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The World War II crisis innovation model: What was it, and where does it apply?[☆]

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ABSTRACT

World War II was one of the most acute emergencies in U.S. history, and the first where mobilizing science and technology was a major part of the government response. The U.S. Office of Scientific Research and Development (OSRD) led a far-ranging research effort to develop technologies and medical treatments that not only helped win the war, but also transformed civilian life. Scholars and policymakers have appealed to the wartime approach as a template for other problems, typically focusing on the Manhattan Project, but overlooking the broader OSRD effort of which atomic fission and dozens of other programs were a part. In this paper we bring OSRD into focus, describe how it worked, and explore what insights its experience offers today. We argue that several aspects of OSRD continue to be relevant, especially in crises, while also cautioning on the limits to generalizing from World War II to other settings.

From war to disease to climate change, crises both natural and man-made have punctuated human history. Since crises present new problems, policymakers often turn to science and technology for solutions. The pressures of a crisis can be fertile ground for innovation, and few moments in history exemplify both the depth of crises and the power of science and technology more than World War II. Anticipating an eventual entry into the war, but fearing that the U.S. military was significantly behind the technological frontier of warfare, a group of prominent American scientists approached President Franklin Roosevelt in June 1940 with a proposal to create a National Defense Research Committee (NDRC)—later reorganized into the Office of Scientific Research and Development (OSRD)—to apply scientific research to military problems. Led by Vannevar Bush, OSRD quickly grew from a one-page proposal to a 1500 person, multi-billion dollar federal agency engaging tens of thousands of scientists around the country in research to support the war effort.

OSRD developed a then-unprecedented approach to organizing crisis R&D, mobilizing American science and engineering to tackle problems the war presented. Its work produced major advances in technologies and medical treatments that not only helped the Allies win the war, but also transformed civilian life and innovation policy itself. In this paper, we examine how it did so, in an effort to identify the "OSRD model" and consider its modern relevance to crisis R&D management. Though World War II has become a canonical reference for crisis innovation policy and other large, directed research projects, in these discussions it is often unclear precisely what features of the World War II model writers have in mind, or how they apply in other contexts.

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Moreover, that it is usually the Manhattan Project which is invoked as the wartime analogy (e.g., Alexander, 2008; Navarro, 2020), rather than OSRD more broadly, may reflect limited awareness of OSRD's role in the war or what lessons it may present for modern policy. With this paper, we aim to improve understanding of how OSRD operated, and its potential relevance for modern R&D problems.

A study of crisis R&D requires first understanding what a crisis is. Whether a given problem rises to the level of a 'crisis' is subjective, but in our view, what makes crisis problems distinctive is their urgency: losses can spiral out of control if the problem is not quickly contained.[2] World War II was unambiguously a crisis for U.S. policymakers by this definition, and it presented a breadth of problems that needed research—not only fission, but also other new weapons, remote detection (of aircraft, ships, U-boats, rockets, torpedoes), electronic countermeasures, automatic fire control, reconnaissance photography, myriad military medical ailments and treatments, and dozens more.

We begin the paper by reviewing how OSRD was organized and operated. In doing so, we distill several of its important features, such as its organizational design (including its organizational form and routines, which balanced structure with flexibility), and its operational approach to setting priorities, selecting researchers, providing incentives, coordinating across efforts and with end users, and translating research into practice. We bring these ideas to life with case studies of four specific OSRD research programs—radar, atomic fission, penicillin, and malaria—that illustrate the range of approaches OSRD adopted at the program level. We then draw on the general model and the case studies to explain the common principles and logic underlying OSRD's choices in different research programs.

The crisis innovation agency, and its R&D management apparatus, was an invention of its own. When Roosevelt commissioned the NDRC (later OSRD) to undertake research on technological and medical problems to support national defense (Appendix Figure A.2), there was little federal funding for extramural research, outside of agriculture. The urgency of wartime problems forced resolutions to complex organizational problems, including the importance of speeding not only research but also downstream activities to get new technology into the field. As James B. Conant (President of Harvard, and a top OSRD administrator) 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, p. 198). As we will see, this was far from straightforward, and OSRD's work grew to include not only R&D, but also diffusion.

OSRD faced a number of other challenges during its short existence, including battles between competing interests and occasional difficulties in its collaboration with the military branches, not all of which were successfully resolved. Yet on the whole, its effort is widely considered to have been successful, and its impact far-reaching. In the space of under five years, this effort produced major developments in a wide range of technologies including radar, computing, jet propulsion, optics, chemistry, and atomic fission, which later became the Manhattan Project. OSRD's Committee on Medical Research, the first serious government funding effort in the life sciences, helped support the mass production of penicillin, the development of a range of vaccines, the malaria treatment chloroquine, new approaches to managing wartime hardships (such as sleep and oxygen deprivation, cold temperatures, nutrient deficiencies, and psychological stress), and new techniques for treating injuries and wounds. Beyond its immediate impacts on the war and on science, OSRD also created the template for federal R&D procurement and laid the foundation for postwar science and technology policy. In recent research, we find that it also shaped the direction of postwar U.S. innovation and catalyzed technology hubs around the country (Gross and Sampat, 2023a).

What can be learned from the OSRD approach to crisis R&D for modern problems? In *Science, The Endless Frontier*, Bush (1945) advocated an expansion of government support for basic research in peacetime, partly on the grounds that existing basic knowledge had been essential to OSRD's work. Though many of Bush's recommendations were not adopted, a large set of research policy institutions subsequently blossomed. None quite mimics OSRD, despite Bush's claiming, shortly after the war, that it provided a "richly suggestive guide for other undertakings" (Bush, as quoted in Stewart, 1948, p. x).

Bush, however, did not point out specific lessons from OSRD for crises or other R&D problems, nor specify where the OSRD approach might apply. After identifying its main elements, we probe its relevance to other problems. A basic point we emphasize is that despite the Manhattan Project being a common (though, per Mowery et al., 2010, often flawed) touchpoint for wartime approaches to big problems, OSRD is in some cases a better analogy, especially in its breadth. We will argue climate change is one context where the OSRD model may be more relevant, though it is also different in important ways. The OSRD approach may be most relevant in acute crises, a point which the COVID-19 pandemic brought into relief: when COVID emerged, dozens of problems needed research. The U.S. government response, however, took a narrower approach focused on vaccine development. Though it was successful with vaccines, we argue it may have benefited from a more sweeping attack, with a single OSRD-like organization managing a broader portfolio and correlating efforts from the center.

That being said, we also live in a different environment. The modern innovation system is far more developed today than in 1940. There are now numerous research funders across the U.S. government and around the world, and the decentralized approach to COVID problems may reflect where capabilities reside. The fractured political environment in which the pandemic response took place may have also made it harder to organize and execute the R&D effort. Even so, the absence of an OSRD-like agency is striking, and the COVID crisis suggests there are times when such an approach could be useful.

Our goal is thus to understand OSRD's history and explore its modern relevance and limits. In reconstructing this history we rely in part on narratives of people involved, whose accounts are on the one hand the most direct evidence available, yet on the other may not be fully objective due to the authors' own policy agendas in OSRD's memorialization (Kevles, 1977b). Although this is a limitation of the narrative approach, we believe first-hand accounts, together with secondary evidence, provide sufficient information to synthesize the key features of the OSRD model and the logic of its choices.

We proceed as follows. Section 1 recounts OSRD's origins and summarizes its work. Section 2 details how OSRD was organized and run, where we emphasize the organization over its individual programs. In Section 3 we use case studies of four programs to illustrate how its principles were applied in practice, and synthesize this evidence into key program design questions and what we perceive was OSRD's approach to them. In Section 4 we then reflect on specific lessons from OSRD's example—particularly through the lens of modern problems—and limits to its generalization. Section 5 concludes.

1. An overview of OSRD

In 1940, the war in Europe (which began with Germany's invasion of Poland in September 1939) was merely a newspaper headline to most of the American public. However, recognizing that the country was at imminent risk of being drawn into the war after the failure of the Maginot line in France, and that the U.S. "was pathetically unprepared from the standpoint of new weapons" (Stewart, 1948, p. 4), a cadre of high-ranking scientists and science administrators approached President Roosevelt to propose that the U.S. put scientists to work on preparations for war. This outreach, led by Vannevar Bush (President

[2] As we write in Gross and Sampat (2022, p. 136), crisis-driven R&D problems are "urgent, high-stakes, and often unanticipated". The most important feature for our purposes in this paper is urgency.

of the Carnegie Institution of Washington and former Vice President and Dean of Engineering at MIT) with the support of Karl Compton (President of MIT), James Conant (President of Harvard), and Frank Jewett (President of the National Academy of Sciences and Bell Labs), resulted in a meeting with President Roosevelt on June 12, where Bush presented his proposal for a new National Defense Research Committee (NDRC), which Roosevelt approved, formally creating NDRC on June 27, with Bush as its chair.

Led by the aforementioned four scientists plus Richard Tolman (CalTech physicist), Conway Coe (the U.S. Patent Commissioner), and one representative each from the Army and the Navy, NDRC ("the committee") was to "coordinate, supervise, and conduct scientific research on the problems underlying the development, production, and use of mechanisms and devices of warfare", and was funded directly out of the President's discretionary budget. It was authorized to perform research directly as well as to contract out research to firms, individuals, and scientific institutions. Its work was meant to supplement (rather than supplant) that of the Armed Services and other agencies like the National Advisory Committee for Aeronautics (NACA).

NDRC began with a grand mission but only eight staff (the committee members themselves) and no precedent to follow. At its first official meeting on July 2, 1940, the committee organized into five divisions by subject (Table 1), with subsections for individual military-scientific problems (Appendix Table A.1), and concurrently began recruiting other top scientists (largely from committee members' personal networks) to fill the new agency's administrative ranks. It also made the decision that it would contract out research rather than performing it directly. For its time, this was a radical move. Although there had been previous attempts at large-scale government support of research, tensions between scientists' desire for autonomy and taxpayers' need for accountability had stalled the idea (Geiger, 1993), and the urgency of an impending war forced a resolution.

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[a]

[a]Lyman Briggs, Director of the National Bureau of Standards.

Over the next year, NDRC initiated over 200 contracts for research in radar, physics, optics, chemical engineering, and atomic fission, engaging many of the country's top academic and industrial institutions in its work.[3] But aspects of its original mandate also limited its reach: its emphasis on research, over engineering and development; its focus on instruments of warfare, versus other critical wartime problems and pursuits; and a lack of coordination with researchers at other agencies, including the military branches and NACA. NDRC's lack of attention to military medicine was another gap: Hoyt (2006, p. 51), for example, notes that "In nearly every war prior to World War II, more men in the U.S. armed forces have died from disease than battle wounds". As such, the ability to outperform the enemy in preventing or treating common diseases such as malaria, influenza, and bacterial infection could provide major battlefield advantage.

NDRC's early successes persuaded Roosevelt to expand the organization. On June 28, 1941, Executive Order 8807 created OSRD as the successor to NDRC to address these deficiencies and be the central agency organizing civilian research for war, with Vannevar Bush at the helm (Appendix Figure A.2 reproduces the executive order).[4] Now funded by Congressional appropriations, OSRD subsumed NDRC and added a Committee on Medical Research (CMR), which was also organized into divisions by subject matter, and led by scientific experts.[5] Whereas the role of the original NDRC (in 1940) was to "engage in research which would establish the practicability and usefulness" of new instruments of war and convey them to the military, which could then develop and manufacture them, OSRD was a combined research and development organization, with more resources devoted to development as the war progressed.

The NDRC branch of OSRD underwent a handful of changes over the course of the war, especially as the scope of its work grew. In December 1942, NDRC reorganized into 18 core divisions, two panels, and two special sections (S-1 and T); one more division and a handful of new committees were introduced over the next three years (see Table 2 for a list). These divisions covered a wide range of subjects and varied equally widely in scale. The two largest divisions were Radar (14) and Rocket Ordnance (3), with the majority of funding going to MIT and CalTech, respectively, to support major research labs such as MIT's Radiation Laboratory (the "Rad Lab") or CalTech's Jet Propulsion Laboratory. NDRC also directed the atomic fission research program (Section S-1 in Table 2) until it was converted into the Manhattan Project in mid-1943, as well as the proximity fuze program (Section T, led by the newly-created Johns Hopkins Applied Physics Laboratory), which used radar detection to detonate artillery shells at fixed distances from targets (such as enemy aircraft or V-1 rockets), and was one of the most militarily impactful developments of its work.

Despite having one-tenth the budget of NDRC, CMR was similarly important to the war effort. It was charged with mobilizing medical researchers and identifying "the need for and character of contracts to be entered into with universities, hospitals, and other agencies conducting medical research activities" (Executive Order 8807, 1941), and was equally radical for its time.[6] Though the National Institute of Health (NIH) had existed since 1930, its budget was small and mostly spent in its own labs. Private foundations had previously funded medical research. But these were different in important ways from CMR, including in their focus on fundamental research. CMR also drove a major shift in emphasis in medical research, away from peacetime problems to specific wartime medical needs.

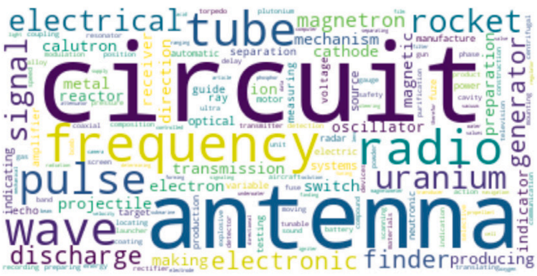
CMR piggybacked on a committee structure created by the National Research Council's (NRC) Division on Medical Sciences (DMS) a year earlier in anticipation of war, organized around "problems with which

[3] Atomic energy research was undertaken by NDRC at the explicit request of Roosevelt, who had been informed of its military potential. The atomic fission research program is described in depth in Section 3.

[4] It was not an inevitability that this research would happen within OSRD. In the early 1940s, various groups were politicking to be in charge of wartime medical research, and some had already started thinking about medical research funding before the war. Bush was initially reluctant to take on medical research (he observed in his autobiography that "medical men seem to have more feuds than the rest of the population"), and agreed only once assured he would have Roosevelt's backing in any inter-agency conflicts (Bush, 1970, p. 48).

[5] In addition to NDRC and CMR, OSRD included an Advisory Council, which coordinated research activities across the government. It later added an Administrative office (responsible for business operations, including contract management), a Scientific Personnel office (to manage personnel issues for employees of OSRD and its contractors, especially draft deferments), an Office of Field Service (to create and operate field offices, and deploy staff to study field problems and assist in ongoing training and the use of OSRD devices in combat operations), and a Liaison office (for coordinating research efforts and exchange of scientific information with research agencies of Allied countries), which we discuss in greater depth below.

[6] Chester Keefer, the "penicillin czar", later described it as "a novel experiment in American medicine, for planned and coordinated medical research had never been essayed on such a scale" (Keefer, 1969, p. 62).



(a) Words in patent titles

(b) Words in publication titles

Fig. 1. Common words in OSRD patent and 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.

the Services expected to be confronted" (Richards, 1946, p. 576). In subjects where not much was known, NRC had hoped to launch investigations, but it never had a budget. Once CMR was funded, it worked closely with DMS to set priorities and evaluate proposals. CMR was chaired by A.N. Richards, a pharmacologist and administrator at the University of Pennsylvania, and its secretariat included three other civilian members—Lewis Weed (Johns Hopkins and the National Academy of Sciences), Alphonse Dochez (Columbia), and Baird Hastings (Harvard)—and representatives of the Army, Navy, and Public Health Service. Though there was some internal reorganization over the war, CMR's main divisions were General Medicine, Surgery, Aviation Medicine, Physiology, Chemistry, and Malaria.

Over the course of the war, OSRD grew to be a large agency, with 850 full-time paid employees and 1500 total personnel at its peak (Stewart, 1948). Table 2 lists its research divisions, along with total contract authorizations issued for the periods shown. These divisions operated relatively independently, and were effectively its operating units.[7] In Table 3 we list the top industrial and university contractors, using data on all OSRD contracts from the agency's official records at the U.S. National Archives (for a description, see Gross and Sampat, 2023a). Here it is evident that OSRD funding was concentrated in a small number of firms and universities. Table 4 shows that the concentration was even greater across states, with ten states accounting for 90% of both NDRC and CMR spending.

Though OSRD was established nearly six months before the attack on Pearl Harbor, once the U.S. was officially at war it embarked on a scientific sprint that lasted into the middle of 1945. OSRD's budget grew quickly, from \$6.2 million in 1940–1941 to \$39.6 in 1941–1942, and \$142.5 million in 1942–1943. By the end of the 1945–1946 fiscal year, OSRD had spent over \$536 million on R&D, across over 2500 contracts—including 1500 contracts let by NDRC, 570 by CMR, and roughly 100 for research on atomic fission before it was spun out into the Manhattan Project to develop an atomic weapon.[8] Fig. 1 illustrates the collective focus of its work, using words in the titles of OSRD-funded patents and CMR publications.

The impacts of OSRD's work were significant, directly affecting not only the war itself, but also U.S. technological progress, scientific manpower, federal science policy, and the postwar economy. Its immediate impact was to support the Allied forces in bringing the war to a victorious ending, but it was also anticipated that its work would eventually permeate civilian life, outliving the war itself (Stewart, 1948). In total, OSRD-funded research generated nearly 8000 inventions, 3000 patents, 2500 scientific articles, and over 10,000 technical reports. Much of this work became foundational to post-war science, applied research,

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[a]
AMP	Advanced Mathematics Panel	2,522.9
APP	Applied Psychology Panel	1,542.5[a]
COP	Committee on Propagation	453.0[a]
TD	Tropical Deterioration	232.4[a]
SD	Sensory Devices	272.5[a]
S-1	Atomic Fission	18,138.2[a]
T	Proximity Fuzes	26,400.0[a]
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. CMR authorizations reported for the entire history of CMR.
[a]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.

[7] Each was led by a division chief and further comprised of sections with section chiefs. Bush claimed that this hierarchy supported OSRD's efficient operation, and assisted him in his advisory role to President Roosevelt: by his own recounting, it allowed questions from Roosevelt to be transmitted down the OSRD chain of command and an answer returned (Bush, 1970).

[8] OSRD's total expenditure is equivalent to over \$9 billion in 2022 dollars, and one to two orders of magnitude more than the U.S. government as a whole was previously investing in research.

Table 3
Top OSRD contractors, by contract obligations.

Top 10 firms			Top 10 universities		
Contractor	Total oblg.	Percent	Contractor	Total oblg.	Percent
Western Electric Co.	$15.2 mil.	3.3%	Massachusetts Inst. of Tech.	$106.8 mil.	23.1%
General Electric Co.	$7.6	1.6%	California Inst. of Tech.	$76.6	16.6%
Radio Corp. of America	$6.0	1.3%	Harvard University	$29.1	6.3%
E. I. Dupont De Nemours & Co.	$5.4	1.2%	Columbia University	$27.1	5.9%
Monsanto Chemical Co.	$4.5	1.0%	University of California	$14.6	3.2%
Eastman Kodak Co.	$4.3	0.9%	Johns Hopkins University	$10.8	2.3%
Zenith Radio Corp.	$4.2	0.9%	George Washington University	$6.9	1.5%
Westinghouse Elect. & Mfg. Co.	$3.9	0.8%	University of Chicago	$5.7	1.2%
Remington Rand, Inc.	$3.7	0.8%	Princeton University	$3.6	0.8%
Sylvania Electric Products, Inc.	$3.1	0.7%	University of Pennsylvania	$2.9	0.6%
Total	$57.8	12.5%	Total	$284.0	61.5%

Notes: Table lists the top 10 firms and universities with OSRD contracts by total obligations. Percentages measure each contractor's percent of total OSRD research spending. The large university contractors were also the hosts of central laboratories for major research projects: 94% of MIT's funding was for radar research at the Radiation Laboratory, and 95% of Caltech's funding was for research on rockets and guided missiles at the Jet Propulsion Laboratory. Other institutions hosted a wider mix of projects.

Table 4
Top NDRC and CMR states, by contract obligations.

Top 10 states for NDRC contracts			Top 10 states for CMR contracts		
Contractor	Total oblg.	Percent	Contractor	Total oblg.	Percent
Massachusetts	$143.4 mil.	32.6%	New York	$4.6 mil.	21.7%
California	$95.5	21.7%	Massachusetts	$4.3	20.1%
New York	$86.3	19.6%	Illinois	$2.5	11.5%
Illinois	$20.2	4.6%	California	$1.6	7.5%
District of Columbia	$15.7	3.6%	Pennsylvania	$1.3	6.1%
Pennsylvania	$13.3	3.0%	Maryland	$1.3	6.0%
New Jersey	$12.0	2.7%	District of Columbia	$1.3	6.0%
Maryland	$11.8	2.7%	Connecticut	$0.8	3.6%
Ohio	$8.0	1.8%	Ohio	$0.7	3.1%
Michigan	$6.2	1.4%	Michigan	$0.6	3.0%
Total	$412.4	93.8%	Total	$19.0	88.7%

Notes: Table lists the top 10 states with NDRC and CMR contracts by total obligations. Percentages measure each state's percent of the given Committee's total research spending.

and industrial development in the fields OSRD supported (e.g., Gross and Sampat, 2023a,b; Gross and Roche, 2023). The wartime experience also appears to have trained a generation of researchers and research managers, deepening U.S. scientific and administrative talent for the Cold War era. It also helped lay the foundation for broad government support of research, including in peacetime.

2. The OSRD model

To put structure to this complex operation, we identify the key elements of OSRD which in our view represent the OSRD model of crisis R&D direction. These include:

1. Organizational design
2. Priority-setting
3. Selecting researchers
4. Incentive mechanisms
5. Coordinating efforts
6. Translation to practice

In this section we describe how OSRD was organized and operated, and how it approached each of these essential functions. We focus on OSRD policy in the form it evolved into over the course of the war, and on what we understand (from contemporaries) to have been its general approach to managing the wartime research effort.

2.1. Organizational design

The structure of the organization was fundamental to how OSRD worked. From the initial kernel of four NDRC divisions and eight Committee members sprouted a sprawling, multidivisional agency, which managed a broad portfolio of research projects from the center and—as we will see below—engaged in a wide range of activities from research, to production, to deployment and field testing. Its organization chart, shown in Appendix Figure A.3, illustrates this structure and scope. The organization was staffed by civilians, and led at all levels by civilian scientists, many of whom were experts in their fields but had no prior experience in applied R&D or R&D management.

The organization benefited from several specific characteristics of its leadership. One was a strong working relationship among its senior leaders, which was rooted in prior personal history. Another was Bush's past government and administrative experience—both as President of the Carnegie Institution of Washington and as a member and later Chairman of NACA, which Zachary (1997) argues provided Bush with a model for OSRD in form and function—as well as the relationships he had cultivated in Washington in the months before and after NDRC was created. His direct access to the President throughout the war, and the President's trust in Bush's judgment, likely afforded him more flexibility than other directors might have had.

Bush's experience as a statesman was valuable in navigating institutional conflict and defending OSRD's turf. The proposal he brought to Roosevelt in June 1940 explicitly stated NDRC was "to aid and supplement ... research activities of the War and Navy departments" (Stewart, 1948, p. 8), a point which Bush emphasized in his first meetings with the service secretaries to limit "bureaucratic jealousies" (Zachary, 1997, p. 109): as Pursell (1979) observes, NDRC had to make alliances. Though OSRD's relations with the Army were good, it was challenged by the Naval Research Laboratory, which viewed NDRC as a competitor. Bush met this challenge by lobbying other Naval offices to support its work, and ultimately prevailed, but research groups across the government would continue jockeying for influence and resources (especially manpower) throughout the war.

OSRD was, at its essence, a new experiment in research administration, pressed on by the urgency of war. Its entrepreneurial character helped it balance structure and organizational routines with the flexibility to adapt, and it repeatedly demonstrated an ability to make significant changes mid-stream, such as the reorganizations of NDRC and CMR, the subdivision of major programs (e.g., radar; see Section 3), or the expansion of field activities. Having an (effectively) unrestricted budget was a boon. Another was the lack of "red tape": with there being little precedent for its work, OSRD invented most of the tools, and guardrails, that it needed as it went.

2.2. Priority setting

A basic question facing any R&D funding program is what research areas to fund, through which mechanisms, and at what stages of maturity (e.g., basic research, applied research, development, and/or testing). NDRC and CMR took distinct approaches to identifying and funding specific research priorities. At NDRC, ideas for research projects could come from within OSRD, the military services, or an Allied government. OSRD's individual sections workshopped these ideas to craft a proposal, including a plan of action, possible contractors, and expected cost and duration. Proposals were then voted on by NDRC leaders at weekly meetings and forwarded to Bush, who made final decisions. Urgent requests could also be taken directly to Bush and authorized on the spot. According to Stewart (1948), this mix of autonomy and review gave NDRC's research divisions the flexibility to apply their imagination to military problems while also ensuring their ideas passed the scrutiny of other experts and aligned with the rest of the OSRD research agenda and the needs (and constraints) of the war effort overall. Bush later wrote, "most of the worthwhile programs ... originated at grass roots, in the sections where civilians who had specialized intensely met with military officers who knew the problem in the field" (Bush, 1970, p. 48).

CMR did things a bit differently, receiving proposals from individual laboratories, which were then evaluated by NRC committees in consultation with medical officers from the Army and Navy, and approved by Bush.[9] On occasion, CMR members also made "missions" to the front-line, which it viewed as helpful to identifying research priorities (Stewart, 1948).

In both cases, research divisions staffed by leading civilian scientists determined research priorities, with input from military users. The committees would then assess scientific feasibility. For problems with high uncertainty, both NDRC and CMR funded multiple rivalrous approaches, organizing multi-front research programs. Within this portfolio they also ranked the priority of specific projects for allocating scarce resources such as elite scientists and materials, emphasizing radar, fission, and penicillin among others (Guerlac, 1987). And in most cases, their focus was on applied research and development, small-batch production, and testing to meet military needs, not fundamental work. As Conant (1947, p. 203) explained, the time for basic research is before a crisis, and urgency meant "the basic knowledge at hand had to be turned to good account".

2.3. Selecting researchers

The second question NDRC faced from the get-go was who would do the work. To build a roster of potential contractors, one of its first undertakings (in the summer of 1940) was to survey academic institutions to gather data on their facilities, research personnel, and ongoing research. This list proved to be an essential resource throughout the war—colloquially known as "the Bible" (Baxter, 1946)—and was updated by OSRD's business office as new research facilities came to its attention. A similar survey of industrial facilities was made after Pearl Harbor, to be used especially for late-stage technology development in between laboratory trials and large-scale production (with the idea that contractors might later double as manufacturers).

NDRC's research divisions were tasked with finding suitable contractors and placing contracts. In making these choices, the agency prioritized speed and quality over cost or distributional considerations, preferencing organizations needing the least new personnel, equipment, or facilities to do the work.[10] Once chosen, the division heads worked with contractors to develop formal proposals to be reviewed by the committee, which sought assurances that "the work would be well done" (Stewart, 1948, p. 13)—which could be founded in the strength of the proposal, the reputation of the researcher or institution, or both. Though NDRC's leadership (correctly) anticipated that the institutional and geographic concentration of its funding and cost of its programs might expose it to criticism (Stewart, 1948), the urgency of the crisis made performance its top priority.

Because CMR solicited proposals rather than proposing the work itself, its process was necessarily different. Once received, these proposals were sent to the NRC Division of Medical Sciences (DMS), where over thirty committees (with hundreds of elite medical researchers) reviewed applications. Peer review was an "unprecedented approach" at the time, and CMR represented "the first sustained, large-scale exercise of the function in a biomedical context" (Mandel, 1996, p. 10). Based on the review feedback, DMS gave each application a letter grade and submitted these reviews back to CMR. Typically—though not always—CMR funded what DMS recommended.

2.4. Incentive mechanisms

2.4.1. Inventing the federal R&D contract

OSRD was willing to fund projects with high upside but uncertain payoffs, with the intent of putting "the best scientific imaginations in the country" (Stewart, 1948, p. 19) on problems of military importance. One of the organizational innovations of NDRC was the development of contractual terms that could balance the need to ensure researchers were focused on true military objectives without excessively constraining their ability to take risks and exercise judgment. No strong precedent existed for government R&D grants or contracts prior to World War II. Dupree (1970, p. 457) would later call OSRD's R&D contract "one of [its] great inventions" and "the glue which held the whole system together". Broadly speaking, OSRD attempted to design contracts to limit "micro-managing" researchers, within broad constraints. Fox (1987, p. 453) notes that although these were nominally contracts, they were "part contract and part grant", as it was research, not specific deliverables, that was being purchased. Though there was monitoring and feedback, once awarded principal investigators had considerable latitude, an approach Vannevar Bush called "giving a man his head". Bush further explained "this is more than a matter of scientific freedom ... it is entirely possible to give a man his head and yet to specify by agreement with him his objectives" (quoted in Hoyt, 2006, p. 43). Stewart (1948, p. 191) described the performance clause as follows:

> [It] was a relatively simple provision. The contractor agreed to conduct studies and experimental investigations in connection with a given problem and to make a final report of his findings and

[9] When there were specific problems that needed research but for which it was not getting proposals, CMR members directly reached out to researchers "whom it regarded as most suitable" (Stewart, 1948, p. 102).

[10] Stewart (1948, p. 22) writes of "a sense of urgency in the selection of contractors", recalling that "the need for speed hung like a sword over the head of the Committee, and speed meant that problems should be assigned to those institutions with the facilities and manpower which promised the best results in the shortest possible time".

> conclusions to the Committee by a specified date. This clause was deliberately made flexible in order that the contractor would not be hampered in the details of the work which he was to perform. The objective was stated in general terms; no attempt was made to dictate the method of handling the problem.

Because rapid mobilization was a priority, the organization also tried to limit the lags from contract negotiation and execution. Bush (1970, p. 48) reported "Once a project got batted into form which the section would approve, with object clearly defined, the research men selected, a location found ... and so on, prompt action followed". Projects could be reviewed within a week, and letters of intent could be sent out so work could begin.[11] Contracts were written for short periods (e.g., six months), with the "informal understanding that they would be extended if the progress of the work warranted" (Stewart, 1948, p. 195). Even reimbursement of expenses was made easy.

2.4.2. Incentivizing participation

With the U.S. conscripting >10 million men into the military, nearly every scientist had friends or family deployed. The drive to help U.S. servicemen survive in battle was thus often personal: a sense of urgency and purpose permeated American society, and it made available "the best scientific talent of the country" (Stewart, 1948), at their full intensity.[12] Nonetheless, OSRD needed to re-orient the research efforts of large swaths of scientists and engineers. This was disruptive, both to profit-oriented firms and to scientists and universities, some of whom were wary of bureaucratic control. Its introduction of indirect cost recovery—novel for its time—was one way it did so, reimbursing contractors for overhead in addition to regular research expenses. A second was its precedent-setting patent policy.

The contract terms initially adopted by NDRC gave itself the sole power to decide whether to file patents on inventions arising from research it funded, as well as who owned the patents. This reflected the principle that the public should control the fruits of publicly-funded research—but left contractors "completely subject to the judgment of the Government" (Stewart, 1948, p. 222). Several firms refused to sign contracts with this provision. Stewart (1948) explained:

> [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 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.

Following objections to these terms, NDRC crafted new language which gave contractors rights to patent inventions produced under contract, and provided the government with an irrevocable, royalty-free license to make and use the invention for military, naval, and national defense purposes (notably, NDRC was unsuccessful at negotiating a license that extended to all government uses). Contractors were required to report all inventions to NDRC prior to contract settlement, and in the event that they elected not to file a patent on any given invention, the government could do so, providing the contractor with a nonexclusive royalty-free license in return. Because of its lengthy terms, this language became known as the "long form" clause.

NDRC (later, OSRD) continued using 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, and training. This became standard for projects hosted at academic institutions like radar (MIT), rocketry (CalTech), and submarine detection (Columbia). Research contracts in atomic fission were initially written with the long form clause but were converted to short form once it became clear that the research might result in an atomic bomb. CMR contracts were also written under the short form clause. These decisions were uncontroversial at the time: in medicine there were strong norms militating against patenting publicly-funded research, and in the fission case, the government had a clear national security rationale for controlling the intellectual property rights. Still, in exceptional cases, OSRD would tailor its patent policy to motivate participation by qualified firms (see Section 3).

2.5. Coordinating research efforts

One of OSRD's explicit responsibilities was to coordinate research with other U.S. agencies and Allied governments. OSRD also coordinated across the portfolio of research it directly supported: for example, CMR organized meetings of investigators to facilitate their cooperation, circulated non-confidential progress reports, and (with the help of various NRC committees) monitored progress and identified which projects should be prioritized or terminated (Stewart, 1948). NDRC divisions working on related research problems could also share members, but for security reasons, information sharing across divisions was restricted to what was necessary to the work.

Coordinating research across U.S. government agencies was the job of OSRD's Advisory Council, which consisted of the Director of OSRD, the Chairmen of NDRC and CMR, the Chairman of NACA, and representatives from the Army and Navy. The Advisory Council was foremost a venue where these agencies could interact. In some cases, research programs begun by one agency might be transferred to another, the most notable being NDRC's atomic fission program being spun out into the Manhattan Project when it became a weapons development project. Concurrent with his appointment as OSRD Director, Bush also served as the Chairman of Joint Committee on New Weapons and Equipment at the Joint Chiefs of Staff (which advised the military on the use of new weapons and ensured that the scientific perspective would remain close to military strategy) and as a member of NACA, and all of Bush, Conant, and Tolman were active advisors to the Manhattan Project—strengthening OSRD ties to these other agencies.

OSRD maintained close relations with the military. It worked with the military representatives in its leadership committee to pick research priorities, and with representatives on the OSRD Advisory Council to avoid duplication. Day-to-day coordination on individual research projects was performed by division-specific military liaison officers at OSRD's lowest levels (Bush, 1970). These officers supported the quick exchange of information, field tests, and at late stages of development, the transition to manufacturing and deployment. Stewart (1948, p. 155) explains that their job was "to speed the project from initiation to the final stage of large-scale Service procurement".

International coordination began shortly after NDRC was created. Scientific exchange between the American and British began in the

[11] Contractors "almost invariably started work under letters of intent which preceded the signing of contracts by weeks or months" (Stewart, 1948, p. 194), ensuring that negotiations would not slow progress.

[12] As Conant (1947, p. 200) wrote, "human beings outdo themselves when their friends and relatives are facing battle". By late 1941, OSRD research had already involved 78 percent of America's top physicists and 52 percent of its top chemists, as measured in *American Men of Science* (Stewart, 1948).

fall of 1940 with a British mission to the U.S. led by Henry Tizard, in which the British shared data, blueprints, and prototypes of a wide range of technologies being developed in England, in exchange for the same from the U.S. The most important of these was the cavity magnetron, which was an essential input to the U.S. radar program, and which Baxter (1946, p. 142) called "the most valuable cargo ever brought to our shores". Other exchanges related to the proximity fuze and the feasibility of an atomic weapon, both of which became important OSRD research programs.

From this point forward, international collaboration was a prominent feature of the research effort. OSRD established an office in London, whose staff was the conduit for information to flow between American and British researchers, and the British similarly established an office in Washington, DC. OSRD's London field office eventually evolved into a formal Liaison division, which managed cross-border scientist and information exchange.

Despite these efforts, coordination was not entirely seamless. Turf battles, and competition for scarce resources like manpower and materials, could complicate working relationships within OSRD and between it and its partners. Its research divisions at times wrestled over individual projects, especially those that spanned boundaries, like radar-driven fire control (Divisions 7 and 14; see Table 2). This was in at least one case resolved by creating an inter-division joint venture, and in another case by decree from Bush (Mindell, 2002). Collaborating with the military on priorities and diffusion was made more challenging by frequent turnover of military liaisons, which was partially relieved by having points of contact with the military at multiple levels of the OSRD hierarchy, but never fully resolved. International coordination, meanwhile, was at times challenged by competing priorities and security restrictions—though in general, defending Britain was as high a priority as defeating Germany and Japan.

2.6. Getting the ideas into practice

Bringing new technology "into operation against the enemy", as Bush described it, proceeded in stages. "For a newly conceived device, these stages involve primary research, engineering development, initial production for extended field tests, and engineering for quantity production. For devices that have gone through these stages, as well as for older devices which are being adapted into new forms or for new uses, there are also the stages of production, installation, maintenance, development of tactics, training and use" (Baxter, 1946, p. 125).

Recognizing the complexities of translation to practice, Bush established an internal Engineering and Transition Office to bridge the divide between R&D and manufacturing. When a device being developed in the lab was ready for testing, it was the responsibility of this office to find a manufacturer which could produce enough units for a field test—which could range from a single unit to thousands. In doing so, it was necessary to ensure that manufacturers could match the specifications and performance of prototypes from the lab. Other basic considerations included the availability of facilities, supply of materials (especially given the materials shortages imposed by the war), and the ability to scale up manufacturing if these tests succeeded.

Field tests were (quite literally) conducted in the battlefield. Without the support of experts, military testers frequently ran self-designed tests, misused the device, or drew incorrect conclusions, and OSRD eventually found it necessary to have scientists accompany OSRD technology into the field (Baxter, 1946). This type of field testing was the initial purpose of OSRD's Office of Field Service, but the division later evolved to also support the deployment and proper use of finished OSRD technology in the theater of war—including (i) ensuring that technology was not distrusted by military users if it experienced bugs or was not properly deployed in their first attempt, and (ii) ensuring that it was not overextended (by being used in settings for which it was not designed and would not actually work).

CMR was also active in development, evaluation, and implementation. Even when there was initial evidence of the therapeutic benefits of new treatments from theory or animals, a key question was whether they worked in humans. Many of its contracts involved testing (e.g., of antimalarials, or an influenza vaccine), sometimes on prisoners and institutionalized populations—practices that would today not be permitted. Members of the Army and Navy also helped arrange field trials on soldiers and reported back results. This user perspective helped facilitate bi-directional feedback, and ultimately utilization. In some cases, CMR helped support manufacturing as well—most famously in the penicillin program, as we discuss in Section 3.

3. Example OSRD research programs

The organizational features and activities in Section 2 characterize OSRD as a research-directing agency and portfolio manager. It was at the program level where operating decisions were made—typically on shared principles, but differences in each problem and its context often necessitated distinct approaches. We use case studies of the radar, atomic fission, penicillin, and malaria programs to illustrate their parallels and differences. These programs shared an urgent military demand; questions over who would do the work, how to do it, and how to get results into the field; and a foundation in existing science. They also differed in organization and the division of labor, the pursuit of serial versus parallel research efforts, policies around patent rights and information sharing, and the end user. Table 5 provides an abridged summary of the following accounts.

3.1. Radar and radar countermeasures

When war broke out in Europe, Germany quickly established air supremacy in its invasions of Poland and France as well as the London Blitz. The results of these campaigns made it clear that defeating Germany would require breaking its hold of the skies. Radar—a technology for detecting fast-moving or distant objects not visible to the naked eye, including ships and aircraft obscured by fog or darkness—was thus a focus of OSRD's work from its inception. Much of the basic science of radar (namely: transmitting, reflecting, and receiving radio waves) was well known before the war broke out, though the technology was too primitive to be useful in military applications Section D-1 of NDRC, colloquially the Microwave Committee, was established with the specific objective to study this problem.

The Tizard mission and its demonstration of the cavity magnetron jump-started the U.S. radar program, which grew to be NDRC's largest in cost and scale. In late 1940, NDRC launched a new radar research laboratory at MIT, deliberately (mis)named the Radiation Laboratory (Rad Lab) to disguise its work. MIT was chosen for three reasons: the presence of a handful of scientists with experience in microwaves, its ability to attract more scientists to work on radar, and its proximity to the ocean and Boston's Municipal Airport for testing. Research at MIT began on November 10, 1940, several months before a contract with the institute was finalized, under the direction of Lee A. DuBridge, a physicist from the University of Rochester. The lab began with a kernel of about 20 scientists but quickly staffed up, largely with physicists and electrical engineers, academic and industrial, faculty and students and recent graduates alike. The Rad Lab operation eventually grew to nearly 4000 people, including several future Nobel laureates, most working out of one building on the MIT campus.

Baxter (1946, p. 146) describes the Rad Lab embarking with a "feverish" pace. By January 1941 it was testing new radar sets from building rooftops, and in February it was asked by the Army to make experimental sets for its planes, setting a precedent for limited "crash" production (most production was both then and later done by industrial partners). By 1943, substantial progress had been made on the core technology, and though some fundamental research continued, much of its work shifted to engineering, production, and deployment.

Table 5
Summary of select OSRD research programs.

Question/Issue	Radar	Atomic fission	Penicillin	Malaria
Research priorities	1. Develop a functional radar system at microwave frequencies; 2. Create (and refine) variants of radar for land, sea, and air; 3. Assist manufacturers' production at scale; 4. Support military on installation and use.	1. Deepen science around nuclear fission; 2. Engineer a controlled nuclear chain reaction; 3. Identify a fissile material that could be produced in enough quantity to make an atomic bomb, before passing the reins to the Manhattan Project.	1a. *Natural*: Produce sufficient quantities of natural penicillin for research and clinical testing; 1b. *Synthetic*: Identify penicillin's molecular structure and how to synthesize it, 2. Conduct clinical tests; 3. Scale up penicillin production for military and civilian use.	Find an effective malaria preventative or treatment, by: 1. Improving understanding of mechanisms; 2. Developing testing and screening protocols; 3. Drug synthesis, production, and evaluation.
Research performers	MIT Radiation Laboratory: a newly-created "central laboratory" hosted at MIT and employing thousands of scientists and engineers from around the U.S., was the locus of radar research. Specific projects sometimes subcontracted. Radar Countermeasures division spun out into the Harvard Radio Research Lab (RRL).	Basic research on fission contracted to several universities. Subsequent work on uranium separation and uranium piles was performed at UC Berkeley (led by Ernest Lawrence), U. of Chicago (Arthur Compton); Columbia U. (Harold Urey).	*Natural*: Initial work in fermentation, production, testing done by NRRL and pharmaceutical firms. CMR funded larger-scale clinical testing through contract to Mass. Memorial Hospital. WPB and OPRD worked with firms to scale up production. *Synthetic*: Contracts to pharmaceutical and chemical firms, universities.	Decentralized effort across many institutions, both industrial and academics. Firms typically not under formal contract.
Contracts and patents	Most work performed under the short-form patent clause, giving the government title. The Rad Lab and RRL had patent offices which filed applications. OSRD led a Government Radar Patent Program which held monthly meetings where representatives from radar research laboratories and the Armed Services shared new inventions on which they planned to file patents, resolved conflicts, and decided the scope of claims.	Early contracts used long-form patent clause, giving contractors title. As the work began to produce results and its consequences were better understood, Roosevelt instructed Bush to arrange for the U.S. government to retain title. All contractors agreed to convert to the short-form clause, effective retroactively. Most nuclear patent applications were also issued secrecy orders by the USPTO (Gross, 2023).	*Natural*: Most projects had short-form clause. Very little patenting, beyond a few USDA process patents. *Synthetic*: Short-form for university contracts. Contracts with firms typically did not provide any financial support, but rather were to promote information exchange. Bush had control over patent application decisions. OSRD had right to compel cross-licensing among the contractors, and retained a government license.	Most academic contracts were short-form. Firms retained patents and submitted information "in confidence" to NRC. After CMR added a malaria division late in the war, it brought new industrial contracts under short-form clauses but this affected few contracts.
Coordination	Project began with the British Tizard mission to the U.S. (1940). Frequent international exchange thereafter. Both Rad Lab and RRL kept field offices near British radar research and hosted British researchers in U.S. Also hosted representatives of manufacturers and military liaisons to assist in handoffs, and worked with military to explore uses of radar, train operators, and support installation and maintenance in the field.	Initiated in 1940 at request of President Roosevelt, with he and Bush communicating regularly on the viability of an atomic bomb. OSRD managed a multi-site research portfolio until a viable technology for producing fissionable material was found. Military built pilot plants while research was ongoing and later took over the project (under the Army Corps of Engineers' Manhattan Project) for weapons development.	*Natural*: CMR staff organized meetings among firms and agencies involved, including British research efforts, collected and shared progress reports, and brokered connections. *Synthetic*: Secured protection from antitrust regulation for firms collaborating on synthesis. *Both*: Worked with WPB to ensure contractors had the equipment and supplies needed. Promoted information flow across efforts.	CMR funded and participated in NRC-based efforts to share information across research projects, collect and report data. Unlike penicillin, an important goal was to distribute projects to different teams to avoid duplication. Developed and diffused standardized testing protocols. Coordinated civilian and military trials of chloroquine.
Downstream activities	Limited "crash production" of experimental radar sets at Rad Lab upon military request; production at scale provided by leading industrial firms. Rad Lab sent staff into the field to aid Allied installations of radar and learn about enemy radar.	Little OSRD downstream activity, which was made the Army's responsibility. OSRD supported pilot plant construction. After fission research transferred to Army, OSRD leaders continued to advise Manhattan Project.	CMR primarily supported clinical testing of natural penicillin. After clinical testing, most downstream work was guided and funded by WPB and OPRD—not OSRD/CMR.	Funded researchers to overcome chloroquine production bottlenecks, to generate enough drug for trials. Supported civilian and military trials of chloroquine.
Number of contracts	183	100	*Natural:* 36 / *Synthetic:* 18	78
Total value	\$156.9 mil.	\$14.4 mil.	\$2.4 mil. / \$0.4 mil.	\$4.8 mil.
Short form patent clause: pct. of obligations	86.2%	100.0%	100.0%	98.1%
Top five contractors	Mass. Inst. of Tech. (64.9%) Harvard Univ. (10.0%) Research Construction Co. (8.2%) General Electric Co. (3.2%) Columbia Univ. (2.3%)	Univ. of California (30.4%) Univ. of Chicago (19.6%) Columbia Univ. (13.4%) Standard Oil Dev. Co. (6.7%) Princeton Univ. (3.7%)	Mass. Mem. Hospital (66.6%) Cornell Univ. (6.8%) Johns Hopkins Univ. (4.7%) Univ. of Michigan (4.1%) Univ. of Pennsylvania (3.67%)	Univ. of Chicago (15.8%) Columbia Univ. (11.0%) New York Univ. (9.7%) Johns Hopk. Univ. (8.7%) Allied Chem. & Dye (5.2%)

Notes: Table summarizes the features of OSRD's radar, atomic fission, penicillin, and malaria research programs. The short form patent clause gave the government title to any patents on inventions produced under contract, unless the government chose not to file, in which case the contractor retained patent rights. Note that some atomic fission research contracts began under the long form clause but were later amended to the short form clause.

Coordination was a prominent feature of the radar research effort. It had close relationships with industrial firms like Bell Labs, General Electric, RCA, Westinghouse, and Sperry Gyroscope from the beginning, who supplied the necessary components, collaborated on radar and radar-enabled technologies, and exchanged technical staff (Guerlac, 1987). As the Rad Lab grew, OSRD began to contract select projects to other institutions when the work was sufficiently distinct, important, or sensitive, and it placed staff with these other contractors to be liaisons. It also placed staff in the field, and it was "at the [battle]front or at Army and Navy bases [that] the possible tactical uses of radar were explored, operating procedures were established, problems of installation and maintenance were met, and the training of operators and maintenance personnel went forward" (Baxter, 1946, p. 156). Collaboration with the British also persisted throughout the war, with the Rad Lab hosting a British liaison officer and running a branch in Britain. With multiple contractors as well as the military services working on radar, OSRD also organized a government radar patent program to exchange inventions and coordinate patent filing.

The Rad Lab's collaborations with manufacturers were just as notable. Although it was initially thought production would be relatively simple, with researchers handing off breadboard models to manufacturers to produce at scale, it was quickly proved to be more complex.[13] The arrangement that evolved typically had companies sending engineers to the Rad Lab to learn about the device they were to produce and prepare drawings, after which prototypes were made and tested before production lines set up. Representatives from the manufacturer, the Rad Lab, and the Army or Navy "held frequent meetings to work out problems of general design, production schedules, choice of subcontractors, specifications for parts and performance, and [other] details", writes Guerlac (1987, p. 689), who notes that in the Rad Lab's later years, "manufacturers' engineers were often associated with a project throughout its course, and the [Rad Lab] research men followed it through the manufacturing design and production process".

As the war progressed, radar countermeasures (i.e., obfuscation and jamming of enemy radar) were proved to be nearly as valuable as radar itself. Shortly after Pearl Harbor, NDRC began work on countermeasures in collaboration with the Naval Research Laboratory and Army Signal Corps. The Rad Lab added a countermeasures division, led by Frederick Terman of Stanford, and due to its distinct objectives, staff, culture, and security requirements, it was soon moved to Harvard, christened the Radio Research Laboratory (RRL), and transferred to a new contract, under a new OSRD division (Division 15, "Radio Coordination"). Like the Rad Lab, RRL quickly added recruits from around the country, peaking at roughly 800 staff.

Between 1940 and 1945, radar developed into a profoundly important instrument of war, allowing soldiers to see enemy craft even when their eyes could not. Despite barely featuring in U.S. military strategy at the start of the war, by 1945 the military had procured over $3 billion of radar and $300 million of radar jamming equipment (>$45 billion in 2022 dollars). The Rad Lab supported R&D in over 100 distinct radar systems. Baxter (1946, p. 149) attributes its performance to a "highly flexible and effective administration, extensive research in fundamentals, steady improvement of components, and close liaison with the Army and Navy, and the British".

[13] As Guerlac (1987, p. 687) explains, "there were very few companies with the facilities and experience" to produce radar components or systems, and these were tied up in other war production contracts. Moreover, there were hundreds of subcontractors involved in supplying parts, which needed to be coordinated. Guerlac continues: "All of these manufacturers had to be introduced to the problem; had to train their engineers to develop production methods; had to be supplied with detailed specifications and then necessary test equipment; had to be given initial educational orders in advance of larger Army or Navy orders; had to be assisted in the design of special tools; and often even had to develop new methods of packing and shipping".

3.2. Atomic fission

The most well-known scientific achievement of World War II is the harnessing of atomic energy to create a weapon of mass destruction. Yet the atomic bomb was the culmination of years of OSRD work on atomic fission which preceded the Manhattan Project and was transferred over only when the basic science was established, and the fission project converted into an all-out effort to produce enough fissile material for a bomb as quickly as possible.

OSRD's atomic fission research was rooted in the scientific breakthroughs of the 1930s, when the nuclear fission of uranium was first demonstrated, and the potential for chain reactions recognized. What made the discovery of fission remarkable was that the resulting fragments had less mass than the original uranium nucleus. By implication, the missing mass had transformed into energy. The finding electrified the physics community, presenting new possibilities in energy production. In the summer of 1939, urged by Leo Szilard and Albert Einstein, President Roosevelt appointed a special Advisory Committee on Uranium to study fission, led by Lyman A. Briggs, the director of the National Bureau of Standards. When NDRC was established in June 1940, this committee was folded in as one of its divisions. Briggs' first request to Bush was for an allotment to research the fundamental constants of nuclear fission, and contracts were let that fall with several universities and two federal agencies to support this work. Notably, NDRC's leadership itself was divided over the military relevance, and thus prudence, of this investment.

This internal dissension led NDRC to appoint an independent committee of physicists *not* deeply involved in atomic fission research to review the issue and provide a recommendation on whether atomic fission research held military promise, and whether or not this project should be prioritized. This committee recommended a "strongly intensified effort" (Baxter, 1946, p. 425), but acknowledged that it would likely take years for this research to yield enough progress to be useful. Based on its report, Briggs requested to increase NDRC spending on atomic fission three-fold, writing over a dozen new contracts to study uranium isotope separation and nuclear chain reactions.

Even then, the scale of the program was relatively small, at a few hundred thousand dollars. But as both this work and parallel efforts in Great Britain made progress, American physicists involved in NDRC-funded research or close to the problem became increasingly convinced that an atomic weapon was feasible, and Bush decided that a course of action needed to be set by the President. In a meeting with Roosevelt in October 1941, Bush explained the state of the project, being conservative in his prediction of the feasibility of an atomic weapon by acknowledging it was based only on experimental laboratory data, and it was unknown if a full-fledged attempt at uranium separation would be successful. Roosevelt told Bush to proceed.

The uranium program was accordingly reorganized around distinct approaches to producing fissile material (especially uranium-235) and accelerated: gaseous diffusion and centrifugal separation of U-235 was centered at Columbia under Harold C. Urey, electromagnetic separation at Berkeley under Ernest Lawrence, and chain reactions in unseparated uranium and its fissionable byproduct plutonium at Chicago under Arthur Compton. The United States' formal entry into the war following the attack on Pearl Harbor on December 7, 1941 triggered an "all-out attack on the uranium problem" (Baxter, 1946, p. 428). On December 16, the President urged Bush to "press as fast as possible on the fundamental physics and on the engineering planning".

Because it was unclear which method would be viable for large-scale production, OSRD invested in all approaches. As of May 1942, there were "five horses running neck and neck" (Baxter, 1946, p. 434): the centrifugal, diffusion, and electromagnetic methods of separating U-235, and the graphite and heavy-water pile methods of making plutonium from uranium. The military urged on this work on the grounds that Germany was likely also pursuing the bomb, and even brief delays could have catastrophic effects. Given this urgency, Briggs, Compton, Lawrence, and Urey proposed to begin building pilot plants for all five methods before they were proven. This proposal was sent by Bush and Conant to the President, Vice President, and Secretary of War, suggesting the Army undertake the construction.

While the Army began building these plants, OSRD continued its work. A major breakthrough occurred on December 2, 1942, when the Chicago effort produced the first controlled chain reaction—but the experimental pile would have had to run for 70,000 years to produce enough plutonium for a bomb. Research on the five methods thus continued, though by the spring of 1943, centrifugal separation had been abandoned, and heavy-water soon after.

This left the military with three viable paths to producing enough uranium or plutonium for a bomb. With the science of atomic fission understood and pilot plants running, OSRD transferred its work to the Army Corps of Engineers on May 1, 1943. Its contracts were subsumed into the recently-organized Manhattan Project, led by Brigadier General Leslie R. Groves, whose mission was to produce a functional atomic weapon, and several OSRD staff members were transferred into the project. In describing this hand-off, Hewlett (1976, p. 470) explains Groves immediately converted the OSRD research groups into "an engineering and production effort" and recruited industrial contractors into the project as administrators of production sites. In all, OSRD wrote over 100 contracts to nearly 50 contractors for research on atomic fission, with total value of $19 million, comparable to the $28 million expended on radar through April 1943. Bush, Conant, and Tolman served in an advisory capacity to the Manhattan Project until July 16, 1945, when all three were present at Alamogordo to witness the successful detonation of the first atomic weapon.

3.3. Penicillin

Infectious disease was the most important military medical problem in World War II. As with other wartime problems, there had been considerable but incomplete progress against infectious diseases in the decades before the war. Sulfa drugs, developed in Germany, were effective against a range of bacterial diseases, but had major toxicity issues and were not useful for many battlefield ailments. The best hope was in penicillin, which in 1929 the Scottish physician-scientist Alexander Fleming had found inhibited the growth of bacteria in the mold *Penicillium notatum*, where it was naturally grown. A decade later, in 1939, an Oxford University laboratory headed by Howard Florey and Ernest Chain was the first to purify the molecule, making it possible to conduct clinical tests. However, they were unable to produce enough for human testing, nor, in war-torn Britain, to engage British pharmaceutical companies to do so (Andrus, 1948).

In 1941, Florey came to the U.S. for help. He was referred to the U.S. Department of Agriculture's (USDA) Northern Regional Research Laboratory (NRRL), which had experience growing mold at high yield, and also met with A.N. Richards at CMR. Though CMR's primary focus was research (rather than production), Richards assured Florey "he would see that everything possible was done to expedite production of penicillin" (FTC, 1958, p. 321). This commitment was made despite skepticism in certain quarters and considerable uncertainty about its feasibility. But it was buffered by CMR's decision to engage in a parallel effort to develop a synthetic penicillin.

CMR took sharply different approaches to the two R&D programs, which presented distinct problems. Research efforts focused on synthetic penicillin, where the key challenges were figuring out penicillin's molecular structure and finding a way to synthesize it. In deciding whether to concentrate resources in top firms or spread its bets, CMR ultimately chose organizations that had experience in or capabilities for synthesis, or an interest in penicillin more generally; this included nine firms, two universities, and the USDA (Swann, 1983). Since several leading firms were already conducting research on synthesis, CMR issued token contracts with no funding, mainly to facilitate intellectual property licensing and information flow (Stewart, 1948).

With natural penicillin, the problem was not research, but rather production. Here, CMR initially had a more limited coordinating role. In late 1941, it organized meetings between Bush, NRRL, and representatives of Merck, Squibb, Pfizer, and Lederle Labs, where it worked to persuade these (reluctant) firms to be involved (Neushul, 1993). The NRRL was to work on techniques for increasing penicillin yields from mold, and firms on production techniques.

This project presented several challenges. One was getting firms to invest in developing (unfunded) production capabilities, which CMR sought to assuage with evidence supporting proof of concept, and by brokering information among firms and negotiating waivers to avoid antitrust scrutiny that cooperative research sometimes attracted. CMR also worked with the War Production Board (WPB) to get the firms needed equipment, and connected them with academics who would evaluate production samples. In all cases, the firms provided their own funding, participating for patriotic, reputation, or competitive reasons—but since natural penicillin was a known molecule, there was no strong intellectual property to be had, save for process patents.

The synthetic program struggled to make headway, but by 1942, firms were producing 40 million units of natural penicillin per month, up from 10 million in 1941 (Baxter, 1946).[14] Because quantity was initially scarce, the firms had agreed that clinical testing would be organized by CMR, which did so in collaboration with the NRC Committee on Chemotherapeutic and Other Agents (COC). CMR acquired supply from the producers (initially for free; later at cost), and COC then distributed penicillin to hospitals free of charge, in return for detailed case reports. Initially the testing contracts went to recognized experts, but as supply of penicillin grew, more physicians could be involved. The COC received reports on over 10,000 patients, sending back its analyses to CMR periodically (FTC, 1958). CMR also supported testing "in the field" on wounded soldiers, in collaboration with the military (Andrus, 1948). The positive results from these tests led to a desire for broad adoption by the military, and to civilian demand.

This meant there was a need to build large scale production facilities. The needs of massive scale-up were a distinct challenge, and one in which CMR was largely on the sidelines, as its expertise was in research and testing. At the encouragement of CMR, WPB's Office of Production Research and Development (OPRD) provided material, and shared technical expertise and some funding, while the Defense Plant Corporation helped support construction (Baxter, 1946). Even as WPB was working to convince firms to invest quickly in plants for scale-up, a lingering risk which allegedly slowed investment was the possibility that CMR might end up succeeding in a synthetic approach to penicillin production—illustrating a potential drawback to the parallel R&D strategy (Neushul, 1993). WPB eventually recruited 20 firms into its production program.

The natural penicillin program succeeded. Monthly output grew to 425 million units in December 1943, 117.5 billion in June 1944, and nearly 650 billion in June 1945. The cost of producing 100,000 units fell from $20 to under $1 (Baxter, 1946). By 1943 there was enough penicillin to treat U.S. and Allied troops and meet civilian demand. The synthesis problem, by contrast, proved more complex, despite initial enthusiasm and scientists who promised results in months. Once natural penicillin production was successful, the synthesis program was shut down. The causes of this "failure" have been examined elsewhere (Swann, 1983), and include unexpected scientific difficulties, lack of information sharing among British and U.S. efforts, and difficulty getting enough penicillin for testing. But Swann (1983) also notes that lack of success during the war does not imply the program was a flop, since knowledge developed during the war "paved the way" for a number of clinically important semi-synthetic penicillins introduced in the 1950s (Gross and Sampat, 2023b).

[14] Baxter (1946) notes that it takes about one million "units" of penicillin to treat one patient.

3.4. Malaria

Malaria has been a major contributor to global morbidity and mortality for centuries. In the U.S., malaria was on the road to elimination by the early 1930s. But much of World War II was fought in areas with high malaria risk, which posed a serious impediment to the Allied effort. Malaria could be treated with quinine—an extract from the bark of the Cinchona tree—and though its side effects (blurry vision, tinnitus, and nausea) were not ideal, it was effective. However, quinine supply routes were vulnerable, and after the Japanese seized Java in 1942, nearly all U.S. supply was cut off. As U.S. General Douglas MacArthur put it, "this will be a long war if for every division I have facing the enemy I must count on a second division in the hospital with malaria and a third division convalescing from this debilitating disease" (Condon-Rall, 2000, p. 58).

Some malaria research was conducted in the 1930s, much of it focused on finding or developing a quinine substitute. In the U.S. this was supported by NRC and the Rockefeller Foundation, but this program was disorganized and not well funded. The Germans were also working on quinine substitutes during the interwar era, partly because their own stock had been cut off by the Allied blockade in World War I (Baxter, 1946). Most of this work was conducted by the conglomerate I.G. Farben, which had sophisticated chemical synthesis capabilities. The German effort yielded several candidates, including a drug called atabrine (which had been marketed globally, including in the U.S. before World War II) and sontochin (which would be the German drug of choice during the war but was not widely known), among others. However, side effects of the U.S. produced version of atabrine (e.g., discoloration, gastrointestinal issues, and a loss of virility) made soldiers reluctant to take it, and generals reluctant to compel them to (Baxter, 1946).

One of the first actions of CMR was to fund some of the efforts already underway, including the 1941 NRC Conference on Chemotherapy of Malaria (Baxter, 1946), to outline and coordinate the needed research activities. This and other NRC and CMR efforts later morphed into CMR's "Board for Co-ordination of Malaria Studies", which included representatives from CMR, NRC, and the Army and Navy, and whose function was to set priorities and coordinate research. According to Baxter (1946, p. 309), "The presence of the service members enabled [the services] to follow developments in civilian laboratories and, through their knowledge of problems in the field, direct the attention of civilian research to particular problems that demanded solution".

CMR supported malaria research by firms and universities across the country in chemistry, biology, pharmacology, and clinical medicine on the disease, preventatives, and treatments. Much of this work was aimed at identifying, developing, and testing substitutes for quinine. Early work focused on atabrine: since the drug was being manufactured in the U.S. using slightly different materials and approaches, it was unclear if its adverse side effects were inherent or due to process. In addition to its research on atabrine, CMR simultaneously initiated a hunt for alternatives. This was a different type of problem than that facing the penicillin effort: CMR funded the synthesis and testing of *thousands* of antimalarial compounds, while managing the portfolio and shepherding compounds from synthesis to screening to testing (Slater, 2009). It also worked with the military to conduct field trials on promising candidates, and Stewart (1948) argues that military involvement on the Malaria Board facilitated "prompt and adequate" clinical testing (Stewart, 1948, p. 115).

An important part of CMR's work was collecting, validating, and disseminating information among the many firms and labs involved in malaria research and development work. The Survey on Malarial Drugs, a "workhorse" of the program (Slater, 2009, p. 119), cataloged information on new compounds and prepared and distributed reports and bulletins (Baxter, 1946). A key issue was how to get firms to contribute compounds, and CMR established categories of information allowing firms to do so in confidence in cases where they had proprietary interests. This was a balancing act, and a source of considerable controversy. In this program, more so than natural penicillin, the leader (William Mansfield Clark) was heavily focused on protecting firms' interests, even as Bush and Richards wanted broader sharing and disclosure. Importantly, many of the firms involved in the malaria program did not sign formal contracts, perhaps deterred by the "short form" patent provisions (Slater, 2009). The final product, *A Survey of Antimalarial Drugs, 1941–1945*, included information on compounds from over 100 firms and institutions (Slater, 2009).

In all, CMR supported research or testing of over 14,000 compounds in animals, and 80 in humans (Baxter, 1946). One product of this effort was chloroquine, which—although it arrived too late to be useful during the war itself—became a revolutionary malaria treatment in the post-war period. Surprisingly, the drug that would eventually be used in the field was, in the end, atabrine. Once it was determined to be safe and effective in 1943, General MacArthur essentially decreed it be used (Condon-Rall, 2000). By 1944, there was a sharp decrease in malaria incidence (Baxter, 1946), making the other developments moot during the war itself.

3.5. Common principles and logic

Through these examples, we can observe the common dimensions over which OSRD had to make choices in each of these programs, and begin to discern the principles and logic that shaped these choices, which we characterize in Table 6. Following the structure of both Section 2 and Table 5, we organize these choices into five categories: research priorities, research performers, contracts and patent policy, coordination, and downstream activities.

Allocating limited resources between priorities—especially manpower, more than funding—required balancing military needs and technical feasibility. Bush's first condition for any project was that it would help win the war. This, for example, led to prioritizing the atomic bomb over rockets because it had "a better chance of being developed during this war" than rocketry, which Bush saw as a weapon of future wars (Zachary, 1997, p. 179). Urgency thus drove its emphasis on applied research and technologies with short-run payoffs, though in cases like atomic fission, where it saw a possibility of particularly high payoffs from advances in nascent fields, it supported fundamental research despite uncertain timetables and outcomes.

Within each of these projects, we see heterogeneity in the choice to invest in one approach or many. Parallel efforts of the type seen in the fission, malaria, and (to a point) penicillin projects, among others, prioritized speed and the probability of discovery over cost. A sequential approach, however, affords the opportunity to improve through iteration, and more aptly characterizes radar. That it followed such an approach may also reflect the more advanced state of its underlying science and that the problem was more one of applying and refining technique than of developing it wholesale, particularly after the cavity magnetron was provided by Britain.

In choosing how to organize and incentivize research efforts, we also observe common principles across OSRD's portfolio. Interdependencies within the R&D problem might suggest concentrating efforts at fewer institutions. Systems engineering problems, for example, were not easily divisible, and thus had this flavor: this was the case with radar, which was concentrated at MIT, and with fission—especially at the stage of bomb design and manufacture, which was sited at Los Alamos.[15] In contrast, penicillin was more mixed, and malaria

[15] For example, as the Rad Lab grew, it was suggested that "[it] was becoming too large for efficient operation and that it might be well to decentralize it by dividing the microwave radar work among various other universities", but NDRC determined that "to subdivide the Laboratory would impair its efficiency" and create difficulties in security and coordination (Guerlac, 1987, p. 289). Guerlac goes on to note that this "was not necessarily true for certain types of fundamental research which could be dispersed [more easily]".

Table 6
Principles underlying OSRD choices.

Category	Issue	Options	Determining factors
Research priorities	*How to select research priorities?*	Demand vs. feasibility	Value of a full solution Degree of urgency Expected timetables
	How many research approaches to fund?	Serial vs. parallel	Solution uncertainty Degree of urgency Slope of learning curve
Research performers	*How to organize research efforts?*	Concentrated vs. diffuse	R&D complexity
Contracts and patents	*Who owns the IP?*	R&D funder vs. performer	Contractor incentives Promoting diffusion Security risks R&D spillovers
Coordination	*Coordination of research efforts*	Hands-on vs. laissez-faire	Spillovers across efforts
	Coordination with users	Hands-on vs. laissez-faire	Size and number of users
Downstream activities	*When to begin production?*	During vs. after R&D	Degree of urgency + cost of scaling up production quickly
	Assist with deployment?	Yes vs. no	Difficulty of integration Training requirements

Notes: Table identifies common dimensions over which OSRD research programs made choices and characterizes their logic.

diffuse—reflecting that discovery, synthesis, and testing of pharmaceutical treatments could be spread more widely across investigators. Setting patent policy was its own challenge, where OSRD faced the traditional tension between incentivizing its contractors and ensuring broad access in deciding whether the results of research it funded should belong to the public. The co-existence of two distinct patent clauses in OSRD contracts reflects the balance OSRD chose to strike, where with private contractors, it often allowed them right of first refusal to new patent applications, but in other cases it retained this right for itself or the armed services—especially where OSRD funded the creation of new labs (e.g., for radar) or provided other significant risk capital or if national security required it (fission).

Coordination was one of the most distinguishing, pervasive features of OSRD's approach to R&D administration relative to the status quo ante (or even today). Spillovers across research efforts made coordination across them desirable, especially when researchers were collaborating or competing for scarce inputs, and when one's successes and failures could impact others. Though the military was a large, bureaucratic, and diffuse customer, the scale of its needs made coordinating with military representatives on priorities, approaches, and outputs desirable. In other settings, absent these conditions, coordination may be less important, unproductive, or even detrimental, especially when time is short and managers are spread thin.

OSRD's involvement in production was also distinctive. Urgency may encourage the "telescoping of stages" (Baxter, 1946, p. 440) we see in the fission and penicillin programs, where manufacturing capacity was developed at risk or production at pilot plants began before any one approach was proven. The MIT Rad Lab too engaged in (limited) crash production of experimental radar, though it generally followed a more sequential path from development and testing to manufacturing and distribution, reflecting the iterative nature of radar improvements. Also notable is how, and where, OSRD was or was not involved in diffusion. Whereas medicine and the atomic bomb were relatively straightforward to incorporate into existing warfighting and military medical practice, integrating radar into military strategy required broader changes, including a trained corps of radar operators. In this and similar cases, OSRD and its contractors (like the Rad Lab) put scientists in the field, serving a key role in supporting deployment.

4. Lessons and limits

These examples help us distill the logic we believe OSRD used to run individual programs. Yet OSRD was broader than these programs alone: as an R&D management organization, it managed a portfolio, and it developed a distinctive model for doing so. One question this accounting raises is where, and in what ways, it may be relevant to other problems—including modern ones. Vannevar Bush summarized the OSRD model at the end of the war, writing:

> "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... [OSRD] brought to being a pattern of administration which aptly met a new and unique need and which stands as a richly suggestive guide for other undertakings".
>
> [Bush, quoted in Stewart (1948), p. x]

It is unclear precisely what lessons, or undertakings, Bush had in mind. Near the end of the war, Roosevelt asked Bush to draw lessons from this "unique experiment", but for peacetime, not crises.[16] Bush's response, *Science, The Endless Frontier*, famously made the case for government funding of "basic" research, on the grounds of its high returns for economic growth, national security, and public health. The 'Bush Report' drew mainly negative lessons from OSRD, emphasizing "we must proceed with caution in carrying over the methods which work in wartime to the very different conditions of peace" (Bush, 1945, p. 12). This emphasis reflected his own concerns (and those of his fellow conservatives) about government micro-management of science in peacetime and the appropriate roles of the state versus the market. Beyond the value of the prewar stock of basic science—e.g., in medicine or nuclear physics—to wartime R&D, the Bush Report did not describe any specific lessons from OSRD for future crisis R&D efforts.

Much has been written on how World War II shaped postwar research policy (e.g., Kevles, 1977a; Geiger, 1993; Kleinman, 1995; Greenberg, 2001, among others). Though the Bush Report shaped the "rhetoric and tone" of these policy debates (Nelson, 1997, p. 42), many

[16] Notably, Roosevelt's request was the product of backroom discussions between Bush and other Roosevelt advisors, who drafted the letter which Roosevelt publicly issued, in an effort to countervail legislative proposals for peacetime science funding recently introduced by Senator Harley Kilgore (Kevles, 1977b).

of the institutional features which Bush advocated were not adopted, most notably his call for a single agency (the National Research Foundation) focused on funding basic research (Kevles, 1977a; Mowery, 1995; Nelson, 1997). Instead, in the five years Congress spent debating aspects of this proposal, other agencies filled the vacuum that OSRD left behind. The Atomic Energy Commission took charge of nuclear research, the National Institutes of Health inherited CMR's portfolio, and the Army, Navy and Air Force (eventually the Department of Defense) weapons R&D. Unlike what Bush and his critics envisioned, these "mission" agencies came to dominate postwar funding (Mowery, 1995, 2010). Though not specifically promoted by Bush, several features of OSRD contracts were incorporated into the postwar funding procedures of some of these agencies, including patent policies and indirect cost recovery. The report also helped shape the division of labor in the U.S. innovation system, with universities specializing in fundamental research (some of it oriented to uses; Stokes, 1997) and firms in applied research, development, marketing, and diffusion.

In the seventy-five years since the Bush Report, the U.S. and global innovation system has grown massively in scale and scope. Whereas OSRD counted hundreds of firms and dozens of universities capable of performing funded research, today there are thousands of firms and nearly 300 active research universities in the U.S. alone, and many more globally. In the 1940s, only a handful of firms were qualified to be involved in CMR efforts; today, there is a large, diffuse global pharmaceutical industry. In general, R&D capabilities are much more dispersed globally than they were during the war (Nelson and Wright, 1992). Science and technology have advanced considerably, as have tools for research, and collaboration, in most scientific fields.

These observations raise two questions. First, what are the lessons of OSRD for crisis R&D policy? And second, given the numerous changes in the innovation system since, is OSRD—a short-lived agency developed on the fly, for a crisis 80 years ago—relevant today? Is it still the "suggestive guide" Bush hinted at? If so, in what ways?

4.1. OSRD beyond the Manhattan Project: Relevance for climate change and other "Grand Challenges"

One part of OSRD's portfolio has attracted considerable attention: the Manhattan Project. Popular calls for "mission-oriented" R&D and R&D to address so-called "Grand Challenges" regularly appeal to the Manhattan Project for inspiration, including in the context of climate change and the COVID-19 pandemic.

Such appeals have drawn some criticism. In an influential article in this journal, Mowery et al. (2010) argued that the Manhattan Project is not a particularly useful model for climate change. They also argue that the approach to Project Apollo—itself inspired by the Manhattan Project—may not be applicable either. Whereas the Apollo and Manhattan projects were focused on a specific technological goal, with a single, government customer, climate R&D has to serve innumerable, heterogeneous users around the world, each with distinct needs. These users also have existing capital investments, such that diffusion faces the headwinds of replacement effects (Arrow, 1962). Many of the implementers will be private sector firms. Whereas the Apollo and Manhattan projects were centralized, climate change research is already more dispersed, involving multiple governments and organizations and lacking mechanisms to identify common needs, coordinate efforts, and allocate resources across problems and researchers.

Columns 1 and 3 of Table 7 summarize these differences. We basically agree with the Mowery et al. (2010) argument. However, the Manhattan Project was but one part of the OSRD portfolio. In some ways OSRD as a whole may be a better fit for climate change, as a comparison of columns 2 and 3 suggests. Far from a singular, focused moonshot, OSRD was in fact many moonshots, pursued all at once. Its portfolio was multidimensional with many efforts and competing priorities, and it had not one customer but many, across the U.S. armed services and even Allied governments. It was centralized in direction but decentralized in performance. It hung close to its users, and provided significant coordination. Diffusion often had to overcome organizational inertia and required changes in military (customer) technology and practices. One insight from unpacking the OSRD model, then, is that it was more general than the Manhattan Project alone, and may be more relevant to some types of modern R&D challenges, especially those with diverse goals and consumers.

However, the table also illustrates that in several important ways, especially the role of the private sector as customer and implementer, climate change is different. The scale of global coordination required for climate change R&D is likely larger and far more difficult than U.S.-Allied cooperation during World War II. The political economy of climate change is also more complex, with vested interests and widely heterogeneous impacts. This challenge thus seems more daunting now, even though the technologies for global coordination in R&D, especially in digital communication and dissemination, are much more advanced today than those relied on by OSRD.

One could thus conclude that was then, this is now, and the OSRD model may not offer many insights to policymakers today. While we recognize this argument, there are also aspects of the approach that we think are relevant to modern problems, and these can be particularly important in a crisis, as we discuss in the context of the COVID-19 pandemic below.

4.2. The OSRD model for crisis R&D: The case of COVID-19

The question of what rises to the level of a 'crisis' is subjective. Cancer, communism, and competitiveness crises have each driven major changes to U.S. R&D policy in the postwar era (e.g., Pavitt, 2000), whereas malaria, poverty, and climate change have not. We opened this article by describing a crisis as a large, urgent problem which will be difficult to contain if not tackled quickly. When a crisis poses new challenges, innovation may be required to resolve them—which is why R&D can, in these contexts, be valuable.

Crisis R&D policy once again became relevant during the COVID-19 pandemic, which presented a wide range of urgent research problems, including vaccines, drug treatments, diagnostic tests and contact tracing technology to limit its spread, models to understand disease epidemiology and design public health interventions, and organizational innovation to mitigate economic and social costs of social distancing, masking, and lockdowns at schools, restaurants, medical practices, and other venues. Prior to vaccines and treatments, front-line doctors and nurses needed new non-pharmacological interventions to handle the influx of COVID patients, including new patient management techniques, hospital workflows, and more. In order to be effective, this innovation not only needed to be generated quickly; it also needed to diffuse broadly to the relevant users.

From early on, observers appealed to the wartime R&D model (Azoulay and Jones, 2020; Lindee, 2020). The U.S. vaccine development effort, Operation Warp Speed, was explicitly inspired by the Manhattan Project (Navarro, 2020). Aspects of its approach, including public–private partnership, a heavy hand by the government in coordinating which technologies would be pursued, developing vaccine candidates and running trials in parallel, building production capacity at risk, the application of military logistics, and heavy funding indeed resembled the World War II fission project.

However, given the breadth of COVID-related problems, the policy response could have benefited from a more coordinated approach Gross and Sampat (2022). In this sense, the COVID-19 challenge resembled OSRD's problem more closely than that of the Manhattan Project (Table 7). The breadth of innovation required, the value of coordination (across researchers, across government agencies, and internationally), and downstream challenges in rapidly scaling up production and diffusion were similar to issues OSRD took on. Yet there was no OSRD-like entity identifying key questions where research was needed, farming

Table 7
Features of big R&D problems: A comparison.

Question/Issue	Prior models		Modern problems	
	OSRD	Apollo/Manhattan	Climate Change	COVID-19
1. Specific technological solution or system?	No	Yes	No	No
2. Customer (implementers) concentrated or diffuse?	Diffuse (within military)	Concentrated	Diffuse	Diffuse
3. Coordination with other agencies/countries valuable?	Yes	Not much	Yes	Yes
4. Requires changes in user practices for adoption?	Yes	No	Yes	Yes
5. Large private sector role in deployment of technology?	No	No	Yes	In some areas
6. Existing capital stock to be upgraded, or replaced?	Small	Small	Large	Small

Notes: Table characterizes features of four "big" R&D problems, including OSRD's problem as a point of comparison.

out the research, synthesizing the (often imperfect) evidence, and—outside of vaccines—transitioning R&D into production and practice. The "science for policy" interface was instead much more decentralized and fragmented, and much of the innovative effort was based on "bottom-up" efforts by individual organizations and academics, rather than top-down planning (Gross and Sampat, 2022).

As with climate change, there were also important differences between COVID and World War II. These included the more diffuse nature of the user and the role of the private sector in implementing solutions. A fractured domestic political environment may have also posed a larger obstacle to the COVID R&D response than OSRD confronted, and the global coordination problem may have been more challenging for both political and pragmatic reasons.

Notwithstanding these constraints, the gaps in the federal COVID-19 research portfolio, and challenges faced by government funders in pivoting to COVID problems, raise questions about whether existing institutions are sufficiently flexible. Perhaps more than its specific policy choices, OSRD's organizational form may be useful for future crises. Bush and others noted that the fact that OSRD was a new agency, with clear lines of command and little red tape, allowed it to move quickly. During the COVID-19 crisis, agencies including the NIH were unable to pivot as quickly to new problems (Balaguru et al., 2022), in part because of the dominance of the investigator-initiated peer review model in biomedicine, but also due to the bureaucratic hurdles now associated with grantsmanship. In this light, the emergence of new funding agencies (like BARDA; see Sampat and Shadlen, 2021) and philanthropic approaches (like fast grants; see Collison et al., 2021) was extremely useful. Building in crisis R&D grant or contract mechanisms at existing agencies, or an autonomous crisis R&D agency to be activated in a crisis, could be useful going forward. Such mechanisms would need to balance the need for urgent solutions against transparency and equity concerns, as OSRD did.

4.3. Applications to non-crisis technology policy

Several of Bush's political adversaries wanted aspects of OSRD to feature in peacetime, non-crisis R&D, including direct government steering of research to target specific outcomes and government involvement in (civilian) applied research. Since then, debates about the feasibility and desirability of these activities have been perennial sources of tension in research policy. Many examples of "technology policy" at least facially resemble OSRD, such as fostering cooperative R&D, promoting diffusion, and using procurement contracts to facilitate development. Nelson (1997) argues that the Bush Report's characterization of the relationships between science and innovation hindered a useful conversation about civilian technology policy in the U.S. Without taking a stand in these contentious debates, we observe that much of what OSRD did would be called "technology policy" today (Mowery, 1995), and the question of whether there is scope for more of it in non-crisis times remains as important now as it was then.

5. Concluding remarks

The OSRD-led effort in World War II represented the first serious government funding of extramural research in the U.S. and marked a major turning point in research policy globally. In this paper we described how it was organized and operated, identified the choices it faced and how it approached them both in general and in specific contexts, and distilled an approach for program-level decisions. Importantly, however, OSRD was larger than any one of these programs alone: paraphrasing Bush, its role was to channel research efforts into a wide array of wartime R&D problems and to coordinate them with its industrial partners and military customers.

Beyond history "for its own sake", understanding the specifics of the OSRD model may contribute to improved policymaking in other settings. Historical analogies are commonplace in policy, especially in crises, and one role for academic history is to make sure that accurate analogies are being drawn (Eichengreen, 2013). As we emphasized in the previous section, appeals to the Manhattan Project in particular may provide a distorted lens on the parallels between World War II and modern-day R&D challenges such as COVID-19 or climate change, and OSRD is a distinct analogy which in other contexts may be more (or less) useful for policy design.

In particular, as our discussion of these R&D problems suggests, there may be insights from the OSRD story that are relevant for modern crises. Working with users to identify key R&D problems, and explicitly coordinating public and private sector research activities (to avoid excess correlation and to plug holes in the portfolio), can be important in a crisis. The need for speed means that certain approaches may be more appropriate to R&D policy in crises than in "normal" times, including parallel R&D and a focus on downstream production and diffusion. New agencies (or mechanisms) may have benefits over established approaches in providing "air traffic control" across a portfolio of research programs and in getting things done at the pace required. It may also be easier to assemble coalitions and funding to accomplish such activities during crises than other times, because both the public and private sectors have interests in rapid resolution, and—if successful—crisis R&D policies are temporally bounded.

With this paper we aimed to clarify (i) what OSRD's World War II crisis innovation model comprised; (ii) to what other problems it might apply; and (iii) how specific features of these problems govern its relevance in each context. While appeals to history are common in research and policy, there remains a need for more attention to the details of modern R&D challenges, and the specifics of historical approaches, to determine the extent to which historical policy models are useful guides.

CRediT authorship contribution statement

Daniel P. Gross: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Bhaven N. Sampat:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data on OSRD contracts are available from the Harvard Dataverse at https://doi.org/10.7910/DVN/POO1ZH.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.respol.2023.104845.

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