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Daniel P. Gross
Bhaven N. Sampat

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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 major research effort to develop technologies and medical treatments that not only helped win the war, but also transformed civilian life, while laying the foundation for postwar innovation policy. Scholars and policymakers have appealed to the wartime model as a template for other crisis responses, but in broad terms. In this paper we describe in detail how it worked. We do so first through an overview of how OSRD approached several questions that may confront any government-led crisis innovation effort: priority setting, selecting and engaging researchers, a funding mechanism, coordinating research efforts, and translation to practice. Next we present case studies of the radar, atomic fission, penicillin, and malaria research programs, illustrating how the principles applied in specific contexts, but also heterogeneity. From these examples, we synthesize a framework for decision-making. We conclude by discussing other lessons from OSRD, such as what makes crisis innovation policy different, how crisis policy approaches may vary, and also the limits to generalizing from World War II for other crises.

Daniel P. Gross
Fuqua School of Business
Duke University
100 Fuqua Drive
Durham, NC 27708
and NBER
daniel.gross@duke.edu

Bhaven N. Sampat
Department of Health Policy and Management
Columbia University
722 W 168th Street, Room 486
New York, NY 10032
and NBER
bns3@columbia.edu

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—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 1,500 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 that the wartime crisis presented, and produced major advances in technologies and medical treatments that long outlasted the war itself. The World War II research effort—including a storied component of it, the Manhattan Project—has become the canonical reference for crisis innovation policy (e.g., Navarro 2020), and sometimes even non-crisis innovation policy, including problems as varied as artificial intelligence (House Armed Services Committee 2020) and clean energy development (Alexander 2008).

What does this metaphor entail, beyond a sense of urgency and large amounts of R&D funding? In this paper, we describe what took place in World War II, how the experience may offer specific lessons, and what we believe the limits to those lessons may be. We begin the paper by reviewing how OSRD was organized and operated, and the full scope of its work. Drawing on its experience, we distill six high-level strategic questions that organizers of crisis innovation efforts are likely to confront in any crisis, and describe OSRD's approach to each: setting research priorities, selecting researchers, designing a funding mechanism, providing incentives, coordinating across efforts and with end users, and translating ideas to 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 that OSRD took to crisis R&D management, and the circumstances supporting each. We in turn fuse insights from the general model with specific lessons from these examples to develop a general framework for decision-making around these issues.

OSRD was ordered by Roosevelt to undertake research on technological and medical problems to support national defense (Appendix Figure A.1). It was, explicitly, a crisis innovation agency. What made its problem different from non-crisis research was its urgency, and the importance of speeding not only research but also downstream activities to get new technology into the field (Gross and Sampat 2021b). 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).

Because there was no precedent for large-scale government funding of research in 1940, when NDRC was formed, it effectively began with a blank slate. Its founding team of administrators—all civilian scientists, save for two military liaisons from the Army and the Navy—immediately organized into a multi-divisional structure by subject matter, emphasizing research on modern weapons and technologies for communications and radar. Its early progress led Roosevelt to expand the scope of its work one year later to include medical research, at which point NDRC became a unit of the newly-created OSRD, alongside a newly-added Committee on Medical Research (CMR)—all before the U.S. was at war. What began as a steady grind turned into a scientific sprint when the U.S. entered the war on December 8, 1941, after the bombing of Pearl Harbor. NDRC and CMR grew to have 26 and 6 divisions, respectively, addressing myriad technological and medical problems facing soldiers in the field. At around $7.5 billion in current dollars, its financial outlay, while perhaps modest by modern comparison, was significant for its time.

Designing a crisis innovation agency from the ground up required making a number of unprecedented choices. We discuss OSRD's organization and operation in depth in the sections that follow, while highlighting six specific dimensions which generalize to most crisis innovation settings and often present tradeoffs. The first of these questions was priority-setting: what to fund. OSRD's priorities were demand-driven, focused on solving specific military problems, and led by input from the Armed Services. The bulk of its work was applied in nature, and while basic studies were sometimes needed, the urgency of the crisis meant that it mostly had to take basic science as given and put it to work. Its approach stands in sharp contrast to the peacetime funding model that followed at agencies such as NSF and NIH, where most of the research is investigator-initiated, often fundamental, and scientists have a more dominant role in shaping the agenda.

A second issue was finding and engaging the most capable researchers. To support this activity, OSRD maintained a directory of potential contractors and took seriously the issue of making their involvement incentive compatible. To avoid disrupting universities by relocating their staff, much of the work was done using university facilities, offering indirect cost recovery on a nominally "no gain, no loss" basis. The leaders of the OSRD divisions themselves were typically volunteers, but contemporary accounts suggest that participation in wartime research was generally through a spirit of volunteerism, powered by a belief in the need to defeat a common enemy. Stewart (1948) wrote that the wartime crisis atmosphere meant "the best scientific talent of the country was available" for OSRD research, and Conant (1947) also pointed to "the ordeal of battle" as a source of cohesion and cooperation above that normally possible in peacetime.

The decision to outsource research, rather than perform it directly, was precedent-setting. To do so, OSRD invented the federal R&D contract, which balanced specificity with the flexibility to explore, accounted for the intrinsic uncertainty of research, and could be amended as the demands of the war evolved. In the end, it effectively procured research services, rather than any specific output. Because results from this work were often patentable, it also developed a novel, contractual patent policy that balanced private incentives with the public interest.

As the principal agency mobilizing research for war, OSRD was also responsible for coordinating research efforts. In many cases—especially in medical research—OSRD funded multiple rivalrous approaches to the same problem. Parallel R&D, a portfolio approach, may have been particularly important where speed was an important consideration and solution uncertainty was high. But as (if not more) important was coordination with the military, other U.S. scientific agencies, and the broader Allied research effort. In cases where there were there were spillovers between research projects, OSRD facilitated information sharing. It also established field offices in Britain, and sent scientists to the battlefield to see military problems first-hand.

A final issue was translation to practice: OSRD's work needed to be advanced from laboratory prototypes to reliable, mass-produced units in the field. It had specific offices to assist in getting new technology from bench to battlefield, with small-batch initial production runs, field tests, and even battlefield deployment. Tight links between the researchers and users enabled rapid feedback and continual tweaking to ensure the technology met the needs in the field. Because the military was the main user, it was also easier to make changes to established practices to accommodate new technology than it may have been otherwise. And because of the way its contractual patent terms were written, there was no risk of technology transfer hold-ups.

On all six of these dimensions, OSRD faced choices and tradeoffs, such as whether to fund parallel R&D efforts, how much to concentrate work with a handful of leading scientists and institutions versus spread its funding more widely, whether to retain title to patents arising from work it funded, how heavy a hand to take in guiding and coordinating research efforts, and how long to wait before scaling up production on technologies still under development.

We use four case studies to illustrate specific approaches OSRD took to these issues in different contexts. Through these examples, we not only introduce several historical points of reference, but can also use them to identify points of departure. Though their details sometimes varied, one thing these programs nevertheless shared was that they had to confront the common set of questions described above. Combining insights from these examples with economic theory, we then develop a framework for organizing crisis innovation responses.

The impact of OSRD was 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 become 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, influenza and other 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 policy, and in recent research, we found that it also shaped the direction of U.S. innovation in the post-war period and catalyzed the growth of technology hubs around the country.

Vannevar Bush offered an overarching perspective of OSRD's work and achievements:

> "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. In the contracting system which it developed, in the methods for safeguarding the public interest through sound patent policy which it created, in the means for effective and cordial liaison with co-operating agencies which it effected, and in a dozen other ways, the office 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)

This paper proceeds as follows. Section 1 recounts the origins of the OSRD and provides a quantitative summary of the operation. Section 2 describes the challenges it faced as a crash innovation program, and its general approach to solving them—the "OSRD model". Section 3 provides case studies of specific OSRD research programs, which illustrate how these principles were applied, but also heterogeneity. In Section 4 we merge this evidence with theory to provide a framework for crisis R&D program design that can be applied in other settings. We then describe OSRD's impacts in Section 5, and reflect on the lessons that OSRD offers for future crises, discussing both the generalizable and distinctive features of the World War II era.

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), 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 of the Carnegie Institute 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 of Bell Labs), resulted in a meeting with President Roosevelt in mid-June, a letter from Roosevelt on June 15 requesting Bush to be the head of a new National Defense Research Committee (NDRC), and an order on June 27, 1940 formally creating the NDRC.

Led by the aforementioned four scientists plus Richard Tolman (CalTech physicist), Conway Coe (the U.S. Patent Commissioner), and one representative from each of the Army and the Navy, NDRC was tasked 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 as well as to contract with firms, individuals, and scientific institutions for research—and its work was 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 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 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 about here]

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.[1] But it was also limited by its emphasis on research, over engineering and development; its focus on instruments of warfare, versus other critical pursuits; and a lack of coordination with researchers at other agencies, including the military and NACA. Military medicine was

[1]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.

a particularly important gap: Hoyt (2006), for example, notes that "In nearly every war prior to World War II, more men in the U.S. armed forced have died from disease than battle wounds." As such, the ability to outperform the enemy in treating common diseases such as malaria, influenza, and bacterial infection could provide major battlefield advantages.

NDRC's early successes persuaded Roosevelt to expand the organization, and 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 science for war, with Vannevar Bush at the helm (Appendix Figure A.1 reproduces the executive order).[2] 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.[3] 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 Lab (the "Rad Lab"), which was the locus of radar research, employed over 4,000 people at its peak, and remains an institutional legend, or CalTech's Jet Propulsion Lab, which still exists today. NDRC also directed the atomic fission research program until it was transferred to the Army in mid-1943.

[Table 2 about here]

Despite having one-tenth the budget of NDRC, CMR was similarly important to the war effort.

[2] 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 tend 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).

[3] 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 shared by OSRD and other government agencies, and to handle personnel issues for employees of OSRD and its contractors, especially draft deferments), an Office of Field Service (to create 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 the exchange of scientific information with research agencies of Allied countries), which we discuss below.

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," and was equally radical for its time.[4] 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 through block grants, and later (after the Depression made these financially infeasible) through grants to specific researchers. But as we discuss below, these were different in important ways from the CMR model, including 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 Division on Medical Sciences (DMS) a year earlier in anticipation of war, organized around "problems with which the Services expected to be confronted" (Richards 1946). In cases where not much was known the NRC had hoped to launch investigations, but it never had a budget. Once CMR was funded, in worked closely with the DMS (under contract) 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.

The OSRD, including NDRC and CMR, grew to be a large agency, with 850 full-time paid employees and 1,500 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 the operating units of OSRD. Each was led by a division chief and further comprised of subsections with section chiefs.[5]

In concurrent research (Gross and Sampat 2020), we have compiled data on all OSRD contracts from the agency's official records at the U.S. National Archives. In Table 3 we list the top industrial and university contractors, where 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.

[Tables 3 and 4 about here]

[4]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).

[5]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).

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 immediately grew many-fold, 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 2,500 contracts—including 1,500 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.[6] Figure 1 illustrates the collective focus of its work, using words in the titles of OSRD patents and publications.

[Figure 1 about here]

2 The OSRD Model

From its inception, OSRD faced several questions that any government-led, government-funded crash research program must address. What specific problems need solving where R&D may be useful? What firms, institutions, and scientists should be put to work on solving them, and how? Should they be allowed to work from their home institutions, or organized into larger units? How (and how much) will they be paid? Who will own the intellectual property rights over their work? What will motivate top firms and scientists to contribute to the public cause? How should efforts be coordinated, and who will do the coordinating? How will research results progress to technology development, large-scale production, and ultimately deployment?

We aggregate these questions into following six categories:

1. Priority-setting (i.e., what to support?)
2. Selecting researchers (whom to support?)
3. A funding mechanism (how to support it?)
4. Incentives for participation
5. Coordination of research efforts
6. Translation to practice

The urgency of war necessitated careful, early decisions but also the flexibility to adapt, especially as OSRD expanded and its research (and the war itself) progressed. Over the next several pages, we describe how OSRD approached each of these issues. 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

[6] OSRD's total expenditure is equivalent to nearly $8 billion in 2020 dollars, and one to two orders of magnitude more than the U.S. government as a whole was previously investing in science.

been its general approach to funding and administering its expansive civilian research effort. As we will later see, at a deeper level there was not one model but rather many, since different R&D problems sometimes necessitated their own approaches.

2.1 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, or even testing). NDRC and CMR took distinct approaches to identifying and funding specific research priorities, though they also had common features, such as their focus on applied research over basic science and collaboration with end users in the military.

At NDRC, ideas for research projects could come from within OSRD, the military services, or an Allied government. It was the job of OSRD's individual sections to workshop these ideas and formulate a basic proposal, including a plan of action, potential contractors, and its anticipated cost and duration. These proposals were then voted on by the committee at weekly meetings, and its recommendations were forwarded to Bush, who made final funding 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 use their imagination to dream up solutions to military problems—such as high-resolution aerial photography, electronic fire control, or infrared night vision goggles—while also ensuring their ideas passed the scrutiny of other experts and were consistent with the rest of the OSRD research agenda and the demands (and constraints) of the war effort overall. Bush later recalled "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).

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.[7] 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 and in some cases collaboration from military users. The committees would then assess scientific feasibility. For problems with high solution uncertainty, both NDRC and CMR funded multiple rivalrous approaches, such as in the atomic fission and penicillin research programs (see Section 3). And in most cases, their focus was on applied research and development, small-batch

[7] When there were specific problems where it wanted research done but for which it was not getting proposals, CMR members actively reached out to researchers "whom it regarded as most suitable" directly (Stewart 1948). However, most CMR research was investigator-proposed, rather than internally proposed.

production, and testing to meet military needs, not fundamental work. As Conant explained, the time for basic research is before a crisis, and since time was of the essence, "the basic knowledge at hand had to be turned to good account" (Conant 1947).[8]

2.2 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 the contractor might later double as manufacturer).

NDRC's research divisions were tasked with finding suitable contractors and placing contracts. The agency followed four guidelines in selecting contractors: (i) prioritization of ability to deliver outstanding results as fast as possible – especially organizations requiring the least new personnel, equipment, or facilities to do the work; (ii) for devices which may later go into production, avoidance of contractors in local areas already overloaded with war production contracts or labor shortages; (iii) spreading work across contractors, as feasible; and (iv) all else equal, reducing cost.[9] 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)—which could be founded in the strength of the proposal, the reputation of the researcher or institution, or both. Though NDRC's leadership (correctly) predicted 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.

[8]Also worth noting is that Bush was deliberate in choosing what research problems OSRD would *not* pursue. These choices were driven largely by Bush's view of where the agency could have the most impact. For example, materials science was not a focus of OSRD research, and was instead relegated to the Office of Production Research and Development at the War Department. Bush similarly kept OSRD out of what were primarily production problems, such as scaling up production of natural penicillin, instead focusing OSRD's efforts on synthesizing penicillin and running clinical trials for its application to specific diseases.

[9]Members of NDRC specifically recognized the long lags in going from a kernel of an idea to its deployment in the battlefield, due to the research and development, mass production, delivery, and user training required, making speed of the essence. As Stewart (1948) writes: "The time interval between the inception of an idea and the use of the finished product upon the battlefield would normally run into several years. There was ever present in the minds of the Committee the possibility that the need would arise before the equipment could be completed. There was thus a sense of urgency in the selection of contractors ... 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 the manpower which promised the best results in the shortest possible time."

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, 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). Based on the review feedback, the DMS gave each application a letter grade and submitted these reviews back to CMR. Typically, not always, CMR funded what the DMS recommended.

2.3 The contract mechanism

OSRD was willing to fund projects which it perceived to have high upside but uncertain payoffs, with the intent of putting "the best scientific imaginations in the country" on problems of military importance. There was also a desire to not impose excessive oversight that might interfere with scientists' ability to take risks and exercise judgment. Yet it was also important to ensure that researchers remained focused on the true military objectives.

One of the organizational innovations of NDRC was the development of contractual terms that could balance these needs. No strong precedent precedent existed for government R&D grants or contracts prior to World War II, but A. Hunter Dupree (1970) would later call the R&D contract "one of the great inventions of the NDRC-OSRD" 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) 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). Stewart (1948) 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 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 caused by contract negotiation and execution. Bush (1970) 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.[10] 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." Even reimbursement of expenses was made easy.

In fields where military need could be divided into unrelated, discrete challenges (as in chemistry or medicine), contracts were drawn widely, including to individual scientists and their personal labs. However, when the need was for entire new systems (like radar or rockets), OSRD often concentrated resources geographically and institutionally, including funding the creation of entire major research centers such as the Rad Lab. In still other cases (most prominently at CMR, e.g., the hunt for malaria drugs) OSRD played a coordinating role between efforts already underway in firms and universities, with limited formal contracting or funding.

2.4 Incentivizing participation

With the U.S. conscripting >10 million men into the military, nearly every scientist had friends and family members deployed. The importance of producing technology to help U.S. soldiers, sailors, and aviators survive in battle was thus much greater than an academic exercise. A sense of urgency, common purpose, and shared destiny permeated American society—especially among civilians supporting the war effort—and it made available "the best scientific talent of the country" (Stewart 1948), who were able to work long hours with intensity.[11]

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 indirect cost recovery policy and patent policy, each of which would be precedent-setting, were designed to help do so.

Overhead

Because the research was contracted out, it would use existing infrastructure at universities and firms. From its inception, contracts were written on a "no gain, no loss" basis, but the committee also recognized that in addition to regular research expenses, "there is a substantial indirect cost of a going concern which must be allocated as a part of the cost of a particular operation" (Stewart 1948). NDRC decided to allow for "overhead" expenses amounting to 50% of labor costs for

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

[11] Conant (1947) later reflected, "human beings outdo themselves when their friends and relatives are facing battle." By October 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).

university contractors, and 100% for industrial contractors. These indirect cost rates were later amended to a sliding scale for universities, declining as more contracts were placed with a given institution. OSRD likewise transitioned to a system of "direct" reimbursement of indirect costs at industrial contractors, whose cost accounting methods could explicitly specify the OSRD share of overhead. In a postwar review of overhead costs at the largest academic and industrial contractors, OSRD cost accountants determined that roughly 50% of contractors had received excess overhead payments, 10% were undercompensated, and 40% broke even.

Patents

The invention of the R&D contract introduced other novel challenges, especially in the assignment of intellectual property rights. The contract terms initially adopted by NDRC gave itself the sole power to determine whether or not to file a patent application on inventions which resulted from the contracted research, and the power to determine disposition of title and any rights to use. This reflected the idea that the public should own the fruits of publicly-funded research. However, this left contractors "completely subject to the judgment of the Government as to the disposition of rights to inventions made under NDRC contracts" (Stewart 1948). Several firms refused to sign contracts with this provision. Stewart (1948) summarized the problem:

> "[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.

After extended negotiations, NDRC crafted new language which gave the contractor first 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 application 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 patent clause became known as the "long form" clause, and it was used with the overwhelming majority of industrial contractors.[12]

NDRC (and later, OSRD) continued using a variant of its original patent clause—now called the "short form" clause—in specific categories of contracts, giving the government presumption of title where it supplied significant equipment, personnel, and even training to support the work. The short form clause became standard for major OSRD-funded laboratory research programs hosted at academic institutions, such as the research efforts in radar (MIT), rockets (CalTech), and submarine detection (Columbia). CMR contracts were also subject to the short form patent clause. Research contracts in the field of atomic energy were initially written under the long form clause but were converted to the short form clause after it became apparent that the research might result in the development of an atomic weapon. These decisions were uncontroversial at the time, since in medicine there were strong norms militating against patenting, especially patenting public research, and in the other cases, the government's interest in controlling the intellectual property rights was clear. Still, in exceptional cases, CMR nevertheless tailored its patent policy in order 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 research it directly supported: for example, CMR organized meetings of investigators to facilitate their cooperation, duplicated and circulated non-confidential progress reports among the community, and (with the help of the various NRC committees) monitored progress and identified which projects "should be prosecuted with vigor" versus "terminated or not recommended for renewal" (Stewart 1948). NDRC divisions working on related problems could also share members, but for security reasons, information sharing across divisions was restricted to that which 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

[12] There were also concerns about allowing firms to own patents resulting from publicly-funded research, especially among New Deal Democrats concerned with concentration of economic power. Bush acknowledged these concerns but argued that letting firms keep patents was important for ensuring their participation in the wartime effort, and the free government use license would be sufficient for wartime purposes. See Sampat (2020).

NACA, and representatives from the Army and Navy. The Advisory Council was foremost a venue where these agencies could interact. When their work overlapped or bore conflicting demands, or when it seemed collaboration may be valuable, it convened ad-hoc expert committees to make recommendations on how to proceed. 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's ties to these other agencies.

Close relations with the military were paramount to OSRD's research efforts. 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. These liaison officers supported the quick exchange of information, field tests, and at the late stages of development, the transition to manufacturing. As Stewart (1948) describes it, their job was "to speed the project from initiation to the final stage of large-scale Service procurement."

International coordination (primarily with Great Britain, but also other Commonwealth countries) began shortly after NDRC was created. Scientific exchange between the American and British first took place in the fall of 1940 with a British mission to the U.S. led by Sir Henry Tizard (accompanied by representatives of the British and Canadian military, and the National Research Council of Canada), 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 event in the Tizard mission was the conveyance of the cavity magnetron, which Baxter (1946) called "the most valuable cargo ever brought to our shores." This was the essential input to radar development, and the cornerstone of the U.S. radar research program. Other exchanges took place on the proximity fuze and the feasibility of an atomic weapon, both of which became important OSRD research programs. The Tizard mission, on its own, may have been the highest-impact scientific event for either country at any point in the war.

From this point forward, international collaboration was a prominent feature of the research effort. OSRD established a "field 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 scientist exchanges (U.S. scientists visiting England or vice versa) in addition to transmitting scientific reports. American radar research labs also established branches in England, near their British counterparts, putting American and foreign scientists in direct contact with each other and enabling them to coordinate their research programs.

2.6 Getting the ideas into practice

The process of 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).

Translation to practice thus involved several key steps, including initial production runs, field tests, and production at scale. 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 (e.g., for radar) to thousands (e.g., for rockets). 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 the tests were successful.

Field tests were (quite literally) conducted in the field of battle. Without the support of experts, military testers frequently imposed self-designed tests, misused the device, or simply drew the wrong conclusions, and OSRD eventually found it necessary to have some 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 or jobs 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. In some cases, where it expected there could be pushback or negative publicity (e.g., testing of gonorrhea treatments on prisoners), CMR worked with contractors to develop protocols (Rothman 1991). 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

Although OSRD had a predominant model for identifying research priorities and supporting the work, there were also differences in how individual research programs were run. We illustrate OSRD's work with four case studies: radar (and radar countermeasures), atomic fission, malaria, and penicillin. What these projects had in common was (i) an urgent military demand, (ii) questions over who would do the work, how the work would be done, and how to get the results into the field, and (iii) a foundation in existing basic science. But they also differed in several ways, such as in the division of labor and organizational structures, the pursuit of serial versus parallel research efforts, and policies around patent rights and information sharing. Our goal here is to illustrate a range of specific approaches that can be taken to crisis innovation.

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 at ultra-high frequencies to be useful in military applications.[13] Section D-1 of NDRC, colloquially the Microwave Committee, was established with the specific objective to study the application of microwaves (radio waves <10 cm in length) to detection problems, guided by Alfred Lee Loomis (an independent inventor, physicist, and wealthy financier who was running a private experimental radar laboratory from his home prior to joining NDRC), and staffed by academic and industrial scientists and engineers from various institutions with experience in the field of microwave communications.

[13] Prior to the war, radar was an emergent technology, and much of the early experimentation in radio detection was done by the U.S. Naval Research Laboratory, the U.S. Army Signal Corps, and the the private laboratory of Alfred Lee Loomis, introduced below, in Tuxedo Park, New York.

Concurrently with American efforts, British scientists were also investing in improving radar, for defense against German attack. When the Tizard mission demonstrated the cavity magnetron to U.S. researchers at Loomis' Tuxedo Park laboratory in the fall of 1940, it jump-started what would grow to be NDRC's most significant research project.[14] In October 1940, in light of the possibilities that radar presented and at the urging of the Tizard mission, NDRC's Microwave Committee voted to create a radar research laboratory at MIT. The institute was chosen over other contenders for four reasons: the presence of a handful of scientists with experience in the microwave field, its ability to attract more academic scientists to work on the radar problem, its proximity to the sea, and the possibility of using Boston's Municipal Airport for testing. Research at MIT began on November 10, 1940, several months before the NDRC contract with the university was finalized, under direction of Lee A. DuBridge, a physicist from the University of Rochester. The lab was quickly staffed up with other scientists, largely physicists and electrical engineers, academic and industrial, faculty and students and recent graduates alike.

Baxter (1946) describes the Rad Lab embarking on its research mission with a "feverish" pace. By January 1941 it was testing new radar sets from the roof of MIT buildings, using it to track planes in the Boston area. In February, the Rad Lab was asked by the Army to make experimental radar sets for installation in planes, setting a precedent for limited "crash production" in addition to its crash innovation, though most production was both then and later done by industrial contractors like General Electric, RCA, AT&T, Westinghouse, or Raytheon.

Throughout the war, radar development was centered at MIT, with parts procurement and various projects subcontracted out to other organizations, such as Bell Labs. The first two years of work at the Rad Lab focused on basic advances in microwave communication, growing from a kernel of perhaps 20 scientists to an organization of thousands, most on-site in a single, three-story building, all working long hours in service to the war effort—including numerous future Nobel laureates in physics. By 1943, substantial progress had been made on the core technology, and its work began shifting to to engineering and production. It was in 1943, according to Baxter (1946), that the Rad Lab's operations expanded to "development, assistance to manufacturers, and field service." To this end, the Rad Lab put staff members on detail at manufacturers, and manufacturers likewise sent personnel to Cambridge for collaboration on prototypes.

Coordination was a prominent feature of the research effort. 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

[14] The significance of the cavity magnetron was its ability to generate enough power to make radar feasible at wavelengths of <50 cm, an achievement that had proved elusive. It sparked further innovation that brought wavelengths down to under 10 cm, and was the critical component in every radar set thereafter.

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). 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 branches working on radar, OSRD also organized a government radar patent program to exchange inventions and coordinate patent filing.

As the war progressed, radar countermeasures (i.e., obfuscation and jamming of enemy radar), and even counter-countermeasures, were proved to be nearly as valuable as radar itself. Shortly after the attack on Pearl Harbor, NDRC was asked to begin work on countermeasures in collaboration with the Naval Research Laboratory and Signal Corps, and it added a countermeasures division to the Rad Lab, to be led by Frederick Terman of Stanford.

The countermeasures project had distinct objectives, staff, culture, and security requirements, and it was soon decided to move it to another institution—with Harvard being the natural choice due to its facilities and proximity. On March 20, 1942, OSRD initiated a new division (Division 15, "Radio Coordination") and a new contract with Harvard to fund the Radio Research Laboratory (RRL) for development of radar countermeasures. In July, Terman moved with his staff of then >100 people to Harvard. The lab quickly grew, with recruits piling in from around the country, including from firms like AT&T and CBS, and even re-training biologists and chemists into radar technicians, reaching a size of 800 staff members at its peak.

Between 1940 and 1945, radar developed into a profoundly important instrument of war, giving soldiers the ability to see from land, sea, or air what their eyes could not. Despite hardly 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 today). OSRD supported R&D in over 100 distinct radar systems for different applications (e.g., ground-, ship-, or air-based; stand-alone or integrated into firing devices; etc.). Baxter (1946) later described radar as "the most versatile instrument in modern warfare," going on to attribute the Rad Lab's success 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." Though it was decommissioned at the end of the war, the Rad Lab lived on through its post-war descendants, MIT's Research Laboratory for Electronics and Lincoln Laboratories. Fred Terman returned to Stanford as Dean of Engineering (later Provost), where he laid the foundation for the post-war ascendancy of the Silicon Valley area in electrical engineering, electronics, and microwave communications, earning a reputation as "the Father of Silicon Valley".

3.2 Atomic Fission

The most widely-remembered 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 Otto Hahn and Friedrich Strassmann, who in 1938 had produced barium after bombarding uranium with neutrons, and Lise Meitner and Otto Frisch, who discovered in a follow-up experiment in early 1939 that the result was achieved through atomic fission. What made the result remarkable was that the resulting fragments had less mass than the original uranium nucleus—and by implication, the missing matter had been transformed into energy, which Albert Einstein's famous formula $E = mc^2$ implied would be very large relative to its mass. This finding alone was revolutionary, earning Hahn and Strassmann a Nobel prize in 1944, but the fact that the fission of uranium released additional neutrons suggested it may be possible to engineer chain reactions. The finding electrified the physics community, presenting new possibilities in the production of energy.

It was well known amongst the tightly-knit physics community in 1939 that U-235 was the isotope in which fission was achieved (Baxter 1946), and uranium was thus the focus of most early research on fission. At this time, only a handful of deposits had been discovered around the world, with isotopes U-234, U-235, and U-238 comprising <0.01%, 0.7%, and 99.3% of material in naturally-occurring uranium. If only U-235 was reactive, scientists faced two possibilities: "One approach was to place unseparated uranium in a 'pile' with carbon or heavy water as a moderator or 'slower down' of neutrons to increase the chances of a chain reaction," whereas the other was "to separate the isotopes and accumulate a stock of U-235" (Baxter 1946).

In the summer of 1939, at the urging of Leo Szilard and Albert Einstein, President Roosevelt appointed a special Advisory Committee on Uranium to initiate study of the fission of uranium, 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 (Table 1). Briggs' first request to Bush was for an allotment to research the fundamental constants of nuclear fission, and contracts were let in the fall of 1940 with several universities and funds transferred to two federal agencies to support this work. Notably, NDRC's leadership itself was divided over the military relevance, and thus prudence, of this investment. As Baxter (1946) recounts:

> To at least two members of NDRC these appropriations seemed questionable. The order creating the agency defined its objective as research and development of instru-

> mentalities of war, and did not seem broad enough to include ... nuclear physics or the development of atomic energy for peacetime use. Eventually atomic power might be harnessed to propel battleships or submarines, but not for many years to come. In view of all the high-priority problems pressing for solution was it desirable to commit many of the limited group of first-rate physicists to the uranium job?

This internal dissension led Jewett (member of 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 it "called for a radical expansion of our efforts" or a continuation of a modest, exploratory research program. This committee, which included Nobel laureates Arthur Compton and Ernest O. Lawrence, met twice in the spring of 1941 and recommended a "strongly intensified effort," but acknowledged that it would likely take years for this research to yield enough progress to be of use in military applications. Based on this committee's report, Briggs requested to increase NDRC expenditures on atomic fission three-fold, writing over a dozen new contracts for the study of "the possibility of a chain reaction and of full-scale equipment for the production of power," as well as "continuation of work on the separation of uranium isotopes", which was thought to be the only material conducive to a chain reaction in a mass small enough to be a bomb (Baxter 1946).

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 who were involved in NDRC-funded research or close to the problem became increasingly convinced of the possibility of separating uranium isotopes and generating an explosive chain reaction, and Bush decided that a course of action needed to be set by the President. In a meeting with Roosevelt and Vice President Henry Wallace in October 1941, Bush explained the state of atomic fission research, 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 to accelerate its progress: gaseous diffusion and centrifugal separation of U-235 was headquartered at Columbia under the direction of Harold C. Urey, electromagnetic separation (through the use of a cyclotron) at Berkeley under the direction of Ernest Lawrence, and chain reactions in unseparated uranium and its (recently discovered) fissionable byproduct plutonium at Chicago under Arthur Compton.[15] The United States' formal entry into the war following the attack on Pearl Harbor on December 7 triggered an "all-out attack on the uranium problem" (Baxter 1946). At a December 16 meeting, the President urged Bush

[15] All Nobel laureates working with exceptional students and colleagues, including other past and future prize winners like Enrico Fermi, Glenn Seaborg, and Luis Alvarez (also of the MIT Rad Lab).

to "press as fast as possible on the fundamental physics and on the engineering planning, and particularly on the construction of pilot plants," with the understanding that when the program was ready for full-scale production, it would be transferred to the Army.

Because it was unclear which method of separation would be viable for large-scale production, OSRD decided to continue investing in all approaches until any was successful or found infeasible. As of May 1942, there were "five horses running neck and neck" (Baxter 1946): 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 the urgency of the project, Briggs, Compton, Lawrence, Urey, and Eger Murphree (a chemist from Standard Oil who was recruited to help manage the diffusion and centrifuge separation work) proposed to begin building pilot plants for all five methods of producing fissionable material at scale before the viability of any one had been proven. This proposal was then forwarded by Bush and Conant to the President, Vice President, and Secretary of War with a supplementary proposal that the Army undertake the construction of these pilot plants.[16]

While the Army began building these plants, OSRD continued its work. A major breakthrough occurred on December 2, 1942—when Chicago's Pile Number 1 produced the first controlled nuclear chain reaction, in effect becoming the world's first nuclear reactor—but the experimental pile would have had to run for 70,000 years to produce enough plutonium for a bomb. Research on five methods of producing fissionable material thus continued, though by the spring of 1943, centrifugal separation was abandoned, and heavy-water soon thereafter.

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 on May 1, 1943. Its contracts were subsumed into the recently-organized Manhattan Project, whose mission was to produce a functional atomic weapon. 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. Several OSRD staff members were then transferred to the Manhattan Project, and Bush, Conant, and Tolman served in an advisory capacity until July 16, 1945, when all three were present at Alamogordo to witness the successful detonation of the first atomic weapon.

[16] Although R&D would normally precede pilot production, "Fear that the Germans would be the first in the field with atomic bombs led to a telescoping of stages, in which pilot plant work often overlapped research in the laboratory, and the design and construction of some of the huge production plants were carried out before lessons could be learned and obstacles surmounted in the pilot plant" (Baxter 1946). The Manhattan Project, under the guidance of the military, engaged numerous industrial contractors to collaborate with the academic labs to build these plants at now-familiar sites: electromagnetic separation and gaseous diffusion plants were built at Oak Ridge, TN, and a plutonium plant at Hanford, WA. Work on the design of a bomb itself was moved to the newly established Los Alamos laboratory near Santa Fe, NM, for reasons of secrecy and safety.

3.3 Penicillin

Infectious disease was the most important medical problem facing soldiers during the war. 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, especially streptococcal infections. But they had major toxicity issues and were not useful for many other 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 (who later shared a Nobel Prize with Fleming) were first able to purify the molecule, making it possible to conduct clinical tests. However, they were unable to produce enough of it for human testing, nor, in war-torn Britain, to engage British pharmaceutical companies to help do so (Andrus 1948).

In 1941, Florey came to the U.S. for help (Baxter 1946). He was referred to the U.S. Department of Agriculture's Northern Regional Research Laboratory (NRRL) in Peoria, IL, which had experience growing mold at high yield, and also met with A.N. Richards at CMR. Though CMR's primary focus was supporting research rather than production (Stewart 1948), Richards assured Florey "that he would see that everything possible was done to expedite the production of penicillin" (Federal Trade Commission 1958). This commitment was made despite the fact that the production program for natural penicillin was viewed with skepticism in certain quarters and there was considerable uncertainty about its feasibility (Federal Trade Commission 1958). But it was buffered by CMR's decision to engage in a parallel effort to develop a synthetic penicillin, which had even greater appeal, as CMR leaders, including Richards, believed large scale production of a synthetic would be cheaper and more technically feasible than production of natural penicillin (Swann 1983, Neushul 1993). Bush's remarks on the natural penicillin program reveals his perspective on these parallel projects: "Synthesis may make all this obsolete, but it may not, and the overall problem is so important that no leads should be neglected." (Neushul 1993).

CMR took sharply different approaches to the two R&D programs, which presented distinct problems. Its research efforts focused on synthetic penicillin, where the key challenges were figuring out penicillin's molecular structure and finding a way to synthesize it. As with other OSRD research programs, CMR had to decide whether to concentrate resources (including the limited stock of penicillin available for testing) in top firms, or spread its bets (Swann 1983). Ultimately it 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 U.S. Department of Agriculture (Swann 1983). Since several leading firms were already conducting research on synthesis, CMR issued token contracts with no funding, mainly to facilitate information flow (Federal Trade Commission 1958, Stewart 1948). The principal terms of these contracts addressed patent rights and information sharing. Firms were allowed to take out patents, with Bush's approval, but were required to grant non-exclusive licenses to other contractors and the government at reasonable royalties. This licensing policy was viewed as a substitute to presumptive government ownership. Under the terms of these contracts, Bush also had the right to inspect contractors' work and records, and contractors were required to provide progress updates through monthly reports. CMR could then share this information amongst other contractors, as useful (Swann 1983).

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

This undertaking presented several challenges. One was getting firms to invest in developing (unfunded) production capabilities. Merck and Pfizer were concerned about cross-over contamination of penicillin on other activities, and (early on) wanted more proof of concept from Peoria before charging ahead—so CMR provided progress reports and other reassurances to assuage concerns (Federal Trade Commission 1958, Neushul 1993). It also served as a broker of information among these firms, and helped them get waivers to avoid antitrust scrutiny that cooperative research sometimes attracted. Finally, CMR helped the firms by working with the War Production Board (WPB) to get needed equipment to the firms, and connecting them with academics who would evaluate the samples they produced. In all cases, the firms provided their own funding, participating for patriotic, reputation, or other reasons. Since natural penicillin was a known molecule, there was no strong intellectual property to be had, save for process patents.

While the synthetic penicillin program struggled to make headway, by 1942, firms were producing 40 million units of natural penicillin per month, up from 10 million in 1941 (Baxter 1946)—enough for testing.[17] Because quantity was initially scarce, the firms had agreed that all testing should be organized by CMR. Testing was done via contract in collaboration with the NRC Committee on Chemotherapeutic and Other Agents (COC). CMR acquired supply from the producers (initially for free, but later at cost), and COC then distributed penicillin to hospitals free of charge, in return for detailed case reports (Federal Trade Commission 1958). 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

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

(Federal Trade Commission 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 for penicillin, beyond pilot plants. The needs of massive scale-up were a distinct technical challenge. On the encouragement of CMR, the Office of Production Research and Development (OPRD) of the WPB provided needed material, and shared technical expertise and some funding, while the Defense Plant Corporation helped support construction (Baxter 1946).[18] Even as WPB tried 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 contacted 175 potential producers, and eventually included 20 in the program (Neushul 1993), chosen based on experience with penicillin, fermentation, and biologic production in general, and the quality of staff. WPB spent a lot of time and energy trying to facilitate information sharing among the firms involved, which Richards later noted greatly increased productivity (Andrus 1948), while OPRD funded academic research to help solve technical bottlenecks in the scale-up process (Neushul 1993). In this effort, CMR was largely on the sidelines: its expertise was in research and testing, whereas military production was the domain of the WPB.

The natural penicillin program was successful. Monthly output grew from 425 million units in December 1943, to 117.5 billion in June 1944, to nearly 650 billion in June 1945. The cost of producing 100,000 units fell from $20 to under a dollar (Baxter 1946). By 1943, there was enough penicillin to treat U.S. and Allied troops and meet civilian demand. CMR was initially involved in rationing, but as civilian demand grew this was turned over to WPB. The government was the major buyer during the war, paying cost-plus prices (Achilladelis 1993).

The synthesis problem, by contrast, proved surprisingly 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 in getting enough penicillin for testing. But Swann (1983) also notes that lack of success during the war does not necessarily mean the program was a flop, since much of the knowledge developed during the war "paved the way" for a number of clinically important semi-synthetic penicillins introduced in the 1950s.

[18] Note that although the government supported plant construction, nearly 75 percent of the $30 million spent on this came from private firms. The government provided authorization for rapid tax amortization of these investments to help defray these expenses (Swann 1983).

In *Science, The Endless Frontier*, Bush (1945) observed that "Penicillin reached our troops in time to save countless lives because the Government coordinated and supported the program of research and development on the drug." As is well known, the drug would also have a major impact on civilian health as well providing treatment for a range of infectious diseases. Firms which participated in the natural and synthetic penicillin programs were also poised to be important players in the antibiotic revolution in the decades after the war. Achilladelis (1993) argues that "OSRD policies for the development of penicillin created a unique opportunity for the American Pharmaceutical Industry to gain experience in R&D and the manufacture of antibiotics which were the major market for pharmaceuticals in the following 25 years."

3.4 Malaria

Malaria—an infectious disease caused by mosquito-borne, protozoan parasites of the *Plasmodium* group—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, reflecting urbanization and public health interventions such as mosquito control. But much of World War II was fought in areas with high malaria risk, and morbidity from malaria was 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" (Slater 2009).

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 the 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 the 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), "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. This work examined whether the U.S. version of atabrine was sufficiently pure, experimenting with different dosage regimens, and developing new approaches to measuring its effectiveness (Andrus 1948).

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, where only one or two compounds were studied: CMR funded the synthesis and testing of *thousands* of antimalarial compounds, trying to find one better than atabrine. CMR took charge of coordinating this research, managing the broad portfolio and shepherding compounds through the pipeline, 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 helped to facilitate "prompt and adequate" clinical testing.

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), 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).

Despite a number of difficulties along the way, including the disagreements about what is proprietary and what belonged in the public domain, by 1942 "research on the disease moved faster in one year than the previous ten," according to one account (Condon-Rall 2000). In all, CMR had supported research or testing of over 14,000 compounds in animals, and 80 in humans (Baxter 1946). Out of this effort came 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 none other than 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 features and differences

Table 5 summarizes these programs, where similarities and differences can be seen. To a first order, what they shared—in addition to their contextual features like urgency, government demand, and a foundation in basic science—is that they had to address more or less the same high-level questions, even if they were answered somewhat differently across programs.

[Table 5 about here]

Each of these programs began with a goal—whether to develop radar systems with end-to-end support, produce penicillin at scale, or engineer a controlled nuclear chain reaction and package it into a bomb. Like OSRD itself, their organizational structures were adapted as they expanded in scope. They also sought out the most capable researchers and organizations to perform the research needed, though in some cases these efforts were concentrated, and in others diffuse. All four programs used the same basic contract vehicle which OSRD developed, though specific terms like patent clauses were at times modified to serve specific needs.

Another dimension in which these programs were similar is that they took a hands-on approach to coordination, as we have emphasized throughout: to varying degrees, they all were coordinated not only across investigators, firms, and research labs, but also with the military to identify specific problems for research and get technology deployed into battle, and often with foreign researchers in Allied countries. Finally, all four programs had a hand in downstream activities such as production and diffusion, though they varied in depth and their specific form.

Interestingly, though these programs were all important, they varied widely in cost. OSRD spending on radar research was an order of magnitude more than fission (though this is overstated, as the fission work was co-funded by the Army when it entered late-stage development and production), which was five times that of penicillin. Variation in cost was largely driven by the nature of the problem: the radar program was tackling complex systems engineering problems, while penicillin required clinical testing and developing process innovations for production at scale. What it illustrates, however, is that not all important crisis problems—or solutions—are necessarily financially expensive to undertake, even if scientifically challenging. The cases also illustrate that beyond funding, coordination can be a crucial part of a crisis response.

4 A Framework for Key Questions

What we have found thus far is that OSRD's research programs generally faced a common set of questions, but they at times approached them differently. In addition to this reference point, what can we take away that may be useful to other crisis problems?

In this section, we endeavor to develop a framework for crisis R&D program design, reflecting on how features of the R&D problem, characteristics of R&D performers, and features of the specific crisis context might shape program choices. We summarize this framework in Table 6, while also summarizing where the above example programs—radar, fission, penicillin, and malaria—came down on each of the elements this framework covers.

[Table 6 about here]

Our framework begins by asking, for any given (technological) crisis problem, what is the main obstacle to a resolution: is it research and development, or getting technology produced and into practice? This question is useful for quickly isolating research problems from operational problems around production and diffusion. The answer will generally depend on existing know-how: when a solution is unknown, research is needed. The hunt for malaria preventatives and treatments, for example, was mainly a drug discovery effort, whereas the penicillin program was focused on testing and production. Radar and fission required both R&D and production.

In either case, once the problem is identified, the next question is whether to focus around one approach or spread them across many—a choice between serial and parallel efforts. In our view, the choice depends on the degree of solution uncertainty: for problems where uncertainty is low, crisis efforts can focus on developing known solutions into functional prototypes and then producing them at scale. Where high, organizers of crisis innovation efforts may want to spread bets across multiple candidate solutions until one is shown to work, and even beyond, into production. This, for example, is what the fission project did, investing in five uranium separation technologies in the race to make the bomb, eventually culling these to three. Radar, on the other hand, was a more focused effort at developing remote sensing technology: the basic principles of microwave communications were understood, and the problem required refining the technology of microwave generation, transmission, reception, and signal processing and adapting it to different field conditions. Similar to fission, penicillin and malaria adopted a parallel approach.

Organizers of crisis R&D programs must similarly decide who should do the work, and whether to concentrate funding with one or a few performers versus distribute it across many. In our view, the decision is a function of R&D complexity and divisibility. Systems engineering problems, for example, are often less divisible and necessitate concentration to take into account the full range of interdependencies in system design, as well as the challenges in use and maintenance over systems' lifecycles. This was the case with radar R&D, which was concentrated at MIT: radar comprises a system whose parts must work together. That radar countermeasures could be spun out from the Rad Lab into its own project (albeit down the road, at Harvard) speaks to divisibility as well. Fission was also relatively concentrated, especially at the stage of bomb design and manufacture, which was sited at Los Alamos due to both the nature of the engineering problem and the security requirements. Penicillin was mixed, and malaria diffuse—reflecting that discovery, synthesis, and testing of pharmaceutical treatments could be spread across investigators.

When R&D is outsourced, funders must also decide how to allocate intellectual property rights, and who will have title to patents. The government, for example, faces the traditional tension between static and dynamic efficiency—incentivizing innovation versus ensuring broad access—in deciding whether IP produced from government-funded research should belong to the researcher or the public. Private funders face similar tradeoffs. Here, a number of factors may come into play: researcher incentives, security risks, R&D spillovers, and public interest, to name but a few. Allowing R&D performers to retain title to patents may be necessary to secure the participation of firms with relevant assets, like physical capital or know-how, or to encourage firms to incur private costs. On the other hand, in some cases, security concerns, spillovers, and the public benefits of ensuring access may warrant that funders maintain control of IP.

Having identified the problem, the portfolio strategy, the performers, and the appropriate incentives and patent policy, organizers must then decide whether and how to coordinate efforts. We consider two dimensions of coordination: horizontal (i.e., across concurrent R&D projects or performers) and vertical (e.g., with the end user). When there are high spillovers across projects—such as when projects are interdependent, or competing for scarce inputs, or if successes and failures can breed lessons for other researchers—coordination across efforts is likely to be desirable. When there is a single, large, and well-defined customer (like the military), coordinating with end users on research priorities, approaches, and outputs may be productive too. Most of OSRD's problems, including the ones we detailed in Section 3, met all of these conditions—hence coordination featured heavily in its approach. Absent these conditions, coordination may be less important, unnecessary, or even a tax, especially when time is short and manpower spread thin.

As we showed above, crisis innovation efforts may not end with research alone: organizers of crisis R&D must also decide what investments to make in production and distribution infrastructure, and when. In many cases it may be desirable to build manufacturing capacity at risk or even ramp up production before a given technology is proven to work, to ensure that production and diffusion can be scaled up quickly. This "telescoping of stages" (Baxter 1946) may be important when the need is large and immediately urgent, and rapid scaling is slow or costly. The fission and penicillin programs exemplify this approach, whereas the radar program followed a more sequential path from development, to testing, to manufacturing and deployment.

From problem specification to production, this framework spans a range of crisis R&D activities. Though specific questions or considerations may be more or less prominent in different contexts, it can be useful even when features of the innovation and policy environment change. For example, non-governmental funders must grapple with many of the same questions. When the U.S. government has better-developed intramural R&D capabilities than it did in 1940, it must still decide who should perform the work and how researchers will be rewarded. It is worth noting, however, that relative to philanthropies or intergovernmental bodies, national governments may have intrinsic advantages in their ability to coordinate other actors (including by fiat), access to talent or financing, and ability or willingness to support innovation through large guaranteed demand, allowing them to put more of this framework into action than other funders.

5 Reflections, Lessons, and Limits

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 U.S. 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 be dual-use and eventually permeate civilian life, outliving the war itself (Stewart 1948). When it was all over, OSRD-funded research had generated nearly 8,000 inventions, 3,000 patents, 2,500 scientific articles, and over 10,000 technical reports. Much of this work became foundational to post-war science and applied research in the myriad fields OSRD supported, and in concurrent research we find that it had long-lived effects on the direction of U.S. invention, the locations where it took place, and employment in related industries (Gross and Sampat 2020). The intense focus of 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. Its most important impact was perhaps more general, laying the foundation for government support of research broadly, including in peacetime.

In light of this track record, policymakers often use war as a metaphor to motivate major R&D

efforts. Beyond large government expenditures, what does it take to mobilize science in an emergency? What lessons can we draw from World War II for future crises? Lacking a counterfactual, it is impossible to say with certainty exactly which features of the wartime effort were essential. Compounding this difficulty, we also must rely largely on accounts of individuals involved in the effort, who may lack perspective or objectivity in their assessments.

Even so, we believe reflecting on OSRD's experience is informative. For one thing, it highlights that crisis innovation policy problems are different from those in non-crisis times. One key difference is that in crises, speed is a paramount objective. Because in a crisis the objective of R&D policy is not just to get research done, but also to get it deployed quickly, OSRD often supported parallel R&D efforts and manufacturing capacity "at risk". Moreover, while non-crisis R&D policy worries about racing and overfishing (e.g., Dasgupta and Maskin 1987), in crisis contexts multiple shots on goal can be valuable, especially for problems with high uncertainty (Nelson 1961, Scherer 2011): the value of a solution is so great that large amounts of funding to increase probability and speed of success, even if much is ultimately wasted, can be cost-effective.

The need for speed in crisis R&D also may require a heavier hand, a tighter focus, and more explicit coordination than ordinary R&D problems. In contrast to the status quo ante, and also modern U.S. research policy, OSRD chose to focus on applied research, involved users in priority setting, and had a heavy hand in coordination and implementation. Hoyt (2006) has called the wartime vaccine push "an integrated research model"—a term which would also apply to the rest of OSRD. The reason for the applied research focus and heavy government hand throughout—despite the fact that OSRD leaders generally supported scientific autonomy and limited government—was the urgency of the moment. For example, by and large there was no time for exploratory research: Conant (1947) recalled "Time set a limit to what could be done ... the basic knowledge at hand had to be turned to good account." This, then, is another lesson from the OSRD model for crisis innovation: the need for clear objectives, tight focus, and active management of the R&D process, beyond simply correcting standard market failures in basic science.

OSRD's history also points to key choices policymakers have to make. A first choice is whether to invest in research or contract for specific outputs. When choosing what to fund, research efforts can be serial or parallel. Research performers can be concentrated or diffuse. The funder can choose to retain patent rights or relinquish them to inventors. It can also actively coordinate across research efforts and with end users, or take a hand-off approach. Finally, it can invest in production at risk, or wait until a scientific solution (or feasibility) is known before scaling. In Section 4, we developed a framework for decision-making around each of these questions, informed by our understanding of how OSRD approached them and broader economic theory.

OSRD leaders and historical scholarship have also pointed to other salient features of the organization that they viewed as important to its success. First, OSRD benefited from the strong working relationship among its leadership, rooted in their prior personal history and mutual trust, and especially benefited from Bush's keen judgment. The organization itself was staffed by exceptional scientists, with a clear chain of command that made it possible for questions, answers, and directions to transmit efficiently up and down the chain. Its ability to make significant changes mid-stream, such as with the reorganizations of NDRC and CMR, was notable. It was willing to take risks, making big bets on uncertain but high-value research proposals. Having an (effectively) unrestricted budget was, in this sense, a boon. Another was the lack of "red tape": having little precedent for its work, OSRD invented most of the tools, and guardrails, that it needed as it went. One of these was the contract mechanism itself, which was simple and quick to execute.[19] More generally, OSRD sought to minimize the transaction costs of research. It is important to recall that this was an era before formal grant and contract procedures were institutionalized at universities and in the federal government—and before IRBs, technology transfer offices and other gatekeepers in the research process were common. Though this is good for speeding results, research may have been too unrestricted: Rothman (1991), for example, has emphasized that in the medical context, the need for speed sometimes resulted in ethically questionable practices, such as experimentation on prisoners, even by the more permissive standards of the day.

The OSRD effort also benefited from some favorable conditions which are not guaranteed to recur in all crises. The U.S. economy was basically functioning and able to operate at high gear, unlike in Britain or Germany. The U.S. also had a head start: it knew the war was coming for several years and OSRD pre-dated the formal U.S. entry into the war. As Bush would emphasize in *Science, The Endless Frontier*, for many of the problems facing the military there was a pre-existing stock of relevant fundamental understanding, developed through basic research before the war, allowing OSRD to focus largely on development and application. Despite considerable controversy about whether the nation's "full" talent was being employed (Kilgore 1943), the R&D establishment was small and it was relatively easy for Bush and his network to identify the most capable individuals and institutions for each research program. Without these favorable conditions, it is possible OSRD may not have succeeded. An additional lesson is thus the importance of strategically investing in science and technology in regular times, to draw on in crises. This may include investing in basic research and developing the scientific workforce, cataloguing top individuals and organizations to enlist for unplanned urgent R&D problems, and insuring supply chains.

Though our framework above is general to other problems and settings, it applies perhaps most

[19]Bush himself noted the fast pace of contracting in his memoir (Bush 1970): "Within a week NDRC could review the project. The next day the director could authorize, the business office could send out a letter of intent, [and] the actual work could start." Bush goes on to emphasize how "this swiftness in getting things started, [and] the flexible scheme of operations, was an important ingredient."

directly to situations like that which OSRD faced: urgent problems where innovation is crucial to a resolution. War, pandemics, and natural or man-made disasters and environmental catastrophes might fit this description (e.g., see Gross and Sampat (2021a) for a comparison of the World War II and COVID-19 innovation policy response). Beyond unexpected crises, it might also be a useful conceptual structure for grand challenges more broadly, including for tackling slower-moving calamities like climate change, or long-standing problems like poverty or degenerative diseases. The particular choices OSRD made, however, may be more appropriate in specific contexts, such as when the government is the final purchaser and controls implementation, and the range of needed technologies and approaches can be clearly articulated. In contexts where the users are diffuse and heterogeneous (e.g., climate change; see Mowery et al. 2010) or where significant behavioral change in the population is needed, the OSRD approach may not be sufficient.

Taking stock, the history of OSRD illustrates how crisis innovation policy is different, and suggests a framework for thinking about appropriate policy responses in different contexts. Yet the particulars of the OSRD model may only work for specific types of innovation problems, such that caution is warranted in appealing to the World War II model as a solution to all crises. These, in our view, are the main lessons from OSRD for organizing crisis innovation.

References

Achilladelis, Basil. 1993. "The dynamics of technological innovation: The sector of antibacterial medicines," *Research Policy*, Vol. 22, No. 4, pp. 279–308.

Alexander, Lamar. 2008. "A New Manhattan Project for Clean Energy Independence," *Issues in Science and Technology*, Vol. 24, No. 4, pp. 39–44.

Andrus, Edwin Cowles. 1948. *Advances in military medicine, made by American investigators.*: Little, Brown and Company.

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

Bush, Vannevar. 1945. *Science, the Endless Frontier: A report to the President*. Washington: Government Printing Office.

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

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

Condon-Rall, Mary Ellen. 2000. "Malaria in the Southwest Pacific in World War II," *Boston Studies in the Philosophy of Science*, Vol. 207, pp. 51–70.

Dasgupta, Partha and Eric Maskin. 1987. "The simple economics of research portfolios," *The Economic Journal*, Vol. 97, No. 387, pp. 581–595.

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

Federal Trade Commission. 1958. *Economic Report on Antibiotics Manufacture, June 1958*. No. 414: Government Printing Office.

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

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

Gross, Daniel P. 2021. *The Hidden Costs of Securing Innovation: The Manifold Impacts of Compulsory Invention Secrecy*. NBER Working Paper No. 25545.

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

——— . 2021a. *Crisis innovation policy from World War II to COVID-19*. Forthcoming in NBER Entrepreneurship and Innovation Policy and the Economy, Vol. 1.

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

House Armed Services Committee. 2020. *Future of Defense Task Force report 2020*.

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

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

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

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

Mowery, David C., Richard R. Nelson, and Ben R. Martin. 2010. "Technology policy and global warming: Why new policy models are needed (or why putting new wine in old bottles won't work)," *Research Policy*, Vol. 39, No. 8, pp. 1011–1023.

Navarro, Peter. 2020. *Memorandum to the Coronavirus Task Force*. Available at https://www.sciencemag.org/sites/default/files/manhattanprojectbrightexhibit21.pdf.

Nelson, Richard R. 1961. "Uncertainty, learning, and the economics of parallel research and development efforts," *The Review of Economics and Statistics*, Vol. 43, No. 4, pp. 351–364.

Neushul, Peter. 1993. "Science, government and the mass production of penicillin," *Journal of the history of medicine and allied sciences*, Vol. 48, No. 4, pp. 371–395.

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

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

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

Scherer, F. M. 2011. *Parallel R&D paths revisited*. HKS Faculty Research Working Paper RWP11-022.

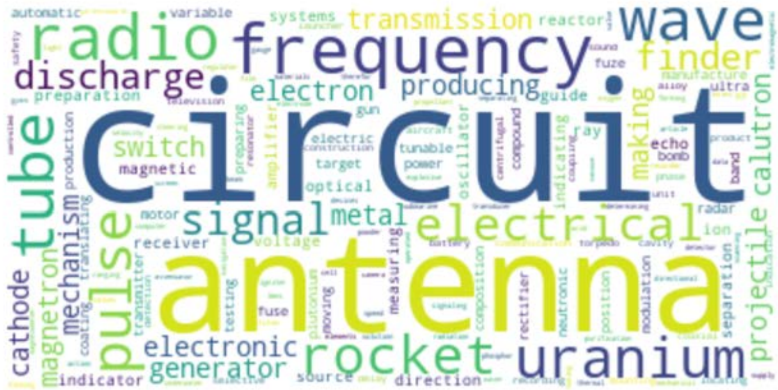
Slater, Leo Barney. 2009. *War and disease: Biomedical research on malaria in the twentieth century*. New Brunswick: Rutgers University Press.

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

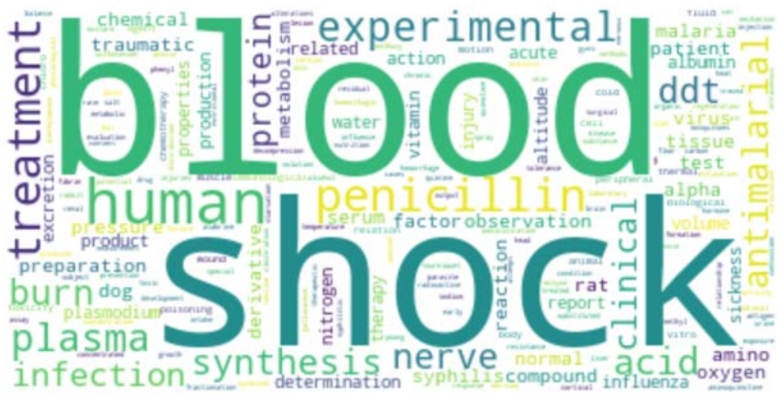
Swann, John Patrick. 1983. "The search for synthetic penicillin during World War II," *The British Journal for the History of Science*, pp. 154–190.

Figure 1: Common words in OSRD patent and publication titles

Panel (A): Words in patent titles



Panel (B): Words in publication titles



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

Table 1: NDRC Divisions (1940-1941)

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

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

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

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

Committee on Medical Research (CMR)		Contract Authorizations
Division	Name/Description	($, '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.
*Authorizations for Division 19 from April 1, 1943; APP, from September 18, 1943; COP, from January 22, 1944; TD, from May 18, 1944; SD, from November 1, 1945. Authorizations for Sections S-1 and T are from June 27, 1940 onwards, with Section S-1 terminating in September 1943.

Table 3: 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.

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 division's total research spending.

Table 5: Summary of select OSRD research programs

Question/Issue	Radar	Atomic fission	Penicillin	Malaria
What needed to be done?	1. Develop a functional radar system at microwave frequencies; 2. Create (and refine) variants of radar for a wide variety of applications from land, sea, or air; 3. Assist manufacturers in 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 preventative or treatment for malaria, by: 1. Improving understanding of mechanisms; 2. Developing testing and screening protocols; and 3. Drug synthesis, production, and evaluation.
Who did the work?	MIT Radiation Laboratory: a newly-created "central laboratory" hosted at MIT, led by Lee A. DuBridge 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.	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 for military use. *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 prepared applications. OSRD led a Government Radar Patent Program which held monthly meetings where representatives from the radar research laboratories and the Armed Services shared new inventions on which they intended 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 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 2021).	*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 didn't have any financial support, were to promote information exchange. Bush had control over any patent application decisions. OSRD had right to compel cross-licensing (subject to reasonable royalties) among the contractors, and retained a government license.	Most academic contracts were short-form. Firms retained patents and submitted information "in confidence" to NRC (though this was a source of tension between NRC and Bush-Richards throughout the war (Slater 2009)). After CMR added a malaria division late in the war, it brought new industrial contracts under short-form clauses (to protect the public interest) but this affected few contracts.
Coordination efforts	Project began with the British Tizard mission to the U.S. (1940), which brought the cavity magnetron. 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 military liaison officers and worked with military to explore possible uses of radar, train operators, support installation and maintenance in the field.	Project initiated in 1940 at the 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 (GE, RCA, Westinghouse, Western Electric). 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 the Army, OSRD leadership served as advisors to the 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 chloroqiune production bottlenecks, to generate enough drug for trials. Supported civilian and military trials of chloroquine.

Table 5: Summary of select OSRD research programs (cont'd)

Question	**Radar**	**Atomic fission**	**Penicillin**	**Malaria**
Number of OSRD 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	86.21%	100.00%	100.00%	98.13%
Top five contractors	Massachusetts Inst. of Tech. (64.9%) Harvard University (10.0%) Research Construction Co. (8.2%) General Electric Co. (3.2%) Columbia University (2.3%)	University of California (30.4%) University of Chicago (19.6%) Columbia University (13.4%) Standard Oil Dev. Co. (6.7%) Princeton University (3.7%)	Mass. Mem. Hospital (66.6%) Cornell University (6.8%) Johns Hopkins University (4.7%) University of Michigan (4.1%) University of Pennsylvania (3.67%)	University of Chicago (15.8%) Columbia University (11.0%) New York University (9.7%) Johns Hopkins University (8.7%) Allied Chemical & Dye Corp. (5.2%)

Notes: Table summarizes the features of OSRD's radar, atomic fission, penicillin, and malaria research programs. Recall that 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.

Table 6: Organizing crisis innovation: A framework for key questions

				OSRD approach			
Issue	**Options**	**Depends on...**	**Explanation**	**Radar**	**Fission**	**Penicillin**	**Malaria**
What needs to be done?	Research vs. production	Stock of existing know-how	If solution unknown ⟶ fund research; if specifiable ⟶ contract for output	Both	Both	Primarily production	Primarily research
How many approaches to fund?	Serial vs. parallel	Solution uncertainty	High solution uncertainty ⟶ Multiple bets	Serial	Parallel	Parallel	Parallel
How to organize research efforts?	Concentrated vs. diffuse	R&D complexity	Complex R&D problems less divisible ⟶ greater concentration (e.g., systems engineering)	Concen-trated	Concen-trated	Mixed	Diffuse
Who owns the IP?	R&D funder vs. performer	Contractor incentives Security risks R&D spillovers Public interest	Contractors with pre-existing relevant assets, high opportunity cost, or large share of investment ⟶ allow contractor title to patents Security concerns, benefits of knowledge sharing, or public interest ⟶ public domain	Funder	Funder	Mixed	Mixed
Coordination across efforts?	Hands-on vs. laissez-faire	Spillovers across research efforts	High spillovers ⟶ coordinate research projects	Hands-on	Hands-on	Hands-on	Hands-on
Coordination with users?	Hands-on vs. laissez-faire	Size and number of end users	Large buyers ⟶ coordinate with end user	Hands-on	Hands-on	Hands-on	Hands-on
When to begin production?	During vs. after R&D	Immediate demand, cost of scaling up production quickly	If need is immediate and rapid production scaling difficult ⟶ build production at risk	Ex-post	At risk	At risk	Ex-post

Web Appendix

A Historical Supplement

Figure A.1: Executive Order 8807 creating OSRD (June 27, 1941)

EXECUTIVE ORDER NO. 8807

ESTABLISHING THE OFFICE OF
SCIENTIFIC RESEARCH AND DEVELOPMENT
IN THE EXECUTIVE OFFICE OF THE PRESIDENT

By virtue of the authority vested in me by the Constitution and the statutes of the United States, and in order to define further the functions and duties of the Office for Emergency Management with respect to the unlimited national emergency as declared by the President on May 27, 1941, for the purpose of assuring adequate provision for research on scientific and medical problems relating to the national defense, it is hereby ordered:

1. There shall be within the Office for Emergency Management of the Executive Office of the President the Office of Scientific Research and Development, at the head of which shall be a Director appointed by the President. The Director shall discharge and perform his responsibilities and duties under the direction and supervision of the President. The Director shall receive compensation at such rate as the President shall determine and, in addition, shall be entitled to actual and necessary transportation, subsistence, and other expenses incidental to the performance of his duties.

2. Subject to such policies, regulations, and directions as the President may from time to time prescribe, and with such advice and assistance as may be necessary from the other departments and agencies of the Federal Government, the Office of Scientific Research and Development shall:

a. Advise the President with regard to the status of scientific and medical research relating to national defense and the measures necessary to assure continued and increasing progress in this field.

b. Serve as the center for mobilization of the scientific personnel and resources of the Nation in order to assure maximum utilization of such personnel and resources in developing and applying the results of scientific research to defense purposes.

c. Co-ordinate, aid, and, where desirable, supplement the experimental and other scientific and medical research activities relating to national defense carried on by the Departments of War and Navy and other departments and agencies of the Federal Government.

d. Develop broad and co-ordinated plans for the conduct of scientific research in the defense program, in collaboration with representatives of the War and Navy Departments; review existing scientific research programs formulated by the departments of War and Navy and other Agencies of the Government, and advise them with respect to the relationship of their proposed activities to the total research program.

Figure A.1: Executive Order 8807 creating OSRD (June 27, 1941)

e. Initiate and support scientific research on the mechanisms and devices of warfare with the objective of creating, developing, and improving instrumentalities, methods, and materials required for national defense.

f. Initiate and support scientific research on medical problems affecting the national defense.

g. Initiate and support such scientific and medical research as may be requested by the government of any country whose defense the President deems vital to the defense of the United States under the terms of the Act of March 11, 1941, entitled "An Act to Promote the Defense of the United States"; and serve as the central liaison office for the conduct of such scientific and medical research for such countries.

h. Perform such other duties relating to scientific and medical research and development as the President may from time to time assign or delegate to it.

3. The Director may provide for the internal organization and management of the Office of Scientific Research and Development and may appoint such advisory committees as he finds necessary to the performance of his duties and responsibilities. The Director shall obtain the President's approval for the establishment of the principal subdivisions of the agency and the appointment of the heads thereof.

4. In carrying out its functions, the Office of Scientific Research and Development shall utilize the laboratories, equipment, and services of governmental agencies and institutions to the extent that such facilities are available for such purposes. Within the limits of funds appropriated or allocated for purposes encompassed by this Order, the Director may contract with and transfer funds to existing governmental agencies and institutions, and may enter into contracts and agreements with individuals, educational and scientific institutions (including the National Academy of Sciences and the National Research Council), industrial organizations, and other agencies, for studies, experimental investigations, and reports.

5. The Director is authorized to take over and carry out the provisions of any contracts which fall within the scope of this Order heretofore entered into by (1) the National Defense Research Committee, established by order of the Council of National Defense on June 27, 1940, (2) the Health and Medical Committee, established by order of the Council of National Defense on September 19, 1940, and (3) the Federal Security Administrator in his capacity of Co-ordinator of Health, Medical Welfare, Nutrition, Recreation, and other related activities as authorized by order of the Council of National Defense on November 28, 1940. The Director is further authorized to assume any obligations or responsibilities which have heretofore been undertaken by the above agencies for and on behalf of the Government of the United States and which fall within the scope of this Order.

6. There is created within the Office of Scientific Research and Development an Advisory Council consisting of the Director as Chairman, the Chairman of the National Advisory Committee for Aeronautics, the Chairman of the National Defense Research Committee (hereinafter described), the Chairman of the Com-

Figure A.1: Executive Order 8807 creating OSRD (June 27, 1941)

mittee on Medical Research (hereinafter described), one representative of the Army to be designated by the Secretary of War, and one representative of the Navy to be designated by the Secretary of the Navy. The Council shall advise and assist the Director with respect to the co-ordination of research activities carried on by private and governmental research groups and shall facilitate the interchange of information and data between such groups and agencies.

7. There shall be within the Office of Scientific Research and Development a National Defense Research Committee consisting of a Chairman and three other members appointed by the President, and in addition the President of the National Academy of Sciences, the Commissioner of Patents, one officer of the Army to be designated by the Secretary of War, one officer of the Navy to be designated by the Secretary of the Navy, and such other members as the President may subsequently appoint. The National Defense Research Committee shall advise and assist the Director in the performance of his scientific research duties with special reference to the mobilization of the scientific personnel and resources of the Nation. To this end it shall be the responsibility of the Committee to recommend to the Director the need for and character of contracts to be entered into with universities, research institutes, and industrial laboratories for research and development on instrumentalities of warfare to supplement such research and development activities of the Departments of War and the Navy. Furthermore, the Committee shall from time to time make findings, and submit recommendations to the Director with respect to the adequacy, progress, and results of research on scientific problems related to national defense.

8. There shall be within the Office of Scientific Research and Development a Committee on Medical Research consisting of a Chairman and three members to be appointed by the President, and three other members to be designated respectively by the Secretary of War, the Secretary of the Navy, and the Administrator of the Federal Security Agency. The members so designated by the Secretaries of War and the Navy and Federal Security Administrator shall be selected from the respective staffs of the Surgeons General and the Surgeon General of the Public Health Service with particular reference to their qualifications in the field of medical research. The Committee on Medical Research shall advise and assist the Director in the performance of his medical research duties with special reference to the mobilization of medical and scientific personnel of the nation. To this end it shall be the responsibility of the Committee to recommend to the Director the need for and character of contracts to be entered into with universities, hospitals, and other agencies conducting medical research activities for research and development in the field of the medical sciences. Furthermore, the Committee shall from time to time, on request by the Director, make findings and submit recommendations with respect to the adequacy, progress, and results of research on medical problems related to national defense.

9. The members of the Advisory Council, the National Defense Research Committee, the Committee on Medical Research, and such other committees and subcommittees as the Director may appoint with the approval of the President shall serve as such without compensation, but shall be entitled to necessary and actual transportation, subsistence, and other expenses incidental to the performance of their duties.

Figure A.1: Executive Order 8807 creating OSRD (June 27, 1941)

10. Within the limits of such funds as may be appropriated to the Office of Scientific Research and Development or as may be allocated to it by the President, the Director may employ necessary personnel and make provision for necessary supplies, facilities, and services. However, the Director shall use such statistical, informational, fiscal, personnel, and other general business services and facilities as may be made available to him through the Office for Emergency Management.

FRANKLIN D. ROOSEVELT

The White House
June 28, 1941

Table A.1: NDRC Divisions and Sections (1940-1941)

Division	Name/Description	Example Sections
A	Armor and Ordnance	Structural Defense; Propulsion; Ballistics; Proximity Fuzes for Shells; Guided Projectiles
B	Bombs, Fuels, Gases, Chemical Problems	Explosives; Detection of Persistent Agents; Aerosols; Absorbents; Protective Coatings; Exhaust Disposal
C	Communications and Transportation	Communications; Transportation; Mechanical and Electrical Equipment; Submarine Studies; Sound Sources
D	Detection, Controls, Instruments	Detection; Controls; Instruments; Heat Radiation