Knowledge Economies: Research and War

Cambridge History of World War II (to appear 2015)

Vol. III, Part A

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World War II marks the transition to a new mode of warfare, one in which scientific and technical knowledge transformed the fighting of war. That summary statement captures the views of the insiders who built their nations' new systems of research and development, as well as the public that stood in awe of the war's spectacular weapons. On a closer look, however, the picture is more complicated. The atomic bomb was only the most obvious of the research-driven developments that signaled the entrance into a new scientized world of military might. How is that forward-looking observation to be reconciled with the argument that the Second World War was ultimately decided by other things than pathbreaking weapons systems: raw materials and manpower, production capacity and economic mobilization, and mass deployment of largely standardized weapons?

To make sense of this contrast, we need to look not simply at new science-based weapons that were brought to deployment, but at the R&D (research and development) systems that guided them into being. These R&D systems were complex social structures uniting human resources, high-tech industrial capacity, and organizational connectivity to bring new knowledge to bear on the conduct of war. By the outbreak of World War II, these systems had been built up at regional, national, and global scales. Their coupling into the machinery of war planning and war fighting created an interlocking set of mechanisms that became part of the mobilization of national strength. This chapter thus situates wartime science and technology in the context of prewar efforts to put new knowledge to work across the industrialized world. Exploring both incremental and transformative change in war-fighting technologies, it takes R&D systems as its overarching category. This choice forces it to move continuously across domains that are typically distinguished as basic science, applied science, and engineering – categories we have inherited from post-WWII analysts, who used them to frame the lessons they wanted to take from the war.

Most historical studies have focused on the outputs of national R&D systems and asked what made them succeed or fail. Instead, this chapter highlights the global character of these developments and their disrespect for the temporal end of the war. It explores national innovation systems as individual experiments within a larger landscape of war-relevant R&D. Finally, it insists on the contingency of the war's ending moment. The biggest story of science, technology, and World War II is not which new weapons systems were ready by mid-1945. It is how wartime knowledge economies crystallized expectations and relationships that set the terms for an unfolding dynamic of high-technology war.

Building the system

The mobilization of scientists in World War II is sometimes thought of as an unusual break, something only a cataclysm on the scale of the war could explain. It is true that the Second World War was fantastically effective in putting researchers to work for military needs. But the R&D systems that were built up by the early twentieth century produced large numbers of scientists, technologists, and engineers for whom collaboration with state, military, and industry was familiar, desirable, even taken for granted. In nearly all of the great powers, what happened in the war was less a break than an intensification, and in every nation it built on connections that had been made in the past.

An appropriate starting point is the late nineteenth century, when the second industrial revolution unfolded across industrialized Europe and reached into North America, late tsarist Russia, and Meiji-period Japan. Over the space of a few decades, new industries were created around electrotechnology, organic and physical chemistry, advances in metallurgy, pharmaceuticals, precision optics, and other science-related areas. Possible payoffs in industrial competitiveness and patenting made it attractive to engage in research toward inventions, improvements, and tuning of processes. As large corporations were consolidated, their resources let them hire technical specialists and invest in laboratories with longer time horizons for financial returns. The great chemical and electrical firms were the standard-bearers of industrial science for decades, as companies such as Bayer, Hoechst, BASF (Badische Anilin- und Soda-Fabrik), Du Pont, Siemens, American Telephone & Telegraph, and General Electric built up large in-house research teams. While it was big business and its laboratories that had the leverage to begin shaping R&D systems at scale, similar moves were visible in smaller units inside medium-sized enterprises, research efforts within firms in closer connection to manufacturing, or sector-wide collaborative settings. Infrastructure for testing materials and improving processes and products found homes inside a wide range of heavy industry, including steel and soon the armaments and parts of the automotive sectors.[1]

The personnel for research had to pass through institutions of specialist training. Around this time, engineering training was being scientized as well. In an era in which mass higher education was still decades off, the needs of students heading into technical employment were a pressure point for increasing the prestige and resources of the technical universities and colleges. Up to World War I and a decade or more past it, students from peripheral countries (e.g., Japan,

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[1] François Caron, Paul Erker, and Wolfram Fischer, *Innovations in the European Economy between the Wars* (Berlin: de Gruyter, 1995); David E.H. Edgerton, ed., *Industrial Research and Innovation in Business* (Cheltenham: Elgar, 1996); Ulrich Marsch, *Zwischen Wissenschaft und Wirtschaft: Industrieforschung in Deutschland und Grossbritannien 1880-1936* (Paderborn: Schöningh, 2000); Michael Stephen Smith, *The Emergence of Modern Business Enterprise in France, 1800-1930* (Cambridge, MA: Harvard University Press, 2006); Naomi R. Lamoreaux, Kenneth L. Sokoloff, and Dhanoos Sutthiphisal, “The reorganization of inventive activity in the United States during the early twentieth century,” in Dora L. Costa and Naomi R. Lamoreaux, ed., *Understanding Long-Run Economic Growth* (Chicago: University of Chicago Press, 2011), 235-74.

Russia, the United States) or imperial dominions traveled to the center for doctoral education, mainly Great Britain, Germany, and France. It was on top of this differentiated educational structure that venues for basic science were built out, above all in the universities. Characteristically, the Nobel Prizes, which were first awarded in 1901, were funded from the estate of the Swedish armaments manufacturer and inventor of dynamite Alfred Nobel.[2]

The progress of research increasingly mattered to governments. As states took on testing and regulatory roles for new technologies, they established modern bureaus of standards, such as the German Imperial Physical Technical Institute (founded 1887) and the British National Physical Laboratory (founded 1902). Other offices that might incorporate teams of technical experts included agencies serving agriculture, public health, and municipal infrastructure. The technicalization of the civil service was highly contested, and it was a local and regional as much as a national story. In the military forces, scientifically trained officers remained largely outsiders. However, there were spaces within where civil and naval engineering expertise were recognized. Technical competence in ballistics, fire control, and munitions had homes inside the services, while industrial fabrication of firearms, artillery pieces, ammunition, and explosives created networks of contracting and information exchange.[3]

Even when these systems had internal frictions, connectivity across them was engineered in. Informal recruiting networks and consulting relationships linked firms to professors and educational institutions. Formally, academies of sciences, whose members were the most distinguished scientific researchers, provided regional or national forums. With the exception of the Royal Society in Great Britain, academies often stood under government sponsorship. Disciplinary professional groups could do similar work on a more focused basis. Advisory boards for government organs – for instance, committees consulting on explosives for the French and British ordnance offices – brought academics into military affairs. (Across continental Europe, professors were employees of the state.) Representatives of large industrial firms moved in these circles, too, particularly in domains viewed as important to state power. The linkages were closest among members of social elites.

With local variations, this model settled in widely. In Germany, most tellingly, it took concrete form in the Kaiser Wilhelm Society for the Promotion of the Sciences. When the KWG was founded in 1911, it was meant to advance cutting-edge fundamental research. While it shared common elements with other extra-university institutes, such as the Institut Pasteur in Paris (founded 1887) and the Carnegie Institution in Washington (founded 1902), the KWG stood apart for its ambition and became the paradigm for organizations such as the Japanese

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[2] For examples of national stories, see Roger L. Geiger, *To Advance Knowledge: The Growth of American Research Universities, 1900-1940* (New York: Oxford University Press, 1986); Dominique Pestre, *Physique et physiciens en France, 1918-1940* (Paris: Editions des archives contemporaines, 1984).

[3] An effective overview is most readily available for Germany: Alan Beyerchen, "On the stimulation of excellence in Wilhelmian science," in *Another Germany: A Reconsideration of the Imperial Era*, ed. Jack R. Dukes and Joachim Remak (Boulder: Westview, 1988), 139-68; Margit Szöllösi-Janze, "Science and social space: Transformations in the institutions of *Wissenschaft* from the Wilhelmine Empire to the Weimar Republic," *Minerva* 43 (2005): 339-60.

Riken (Rikagaku Kenkyūjo, Institute of Physical and Chemical Research, founded 1917). In the KWG the elite of German banking and the chairmen of the board of Krupp, Bayer, and others joined forces with the highest levels of science and Prussian ministry officials. In the next few years the first Kaiser Wilhelm Institutes opened their doors, including institutes for chemistry, physical chemistry and electrochemistry, biology, labor physiology, and coal research. As well-endowed as it was connected, the KWG was a private organization drawing on public funds along with significant individual and corporate donations.[4]

Pointing toward war

World War I drew these threads together more tightly – or, better, suggested how tightly they might be drawn. Fought with massive material infrastructures, the war drew on products of industrial transformations that were partially integrated into the European arms race: refined munitions, capacities for gunlaying on land and at sea, communications by telephone and wireless telegraphy (radio), the sheer availability of electrical components and motorized equipment. German U-boats opened the door to underwater warfare. The British, French, and Americans countered not just with mines, depth charges, and torpedoes but brand-new sound detection techniques, precursors of sonar that supported the convoy system in keeping the shipping lanes open. The war saw the rapid development of gas warfare in multiple forms (irritants like tear gas, chlorine and phosgene for asphyxiation, mustard gas for its blistering effect). Fritz Haber, director of the Kaiser Wilhelm Institute for Physical Chemistry, put his institute at the German army's disposal for work on poison gases, and by the end of a war that the United States had been late to join, the Chemical Warfare Service had networked American industrial, academic, and government chemists to an extent never before seen. Chemical weapons generated widespread revulsion, leading to the Geneva Protocol forbidding their use in 1925, although some commentators asked why death by chemical attack was worse than death by less scientific means. Chemistry also figured into the wartime materials economy. The Haber-Bosch process, discovered during Haber's university career and scaled up by BASF in 1913-16, allowed the fixation of atmospheric nitrogen to produce ammonia that supplied both German munitions factories and crucial agricultural fertilizer. After the war Haber briefly feared indictment for war crimes; within a year he won the Nobel Prize for his ammonia research.[5]

Besides specific technologies, World War I brought about other changes. To make the feedback loops tighter and faster, there was urgent experimentation in organizational forms. Well-placed civilian scientists caucused to form organizations to give high-level advice to

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[4] Rudolf Vierhaus and Bernhard vom Brocke, *Forschung im Spannungsfeld von Politik und Gesellschaft* (Stuttgart: Deutsche Verlags-Anstalt, 1990).

[5] Guy Hartcup, *The War of Invention: Scientific Developments, 1914-18* (London: Brassey's, 1988); Margit Szöllösi-Janze, *Fritz Haber, 1868-1934: Eine Biographie* (Munich: Beck, 1998); Daniel J. Kevles, *The Physicists: A History of a Scientific Community in Modern America* (New York, Knopf, 1977), ch. 8-9.

governments. Among the critical wartime outcomes were a new National Research Council in the United States (a semi-free-standing body) and the Department of Scientific and Industrial Research in Britain. Even with the successes, however, what outside experts often took away was frustration. Critics created a public drumbeat of complaints about the the failures of governments and the military to attend to scientific expertise. Big institutional arguments tended to make little headway. However, seemingly smaller choices started other kinds of change. One important pathway was through higher education. Small numbers of military officers in technicized branches found ways to go back to school for more training. These pathways would get somewhat more routinized over the interwar decades. By the 1930s the United States and Germany had programs supporting officers in intensive advanced studies; the German system of secret dissertations stands out.

A further outcome of the Great War was surging attention to aviation. At the start of the war, sustained powered flight had been possible for scarcely a decade. Aircraft were rushed into war production with rapid technological modifications, serving for strategic bombing, reconnaissance, and other uses. In the aftermath, the R&D machinery kicked into high gear. Building on existing foundations where they were any, starting from scratch where there were not, research centers grew up in all the major industrial powers – even Germany, where military aviation was proscribed by the Treaty of Versailles. These aerodynamics facilities became next-generation interfaces among private institutions, education, industry, and the state. The questions they addressed ranged from fundamentals of fluid mechanics to airfoil design to materials to propulsion. Like heavy machinery, aircraft were technologically ambivalent between civil and military uses; like some parts of the chemicals sector, their progress relied on continuous developments in new technical knowledge.[6]

The R&D systems that crystallized between the wars were nationally anchored, of course. The European powers all invested in securing their technical capacity; with an increasingly sharp sense of competition, Germany and Great Britain led the way.[7] While military procurement dropped off sharply at the end of World War I, other nationally oriented projects took up some of the slack. By the end of the 1920s, the Soviet Union would launch a massive program of accelerated industrialization, as part of which it built up scientific and engineering capacity across a large number of fields. In Japan a political strain of modernization for national strength lent at least rhetorical support to advocates for science. In the United States, interestingly, the linkages were strongest between universities, private research institutions, and industry, while federal support for research was limited to scientific bureaus and the National Advisory Committee for Aeronautics. Simultaneously, large corporations with strong technical departments often worked across multiple countries. Even as nationally based industrial groupings came together – the 1920s saw the consolidation of research strongholds such as IG

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[6] Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915-1958* (Washington, DC: NASA, 1985); Helmuth Trischler, *Luft- und Raumfahrtforschung in Deutschland 1900-1970: Politische Geschichte einer Wissenschaft* (New York: Campus, 1992).

[7] Strong arguments for the interpenetration of science and military interests between the wars can be found in David Edgerton, *Warfare State: Britain, 1920-1970* (Cambridge: Cambridge University Press, 2006), and Helmut Maier, *Forschung als Waffe: Rüstungsforschung in der Kaiser-Wilhelm-Gesellschaft und das Kaiser-Wilhelm-Institut für Metallforschung 1900-1945/48* (Göttingen: Wallstein, 2007).

Farben and the Vereinigte Stahlwerke in Germany and Imperial Chemical Industries in Britain – the circulating expertise of industrial personnel in multinational corporations was the counterpart to the international community of professors and students. By the 1920s and 1930s a new wave of scientization hit existing knowledge-based sectors, including vacuum-tube electronics, organic chemistry, synthetic materials, and metallurgy. With the Depression only temporarily holding back corporate investment, laboratory-based research also made inroads into new industries such as rubber, photographic chemicals, and petroleum refining. Other kinds of information-sharing took place across borders as Japanese experts made extended tours conferring with experts in Germany and the United States, while technical cooperation had helped both the Red Army and the German military back when both were trying to rebuild.

Into the conflict

After the Nazis came to power in 1933, Germany exited the clandestine phase of rearmament. Its across-the-board if sometimes wildly seesawing mobilization of the industrial economy was carried out through sharp coordination of private resources with government directives. Britain's preparations in the later 1930s concentrated first of all on its navy and expanded domestic industrial capacity; France invested heavily in tank production and manpower and looked to purchase American planes. Japan's industrial and financial conglomerates benefited from military orders, and the Soviet Union prepared for a war of men and materiel with mass increases in equipment for both air and ground forces. In the United States, national economic strengthening was formally decoupled from war preparations, but its capacity as a resource for other nations was clear. Once the U.S. entered the conflict, its reserve force of academic and industrial researchers was mobilized as massively as its manufacturing power.

It is hard to identify any part of war-related industry that was not shaped by demands for technical advances. Those demands might not be met – the hopes of military innovators could exceed even nature's capacity to deliver – but the Second World War can be seen as a vast terrain of technical improvements all the way from the laboratory to the manufacturing floor. Monumental efforts for mobilization included the chemical engineering and metallurgical innovation that underwrote ambitions of materials autarky in Germany's Four-Year Plan (1936-1940). Synthetic fuel was key to the Third Reich's war planning, since its access to oil was dependent on trade or military conquest. The challenges associated with synthetic fuel were mainly around scaling up coal liquefaction processes. (Germany's number one plentiful resource was coal.) The synthetic rubber called buna derived from the work of macromolecular chemists in Germany in the late 1920s. By the time the war was launched, their processes became the foundation of large-scale production. Both these efforts were driven forward by a partnership between the regime and the chemical giant IG Farben, embodied in the multiplicity of organizational roles held by the IG industrial chemical leader Carl Krauch. On the side of metallurgy, the limited domestic supply of key constituents in aluminum and steel alloys led to intensive research in the laboratories of the metal-based industries and the Kaiser Wilhelm Institute for Metals Research.[8]

This upscaling was not simple in war economies that were stretched to the limits. One key shortage was trained personnel. With the expansion of technical higher education, huge numbers of scientists and engineers were of draft age. Nearly every country's technical organizers struggled with securing exemptions from call-up orders. By war's end, American war laboratories were bringing aboard students before they completed their graduate or undergraduate degrees. The human resources pressure was intensified when ideological reliability was made part of the equation. Stalin's purges had picked off key figures in the USSR's technical leadership, and an unsettling feature of the Soviet R&D landscape was the system of *sharashkas*, or prison laboratories run by the Department of Special Design Bureaus of Beria's NKVD. For its part, Nazi Germany had driven away huge numbers of trained scientists with its attacks on the Jews. While it is impossible to scope out the effects of the brain drain, the roster of Allied war research was filled with émigrés in hugely responsible positions – leading the Theoretical Division at Los Alamos, for instance (Hans Bethe). Among the Western Allies there was less political scrutiny, more trust in a shared sense of purpose. Even in a classified world, hatred of Germany went a long way.

War research stretched across profound organizational divides. Going into World War II, R&D systems were only spottily mediated through formal coordinating structures. Connections across government, industry, academia, and private research institutions were as often as not made in committees, creating linkages that were often subject-specific and did not necessarily scale. In Great Britain, for instance, where military-oriented research was significantly advanced in the 1930s, mobilization was mainly the work of individuals and departments committing to work on relevant projects, rather than a mass hue and cry about technical war. Coordination was done through personal consultations. Those relatively loose centralizing mechanisms did not prevent key areas from making huge progress by the war's outbreak. By the time the British reached out across the Atlantic in the summer of 1940, when the Tizard Mission brought over key technologies, data, and the invitation to collaborate, British military-relevant R&D was significantly advanced relative to its key ally, the United States.

In some combatant nations, wartime centers of power grew up in different organizational sectors, such as the army, the industrial commissariats, and the Academy of Sciences in the Soviet Union. The Soviet arrangement was probably partly a conscious strategy to ensure political control, partly a tribute to the spurring power of competitive development. In Germany, beyond the technocratic appeal of reducing duplication and friction, the rhetoric of coordination in single national will was politically potent. When Carl Krauch made his move to dissolve the Kaiser Wilhelm Society in 1941, he proposed reconstituting it in a larger organization named for Reich Marshal Herman Göring, who was (among other things) a key patron of aviation research. In the end, the German system sat in an unstable equilibrium among these players, Todt's and

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[8] Peter Hayes, *Industry and Ideology: IG Farben in the Nazi Era* (Cambridge: Cambridge University Press, 1987); Adam Tooze, *The Wages of Destruction: The Making and Breaking of the Nazi Economy* (New York: Penguin, 2006); Jonas Scherner, *Die Logik der Industriepolitik im Dritten Reich* (Stuttgart: Steiner, 2008); Maier, *Forschung als Waffe*.

then Speer's Armaments Ministry, the Reich Education Ministry's organizations, the different military research offices, and even the research ambitions of the SS. Whether these conflicts damaged the progress of German wartime research is an open question. Under certain political constellations, projects could be mobilized very effectively in smaller circles, as examples will show. In such cases, success had as much to do with the preexisting base of research capacity, personnel, and access to resources, often through personal connections, as with formal authority structures. This meant that calling for coordination at the highest level could be as much a political play as a practical move. When it was used, it was a strategy of mobilizing frustration to stake claims for control. Across all the combatant nations, complaints about military/non-military coordination were in fact endemic to wartime research. Interservice rivalry was a common theme, too. The case can be made that Japanese researchers, for instance, contributed relatively little to their country's war efforts because Japan lacked a centralizing R&D authority. However, it is also true that there was less to centralize.

One instance does stand out of relatively successful central coordination – despite critiques of friction and compartmentalization all the same. That is the United States. The curious and perhaps decisive feature of American R&D coordination was that it originated in an initiative of academic and industrial, not government researchers. Looking ahead in 1940 to an American entry into the war that they saw as inevitable, a handful of powerful figures in American science came together behind Vannevar Bush, a former engineering dean at MIT, head of the Carnegie Institution and chairman of the National Advisory Committee for Aeronautics. Bush's National Defense Research Committee was set up in summer 1940 when President Roosevelt approved a one-page proposal. Almost immediately, the NRDC was connected via the Tizard Mission to R&D leaders in Britain. Starting from the NRDC's small staff and Bush's excellent skills in working with the military, there emerged an immensely wide-ranging organization, the Office of Scientific Research and Development. The OSRD was formed in mid-1941, some months before the U.S. entered the war. It reported to the President directly and grew into a research agency of a sort the world had never seen, contracting its work out across the American academic and industrial landscape and reaching into nearly every domain of military-relevant R&D.[9]

Incremental R&D

War-related research made a difference in two distinct ways. It could take an existing technology to a new level, or it could create a new one *tout court*. Of those two paths, incremental improvement was typically simpler, faster, and – technically and politically – safer. It took a system that was known to perform and tried making it better. Even when it had to generate new knowledge to do that, it was clear what the baseline was. It was also potentially easier to implement: rather than changing a entire weapons system and rebuilding a whole production line, it might be enough to improve a component. But incremental improvement did

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[9] G. Pascal Zachary, *Endless Frontier: Vannevar Bush, Engineer of the American Century* (New York: Free Press, 1997); Kevles, *The Physicists*.

not have to mean marginal payoff. Some technical developments rebalanced the balance in particular match-ups of forces. Others were broadly enough deployed that a decent increase in effectiveness had large cumulative consequences. We can see different aspects of incremental R&D with examples from weapons and weapons systems, innovation in chemical and biomedical research, and the large arena of air defense.

Weapons and weapons systems

Artillery and munitions were central to the fighting, and quality and killing power left plenty of room for innovation. One of the most widely deployed incremental technologies of World War II was rocket artillery. Rockets rapidly oxidize (burn) chemical propellants to generate gas that is directed backwards through a nozzle, using the thrust created by the exhaust to propel their payloads at high speed. Reactive propulsion had been one of the desiderata of military innovators worldwide since the 1920s, with many technical variants and possible uses. One line of development that showed early promise was the small solid-fuel rocket. Compared to liquid propellants, these could be technologically less finicky, though also in some ways less excitingly cutting-edge. At least as important, they could be built in ways that were conceptually similar to established forms of artillery with their range of options for shells. Rockets' overwhelming benefit was that they were recoilless, which meant that they just needed to be carried and aimed, not fired from a big, heavy gun capable of holding up to significant force.

The Katyusha rocket launcher is illustrative of the war's rocket artillery weapons. It was developed as part of the Soviet rearmament drive in the Reactive Scientific Research Institute within the People's Commissariat for Heavy Industry. Serious development started in the later 1930s and was wrapped up with power struggles over different directions in rocket technology, which mapped unhappily onto deadly denunciations in Stalin's purges. Rocket artillery was not a Soviet invention alone; the German army produced its own Nebelwerfer series, while the Allies all used rockets for assaults in multiple theaters and fit them for firing from planes. But the Katyusha's distinctive success had much to do with its suitability to Soviet needs. When the launcher was field-tested, it was not more accurate or capable of sustaining a higher rate of fire than conventional options; in fact, the opposite was true. The strength was the package. As deployed starting in 1941, the BM-13 multiple rocket launcher had 16 rockets of 13.2 cm diameter. Without the need to brace against recoil, it could be mounted in a rack on a truck. The Katyusha became a favored Soviet weapon because it was light, mobile, and impressively destructive in barrages, well-tuned to the character of war on the Eastern Front. It was also good for mass production, since it was cheap and called for none of the careful machining that conventional artillery required.[10]

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[10] Asif A. Siddiqi, *The Red Rockets' Glare: Spaceflight and the Soviet Imagination, 1857-1957* (Cambridge: Cambridge University Press, 2010), ch. 4-5.

Other solid rocket technologies filled different niches. The U.S. bazooka and the German Panzerfaust were short-range, shoulder-fired weapons that came into use in 1942. By this time, the conceptual innovation was not the rocket propulsion technology, but rather the warhead, which used a distinctive design known as the shaped charge. Shaped-charge weapons took advantage of the fact that a quantity of explosive layered around an appropriately dimensioned lined cavity would focus the blast energy into an extremely narrow, extremely fast jet. If the explosive were detonated the right way, the jet could perforate a significant thickness of armor. The key delivery requirement was that the shaped-charge warhead be accurately projected nose-first. It could not be thrown like a grenade because of the directionality, or fired from a rifle because of the recoil. A kilo of high explosive deployed with a reusable tube for a rocket launcher could be a close-combat weapon against that mechanized monster, the tank.[11]

The shaped-charge phenomenon had been explored in the 1930s, with an eye to more general explosive use as well as specific-purpose weapons. The key players were German Army Ordnance and the Technical Academy of Luftwaffe and a Swiss private inventor who licensed his discoveries to Great Britain and the U.S. If the jet phenomenon was to be exploited most effectively, however, it needed to be better understood. High-speed photography, critical to tracking the progress of jets, was significantly advanced during the war by ballistics experts in Germany and in the OSRD's Explosives Research Laboratory. A fluid-dynamical explanation of how the shaped charge worked was worked out in 1943 by two superb mathematicians, G.I. Taylor and Garrett Birkhoff. And plenty of empirical testing was needed to get a grasp of penetration phenomena, which had implications for detonation and timing.[12] The cycle of research and development never in fact ended. Early versions of the bazooka and the Panzerfaust were presented to the public as spectacular successes. But they were not without flaws, leaving the anti-tank infantry role still very dangerous. And the classic countermeasures dynamic meant that each new increment in armor-penetrating weapons was matched by improvements in tank armor. The German Panzerschreck, playing off captured bazookas, was the fullest wartime development of the rocket-launched shaped charge, while the American super-bazooka was not deployed before the end of the war.

Sectoral innovation

Other domain-area improvements mobilized human resources across a wide research front within a sector of technical knowledge. Chemists and chemical engineers were understood to be great R&D assets and well-integrated into war planning. In fact, despite the fascination with flashier branches of science, the chemists' pre-World War II successes arguably made them the

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[11] John E. Burchard, ed., *Rockets, Guns and Targets* (Boston: Little, Brown, 1948), 50-54.

[12] Peter O.K. Krehl, *History of Shock Waves, Explosions and Impact* (Heidelberg: Springer, 2009); Donald R. Kennedy, *History of the Shaped Charge Effect* (Mountain View, CA: D.R. Kennedy & Associates, 1983).

leading incremental innovators of the war.[13] Rocket propulsion (described above) called on them centrally. Along with substitute materials and new alloys, chemists put a diversified effort into next-generation explosives. Gas warfare research took up both offensive and defensive needs. Nerve agents such as tabun (1937) and sarin (1939, both discovered by an IG Farben chemist) and soman (1944, in a Kaiser Wilhelm Institute) were secret developments that Germany brought to factory-scale production. Research on protection and countermeasures against chemical agents was common to every combatant nation. Yet although every country stockpiled chemical weapons, and Japanese forces made some use of them, widespread deployment was apparently forestalled by fears of retaliation. The exception, if it can be thought of this way, was Zyklon B, which was an ordinary industrial chemical originally developed as a pesticide and repurposed for killing a million human beings in the death camps of the Third Reich.

If undetectably small deployments leading to indiscriminate mass killing seemed a particularly threatening aspect of chemical warfare, the chemistry of flamethrowers and incendiary bombs struck observers as less fearsome somehow. Flamethrowers were a modest innovation technically, but coming out of World War I (and interwar rebellions), they needed work on jelling, nozzles, and ignition. If flamethrower R&D served the purpose of killing human beings standing nearby, incendiary bombs were for delivering death from a distance. Tried out in the First World War, relatively simple incendiaries were available at the start of the Second. When used by the German Air Force in 1939-40, they were quickly seen to be an important component of the strategic bombing arsenal, as the fires they started were considerably more destructive per ton of payload than high explosives. The NRDC/OSRD and Chemical Warfare Service were thus spurred to develop mass-production alternatives of many varieties, which were used to devastating effect in the Allies' strategic bombing campaigns.

Equally, military medicine adapted to new possibilities. Modern methods of blood transfusion proved field-worthy in the Spanish Civil War and were rapidly scaled up in World War II. More complex problems on the side of research had to be solved for penicillin production. By the end of the war, however, penicillin, the first antibiotic, was joining the sulfonamides, the miracle drugs of the 1930s, in Allied physicians' arsenal for treating infections. New treatments were de facto explored for burns, epidemics, frostbite, tropical diseases, and other medical consequences of how the war was fought. Not all of this experimentation was in the interest of the patient. Researchers in Germany and Japan exploited prisoners of war and concentration camp inmates in horrific human experiments. Whether or not the results had scientific value, they were carried out in part by trained researchers in established research institutions, including both military-controlled and formally civilian institutions such as the Kaiser Wilhelm Society.[14]

It is hard to imagine, finally, that decades of experience with public health and disease would not have become part of wartime R&D. The military possibilities of bacteriological agents

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[13] W.A. Noyes, Jr., ed., *Chemistry* (Boston: Little, Brown, 1948).

[14] Carola Sachse, *Die Verbindung nach Auschwitz: Biowissenschaften und Menschenversuche an Kaiser-Wilhelm-Instituten* (Göttingen: Wallstein, 2003); Gerhard Baader et al., "Pathways to human experimentation, 1933-1945: Germany, Japan, and the United States," in *Politics and Science in Wartime*, ed. Carola Sachse and Mark Walker (Chicago: University of Chicago Press, 2005), 205-231.

had been watched intently by the eventual combatants during the interwar years. Biological warfare, too, was prohibited by the Geneva Protocol of 1925. However, even if it was unclear that pathogens could be used in a practical weapon, defensive needs were a starting point for research. Alongside British wartime work at Porton Down and its American counterpart at Fort Detrick, the largest biological weapons R&D program was based in Japan, sponsored by the Army Medical College and the Kwantung Army. The experiments conducted by Unit 731 began early, in the 1930s, after Japan occupied territory in Manchuria. This work focused on known pathogens such as typhus, cholera, and bubonic plague, which were used in limited deployments in the China theater but only ineffectively weaponized.[15]

Air defense

Air defense may be the most pointed example of military possibilities opened up by incremental R&D. World War II was the conflict in which air forces grew into maturity. The technical glory of aerial warfare went to offensive innovators; aircraft technologies were spectacular, and their designers were celebrated. But the dynamic of defense was arguably more important. And despite broad fascination with counter-air warfare and brave ground-based defenders, here the story was not so much about guns or ammunition. It was about how to get gunners to hit fast-moving targets before they did damage.

The elements of air defense were incubated during the worried interwar years, with Britain leading the way. It took the outbreak of the air war to drive the components forward and build them into a system that transformed the fighting of the war. The most familiar part of the challenge was directing fire accurately – not to the spot where targets were sighted, but where they were going to go. This was a task of calculation and actuation, coupling human operators to assemblages of electrical and mechanical components. The naval fire control needs of World War I, hitting moving ships from a platform that was itself rolling and pitching, were reframed for the airplane in the interwar years. Even when anti-aircraft guns sat stable on land, they had to predict the future position of an object moving in three dimensions, then move heavy equipment into position to fire – and fast. Naval anti-aircraft weapons had to meet even higher demands. The mechanical calculators (or computers) that did this work had their analogues in navigation systems and bombsights. Viewed abstractly, the problems they tackled were kin to problems in electrical transmission networks and other engineering domains. Improving fire-control systems was a high priority in Britain and the United States in particular, in the latter in part because of the early attention of the NDRC through the person of Vannevar Bush. Over the course of the

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[15] Brian Balmer, *Britain and Biological Warfare: Expert Advice and Science Policy, 1930-65* (Houndmills: Palgrave, 2001); Grunden, *Secret Weapons*.

conflict, advances in fire control redefined the human-machine relationship in ways that continued to transform the experience of war.[16]

Of course, fire control depended on identifying targets. And as targets moved faster and faster, gunners had less time to confirm and react. With air war, early, accurate detection moved high up on the priority list. One huge opening was radio. Through the first decades of the century, there had been considerable progress in working with radio waves, those man-made electromagnetic signals generated using antennas and vacuum tubes that could carry information through empty space. Developed for wireless communications, radio technology was also recognized for an interesting secondary use: an object passing through a radio beam bounced some small part of the waves back. This understanding of the uses of radio echoes was the basis of military-industrial R&D projects in the 1930s in multiple countries, including Great Britain, Germany, the Soviet Union, Japan, France, Italy, the Netherlands, and the United States. The technical challenges around radar – radio detection and ranging, to use the eventually dominant nomenclature – were not small. German early warning devices were ready by 1939 to serve both gun-laying and ground-based guidance of interceptors. The Chain Home system watching Britain's south and east coasts was simple in design and limited technically. However, its integrated operations network was critical for the Royal Air Force in 1940 in the Battle of Britain. For later entrants into the conflict, the situation was different because of the state of the war. Japanese radar development for the Navy and the Army benefited from contacts with Germany. The United States took major impulses from the British; that partnership will be touched on again below. The character of the Soviet war effort made indigenous development of radar less important than acquiring equipment through Lend-Lease. (The USSR had made substantial investments in radar in the 1930s, but the purges drove the effort into the ground.)

This first level of radar technology was tackled by electrical engineers worldwide. Where the balance shifted was a second round of innovation starting in 1940. This centered on refining a new kind of vacuum tube that delivered much more powerful signals at shorter wavelengths, allowing for systems with much higher resolution that could be squeezed into significantly smaller devices. Developed in Britain and secretly ferried across the Atlantic on the Tizard Mission of 1940, the cavity magnetron was immediately made the center of a broad-reaching American R&D relying on American industrial electrical engineering strength. The MIT Radiation Laboratory's radar technologies were small enough to be built into aircraft, assisting in bombing and sub-hunting as well as air combat. They were pervasively integrated into mobile fire-control systems, becoming part of the landscape of ground and naval warfare. In the form of the proximity fuze, they were even designed into artillery shells and rockets to optimize their

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[16] David A. Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics* (Baltimore: Johns Hopkins University Press, 2002); Chris C. Bissell, "Forging a New Discipline: Reflections on the Wartime Infrastructure for Research and Development in Feedback Control in the US, the UK, Germany and the USSR," in *Scientific Research in World War II*, ed. Ad Maas and Hans Hooijmaijers (London: Routledge, 2009), pp. 202-212.

effect by timing their explosion. Under wartime conditions of secrecy, the advances in detection and ranging enabled by the cavity magnetron were essentially confined to the Allied side.[17]

Well beyond anti-aircraft defenses, radar's uses reached into multiple branches of war fighting, from the battle for control of the Atlantic to execution of bombing campaigns to coordinating air-naval assaults. Radar was a key testing ground for the new mathematical and analytical techniques that came to be known as operations research. Calling radar an incremental improvement can seem counter-intuitive. And yet the case shows what an effect such innovations could have. The key insight is the setting: a technologized war of mass deployment of incremental advantage. The cumulative effect of the Allied-Axis differential in radar was to bring the balance of power down to material conditions, without war-changing "wonder weapons."

Transformative openings

As an R&D strategy, incremental improvement was low-risk. It started from a weapon or system that was already fixed in a niche. When it tried to do better, the outcome might be one among mutiple options – if tank-killing with bazookas was ineffective, anti-aircraft guns could fill in. There could be tough patches along the way, but it was not wholly new territory, with multiple decision points to call the result good enough. And if the effort failed, the investment that had to be written off was manageable. By contrast, the small number of big gambles of World War II R&D focused on dark spots on the technological map. For jet-propelled aircraft, liquid-fueled ballistic missiles, and explosives based on nuclear fission, anyone could agree that a huge impact was theoretically possible. A rational calculus would weigh the strategic effects of introducing the weapon, the chance the enemy would do it first, the resources that would have to be thrown at the problem, and the time to the end of the war. But rational calculation about the future is an exercise in imagination, and that is even truer in wartime when gaps in the knowledge base leave key factors unclear. Above all, in war, success or failure depends on what military effect can be delivered by what critical moment. Whether a technology is transformative depends on staging and time.

Jet aircraft

Between the World Wars, significant efforts in government and private R&D establishments delivered huge improvements in conventional aircraft propulsion. The upward

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[17] Louis Brown, *A Radar History of World War II* (Bristol: Institute of Physics Publishing, 1999); Robert Buderi, *The Invention that Changed the World* (Simon & Schuster, 1996).

performance curve of piston engines and propellers relied on intensive engineering of engine components and the new aeronautical research tools of the 1920s and 1930s, such as wind tunnels. Those developments were coupled back into the refinement of aerodynamic theory in a classic and extremely successful feedback loop, while the overall process of incremental improvement in engines was supported by simultaneous evolution in aircraft structures, materials, and fuels. As performance improved, however, some of the limits of conventional propulsion came into view. Whether those limits were important or not depended on what airplanes were needed to do. At speeds approaching supersonic and at exceptionally high altitudes, conventional engines were going to hit a performance wall. The jet engine was the work of a small number of aero-engine outsiders in Britain and Germany who followed theoretical developments in advanced airfoil research. When new options emerged in compressors and gas turbines by the end of 1930s, they could be engineered into a potentially radically more powerful aircraft propulsion system, the turbojet.

In some sense, the jet engine was a reality by 1939. That was the moment at which impressive demonstrations in both Germany and Britain made its technical feasibility plain. A demonstration engine, however, even a demonstration plane, was not yet a deployable technology. And if the jet was not yet ready for deployment, it was even less of a system that could strong-arm its way into delivering transformative improvements in a highly-developed space of alternatives competing for priority. The pace of wartime development that followed was not so much a matter of lack of high-level enthusiasm (though it was often experienced that way by the turbojet's advocates) as it was material, resource, and engineering constraints that it proved hard to break through in conditions of war. Above all, the loop of testing and refining could barely get started. The long road to jet aircraft only began with the two fighters that reached use by 1944, the Messerschmidt Me 262 and the Gloster Meteor. In fact, the real payoff of the jet engine came once the countries that sat out serious wartime deployment, including the United States and the Soviet Union, joined in launching high-pressure development programs. In sheer internal terms, the jet engine was transformative in its possibility, but to make it into a transformative package took it past the end of the war.[18]

Ballistic missiles

Long-range rocket propulsion, for its part, was an enthusiast's dream, at the heart of interwar fascination with interplanetary travel. The military interest was never hidden: a rocket

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[18] Edward W. Constant II, *The Origins of the Turbojet Revolution* (Baltimore: Johns Hopkins University Press, 1980); Ralf Schabel, *Die Illusion der Wunderwaffen* (Munich: R. Oldenbourg, 1994); Hermione Giffard, "Engines of desperation: Jet engines, production and new weapons in the Third Reich," *Journal of Contemporary History* 48 (2013): 821-44; Mark Harrison, "A Soviet quasi-market for inventions: Jet propulsion, 1932-1946," *Research in Economic History* 23 (2005): 1-59; Philip Scranton, "Turbulence and redesign: Dynamic innovation and the dilemmas of US military jet propulsion development," *European Management Journal* 25 (2007): 235-48.

that can travel fast and far can come screaming back to earth. If it follows a ballistic trajectory, it requires fuel only for the boost phase and can concentrate its weight in its warhead. After the rocket engine cuts out, the missile follows its pre-determined path at supersonic speed, leaving it nearly impossible to defend against. To access those regimes of distance and speed, however, liquid fuel is necessary, and that fact creates serious technical complications. Combining the challenges of a liquid-fuel propulsion system with aerodynamics and guidance, the feasibility of ballistic missiles was an entirely open question through 1930s. The United States, France, and Britain had small-scale, relatively uncoordinated efforts; the Soviet Union did more substantial R&D through the mid-1930s but cut it off real conflict loomed – just too long range to invest in when so much else needed to be done. Germany, on the other hand, pushed forward within the Army Ordnance Office under Wernher von Braun (PhD in aeronautical engineering, Berlin, 1934). One of these projects became the A4 or, as it was named by Goebbels, the V-2, the second of Nazi Germany's "vengeance weapons."

The A4's development is a story of its advocates pushing the envelope on a technology whose promise could only be scoped out as it was actually tried. By the end of the 1930s, rocket patrons in the military had placed their bets. They pushed the case for massive investment of resources by promising a devastating surprise weapon on a war-deciding timescale. Getting high-level go-ahead, the Army and the Luftwaffe partnered to build a secret research and production facility on the Baltic coastline at Peenemünde, where huge rockets could be tested without fear of discovery. As the war was launched and as the project progressed, ever more ambitious visions were floated – incredibly accelerated timelines, missiles beyond the A4 with the capacity to deliver a payload all the way across the Atlantic. By the war's later years, the dream of a devastating offensive weapon kept the rocket's priority high, even as planning about its deployment modes was left aside. As Armaments Minister, Albert Speer joined forces with the SS in 1943 to move production into a hellish underground complex called Mittelwerk built and manned by concentration camp inmates, who died by the thousands.

By the end of the war, several thousand A4 rockets had been built. They were launched against London and other Allied-held cities starting in the fall of 1944. Together with Germany's other vengeance weapon, the V-1, a proto-cruise missile, the V-2/A4 was terrifying, truly. But given the state of the war and a body count not much larger than the number of missiles, the effect was negligible in World War II. The A4's accuracy was limited, and its explosive payload was small because the thermal engineering of the warhead had not gotten very far. There was no great strategic plan for its use besides surprise and terror. The range of the A4 was about 200 miles. The other weapons that were dreamed of by the rocketeers – the intercontinental ballistic missiles for which it was a prototype – would not be ready for more than a decade. They were, of course, built on its model.

Nuclear fission

Nuclear weapons are often viewed as the war's crowning scientific achievement. The United States, in collaboration with the British, gambled that a secret Army effort codenamed the Manhattan Project (for the Manhattan District of the Army Corps of Engineers) could bring an atomic bomb to fruition in time to be used during the conflict. In a compressed timeframe driven by fears of competing developments in Germany, a laboratory discovery in a frontier area of science was turned into into a functioning weapon of a level of destructiveness never previously reached.[19] Nuclear fission was not even discovered until late 1938, the outcome of basic research in nuclear physics and chemistry. Under certain conditions, the nuclei of particular heavy elements, such as uranium, can be split by a subatomic particle called a neutron, releasing a large amount of energy and likely other neutrons as well. The discovery was made in Germany, whose ranks of nuclear scientists had been thinned by Nazi measures against Jews, but which still had significant strengths to show. The findings were quickly published in the open literature, and they set the members of the small community of nuclear scientists into agitation worldwide. Against the backdrop of academic theorizing and experimentation, it seemed that if certain yet-to-be determined conditions obtained, an uncontrolled chain reaction would be possible, opening the door to nuclear explosives far more powerful than those enabled by chemical reactions (such as TNT). Also on the horizon were controlled uses of fission to power massive engines with almost negligible consumption of uranium fuel.

Scientists pushed the issue into view in multiple nations' scientific-military networks. In Germany, consulting relationships between university scientists and government officials brought fission to state attention by late spring 1939. By fall, amid the overall mobilization, leading nuclear scientists were reporting to the Army Ordnance Office. In Japan and the Soviet Union similar contacts were made, though without the same urgency of potentially war-deciding prospects. In France, too, scientists were actively tracking developments.[20] In Britain and the United States, partnerships of German émigré scientists and domestic colleagues stirred up attention in government to begin a focused program of research in the first half of 1940. As the war in Europe churned forward, the next eighteen months delivered results showing that a bomb in principle was feasible. However, it would take large supplies of uranium and a massive and unproven industrial effort to pick out that tiny fraction that was suitable for a nuclear explosive. Possibly easier was controlled power generation in a reactor. Along the way, all the same, it became clear that a running reactor would generate a new element that was soon named plutonium – another potential nuclear explosive, assuming that theory could predict its properties before it was even observed in the lab.

By the time of Pearl Harbor and the Soviet counteroffensive around Moscow, this situation was known in all the nations that had invested in serious scientific research. In Germany, any project to develop a nuclear explosive would take several years, and it would be a huge challenge to execute under conditions of total war. In 1942 Speer confirmed that assessment and continued

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[19] Richard Rhodes, *The Making of the Atomic Bomb* (New York: Simon & Schuster, 1986); Margaret Gowing, *Britain and Atomic Energy, 1939-1945* (New York: St. Martin's, 1964).

[20] Mark Walker, *German National Socialism and the Quest for Nuclear Power* (Cambridge: Cambridge University Press, 1989); Grunden, *Secret Weapons*; David Holloway, *Stalin and the Bomb: The Soviet Union and Atomic Energy, 1939-1956* (New Haven: Yale University Press, 1994); Spencer R. Weart, *Scientists in Power* (Cambridge, MA: Harvard University Press, 1979).

the project at a prospecting level. Army and civilian scientists in Germany kept it going as a research program with an eye to long-term development of reactors; there was no advocate for the German nuclear effort with the crazy ambition of the advocates for the A4. In the United States and Britain, by contrast, spare capacity was imaginable, fear of German progress loomed large, and the time horizon for war-changing weapons was longer. Roosevelt authorized the Manhattan Project, and Churchill coordinated the Anglo-Canadian Tube Alloys project with it. What unfolded was a high-end R&D effort that stretched from fundamental nuclear physics to detonators to shock waves, and in the same breath a gargantuan undertaking spread across the North American continent to produce critical masses of fissionable materials. In a big gamble, the Manhattan Project tackled two routes to a bomb simultaneously. On the uranium path, one of several front-runner methods to pick out the best isotope for a weapon was scaled up to be housed in the largest building on earth. The plutonium path went through building the world's first nuclear reactors, then chemically picking through the radioactive detritus to separate an element that had never existed in isolated form on earth. The U.S. Army Corps of Engineers under Brig. General Leslie Groves, the all-encompassing materials priorities system, and the strength and reach of the industrial contractors (such as Westinghouse, Stone & Webster, and DuPont) were coupled in to the network of scientists who had built up the OSRD and their working relationships with colleagues in Britain. The administration of the Los Alamos weapons design laboratory was contracted to the University of California, and its leadership was entrusted to the Berkeley theoretical physicist J. Robert Oppenheimer.[21]

In late 1944, intelligence showed there was no threat of a German nuclear weapon. By that time, however, the Manhattan Project had made it past key technical hurdles. With the war in Europe winding toward its end, options for demonstrating the bomb on Germany evaporated. It was the Trinity test of July 16, 1945, secretly staged in the New Mexico desert, that showed that the project would in fact pan out. A sphere of less than 10 kg of plutonium was detonated with the force of an eighteen-thousand-ton cache of TNT. The main purpose of Trinity was to test how the plutonium implosion design and the detonation mechanism worked. On August 6, the United States exploded the first uranium weapon, untested, over the Japanese city of Hiroshima – one bomber, one bomb, 13 kilotons of conventional explosives' equivalent. On August 9, Nagasaki was the target of a plutonium device that yielded 21 kilotons. The immediate death toll of the two attacks was 100,000. Japan surrendered on August 14.

Nuclear weapons overshadowed every other wartime scientific-technical development. Their proximity to V-J Day almost guaranteed that effect. But the bomb came very close to being a failure. With a few months' advance in the war, or a few months' delay in the technology, the Manhattan Project would have delivered no weapon at all. In this first pass at development, the hard aspects of making the bomb were managing the explosive process, designing the detonator, and building the entirely new industrial processes that delivered the fissile material. Once those were demonstrated, the way forward was clear; it was a matter of putting the resources in place. That is, there was no great secret around designing nuclear weapons. Thus as soon as the Stalin

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[21] Lillian Hoddeson et al., *Critical Assembly: A Technical History of Los Alamos During the Oppenheimer Years, 1943-1945* (Cambridge: Cambridge University Press, 1993); Kai Bird and Martin J. Sherwin, *American Prometheus: The Triumph and Tragedy of J. Robert Oppenheimer* (New York: Alfred A. Knopf, 2005).

heard of the American proof of concept in mid-summer, he put the Soviet nuclear project on a fast ramp-up. Espionage helped, but it was by no means decisive. And what made the atomic bomb a usable weapon in August 1945 was the simple delivery system – no guidance system, no aerodynamics, just drop it from a plane. In 1945 nuclear weapons were no more mature a technology than jet engines or the V-2. But the surrounding package was simpler. Success in wartime depends on staging and time.

Conclusion

In focusing on a small number of examples, this chapter has skipped past other arenas. Operations research, encryption and codebreaking, sonar, weather prediction, pest control, plant breeding, social science – the experience of fighting World War II was broadly shaped by the uses of new knowledge. What mattered as much as the domains where R&D was put to work was the vision and the practice of integrating it. Both vision and practice carried forward into the postwar world. After 1945 scientists were reimagined as the leading figures in a new mode of warfare, continuing hard-earned relationships and ways of getting things done.

That continuity was explicit, obviously, in the victorious powers, where wartime R&D leaders became postwar policymakers and government advisors. The same was true in more subtle ways. Even if IG Farben's leaders were tried for war crimes in Nuremberg, its chemists were put back to work. Iconically, Wernher von Braun's V-2 team was reassembled in the United States, along with his rockets, becoming the technical core of the American space program. German specialists ended up in the Soviet Union working on ICBMs or nuclear weapons, while others were welcomed in smaller countries that were looking to upgrade their capacity. Domestically, the global leitmotif of the post-World War II decades was massive state investment in scientific and technical training. Researchers were the civilian reserve force for the conflicts of the future, ready to be redeployed as needs should require. It is not an accident that the postwar decades were equally the high-water mark of the idea of pure science. Trained in basic research, scientists could be remobilized on short notice. Along with industrial capacity, human resources were central to planning for scientized war. They allowed R&D systems to spin up new innovations quickly and get them out to deployment to fit the rapid dynamic of measure-countermeasure warfare. Post-WWII science was an arena of standing reserves.

In this respect, World War II research crystallized a societal configuration that had been forming since the second industrial revolution. Knowledge and its bearers were understood as the key agents of change in the new social order. The theorists of knowledge economies were looking at post-1945 America, which meant they were observing that setting where the fullest effects of wartime R&D mobilization carried forward into the postwar order.[22]

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[22] Fritz Machlup, *The Production and Distribution of Knowledge in the United States* (Princeton: Princeton University Press, 1962), ch. 5, "Research and development"; Peter Drucker, *The Age of*

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The scholarly literature is largely organized by national frames. For the U.S. case, Kevles, *The Physicists*, is still the easiest entry point, supported by scholarship on aeronautics, radar, and the Manhattan Project as cited in this chapter. Technical histories written after the war are stilll valuable sources, including the OSRD series *Science in World War II*. The official Manhattan Project report of 1945, Henry De Wolf Smyth, *Atomic Energy for Military Purposes* (Princeton: Princeton University Press, 1945), remains a classic source. Work on Britain is well-developed. David Edgerton, *Britain's War Machine: Weapons, Resources, and Experts in the Second World War* (Oxford: Oxford University Press, 2011) is a sharply argued synthesis that engages much previous scholarship. On France, the histories of science, military technology, and industry have largely remained distinct literatures. Some beginnings for a synthetic story can be found in Amy Dahan and Dominique Pestre, *Les sciences pour la guerre, 1940-1960* (Paris: Éditions de l'École des Hautes Études en Sciences Sociales, 2004); Dominique Pestre, ed., *Deux siècles d'histoire de l'armement en France* (Paris: CNRS Editions 2005).

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