technology adoption.

1.3 The OSRD model in action: Atomic Fission

As Table 2 shows, OSRD managed a broad portfolio. Here we use the fission program—one of OSRD's larger research endeavors—to illustrate several features of its approach.

The atomic fission project originated in the pre-war discovery of nuclear fission in Germany and Denmark in 1938-1939. Scientists quickly discovered that the uranium isotope U-235 was fissile, and that because its bombardment with neutrons and subsequent fission released additional neutrons, it could be engineered to create chain reactions that released an immense amount of energy. In 1939, at the urging of Leo Szilard and Albert Einstein, President Roosevelt established a secret committee to study the matter, which was folded into NDRC at its founding in 1940 (the Committee on Uranium, Table 1).

Because atomic fission was new, NDRC first contracted with several universities to deepen the basic science of fission—an undertaking that was relatively distinctive for OSRD, which otherwise mostly funded applied research. Among the questions that needed to be answered was what elements and isotopes were fissile, or how to separate U-235 from the more common isotopes U-238 at scale or produce chain reactions in U-238. As Baxter (1946) explained, "One approach was to place unseparated uranium in a 'pile' with carbon or heavy water as a moderator or 'slower down' of neutrons to increase the chances of a chain reaction;" the other was "to separate the isotopes and accumulate a stock of U-235."

By the fall of 1941, the project was beginning to show promise, despite relatively modest funding, but the bottleneck was the ability to produce enough fissile material for a bomb. The program was scaled up into five parallel efforts: electromagnetic separation at UC Berkeley; gaseous diffusion and centrifugal separation of U-235 at Columbia University; and graphite and heavy-water pile methods of obtaining plutonium from uranium at University of Chicago. The bombing of Pearl Harbor on December 7, 1941 intensified this effort into an "all-out attack on the uranium problem," with Roosevelt urging them to "press as fast as possible on the fundamental physics and on the engineering planning" (Baxter 1946).

Until it became clear which enrichment method would succeed, OSRD invested in them all. In early 1942, OSRD began planning pilot plants for all five methods, with the Army taking charge of construction. Baxter (1946) later explained that "Fear that the Germans would be the first in the field with atomic bombs led to a telescoping of stages, in which pilot plant work often overlapped research in the laboratory, and the design and construction of the huge production plants were carried out before lessons could be learned and obstacles surmounted in the pilot plant." Throughout 1942, as the OSRD's R&D continued, the Army began building reactors and separation plants at Oak Ridge and Hanford (among others) and a weapons manufacturing facility at Los Alamos, under the umbrella of the Manhattan Project. By early 1943, two of the enrichment methods had failed, leaving gaseous diffusion and electromagnetic separation, and the graphite pile, as frontrunners. In May 1943, with the science established and pilot plants running, the fission project was transferred to the Army, whose job was then to produce a functioning atomic weapon. The British had been simultaneously advancing a nuclear weapon program, and shortly thereafter agreed to fold its effort into the Manhattan Project. Bush and Conant continued on in an advisory capacity until July 16,

1945, when the first nuclear weapon was detonated in the Trinity test.

The fission program illustrates several of OSRD's core features in practice, including coordination, outsourcing research, and a focus on technology diffusion. Other aspects of the program, such as funding parallel R&D and investment in production at risk, were more idiosyncratic, though they illustrate the general principle that in a crisis, getting a solution developed and diffused quickly is a key objective.

Other programs also deviated in ways from the four features highlighted above. Though in many ways the radar program exemplified the OSRD features—including demand-driven priorities, focus on top scientists and engineers, coordination with the military, international coordination, and funding for production and diffusion activities—it was also highly centralized, operating primarily out of a single building on the MIT campus. This reflected the nature of the problem (building a technological system) and the importance of feedback and spillovers across the innovation chain (Gross and Sampat 2020b).

At CMR, several of the major efforts also did more than just outsource research (Bush 1970). The malaria program (aiming to find a better malaria treatment than the drug that was broadly used, atarabine) helped oversee and coordinate private-sector efforts to synthesize and test thousands of candidates, even without formal contracts. Similarly, the large synthetic penicillin effort promoted knowledge and information sharing among private sector firms. Interestingly, each of these programs were nominally failures during the crisis itself. The major development from the malaria effort, chloroquine, arrived too late to be used in the war. And the costly effort to synthesize penicillin, originally viewed by Bush and others as the best route to the production of large quantities, was unsuccessful during the war (and rendered moot by the progress in the natural penicillin production program), though historians have argued it helped pave the way for synthetic penicillins that came to the market in the 1950s (Swann 1983).

1.4 Criticisms and difficulties

Overall policymakers and the public were broadly impressed with the effort, as we will discuss below. However there were strong critics of various aspects of the efforts during the crisis. One line of criticism came from liberal critics of OSRD, led by Senator Harley Kilgore (D-W.Va) who expressed concerns that OSRD focused exclusively on elite institutions and scientists/engineers known to its leadership, an approach which, in his view, would not only contribute to long-term inequities and concentration but also limit the range of useful ideas brought to its attention and thus delay crisis resolution (Kevles 1977). Associations representing specific scientific disciplines (e.g., mathematics and biology), regions (western states), and small businesses expressed disgruntlement at being overlooked by the OSRD (Owens 1994, Kevles 1977, Appel 2000). Related to the concerns about concentration, Kilgore and others questioned OSRD's patent policy, which often gave rights to contractors, arguing that doing so may create legal bottlenecks hindering the response and monopolies based on taxpayer research after the war (Kevles 1977, Sampat 2020).

Throughout the war there were complaints about the lack of political accountability of the new organization as well, and about stepping on the toes of scientists and engineers in the Navy and War departments (Owens 1994). The flexibility that Bush viewed as important to OSRD's success sometimes also drew scrutiny. Bush

(1970) wrote in his memoirs, "There were those who protested that the action of setting up NDRC was an end run, a grab by which a small company of scientists and engineers, acting outside established channels, got hold of the authority and money for the program of developing new weapons. That, in fact, is exactly what it was. Moreover, it was the only way in which a broad program could be launched rapidly and on an adequate scale." Other decisions made in the name of speed, including at CMR "challenge trials" of therapies on prisoners, raised ethical concerns even at the time (Rothman 1991).

Though after the fact the effort was widely celebrated, it certainly had struggles along the way, unsurprisingly for a new agency operating under tremendous pressure with little precedent. OSRD made numerous policy changes and realignments during the course of the war to adapt to new information from the field or feedback from contractors on what was and was not working (Stewart 1948). One example of the challenges it faced was in liaison with the military. We suggested above that close relations with the military were important, and the evidence suggests that they helped facilitate priority setting and diffusion, but this process was by no means seamless. The military was a complex, bureaucratic organization, and liaison was complicated by frequent turnover of military attachés. This challenge was partially relieved by having points of contact with the military at multiple levels of the OSRD hierarchy, though never fully resolved, as the relevant knowledge was more embodied in these individual people than the organization.

2 The Evolution of the Postwar Innovation System: Science and Technology Policy in "Normal" Times

Despite these difficulties, the wartime R&D effort advanced scores of technologies crucial to the resolution of the crisis. These included radar, the atomic bomb, the mass production of penicillin, and a number of other technologies and medical and treatments (Baxter 1946). Near the end of the war, President Roosevelt asked Bush to reflect on lessons from OSRD—"a unique experiment of team-work and cooperation in coordinating scientific research and in applying existing scientific knowledge to the solution of the technical problems paramount in war"—for postwar innovation policy. Roosevelt wrote:

> There is, however, no reason why the lessons to be found in this experiment cannot be profitably employed in times of peace. The information, the techniques, and the research experience developed by the Office of Scientific Research and Development and by the thousands of scientists in the universities and in private industry, should be used in the days of peace ahead for the improvement of the national health, the creation of new enterprises bringing new jobs, and the betterment of the national standard of living.

In July 1945, Bush responded with *Science, The Endless Frontier*, sometimes considered the blueprint for postwar U.S. innovation policy (Bush 1945). The "Bush Report", as it came to be known, did not explicitly discuss crisis innovation much, beyond noting that most of the applications of technology during the war relied on pre-existing basic knowledge. Instead, it mainly focused on the need for government support of basic research in peacetime (anticipating aspects of the Nelson-Arrow "market failure" theory of innovation

policy), the importance of basic research for technological progress, the need for scientific autonomy in setting priorities, and the role of universities in performing basic research.[2] Some economists (Nelson 1997, Romer 2020) have argued that the Bush ideology has fixated U.S. innovation policy on science and blinded it to possibilities of technology policy, including the kinds of applied endeavors that were essential to the wartime effort (and later would be in the COVID-19 crisis).

While Bush, Kilgore, and their allies introduced and debated a slew of competing bills embodying the different visions, OSRD research was spun off to existing agencies rather than the single foundation both Bush and Kilgore wanted. The Office of Naval Research absorbed military contracts, the Atomic Energy Commission (AEC) nuclear work, and the National Institutes of Health (NIH) medical research (Kleinman 1995, Brooks 1996). By the time the National Science Foundation (NSF) Act was signed by President Truman in 1950, the agency it created had become a "puny partner" in the overall enterprise (Kevles 1977). The U.S. system was instead fragmented and pluralistic, as different agencies had different responsibilities and modi operandi. In the Cold War and expansion of federal R&D over the ensuing decades, "mission-oriented" R&D funders would come to dominate the funding landscape (Smith 2011).

Of particular relevance for the COVID-19 era is the NIH. The National Institute of Health (then singular) was created in 1930. Though it had its roots in the Marine Hygienic Laboratory, a bacteriology lab created in 1887 which made significant contributions to vaccine development against infectious diseases in the early twentieth century, the Institute focused on basic studies on chronic diseases like cancer. By the 1930s it had expanded its focus to chronic diseases as well, including through the 1937 National Cancer Act. But before the war, it did not have a broad research funding program (Swain 1962).

We previously described how during World War II the OSRD's Committee on Medical Research coordinated and funded medical research activities. After the war was over, and as Bush's proposed National Research Foundation faced legislative delays, CMR's open contracts were transferred to NIH and became the foundation of its extramural grants program (Swain 1962, Fox 1987). Buoyed by the wartime demonstration of the value of medical innovation and the returns to government research funding, the NIH grew rapidly in the decades that followed, adding myriad new Institutes focused on specific diseases, organs, professions, and fields of research. It inherited not only CMR funds, but also its peer review system and administrative personnel.[3] Unlike CMR, the NIH focused primarily on basic research. Though Congress made allocations to individual institutes, by and large priority setting at NIH has been investigator initiated. Disease advocates (and Congress) have at times questioned the wisdom of this, especially in years of tight budgets and in the

[2] As Mowery (1997) has argued, the Bush Report had a strong imprint on the ideology of S&T policy, including on the importance of basic research and the appropriate division of labor between the government, firms, and universities. Its actual policy recommendations had less of an impact. Its flagship recommendation was a single major foundation supporting basic research, the National Research Foundation. The idea that a single major agency should support research was uncontroversial. But critics of the Bush approach, most prominently Senator Harley Kilgore (D-W. Va), objected to the limited public accountability of the proposed foundation, geographic and institutional inequity in funding, and lack of attention to applied research guided by specific socio-economic priorities. Kevles (1977) summarizes: "The differences between Bush and Kilgore boiled down to a basic issue: Kilgore wanted a foundation responsive to lay control and prepared to support research for the advancement of the general welfare; Bush and his colleagues wanted an agency run by scientists mainly for the purpose of advancing science."

[3] For example, James Shannon, the NIH head who presided over its postwar expansion during the 1950s and 1960s, was a central part of the CMR malaria research program. Similarly, when the National Science Foundation was eventually enacted, its first director was Alan T. Waterman, who had been OSRD's director of field operations.

context of specific health crises (e.g., cancer or AIDS; see Sampat 2012).

With some exceptions, the postwar division of labor in medicine was that the public and academic sectors focused upstream, and the private sector was responsible for more "applied" activities, including development, costly clinical trials, and diffusion. The "integrated research model" (Hoyt 2006) that characterized wartime medical research was largely abandoned at NIH for a more "linear" approach to innovation like that advocated by Bush (Balconi et al. 2010). Since the late 1990s the NIH has begun to emphasize "translational research" as well, partly in response to criticisms of the linear model (Butler 2008).[4]

The NSF also focused on fundamental research activities, also driven by investigator-initiated research, and also faced tensions historically (Brooks 1996). Both agencies have emphasized funding top scientists, mainly though grants rather than contracts. However, aspects of the wartime approach were present in other fields, particularly military research funded through the Department of Defense (DOD) and space research at the National Aeronautics and Space Administration (NASA). Within DOD, the Defense Advanced Projects Research Agency (DARPA, initially known as ARPA) has a focused approach to technology development (Azoulay et al. 2019) that in many ways resembled OSRD, and there have long been calls for bringing aspects of that approach to biomedical research (Cook-Deegan 1996). As we will describe below, one such experiment, BARDA, would have an outsized role during the COVID-19 response.

Three other aspects of the postwar biomedical innovation system help frame the COVID-19 response. We noted above that the postwar system involved the public sector supporting fundamental research, and private firms supporting clinical development, development and manufacturing, and marketing. A long history of empirical research in economics suggests that patents are important for incentivizing private sector research and development activities, especially in the life sciences (Levin et al. 1987). However, frustrations that patents restrict access and diffusion (some of which became prominent in a previous global health crisis, HIV-AIDS) and that they may not work effectively for some types of research (including vaccines without large rich country markets) has led to proposals for alternative "pull" mechanisms, including prizes and advance market commitments (Kremer and Williams 2010).[5]

Second, in response to concerns about a lack of commercialization of publicly funded research, the 1980 Bayh-Dole Act created a uniform patent policy allowing universities and small businesses to retain rights to patents resulting from publicly funded research, and to license these patents exclusively at their discretion.[6] Bayh-Dole was a culmination of decades of debate about whether the government or contractors should retain patent rights. These debates had their roots in criticisms by Harley Kilgore that OSRD's "long form" patent policy effectively gave ownership of the results of publicly funded research to private firms (Sampat 2020)—an issue we return to in Section 4. These debates have since continued in pharmaceuticals (e.g., in debates about prices of/access to HIV-AIDS drugs during this crisis) and, as we will discuss, have resurfaced in the context of COVID vaccines and treatments.

Finally, the innovation system grew massively over the postwar era. OSRD's budget was about $2.5 billion

[4] Gittelman (2016) and others have argued, however, the translational approach largely adheres to the linear paradigm.
[5] Notably, these mechanisms featured much more prominently in the U.S. COVID-19 effort than have in regular times.
[6] The Act was later extended to large businesses as well, through executive order.

annually at its height, and $7.5 billion total (both in 2020 dollars). In FY2019 the federal R&D budget was over $130 billion (of which $40 billion went to the NIH), about a 50-fold increase.[7] While Bush wrote that only a handful of universities had adequate resources for research in 1940, seventy-five years later hundreds of universities and thousands of firms and researchers in the U.S. and globally were actively involved in research and innovation (Moses et al. 2015). Globally, scores of agencies and philanthropies now fund research, with their own missions, procedures, and idiosyncrasies. For all these reasons, when the COVID-19 crisis hit in early 2020, it encountered a much larger, mature and established innovation system than what existed during World War II, including large and sophisticated government research bureaucracies with established procedures, norms, and missions, as well as a wider set of research-performing firms and institutions that could be mobilized in a crisis. The crisis has illuminated both strengths and weaknesses of this system, one that had changed considerably since it emerged in the aftermath of World War II. We will return to these issues in later sections of this essay.

3 The COVID-19 Innovation System

Seventy-five years later, COVID-19 presented a new crisis where science, technology, and innovation were crucial to an effective response. From early on, scientists and policymakers focused on developing a safe and effective vaccine. Drugs to treat the disease were also required. Diagnostic tests and contact tracing technologies were needed to reduce spread, as were models to understand the epidemiology of the disease and designing the needed public health interventions. Since fighting the virus also necessitated suppression, and thus social distancing, masking and lockdowns, there was also value in innovation to mitigate the economic and social costs of these interventions. There was a need for new business models at schools, restaurants, medical practices, and other organizations that could accommodate social distancing, often enabled by the rapid adoption and improvement of digital conferencing tools. Firms needed risk-mitigating technologies to protect employees and customers. In the absence of vaccines and treatments, front-line doctors and nurses required non-pharmacological interventions to manage the COVID patients, including patient management techniques (e.g., proning), hospital workflows, and others. In order to be effective, innovations not only needed to be generated quickly, but it was also essential they diffuse broadly to the relevant users, another important aspect of crisis innovation policy (Gross and Sampat 2021).

This breadth may be informative about the different nature of the innovation challenge, and the innovation system, relative to the 1940s. Unlike the U.S. World War II research effort, where there was essentially one major user that helped articulate a specific set of priorities, in the pandemic the demand was widespread, diffuse and in some cases the needed innovations quite specific to particular actors. There were no generals in the field reporting back key problems and bottlenecks.

Innovations to combat COVID-19 had high potential social value. Cutler and Summers (2020) estimate the cumulative U.S. economic and health costs of COVID-19 through 2021 to be $16 trillion, or about 90 percent of U.S. annual GDP. Reflecting the high social value, and the importance of time in addressing a spreading

[7] By comparison, real gross domestic product grew about 10-fold over this period.

pandemic, policymakers worldwide mobilized. As we have argued previously (Gross and Sampat 2021), the urgency of a crisis may magnify traditional market failures, increasing the scope for productive government intervention beyond what a decentralized market can achieve on its own.

Vaccine innovation, the "silver bullet" many sought since early 2020, is particularly prone to a range of supply- and demand-side market failures beyond those present for other types of technologies (Xue and Ouellette 2020).[8] Beyond incentives, scholars and policymakers had also expressed concerns about the current lack of U.S. capacity for targeted vaccine development and failure of existing policy models for vaccines (Hoyt 2006, 2012). Partly reflecting these market failures, the U.S. response appears heavily focused on vaccines. It is interesting that, at least in financial terms, much of the response would be not through the crown jewel of the biomedical research enterprise—the NIH—but instead the previously-small agency BARDA. Despite the vaccine focus of the U.S. policy response, a range of decentralized innovative efforts appear to have been active in many of the other types of innovation described above, collectively resulting in a massive pivoting of the innovation system to working on COVID-related research.

3.1 The U.S. federal policy response

As of the beginning of March 2021, the U.S. government had appropriated $4 trillion to COVID-19 recovery and spent nearly $3 trillion. Of this, less than one percent was allocated to vaccine and treatment R&D (Whoriskey et al. 2020). This was small relative to what some economists had recommended given the high social value of such interventions (Athey et al. 2020, Tabarrok 2020). Some R&D funding for treatment and vaccine research came from agencies' existing budgets, but most funding was provided by special appropriations via the Coronavirus Preparedness and Response Supplemental Appropriations Act, or CARES Act, and the Paycheck Protection Program and Health Care Enhancement Act. Beyond funding earmarked for R&D, some of the broader funds in these packages may have been rerouted to R&D, especially through Operation Warp Speed, which we describe below (Cohrs 2021).

3.1.1 The NIH and NSF

Given that NIH is the biggest single funder of biomedical research in the world, it is not surprising that it has been part of the U.S. innovation response. By late April 2020, through a series of emergency supplemental appropriations, NIH had received an additional $3.5 billion for COVID-19 research. Unlike previous instances of emergency funding (e.g., the American Recovery and Reinvestment Act in 2009) which had to be spent quickly, the COVID-19 appropriations do not need to be spent for several years. Facing the need to respond more quickly than its normal peer review process would allow, and a large number of applications for funding, the NIH decided to prioritize one-year supplements to existing grants, which do not require peer review, and it accelerated peer review for new applications (Kaiser 2020). Nonetheless, the crisis did reveal some of the

[8] Reflecting these issues, well before the pandemic economists and others had called for new policy instruments (e.g., advanced market commitments and prizes) beyond the standard biomedical innovation policy tools to stimulate vaccine innovation and development for tropical infectious diseases (Kremer and Williams 2010). Though there were some notable successes (Kremer et al. 2020), previously these did not attract broad policy support in the U.S. and other developed countries, perhaps because many of the needed vaccines were for diseases that did not affect rich-country taxpayers.

difficulties of crisis response through standard peer review approaches, which may be better suited to other goals, such as promoting basic science (Azoulay and Li 2020).

NIH has helped fund a number of the important trials of COVID-19 vaccines (including the mRNA vaccine developed by Moderna, where pre-pandemic NIH-funded research also contributed to the basic platform technology, and the Johnson & Johnson/Janssen vaccine), and treatments including remdesivir and convalescent plasma. Funding of late-stage trials is atypical for the agency, and also illustrates the uniqueness of the crisis. As of April 1, 2021, NIH has funded 2,126 COVID grants, totaling $3.9 billion.[9] Figure 2, Panel (A) shows a word cloud illustrating topics NIH has supported.

In addition to funding research, NIH has also taken a coordinating role, including through its ACTIV program (Accelerating COVID-19 Therapeutic Interventions and Vaccines), which tries to promote information sharing, coordination, and standardized trial protocols among public and private actors. Its Rapid Acceleration of Diagnostics initiative (RADx) aims to accelerate diagnostic innovation, and engages in a range of downstream development activities beyond the agency's traditional ambit.

Figure 2: Common words in NIH and NSF COVID-related award titles (through April 1, 2021)

Panel (A): Words in NIH awards



Panel (B): Words in NSF awards



Notes: Figure illustrates the most common words appearing in the title of NIH and NSF COVID-related research grants, weighted by frequency and contract value. COVID-related contracts were identified with Boolean searches for COVID (as in COVID-19), CoV (as in SARS-CoV-2), and nCoV (as in 2019-nCoV) in the title, abstract, or keywords of research grants from 2020 and 2021. Data as of April 1, 2021.

The NSF also pivoted to COVID-19. In April 2020 it invited researchers to propose non-medical, non-clinical research on COVID epidemiological modeling, transmission, and prevention. It expanded its Rapid Response Research program (RAPID) to advance research quickly, recognizing the need for speed and the slow pace of traditional peer review mechanisms. As of April 1, 2021, it has funded 1,339 grants, totaling $278 million.[10] The word cloud in Figure 2, Panel (B) illustrates topics NSF has funded.

3.1.2 Operation Warp Speed and BARDA

In a February 9, 2020 memo to the newly-created White House Coronavirus Task Force, three weeks after the country's first confirmed COVID case and three days after the first death, economic advisor Peter Navarro

[9]Source: NIH RePORTER keyword search for COVID (as in COVID-19), CoV (as in SARS-CoV-2), and nCoV (as in 2019-nCoV) in the title, abstract, or keywords of research grants from 2020 and 2021. Data as of April 1, 2021.

[10]Source: NSF Advanced Search tool, keyword search for COVID (as in COVID-19), CoV (as in SARS-CoV-2), and nCoV (as in 2019-nCoV) in the title or abstract of research grants from 2020 and 2021. Data as of April 1, 2021.

called for an immediate "Manhattan Project" for vaccines (Navarro 2020). Mimicking the original Manhattan Project, Navarro called for "multiple shots on goal" and "flexible funding" that could be redirected to more promising candidates "as the science develops." Though NIH had early plans to coordinate the vaccine and therapeutics research efforts (Cohen 2020), these were superseded in April 2020 by the announcement of Operation Warp Speed (OWS), which took the lead on these problems. Warp Speed was an "America First" approach to vaccine development, with the bold goal of developing, approving, and delivering hundreds of millions of doses of safe and effective COVID-19 vaccine doses by the end of 2020. Its name alone conveys that in this crisis, like World War II, speed was a paramount objective.

Operation Warp Speed has been notoriously opaque (Cohen 2020), making it difficult to provide a comprehensive assessment at this time. As was true with World War II, we expect the records of this effort and a much more complete picture of its work will be available to future scholars. Based on the data currently available, we can nevertheless describe the broad contours of the effort.

Warp Speed was organized as an interagency collaboration that brought together organizational elements, funding vehicles, and staff from several government agencies—including BARDA, NIH, the Federal Drug Administration (FDA), the Centers for Disease Control and Prevention (CDC), and the military—and private sector firms in a public-private partnership. Its leadership reflected all three constituencies (public health officials, military officers, and executives), though a leaked organizational chart reveals heavy DOD staffing (Florko 2020). The extensive military involvement is in part a reflection of the needs and ambitions of the effort, which were as much the logistics of production and distribution as they were R&D—activities which the military may have comparative advantage in. Paul Mango, the HHS Deputy Chief of Staff, explained "There's really not a need for anyone to place scores of scientists inside HHS or DOD to get this done," as Warp Speed was not itself performing research directly (Florko 2020).

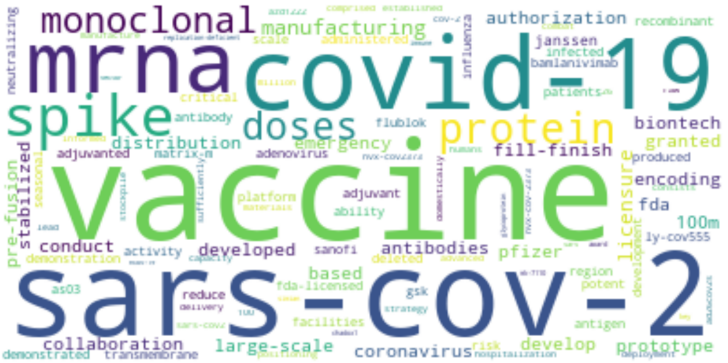
Warp Speed routed most of its funding not through NIH, but through the Biomedical Advanced Research and Development Authority (BARDA). BARDA was created through the 2006 Pandemic and All-Hazards Preparedness Act (PAHPA) as part of a broader effort "to improve the Nation's public health and medical preparedness and response capabilities for emergencies, whether deliberate, accidental, or natural." This was a response to perceived market failures and risks in medical counter-measures that were limiting private investment in such technologies. The Act tasked BARDA with funding "advanced development" activities (product development, clinical trials, manufacturing scale-up, and getting FDA approval) on medical counter-measures including drugs and vaccines (Matheny et al. 2008, Tucker 2009).[11]

Before the COVID-19 crisis, BARDA was a minor actor—in dollar terms, authorized to spend less than $3 billion over the 2014-2018 period (Larsen and Disbrow 2017). With Warp Speed, however, BARDA took center stage. Compared to the roughly $4 billion spent by NIH during the pandemic, BARDA's COVID

[11] BARDA was explicitly intended to bridge the "valley of death" where NIH research failed to enter development and commercialization. BARDA's funding mechanisms included various flexibilities that NIH lacked, including the ability to provide large advanced payments to companies before delivery of products, and the ability to circumvent some antitrust rules to facilitate cooperation among firms. It funded research with an eye toward procurement by the National Strategic Stockpile of medical countermeasures and at least initially had a heavy biodefense focus—though more recently that has expanded to include other subjects, such as research on new antibiotics. It used both "push" funding (including late stage R&D contracts) and "pull" incentives (market commitments) to support innovation (Larsen and Disbrow 2017).

contracts now total $26.5 billion. Based on available data, about 75 percent is on vaccines. Though there are no comprehensive public data on BARDA contracts, information from contracts published on its website illustrate the heavy vaccine focus in dollar terms (Figure 3).[12]

Figure 3: Common words in BARDA contract titles (through April 1, 2021)



Notes: Figure illustrates the most common words appearing in the title of BARDA COVID-related research contracts, weighted by frequency and contract value. Data as of April 1, 2021.

Its exact priority-setting process is unclear. According to the former director of Warp Speed (Moncef Slaoui), the effort focused on vaccine candidates that, based on evidence from preclinical and early-stage data, would have a chance at entering trials by the end of 2020, and had the potential to be manufactured at scale quickly (Slaoui and Hepburn 2020). It chose candidates across four different platforms (mRNA and three others) it believed held the most promise. Reflecting the "Manhattan Project" approach, one of its guiding principles was portfolio diversification and advancing candidates in parallel. It also funded clinical trials, manufacturing capacity at risk, and production of doses before trials were complete. This represented a sharp departure from the types of activities public-sector research supported before COVID—though as noted, several of these were always part of the BARDA playbook (Sampat and Shadlen 2021).

In addition to "push" funding, BARDA's contracts typically included "pull" incentives via large advanced procurements. These contracts include options to pre-purchases doses if successful, at set prices. This differed from theoretical advanced market commitments in that they were producer-specific, which seemingly misses out on one attractive benefit of prize-based approaches: avoiding the need to "pick winners" in advance (Kremer and Williams 2010). Nonetheless, the commitments de-risked the process for participating firms.[13]

The specific instruments varied by contract (see Sampat and Shadlen 2021), but through these push and pull approaches, Warp Speed/BARDA supported eight vaccines. The six which are publicly announced include mRNA approaches (Moderna, Pfizer/BioNTech), live-vector approaches (AstraZeneca, J&J/Janssen), and recombinant-subunit-adjuvanted protein approaches (Novavax, Sanofi/GSK).

[12]Source: https://www.medicalcountermeasures.gov/. Accessed April 1, 2021.

[13]Another way in which these commitments differed from standard ones is that they put the U.S. near the front of the queue for purchasing the vaccines once developed. That is, they may also have been an instrument of so-called "vaccine nationalism" (Sampat and Shadlen 2021, Price et al. 2020).

This appears to have been extremely successful. On April 30, 2020, early in Warp Speed's effort, an editorial in *The New York Times* predicted "The grim truth ... is that a vaccine probably won't arrive any time soon," noting high failure rates in vaccine development and that the previous record time was four years. As of this writing, the Pfizer/BioNTech, Moderna, and J&J/Janssen vaccines have been approved in the U.S. (through emergency use authorizations) and are being administered across the country, and two others (AstraZeneca and Novavax) are in late-stage trials. As was true of the penicillin, radar, and fission efforts during World War II, and as Bush later emphasized in *Science, The Endless Frontier*, the fact that we had invested in some of the key platform technologies before this crisis seems to have been crucial to the success of COVID-19 vaccine development efforts in 2020 (Kiszewski et al. 2020).

3.2 International and other efforts

Beyond the U.S., other governments also contributed to funding COVID-19 therapies and vaccines, including the European Union (EU), individual EU member states, and the United Kingdom, albeit at levels much lower than the U.S., based on available data (Sampat and Shadlen 2021). The Chinese and Russian governments also funded vaccines that are now approved and being administered in multiple countries (CoronaVac, Sputnik V). Another major set of actors are internationally-funded non-governmental organizations, including the Coalition for Epidemic Preparedness Innovations (CEPI), which has also been funding vaccine candidates—albeit at much lower levels than national governments—and its partner global purchaser COVAX, which has entered advanced purchase commitments and post-approval purchases with vaccine manufacturers for distribution to low-income countries (Sampat and Shadlen 2021).

Researchers globally have pivoted to working on COVID-19 related research, often crossing field, geographic, and institutional boundaries to do so. Like World War II, the crisis has (at least anecdotally) spurred new collaborations. Some observers believe the pandemic response ushered in a new era of "open science". *The New York Times* has asserted "COVID-19 Changed How the World Does Science, Together." Reflecting the need for speed, much of the dissemination has been through scientific pre-prints, which now number in the hundreds of thousands for COVID-related research. Many journals have also expanded their capacity and accelerated review. The speed and openness have been accompanied by concern about the quality of the research (Yong 2021), reflecting the challenge facing journals and the public of screening this flood of papers on a new disease. The open science approach has also enabled real-time public critiques and debates of specific findings, at times leading to retractions (Kupferschmidt 2020)—though these retractions have in many cases gone unseen or ignored by subsequent work (Piller 2021).

3.3 How does the response to COVID compare to World War II?

Parallels and contrasts between the World War II and COVID-19 efforts are already becoming apparent. In some respects—such as parallel funding, manufacturing at risk, the government's role in applied activities, and an emphasis on speed—Warp Speed has borne similarities to OSRD programs. But there are several important differences. One is that OSRD took a broad coordinated approach to identifying and contracting

out work on dozens of problems, whereas the COVID-19 response seems to have been more fragmented, with several R&D funding agencies setting their priorities and operating independently. The COVID-19 effort has also involved firms as key performers of government-funded research to a greater degree than in World War II, in part reflecting the nature of the problem (drug development) and where the R&D capabilities to address it reside in the modern innovation system. Moreover, while OSRD had one customer, the military, which could have a voice in setting priorities and could diffuse technologies, COVID-19 problems had many customers—up to the complete population, in the case of vaccines. The initial difficulties in distributing the vaccines may illustrate the differences between military officers diffusing technologies by fiat and decentralized diffusion by states and through the fragmented U.S. healthcare system.

The public posting of the SARS-CoV-2 gene sequence by Chinese researchers in January 2020 was perhaps the COVID-19 equivalent of the World War II Tizard Mission (through which the British shared key military technologies with U.S. researchers in 1940), and set off the international sprint to produce a vaccine. While vaccine innovation appears to have been a success, vaccines are only one of the many innovations recognized as valuable at the start of the pandemic, which included rapid, scaled-up testing, contact tracing, therapeutics and other treatments, strategies for protecting health care workers, changes in social behaviors, changes to the organization of work, and other public health interventions. Economists and others have raised concerns about the lack of coordinated investments: as far as we know there is no CMR-like entity looking for holes in the portfolio or preventing duplication, as illustrated by the large number of trials on just one therapy (hydroxychloroquine).[14] Lack of coordination is particularly problematic for clinical trials competing to enroll sick patients, who are limited in number. It is notable that during the war, CMR was active in this problem, allocating patients and scarce penicillin stock across investigators and across the natural/synthetic penicillin programs. Conti et al. (2020) have argued that better coordination in re-purposing off-patent drugs in particular could yield high returns, given that they can be deployed more rapidly than new molecules and that private firms may lack adequate incentives to conduct the needed trials.

That Warp Speed ran mainly through BARDA suggests that more entrenched agencies with routines (such as peer review) may have a harder time pivoting quickly to new problems or activities (like NIH and downstream development). However, we do not currently know the precise logic for the specific institutional choices that were made—including the role of politics and other factors—so we also caution against premature conclusions. International coordination is a second area where the U.S. federally-organized effort has been weak, almost by design. Although Warp Speed coordinated among the firms it funded, the U.S. vaccine effort in particular has not collaborated with Chinese and Russian vaccine development efforts, which stands in contrast to the strong Allied cooperation during a global war against a common enemy.

Another way in which the COVID-19 innovation response differs from World War II is in the broad, decentralized mobilization of researchers worldwide. Overall, a large share of the innovative effort was based on "bottom-up" efforts by individual organizations and academics, rather than through top-down planning. Since the COVID-19 pandemic began, over 130,000 academic articles on the disease have been written (over

[14] The lack of coordination may in part reflect the much broader scale and finer division of labor in the innovation system today, which might make coordination more challenging than it was in past crises.

100,000 in the biomedical literature alone), attacking questions on the science of COVID from transmission to therapeutics, on social phenomena from social distancing to mask wearing, and on engineering problems from sanitation to ventilation.[15] This is in some ways similar to what happened during World War II vis-à-vis distributed invention, when independent inventors around the country were creating and volunteering their inventions to OSRD (Stewart 1948), albeit on a much smaller scale. It is striking that much of this pivoting came without specific federal policy direction, at least if we define innovation broadly. However, it is almost certainly the case that the infrastructure created by decades of previous federal funding helped create the capacity for the broad decentralized response.

4 Policy Tradeoffs for Crisis R&D Efforts

Public officials must make a number of choices in a crisis which the World War II and COVID-19 experience can inform. One high-level choice is how involved (versus laissez-faire) an approach to take to crisis innovation. Organizers of *centralized* crisis R&D efforts, in turn, have to set research priorities, select R&D contractors, allocate intellectual property rights, and make plans for production and distribution at scale. Individually, these questions present complex tradeoffs, but collectively the challenge is even greater, because an effective strategy has to thread all of these needles at once.

In this section we explore four specific tradeoffs in crisis R&D policy:

1. Priority setting: Top-down vs. bottom-up
2. R&D performance: Elite vs. distributed
3. Appropriability: Promoting innovation vs. diffusion
4. Managing disruptions to the innovation system

This set is by no means exhaustive, and we consider a wider range of questions and considerations in other recent writing (Gross and Sampat 2020b). Our focus here is on those which we see as likely to be either the most contentious or consequential. There is another category of issues which may be policy goals in ordinary times but which could potentially impede a crisis response, such as distributional considerations or reporting requirements. Forgoing some non-crisis policy goals can be justified by the extraordinary returns to resolving a crisis (Gross and Sampat 2021), and are not our focus here. A third set of issues for crisis R&D policy is related not what to do in a crisis, but what can be done in advance to prepare for one. We defer discussion of this question to Section 5.

4.1 Top-down vs. bottom-up priority setting

A basic question for crisis R&D is how to set research priorities—including who should decide. When time is short, directing funding and labor to top-priority projects is a first-order problem for leaders of crisis R&D efforts. The approach to priority setting can thus be consequential.

[15] Article counts obtained by searching Google Scholar and the National Library of Medicine's PubMed database for articles with the phrase "COVID-19". Results as of April 1, 2021.

Modern U.S. S&T policy takes a range of approaches. The primary "pull" mechanism, patent policy, is largely bottom-up. In principle, patents reward any invention that is novel, non-obvious, and useful, without ex-ante delineation of priorities. The theoretical benefit is that the private sector may have better information on the costs and benefits of different approaches to solving problems than policymakers. However, the downsides of pull approaches such as excess correlation of portfolios, a lack of idea sharing, and competition for scarce resources (e.g., patients in clinical studies) may be particularly problematic during a crisis, suggesting a role for government funding and coordination. As we discuss below, using patents to incentivize innovation may have other drawbacks in a crisis, including high prices and restricted diffusion.

"Push" mechanisms are more mixed in their approach. Science funding agencies like NSF and NIH are also largely bottom-up: while they at times announce broad categories they plan to support (like *nanotechnology* or *climate science*), most funding is distributed through disciplinary programs, and scientists do the proposing. The rationale for the "investigator-initiated" model is that scientists have better knowledge of feasibility and scientific importance than policymakers do. Though review panels screen these proposals, the research ideas begin with the research performers, who get funded to do the work they propose. The Department of Defense (DOD), in contrast, funds more applied research and engineering than basic science, often for specific uses related to its mission, and more often top-down.[16] The Department of Energy (DOE) supports both, including substantial intramural work.

Like DOD today, in World War II OSRD largely defined R&D priorities and contracted for specific research such as "Gyroscopic director" or "Cholera vaccine", reflecting the applied nature of wartime problems. The proposing process at NDRC is illustrative. Research ideas could originate with internal scientific staff, the military services, or an Allied government, but generally did not come from the scientific community at large. NDRC's study sections—which included staff scientists and military liaisons—workshopped these ideas into formal proposals that included an action plan, candidate contractors, and the anticipated cost and duration, which were forwarded up the chain of command and voted on by OSRD leadership. This approach fused scientific expertise with user insight into the nature of a problem and its military importance (Bush 1970). CMR took a somewhat different approach, setting priorities jointly with the National Research Council's Division on Medical Sciences (DMS), which a year earlier had organized a set of committees around "problems with which the Services expected to be confronted" (Richards 1946). CMR then solicited proposals from investigators on problems of importance. These proposals were reviewed by elite medical researchers on the DMS committees, graded, and high-scoring proposals were funded. CMR's approach thus mixed centralized priority setting with investigator proposing, mediated by peer review.

The COVID-19 effort has been more difficult to pierce, and details on any internal deliberations over priorities may only become known over time. What we do know is that agencies involved in the effort had to choose both the scope of what they would support (e.g., vaccines, therapeutics, or non-pharmaceutical measures) and specific projects and performers. As far as we can tell, OWS has taken a top-down approach to vaccine development, focused on known firms with capabilities to deliver them quickly.

[16] Individual DOD branches, namely the Air Force, have also recently experimented with bottom-up approaches to small business innovation research (SBIR) awards (Howell et al. 2021).

Why would a top-down approach be appropriate in a crisis? From an economic perspective, decision rights are best delegated to the party with the most information. A central agency may have a clearer view of what the important problems are and the means to coordinate efforts. It can also take a broader perspective that goes beyond R&D to manufacturing and distribution, and consider how constraints in these downstream activities should influence R&D (e.g., quality control in the production of radar sets and engineering tolerances, or the availability of cold storage for COVID vaccines and storage temperatures). User needs and supply constraints are issues which scientists are not always positioned to evaluate or perhaps even recognize—whereas central organizations like OSRD or OWS are more likely to be able to.

4.2 Concentrated vs. distributed R&D funding

Another question—especially for government sponsors of crisis R&D efforts—is whether to concentrate crisis R&D funding in elite scientists, firms, and institutions or to solicit efforts from a wider group. In short, who should do the work? Answering this question may require weighing competing objectives, like maximizing the return on the public investment in R&D versus the (at times) political necessity of attracting broad-based political support. But even when the principal goal is to achieve "the best results in the shortest possible time" (Stewart 1948), the optimal distribution of funding is less than clear. We see this tension as boiling down to a mean-variance tradeoff: relative to engaging a broad population, concentrating R&D efforts with top scientists raises expected quality but may sacrifice tail innovation.

In World War II, the OSRD primarily contracted with top firms and institutions. It had multiple criteria for selecting contractors, with the first being the ability to deliver outstanding results as fast as possible, and secondary criteria including spreading the work and reducing cost. As we noted in Section 1, it placed over one-third of all funding with just two institutions—MIT and CalTech—and spent over 90% of its obligations in ten states. This concentration exposed it to criticism from some contemporaries that it was not employing the nation's full scientific talent in the war effort (Kilgore 1943).

But this was partly driven by necessity. Work on large, complex systems engineering problems like radar or rockets was less divisible and generally benefited from centralization.[17] Centralization also characterized the atomic fission research effort, which was based at UC Berkeley, Chicago, and Columbia. Yet where research problems were divisible—as in the hunt for antimalarials, or more generally for most medical research—OSRD permitted a decentralized effort. Stewart (1948) explains:

> [For] problems which ... had a lower order of urgency, a wider distribution of contracts was possible. This was also the case where problems were of such a nature as to permit their division into a number of unrelated parts upon each of which a few men at a number of different institutions might be engaged. In the field of chemical warfare, for instance, there were cases where a competent chemist with a small number of assistants could attack a discrete problem. On the

[17] In some cases, these agglomeration benefits were very explicit. For example, MIT Rad Lab spun out a radar countermeasures research group which set up shop two miles away at Harvard—and the two could test new radar sets, radar-jamming, and anti-jamming technology on each other from the rooftop.

> other hand, concentration was demanded by many problems in the field of physics where each part had an intimate connection with all other parts of an over-all system.

Operation Warp Speed's focus on vaccines over other technologies left relatively less room for decentralization: with only a handful of vaccine candidates, there is only need for a handful of R&D performers, though some observers have argued that given the ex-ante uncertainty as well as intrinsic market failures due to racing, it should have funded more vaccine candidates than it did (e.g., Athey et al. 2020, Bryan et al. 2020).

The choice between concentrating R&D efforts with elite scientists versus a more distributed approach thus comes down to a handful of considerations: how capable is the wider pool of scientists, firms, and institutions; how divisible is the work; and how easy is it to screen results. When any of these conditions fails, concentration may be a more attractive strategy.

4.3 Patent policy for innovation and diffusion

The traditional tradeoff of patent policy is between dynamic and static efficiency, balancing incentives for innovation against the benefits of broad access (including diffusion and low prices). The urgency of a crisis only heightens this tension, as the willingness-to-pay for a quick solution is high, but patents can also delay a resolution if they impede diffusion, production, and implementation.

Reflecting this concern, in both World War II and the COVID-19 crisis there were early calls for compulsory licensing, patent pooling, and other approaches to relaxing intellectual property rights to promote diffusion (see Contreras (2020) for an overview). There are two potential limits to these approaches. One is feasibility: for many important technologies, like penicillin, synthetic rubber, and vaccines, the scale-up problem require costly know-how transfer as well, which may limit the impact of relaxing patents alone. A second is desirability: proposals to relax patent rights in crises must consider not only the effects on innovation during the crisis, but also the dynamic effects on pre-crisis incentives to do research on potential solutions.[18]

In the context of government-funded research, there is also the narrower question of who should bear title to resulting inventions. This issue was contentious during World War II and is again today. Private actors bring advanced R&D capabilities and must be assured return on investment to incentivize their participation. At the same time, the government may wish to guard against profiteering and promote broad diffusion.

Highlighting this tension is that although OSRD initially sought the right to decide whether to file patents on inventions it funded, and the disposition of title and licenses, a number of leading firms refused to sign contracts under these terms. Stewart (1948) summarized the problem:

> [The] NDRC was asking America's leading companies to take their best men off their own problems and put them (at cost) on problems selected by NDRC, and then leave it to NDRC to determine what rights, if any, the companies would get out of inventions made by their staff

[18] It is notable, however, that at least two firms, AstraZeneca and Moderna, have committed to not enforce their patents during the pandemic. While there is some uncertainty about these pledges—including who decides when the pandemic is over—we have not yet seen broad "generic" entry into the fields, suggesting that either patents may not be the binding constraint on competition or diffusion, or profitable generic entry requires longer horizons.

> members ... These companies had acquired a great deal of 'know-how' as a result of years of effort and the expenditure of their own funds, often in large amounts. The research they were being asked to undertake was in many cases in line with their regular work ... and might result in some cases in inventions they might be expected to make at some future date at the appropriate place in their own programs. In some cases the Government contract involved minor adaptations of past inventions made by the contractors, and in such cases the contribution to the final product attributable to the work financed by the Government was relatively insignificant. But under the patent clause thus far offered by NDRC a company might be excluded from using its inventions under an NDRC contract in its own business, and might even find its competitors licensed by the Government while licenses were refused to it.

These concerns are representative of the challenge facing crisis R&D efforts, and Stewart points to many reasons why ceding patent rights may be a smart policy choice. Many of these concerns could be compensated by cash, but one requires assigning rights: firms which retain title are incentivized not only to participate in crisis R&D, but also to put top talent and other resources into the crisis problem. Facing this imperative, the OSRD developed contract language giving contractors right of first refusal in patenting inventions produced under contract, plus title, subject to a royalty-free license for military use.[19]

This policy led to one of the main criticisms of OSRD by Kilgore and its other liberal critics, who objected to giving away publicly funded technologies to private firms, contributing to concentration of economic power and effectively forcing taxpayers to pay twice for technologies—first by funding them, then through monopoly prices (Sampat 2020). Bush acknowledged these concerns but feared that asserting government ownership would throw a "monkey wrench" into the public-private partnership that had developed during the war and dissuade participation by firms with the requisite capabilities (Bush 1943).

These issues resurfaced in the pandemic. There have been calls by state attorneys general to invoke the never-used "march in" provisions of the Bayh-Dole Act to promote broader access to Gilead's antiviral remdesivir, which—according to several legal scholars—the NIH helped develop. Scholars, activists, and others have also pointed to NIH and BARDA funding of, and potential government patent rights in, Moderna's mRNA platform, and some have proposed leveraging these rights to promote broader access as well (Stone 2020). Activists also called on the government to build access and diffusion provisions into Warp Speed contracts as a condition of public funding (e.g., Kashyap and Wurth 2020). Others have argued that firms are putting in much of the funding and taking most of the risk, and they would not have participated in Warp Speed absent patent rights (Brown 2021). A spokesperson for the Department of Health and Human Services (HHS), the parent agency of BARDA and NIH, reflected a similar position with regard to waiving government ownership in the vaccine contracts with Pfizer (which did not including push funding, unlike the contracts with other

[19] This language became known as the "long form" clause, reflecting its length, and it was used with most industrial contractors. OSRD continued using a variant of its original patent clause—the "short form" clause—in specific categories of contracts, giving the government presumption of title where it supplied significant equipment, personnel, or training to support the work. The short form clause was standard for major OSRD-funded laboratories at academic institutions. CMR contracts were also subject to the short form clause, and atomic energy contracts were converted to short form to ensure that the government controlled intellectual property rights in this field.

firms), arguing "When the U.S. government does not fund creation of any of the intellectual property, as is the case in our agreement with Pfizer, the government is not entitled to any rights to a company's intellectual property," adding that "The most critical factor was the need to obtain as quickly as possible sufficient doses of safe and effective vaccines against COVID-19 to save lives" (Lupkin 2020).

The key tradeoff for crisis patent policy is between incentivizing innovation and diffusing the results rapidly and broadly, each of which can contribute to timely resolution of a crisis. The relative importance of these factors can guide policies over the allocation of property rights—though in practice, this can be difficult to calibrate, and more evidence on striking this balance would be useful.

4.4 Managing disruptions to the innovation system

A fourth tension we want to highlight is a result of re-allocating inventive activity from regular R&D to crisis R&D. By diverting funding and human capital to new problems, crisis R&D efforts disrupt the regular functioning of the innovation system. This diversion can interrupt ongoing research—some of which might depreciate quickly (e.g., if specimens spoil) or get abandoned entirely (e.g., if crises breathe life into new fields (Section 5) or reduce costs of switching fields). It might also crowd out new projects. For example, the race for COVID-19 vaccines and therapies required organizational pivoting and may have displaced other research or trials in the R&D pipeline (e.g., Agarwal and Gaule 2021).[20,21] This may have likewise been the case for academic research, as investigators pivoted to COVID-inspired work (e.g., Pai 2020).

When university faculty or students are involved, these disruptions can extend beyond research to education and scientific training. Crisis R&D organizers can nevertheless take steps to limit interference. For example, to avoid disrupting universities by relocating their staff, much of the OSRD's work was done using university facilities, sometimes in investigators' own labs. Disruptions to the normal functioning of the innovation system can also arise by other means. In recent work, one of us has studied compulsory secrecy policy in World War II, which enabled the patent office to suspend patent examination on inventions whose disclosure was considered a security risk, and order the inventor to "in nowise publish or disclose the invention or any hitherto unpublished details" (Gross 2019). The USPTO's secrecy program effectively suspended the normal functioning of the patent system for a subset of technologies.

Though crisis R&D can create collateral damage, this of course does not imply inefficiency: the large social returns can significantly outweigh its costs. Moreover, insofar as there are consequences to scientific disruptions, they borne in the future, in the form of innovation that has gone missing. Whether this is a favorable tradeoff ultimately depends on the urgency of the crisis problem. In the most extreme cases, the intertemporal elasticity of substitution is infinite: without short-run impact there may not be a long run. In these cases, the only option is an all-out attack. More generally, the level of urgency in a crisis implies the

[20] Interestingly, recent evidence suggests the effect on clinical trial launches for drugs targeting non-COVID-19 diseases was limited to a fairly modest, but statistically significant, 5% decline (Agarwal and Gaule 2021).

[21] Note that distortions can arise even within a crisis R&D portfolio: as Bryan et al. (2020) argue, racing behavior can result in too much investment in quicker-to-develop partial solutions (e.g., COVID-19 therapies or repurposed treatments), which undermine incentives for longer-horizon, higher-value innovation (e.g., vaccines) by reducing the size of the remaining market. This intuition is similar to that of Hill and Stein (2021).

degree of acceptable interruption to business as usual.

5 Long-run Effects of Crisis R&D

The effects of crisis R&D can also outlive the crisis itself. The impacts of the OSRD's work were significant and far-ranging, influencing not only the war's outcome, but also postwar entrepreneurship and innovation, innovation policy, and the postwar U.S. economy. Might the same be the case for COVID-19? The book has yet to be written, but there are already signs of lasting effects, from durable shifts to remote work (e.g., Barrero et al. 2020) to a surge of vaccine R&D (Regalado 2021). Here we review what some of these impacts were in the World War II crisis. If the past is an indication, the COVID-19 pandemic could have lasting effects on what innovation is produced, by whom, and how for years to come.

Contemporary impacts

Contemporaries and historians view OSRD as having had a major impact on the Allied war effort (Bush 1945, Baxter 1946). Yet the OSRD's work also set the agenda for military R&D in the Cold War era, where missiles, missile detection, and nuclear weapons were focus points, among others—technologies which built directly on the work of the OSRD's Rad Lab, Jet Propulsion Lab, and nuclear fission project. Much of its work also led to development of dual-use technologies like microwave communications and computing, and drugs and medical therapies like penicillin that transformed civilian medical care. Stewart (1948) wrote of the dual-use nature of OSRD's work, noting that "its part in the winning of the war was its greatest contribution," but its full impact would be realized when "the civilian counterparts of its military developments begin to exert their influence upon life in the United States and in the world at large."

Yet the war also interrupted research pipelines and careers, causing some research inputs to be rationed, diverting resources and attention to problems of military importance, and even drafting scientists into the military (much like COVID-19 temporarily forced labs to shut down and severed ongoing experiments, led many researchers to re-orient their work to COVID-related problems, and saw some scientists re-deployed to hands-on pandemic response). Though OSRD's work yielded numerous high-impact dual-use technologies, this may not have come free if it crowded out research in other fields—especially if these directional shifts outlived the war itself. While it is difficult to know what would have been invented absent the war, some research streams were likely abandoned as wartime demands took over the agenda.

Long-run effects on innovation, entrepreneurship, and economic growth

Though the war ended in 1945, OSRD's impact reverberated for decades after. Anecdotally, it did more than simply advance the state of the art: it opened up entire new fields of research. Stewart (1948) wrote of the CMR: "The shift in emphasis and even in direction was enormous. Many subjects of minor importance in peacetime become of controlling importance in war," with some even "born of war." This was in part because some problems were introduced by the conditions of war, but in other cases a result of new technologies opening up new frontiers for research, like penicillin and infectious disease, or pre-existing science advancing to a stage where more applications could be explored, such as with nuclear energy.

In Gross and Sampat (2020a) we show that OSRD had long-lasting effects on the direction and domestic geography of U.S. technological innovation, catalyzing fields and locations which were a locus of OSRD activity, and leading innovation in the treated fields to be increasingly concentrating in a handful of technology hubs, including regions like Boston/Route-128 and Silicon Valley. Notably, this innovation appears to have translated into entrepreneurship and ultimately job growth: counties with more OSRD funding in the 1940s saw faster startup growth in high-tech industries like communications and electronics over the next 30 years, as well as higher manufacturing employment in these industries. Broadly, it appears that entire local innovation ecosystems sprung up in these regions, supported by universities, federally-funded research centers, and private invention. An important residual question which we are continuing to study is to what degree the "OSRD shock" was self-sustaining or fed by continued federal R&D spending in the Cold War era, to the extent it mirrored the distribution of OSRD spending.

CMR may have had similar effects on medical research, pharmaceutical innovation, and the life sciences—a topic we are currently exploring in ongoing work. The above quote from Stewart claims this is so, to say the least. Anecdotally, the wartime effort also endowed participant firms with IP, tacit knowledge, and other advantages that persisted in the postwar era. For example, this is thought to be true for firms which participated in penicillin research and production, among others.

Pfizer is a case in point. Prior to World War II, Pfizer was a chemical manufacturer which in the 1910s and 1920s developed a method of fermenting citric acid. Because of its expertise in fermentation, in the 1940s it was contracted into the effort to scale up production of penicillin, which succeeded and led to its discovery of one of the first tetracycline antibiotics in 1950 (oxytetracycline). These discoveries, combined with a shift in strategic focus, transformed the firm into a pharmaceutical company. Between 1930 and 1945, Pfizer filed on average 3.4 patents per year. By the 1950s, it was filing 42.8 patents per year. Today it is the second-largest global pharmaceutical company with over $50 billion in revenue.

Impacts on S&T policy

As we described in Section 2, OSRD laid a foundation for postwar S&T policy, which was led in peacetime by a constellation of federal agencies described in Section 2, including DOD, AEC, NASA, NSF, and NIH. The Bush Report (Bush 1945) was itself a product of World War II, and one of the channels through which OSRD had a lasting impact on science policy—though it focused on peacetime and did not offer a framework for crisis innovation policy per se. Several institutional innovations developed or refined during the war remained features of the postwar era. The federal R&D contract itself was one: A. Hunter Dupree (1970) has called it "one of the great inventions of the NDRC-OSRD" and "the glue which held the whole system together," and its use continues today. Modern indirect cost recovery and government patent rights also trace back to OSRD (Rosenzweig 2001). In medicine, the NIH "dual" peer review model which emerged in the postwar era was based on the CMR/DMS approach we described above (Mandel 1996).

Impacts on the organization of science

Finally, it also seems the scale and intensity of the wartime effort left a lasting impact on the organization of science. This in part took shape in the birth, and growth, of federally-funded research centers and the rise of the research university (Geiger 1993). But wartime experience also trained a generation of researchers and R&D managers, and established new partnerships (i) among researchers and (ii) between firms, institutions, and the federal government which persisted into the postwar era.

In more ongoing work we are also evaluating these impacts. World War II research labs employed thousands of recent college graduates, PhD students, and recent PhDs, providing hands-on experience and serving as a feeder to graduate study, faculty positions, and industry jobs. Managing a sprawling research organization was itself a distinctive talent, and many of OSRD's senior scientists and lab directors went on to become university presidents, provosts, and deans after the war. Moreover, the collaboration of researchers involved in the crisis effort may have forged new productive relationships among scientists. The war effort drew established academics from around the country to major research labs and research hubs, where they often worked together before dispersing at the end of the war, with most returning to their home institutions. Examples include the scientists who relocated to Los Alamos, or Fred Terman (colloquially, "the father of Silicon Valley"), who was drawn to Harvard to direct research on radar countermeasures, brought colleagues, and later returned to Stanford, bringing new students with him.

These partnerships are not limited to the academy. World War II effectively gave birth to the defense R&D contractor: firms like Western Electric and General Electric were top OSRD contractors in the 1940s and remained top defense R&D contractors 25 years later (Office of the Secretary of Defense 1966-1975). Not surprisingly, major aircraft suppliers to the War Department like Boeing, Lockheed, and Douglas could also be found at the top of this list in the 1960s, as they remain today.

6 Insights for the Post-COVID Era

Looking forward, one of the major lessons from World War II and COVID-19 alike is that crisis innovation problems are different from those in ordinary times, presenting distinct pressures, challenges, and opportunities (Gross and Sampat 2021). Urgency is a paramount feature of crisis problems, and with it the large social returns to a successful response. Crises raise difficult tensions around appropriability, but may also in some cases inspire a kind of altruism as those who can contribute their efforts to the cause. Crisis innovation may also benefit from top-down coordination, parallel efforts (e.g., multiple vaccine candidates, approaches to penicillin production, or uranium enrichment techniques) until one succeeds, and manufacturing capacity at risk—approaches which may be infeasible or inefficient in regular times.

It is notable that both crisis R&D efforts were built on the available stock of basic knowledge. In World War II, this included advances in electrical engineering and microwave communications, the recent discovery and purification of penicillin, and initial results on nuclear fission, among others. Similarly, the first two FDA-approved COVID-19 vaccines built on decades of basic research on messenger RNA—work which science

funding agencies had in fact initially declined to support, but which experienced breakthroughs in the mid-2000s (Garde 2020). Numerous other COVID treatments and countermeasures, from the antiviral drug remdesivir to indoor ventilation, have also benefited from basic research or basic understanding. The ability of the scientific community to pivot to crisis problems, even when funding agencies were slower to do so, points to the value of a highly-trained research corps. A second lesson, or perhaps reminder (echoing Bush), is thus the importance of investing in basic science, scientific training, and scientific institutions in regular times: these are the resources that crisis innovation efforts will draw from.

Returning to the World War II context, economists have argued that wartime medical research pointed to new technological opportunities that were pursued in the pharmaceutical industry after the war (Temin 1980, Malerba and Orsenigo 2015). There is considerable enthusiasm among both the scientific community and the public that many of the scientific and technological advances made in the present crisis, especially surrounding mRNA vaccine development approaches, may do the same. As in the aftermath of World War II, the COVID-19 crisis may usher in new forms of R&D management and collaboration, such as new models of public-private partnerships or increasingly more open and collaborative science, as materialized in the early days of the pandemic (Kupferschmidt 2020). Norms around scientific communication might also change with the use of pre-prints and crowdsourced peer review as means of scientific dissemination. Reflecting on the ACTIV program, NIH director Francis Collins has stated "I can't imagine we'll go back to doing clinical research in the future the way we did in the past" (Yong 2021).

If past is prologue, we may yet see a rethinking of U.S. science and technology policy frameworks as well. Beyond more funding for basic research, it seems plausible that aspects of the COVID-19 model, including more downstream government funding in applied activities, and the use of large procurement agreements as R&D incentives, could outlive the pandemic. The pandemic may also prompt a re-assessment of the extent to which government-funded biomedical research should be targeted at specific outcomes (including planning for future crises) and how to set priorities across them, issues that the Bush framework and the institutions built around it side-stepped (Nelson 1997, Nelson and Romer 1996, Stokes 1997). Aspects of the response, in particular difficulties large funders had in pivoting to crisis problems, also raise questions about whether the existing institutional setup is sufficiently flexible, or whether we need to invest in new agencies to respond quickly and nimbly in a coordinated way (à la OSRD) to activate in future crises. The tradeoffs here are delicate, and as we have emphasized throughout, we still need much more systematic evidence on what worked and what didn't during the pandemic, or other crises where innovation was key to the response. Notwithstanding that, it is a fair bet that like World War II, the pandemic is poised to have lasting effects not only on the direction of innovation, but also on innovation policy.[22]

[22]Recent guidance from the White House suggests that change may indeed be in the offing. In a letter to the incoming White House science advisor Eric Lander in January 2021, echoing President Roosevelt's request of Bush in 1944, (then) President-elect Biden asked Lander to make recommendations for science policy in relation to public health, climate change, broader technological leadership, and shared prosperity (see Biden 2021).

References

Agarwal, Ruchir and Patrick Gaule. 2021. *What drives innovation? Lessons from COVID-19 R&D*. IZA Discussion Paper No. 14079.

Appel, Toby A. 2000. *Shaping Biology: The National Science Foundation and American Biological Research, 1945-1975.*: JHU Press.

Athey, Susan, Michael Kremer, Christopher Snyder, and Alex Tabarrok. 2020. "In the race for a coronavirus vaccine, we must go big. really, really big," https://www.nytimes.com/2020/05/04/opinion/coronavirus-vaccine.html (Accessed on 03/05/2021).

Azoulay, Pierre, Erica Fuchs, Anna P. Goldstein, and Michael Kearney. 2019. "Funding breakthrough research: Promises and challenges of the "ARPA Model"," *Innovation Policy and the Economy*, Vol. 19, No. 1, pp. 69–96.

Azoulay, Pierre and Danielle Li. 2020. "Scientific grant funding," in Goolsbee, Austan and Benjamin Jones eds. *Innovation and Public Policy*, Chicago: University of Chicago Press.

Balconi, Margherita, Stefano Brusoni, and Luigi Orsenigo. 2010. "In defence of the linear model: An essay," *Research policy*, Vol. 39, No. 1, pp. 1–13.

Barrero, Jose Maria, Nicholas Bloom, and Steven J. Davis. 2020. *Why Working From Home Will Stick*.

Baxter, James Phinney. 1946. *Scientists against time*. Boston: Little, Brown and Company.

Biden, Joseph R. Jr. 2021. "A Letter to Dr. Eric S. Lander, the President's Science Advisor and nominee as Director of the Office of Science and Technology Policy," https://www.whitehouse.gov/briefing-room/statements-releases/2021/01/20/a-letter-to-dr-eric-s-lander-the-presidents-science-advisor-and-nominee-as-director-of-the-office-of-science-and-technology-policy/.

Brooks, Harvey. 1996. "The evolution of US science policy," in Smith, Bruce L. R. and Claude E. Barfield eds. *Technology, R&D, and the Economy*, Washington: Brookings Institution.

Brown, Alex. 2021. "Bayh-Dole Act marks 40 years of innovation," https://www.insideindianabusiness.com/story/43142910/bayhdole-act-marks-40-years-of-innovation (Accessed on 03/05/2021).

Bryan, Kevin A., Jorge Lemus, and Guillermo Marshall. 2020. *Crises and the direction of innovation*. Working paper.

Bush, Vannevar. 1943. "The Kilgore Bill," *Science*, Vol. 98, No. 2557, pp. 571–577.

——— . 1945. *Science, the Endless Frontier: A Report to the President*. Washington: Government Printing Office.

——— . 1970. *Pieces of the action*. New York: William Morrow and Company.

Butler, Declan. 2008. "Translational research: Crossing the valley of death," *Nature News*, Vol. 453, No. 7197, pp. 840–842.

Cohen, Jon. 2020. "Operation Warp Speed's opaque choices of COVID-19 vaccines draw Senate scrutiny," https://www.sciencemag.org/news/2020/07/operation-warp-speed-s-opaque-choices-covid-19-vaccines-draw-senate-scrutiny (Accessed on 03/05/2021).

Cohrs, Rachel. 2021. "The Trump administration quietly spent billions in hospital funds on Operation Warp Speed," https://www.statnews.com/2021/03/02/trump-administration-quietly-spent-billions-in-hospital-funds-on-operation-warp-speed/ (Accessed on 03/05/2021).

Conant, James B. 1947. "The mobilization of science for the war effort," *American Scientist*, Vol. 35, No. 2, pp. 195–210.

Conti, Rena M., Susan Athey, Richard G. Frank, and Jonathan Gruber. 2020. "Generic drug repurposing for public health and national security: COVID-19 and beyond," https://www.healthaffairs.org/do/10.1377/hblog20201204.541050/full/ (Accessed on 03/05/2021).

Contreras, Jorge L. 2020. "Expanding access to patents for COVID-19," in Burris, Scott, Sara de Guia, Lance Gable, Donna E. Levin, Wendy E. Parmet, and Nicolas P. Terry eds. *Assessing Legal Responses to COVID-19*, Boston: Public Health Law Watch.

Cook-Deegan, Robert Mullan. 1996. "Does NIH need a DARPA?" *Issues in Science and Technology*, Vol. 13, No. 2, pp. 25–28.

Cutler, David M. and Lawrence H. Summers. 2020. "The COVID-19 pandemic and the $16 trillion virus," *JAMA*, Vol. 324, No. 15, pp. 1495–1496.

Dupree, A. Hunter. 1970. "The great instauration of 1940: The organization of scientific research for war," in Holton, Gerald ed. *The twentieth-century sciences: Studies in the biography of ideas*, New York: W. W. Norton and Company.

Florko, Nicholas. 2020. "New document reveals scope and structure of Operation Warp Speed and underscores vast military involvement," https://www.statnews.com/2020/09/28/operation-warp-speed-vast-military-involvement/ (Accessed on 3/28/2021).

Fox, Daniel M. 1987. "The politics of the NIH extramural program, 1937-1950," *Journal of the History of Medicine and Allied Sciences*, Vol. 42, No. 4, pp. 447–466.

Garde, Damian. 2020. "The story of mRNA: How a once-dismissed idea became a leading technology in the Covid vaccine race," https://www.statnews.com/2020/11/10/the-story-of-mrna-how-a-once-dismissed-idea-became-a-leading-technology-in-the-covid-vaccine-race/ (Accessed on 3/28/2021).

Geiger, Roger L. 1993. *Research and relevant knowledge: American research universities since World War II*. Oxford: Oxford University Press.

Gittelman, Michelle. 2016. "The revolution re-visited: Clinical and genetics research paradigms and the productivity paradox in drug discovery," *Research Policy*, Vol. 45, No. 8, pp. 1570–1585.

Gross, Daniel P. 2019. *The consequences of invention secrecy: Evidence from the USPTO Patent Secrecy Program in World War II*. NBER Working Paper No. 25545.

Gross, Daniel P. and Bhaven N. Sampat. 2020a. *Inventing the endless frontier: The effects of the World War II research effort on post-war innovation*. NBER Working Paper No. 27375.

——— . 2020b. *Organizing crisis innovation: Lessons from World War II*. NBER Working Paper No. 27909.

——— . 2021. *The economics of crisis innovation policy: A historical perspective*. NBER Working Paper No. w28335.

Hill, Ryan and Carolyn Stein. 2021. *Race to the bottom: Competition and quality in science*. Working Paper.

Howell, Sabrina T., Jason Rathje, John Van Reenen, and Jun Wong. 2021. *Opening up Military Innovation: Causal Effects of 'Bottom-Up' Reforms to U.S. Defense Research*. Working paper.

Hoyt, Kendall. 2006. "Vaccine innovation: Lessons from World War II," *Journal of Public Health Policy*, Vol. 27, No. 1, pp. 38–57.

——— . 2012. *Long shot: Vaccines for national defense*. Cambridge: Harvard University Press.

Kaiser, Jocelyn. 2020. "NIH organizes hunt for drugs," *Science*, Vol. 368, No. 6489, p. 351.

Kashyap, Aruna and Margaret Wurth. 2020. "Whoever finds the vaccine must share it," https://www.hrw.org/report/2020/10/29/whoever-finds-vaccine-must-share-it/strengthening-human-rights-and-transparency (Accessed on 3/28/2021).

Keefer, Chester S. 1969. "Dr. Richards as Chairman of the Committee on Medical Research," *Annals of Internal Medicine*, Vol. 71, No. 8, pp. 61–70.

Kevles, Daniel J. 1977. "The National Science Foundation and the debate over postwar research policy, 1942-1945: A political interpretation of Science–The Endless Frontier," *Isis*, Vol. 68, No. 1, pp. 5–26.

Kilgore, Harley M. 1943. "The Science Mobilization Bill," *Science*, Vol. 98, No. 2537, pp. 151–152.

Kiszewski, Anthony E., Ekaterina Galkina Cleary, Matthew J. Jackson, and Fred D. Ledley. 2020. *The role of NIH funding in vaccine readiness; foundational research and NIH funding underlying candidate SARS-CoV-2 vaccines*.

Kleinman, Daniel Lee. 1995. *Politics on the endless frontier: Postwar research policy in the United States*. Durham: Duke University Press.

Kremer, Michael, Jonathan Levin, and Christopher M. Snyder. 2020. "Advance market commitments: Insights from theory and experience," in *AEA Papers & Proceedings*, Vol. 110, pp. 269–73.

Kremer, Michael and Heidi Williams. 2010. "Incentivizing innovation: Adding to the tool kit," *Innovation Policy and the Economy*, Vol. 10, No. 1, pp. 1–17.

Kupferschmidt, Kai. 2020. "'A completely new culture of doing research.' Coronavirus outbreak changes how scientists communicate," https://www.sciencemag.org/news/2020/02/completely-new-culture-doing-research-coronavirus-outbreak-changes-how-scientists (Accessed on 03/28/2021).

Larsen, Joseph C. and Gary L. Disbrow. 2017. "Project BioShield and the Biomedical Advanced Research Development Authority: A 10-year progress report on meeting US preparedness objectives for threat agents," *Clinical Infectious Diseases*, Vol. 64, No. 10, pp. 1430–1434.

Levin, Richard C, Alvin K Klevorick, Richard R Nelson, Sidney G Winter, Richard Gilbert, and Zvi Griliches. 1987. "Appropriating the returns from industrial research and development," *Brookings Papers on Economic Activity*, Vol. 1987, No. 3, pp. 783–831.

Lupkin, Sydney. 2020. "How Operation Warp Speed's big vaccine contracts could stay secret," https://www.npr.org/sections/health-shots/2020/09/29/917899357/how-operation-warp-speeds-big-vaccine-contracts-could-stay-secret (Accessed on 03/05/2021).

Malerba, Franco and Luigi Orsenigo. 2015. "The evolution of the pharmaceutical industry," *Business History*, Vol. 57, No. 5-6, pp. 664–687.

Mandel, Richard. 1996. *A half century of peer review, 1946-1996*. Bethesda: National Institutes of Health.

Matheny, Jason, Michael Mair, and Bradley Smith. 2008. "Cost/success projections for US biodefense countermeasure development," *Nature Biotechnology*, Vol. 26, No. 9, pp. 981–983.

Moses, Hamilton, David H. M. Matheson, Sarah Cairns-Smith, Benjamin P. George, Chase Palisch, and E. Ray Dorsey. 2015. "The anatomy of medical research: US and international comparisons," *JAMA*, Vol. 313, No. 2, pp. 174–189.

Mowery, David C. 1997. "The Bush report after 50 years: Blueprint or relic?" in Barfield, Claude E. ed. *Science for the 21st century: The Bush Report revisited*, Washington: American Enterprise Institute.

Navarro, Peter. 2020. *Memorandum to the Coronavirus Task Force*. Available at https://www.sciencemag.org/sites/default/files/manhattan project bright exhibit 21.pdf.

Nelson, Richard R. 1997. "Why the Bush Report has hindered and effective civilian technology policy," in Barfield, Claude E. ed. *Science for the 21st century: The Bush Report revisited*, Washington: American Enterprise Institute.

Nelson, Richard R. and Paul M. Romer. 1996. "Science, economic growth, and public policy," *Challenge*, Vol. 39, No. 1, pp. 9–21.

Office of the Secretary of Defense. 1966-1975. *Military Prime Contract File*. Available from the U.S. National Archives and Records Administration, Record Group 330 (Records of the Office of the Secretary of Defense).

Owens, Larry. 1994. "The counterproductive management of science in the Second World War: Vannevar Bush and the Office of Scientific Research and Development," *The Business History Review*, pp. 515–576.

Pai, Madhukar. 2020. "Covidization of research: What are the risks?" *Nature Medicine*, Vol. 26, No. 8, pp. 1159–1159.

Piller, Charles. 2021. "Many scientists citing two scandalous COVID-19 papers ignore their retractions," https://www.sciencemag.org/news/2021/01/many-scientists-citing-two-scandalous-covid-19-papers-ignore-their-retractions (Accessed on 03/28/2021).

Price, Nicholson, Rachel Sachs, Jacob S. Sherkow, and Lisa Larrimore Ouellette. 2020. "Are COVID-19 vaccine advance purchases a form of vaccine nationalism, an effective spur to innovation, or something in between?," https://writtendescription.blogspot.com/2020/08/are-covid-19-vaccine-advance-purchases.html (Accessed on 03/05/2021).

Regalado, Antonio. 2021. "The next act for messenger RNA could be bigger than covid vaccines," https://www.technologyreview.com/2021/02/05/1017366/messenger-rna-vaccines-covid-hiv/ (Accessed on 03/05/2021).

Richards, A. N. 1946. "The impact of the war on medicine," *Science*, Vol. 103, No. 2680, pp. 575–578.

Romer, Paul. 2020. "What it takes to be a leader in both basic science and technological progress," https://paulromer.net/statement-for-house-budget-comittee/ (Accessed on 03/04/2021).

Rosenzweig, Robert M. 2001. *The political university: Policy, politics, and presidential leadership in the American research university*. Baltimore: JHU Press.

Rothman, David J. 1991. *Strangers at the bedside: A history of how law and bioethics transformed medical decision making*. New York: Basic Books.

Sampat, Bhaven N. 2012. "Patents, patients, and profits: Winners and losers in drug patent challenges."

——— . 2020. "Whose drugs are these?" *Issues in Science and Technology*, Vol. 36, No. 4, pp. 42–48.

Sampat, Bhaven N. and Kenneth C. Shadlen. 2021. "The COVID-19 innovation system," *Health Affairs*, Vol. 40, No. 3, pp. 400–409.

Slaoui, Moncef and Matthew Hepburn. 2020. "Developing safe and effective Covid vaccines—Operation Warp Speed's strategy and approach," *New England Journal of Medicine*, Vol. 383, No. 18, pp. 1701–1703.

Smith, Bruce L. R. 2011. *American science policy since World War II*. Washington: Brookings Institution Press.

Stewart, Irvin. 1948. *Organizing scientific research for war: The administrative history of the Office of Scientific Research and Development*. Boston: Little, Brown, and Company.

Stokes, Donald E. 1997. *Pasteur's quadrant: Basic science and technological innovation*. Washington: Brookings Institution Press.

Stone, Judy. 2020. "The people's vaccine: Moderna's coronavirus vaccine was largely funded by taxpayer dollars," https://www.forbes.com/sites/judystone/2020/12/03/the-peoples-vaccine-modernas-coronavirus-vaccine-was-largely-funded-by-taxpayer-dollars/ (Accessed on 03/05/2021).

Swain, Donald C. 1962. "The rise of a research empire: NIH, 1930 to 1950," *Science*, Vol. 138, No. 3546, pp. 1233–1237.

Swann, John Patrick. 1983. "The search for synthetic penicillin during World War II," *The British Journal for the History of Science*, Vol. 16, No. 2, pp. 154–190.

Tabarrok, Alex. 2020. "The case for going big is still strong," https://marginalrevolution.com/marginalrevolution/2020/12/buy-capacity-not-doses.html (Accessed on 03/05/2021).

Temin, Peter. 1980. *Taking your medicine: Drug regulation in the United States*. Cambridge: Harvard University Press.

Tucker, Jonathan B. 2009. "Developing medical countermeasures: from BioShield to BARDA," *Drug Development Research*, Vol. 70, No. 4, pp. 224–233.

Whoriskey, P., D. MacMillan, and J. O'Connell. 2020. "'Doomed to fail': Why a $4 trillion bailout couldn't revive the American economy," https://www.washingtonpost.com/graphics/2020/business/coronavirus-bailout-spending/ (Accessed on 03/05/2021).

Xue, Qiwei Claire and Lisa Larrimore Ouellette. 2020. "Innovation policy and the market for vaccines," *Journal of Law and the Biosciences*, Vol. 7, No. 1.

Yong, Ed. 2021. "How science beat the virus, and what it lost in the process," https://www.theatlantic.com/magazine/archive/2021/01/science-covid-19-manhattan-project/617262/ (Accessed on 03/05/2021).