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Science and Technology

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Wartime science and technology developed in the context of the Second Industrial Revolution, with far-reaching consequences for national and international scientific institutions and social structures. Trench warfare posed new problems requiring scientific and technical expertise in areas such as artillery, chemical warfare, cartography and reconnaissance, aviation, infantry weapons and body armor, armored vehicles, communications, logistics, and military medicine. Meanwhile, the submarine revolutionized naval warfare. The greater integration of science and warfare set the pattern for modern "total war" by blurring the line between soldiers and civilians, as well as by nullifying pre-war international conventions intended to limit wartime excesses.

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Introduction

The Great War of 1914-1918 was the first European war in a century to reach a scale, length, and character such that technological innovations within the course of the war itself could be of decisive influence. Moreover, it was the first war in history in which both sides mobilized groups of scientifically trained professionals for the purpose of systematically researching and developing technological innovations for military purposes. To understand why this had become possible, the war needs to be viewed in the context of European industrialization. Unlike earlier European wars, the principal opponents in the Great War were fully engaged in the Second Industrial Revolution, which entailed a far more systematic integration of scientific research into the process of industrial innovation in a host of areas related to the physical sciences (chemicals, electric power and communications, metallurgy, and mechanical engineering including internal combustion engines for transportation), with most changes occurring since the 1880s. Although many of these innovations already had their counterparts in military technology, in 1914 the most influential generals and political leaders, whose direct experience of war lay in an earlier era, scarcely appreciated their full implications. Following the initial, bloody failures of the early war plans calling for a quick offensive victory, the prospect of a long war finally forced leaders on all sides to confront the problems and possibilities posed by the new technologies, and to mobilize appropriate expertise to deal with them.

A process of innovation began, often protracted due to resistance in some quarters, combined with the inherent limitations of the innovators or the technologies themselves, and not least the difficulties and risks of field-testing previously untried approaches. Despite the pre-war Hague conventions intended to make war more "civilized," legal or moral constraints unfortunately did little to retard innovations that made the war both more destructive and more "total" in the sense of blurring pre-war distinctions between combatants and noncombatants. The Armistice of November 1918 prevented an even more drastic technological transformation of the war by canceling the plans of the western allies for such innovations as mass aerial bombing with poison gas. The more recent historiography of the war has begun to stress these "total" aspects as well as its technological dimensions.[1]

Obviously there is considerable overlap between scientific and technological knowledge, but one could argue that the former is concerned primarily with producing knowledge regardless of its practical use, while the latter is fundamentally concerned with techniques for solving practical problems, in this case related directly or indirectly to military purposes. For probably a majority of the most significant innovations of the war, this meant repurposing knowledge or tools that had emerged during the Second Industrial Revolution in peacetime, commercial contexts, but now took on quite different, war-related purposes. Indeed, the Great War led to a far wider recognition of the importance of what are now called "dual-use" products or processes, or in a broader sense the "double-edged sword” of scientific and technological innovation.

It must also be recognized, however, that given the conservative nature of military institutions, the most innovative technologies were not always easily or effectively integrated into military practice. Even so, the war lasted long enough to demonstrate the potential and achieve the integration into warfare of the most significant innovations in the areas of artillery and explosives, chemical warfare, tanks, communications, aviation, and submarines. Indeed, one historian has recently reminded us that the military itself became the major promoter of innovation in many of these areas; but mainly, it should be added, when the innovations occurred in the context of “old,” well-established technologies that were already adapted to existing military forms and priorities, such as artillery.[2]

The following article approaches science and technology in the Great War first by addressing the impact of the war on the international and social-institutional structure of science and technology in general, including the social composition of scientific disciplines (class, gender, and ethnicity). The article then considers the unexpected technical problems that the war presented with the advent of trench warfare, and goes on to examine various solutions to these problems in various disciplines or technical areas from artillery and chemical warfare to communications, with a final section on naval warfare. Except in passing, the article will not discuss several topics that are well-covered in separate articles.[3] It will conclude with some general reflections on the ways in which the increasingly complex interconnection of military and scientific technology has transformed both war and science.

War and the institutional structure of science and technology

Up to 1914, the 20th century in Europe had been marked by increasing international cooperation in science and technology, as reflected in such institutions as the International Association of Academies, which had first met in Paris in 1900, the Nobel Prizes first awarded in 1901, the first International Solvay Conference in Physics in Brussels in 1911, and the International Association of Chemical Societies, founded in 1911. Every field of advanced technology seemed to have regular international conferences that had produced a host of international agreements dealing with the countless adjustments needed to secure the smooth functioning of a modern world economy and civilization shaped by scientific technology, such as agreements on standard time, electrical units, chemical nomenclature, and so on. The European political and cultural imperialism of the preceding generation had disseminated fundamentally European perceptions of science and technology throughout the world, so that anyone with a scientific education shared a similar understanding of the essential nature of mature disciplines such as physics and chemistry – aside, of course, from differences of theoretical opinion, experimental practice, and contextual linkages to academic and industrial institutions.[4] This sort of international consensus did not, however, extend in most cases to the social sciences and humanities, where linguistic, national, and educational differences were far more pronounced.

With the outbreak of war in 1914, the existing international structure of scientific cooperation quickly collapsed. Scheduled conferences were postponed and international organizations were either disbanded or became dormant. After several prominent German scientists appeared among the ninety-three signers of the infamous manifesto “To the Civilized World” (4 October 1914), which (among other assertions) flatly denied the existence of deliberate atrocities by the German military against civilians in Belgium while expressing unreserved solidarity with “our so-called militarism,” scientists in the opposing allied nations angrily demanded to strike these German scientists from the roles of honorary or regular members in academies and scientific societies. This in turn produced similar demands in German academies and societies. Outcomes varied; in Berlin, the internationally-minded chemist Hermann Emil Fischer (1852-1919), who won the Nobel Prize in Chemistry in 1902, was able to postpone action until after the war. Albert Einstein (1879-1955), who hated Prussian militarism, made a futile effort to uphold the banner of scientific internationalism by drafting a counter-manifesto with Georg Friedrich Nicolai (1874-1964), but it obtained only two other signatures.[5] Ironically perhaps, Einstein’s initial isolation from the distractions of war work may have been just what he needed to produce the general theory of relativity announced in 1915, the most important scientific achievement to emerge from the war years.[6]

The war affected scientific institutions and especially scientific education in all of the contending nations. From the beginning in 1914, young men either volunteered or were inducted in droves, leaving laboratories and lecture halls half-deserted. As a result, many men with potentially brilliant futures in science and technology were to die as ordinary soldiers on the battlefield, including the British physicist Henry G. J. Moseley (1887-1915), who would surely have won a Nobel Prize for his work establishing atomic numbers in 1913-14, which created the basis for the modern periodic table of the elements. But Moseley volunteered in 1914 and died in the futile British campaign on the Gallipoli peninsula in 1915, prompting the British atomic physicist Ernest Rutherford (1871-1937) to publicly lament this “striking example of the misuse of scientific talent.”[7] Such losses, combined with the growing recognition of the value of science for war, ultimately prompted the contending nations to develop systems for keeping their most valuable talents at home in war-related work. Recent work on the universities has highlighted ways in which they became integrated into the war effort, particularly among the western allies.[8]

In the meantime, female science or medical students, previously a rarity, had become more prominent in those institutions where they were permitted, and several even became assistants. Many talented female students or graduates also replaced men doing technical jobs in workshops, factories and industrial research laboratories. Although women often encountered considerable resistance in the engineering colleges and universities, they were far more likely to be welcomed by professors on the less-demanding levels of technical education and by employers as technicians, in part because, for social reasons, many employers were more willing to hire women from middle-class backgrounds to replace technicians from the working classes. The result was that these women were more likely to feel frustrated than liberated in technical occupations. A few women scientists did, however, play more significant roles. Most prominent among them was Marie Curie

(1867-1934), already in possession of two Nobel Prizes, who established a military radiological service with eighteen mobile and 200 stationary X-ray units under Red Cross auspices, set up training facilities for women operators, and finally created a military radiotherapy service using radon gas produced in her Radium Institute.[9]

As many scientists and engineers patriotically volunteered their professional services to their respective military authorities, some civilian scientific institutions took up military tasks, and for some purposes new military institutions or organizations were formed or old ones greatly expanded to make use of the professionals' services. The Germans created the first such organization in August 1914 with the *Kriegsrohstoffabteilung* (KRA), or War Raw Materials Office, located within the Prussian War Ministry, but headed by the scientifically-trained civilian (and German Jew) Walther Rathenau (1867-1922) of the AEG electrical corporation. A series of "war corporations" and special commissions followed, in which corporate leaders, scientists, military officers and government officials collaborated to regulate the production and supply of critical resources. For the Germans, the British blockade made the effective development of substitute materials and alternative resources a critical priority, and it became the most fruitful field of military-industrial cooperation mediated by academic scientists such as Emil Fischer and Fritz Haber (1868-1934).

On the Allied side, analogous organizations began to appear in the spring of 1915, when the new circumstances of the war were becoming all too clear: the huge demand for artillery shells forced the creation of the Ministry of Munitions in Britain and a similar organization in France. At almost the same time, a similar shell shortage led the Germans to introduce chemical warfare in the form of chlorine clouds discharged from massed canisters during the Second Battle of Ypres in April 1915. This in turn provoked the French (who had like the Germans already experimented with non-lethal agents in shells) and British to create various organizations to mobilize their chemists and medical personnel to deal with this "unconventional" weapon – which indeed violated the spirit of the Hague Conventions' prohibitions against the use of poison in war.[10] Both sides proceeded to create large organizations to promote chemical warfare research and testing. Perhaps the most notorious was the Kaiser Wilhelm Institute for Physical Chemistry in Berlin-Dahlem, founded in 1911 and directed by Fritz Haber, who first applied his expertise with gas chemistry to the use of chlorine clouds at Ypres. By the end of the war his initially modest, civilian institute had become militarized, temporarily taken over many facilities of the neighboring Kaiser Wilhelm Institutes in Berlin-Dahlem, and become the principal German center for the technical development of chemical warfare. Later the British organized the Department of Scientific and Industrial Research (DSIR). The Germans responded in late 1916-early 1917 with the Kaiser Wilhelm Foundation for Military Technical Science, which featured several expert committees headed by prominent scientists recruited from the universities to solve technical problems under contract with the military.[11]

As German defeat loomed in 1918, Allied scientists agreed to recreate the international system of science in a form that would carry on a cultural "war after the war." The result was the International Research Council, to which the National Research Councils of the various Allied and neutral nations were admitted, but not the Germans, Austrians, or Russians. The pre-war international disciplinary associations to which the Germans had belonged were also replaced by several new international scientific unions such as the International Union of Pure and Applied Chemistry, or IUPAC. The Germans would not be fully reintegrated into the international structure of science until after the Second World War, by which time English had replaced German as the principal language of science.[12]

A War of Expertise

The Science and Technology of Trench Warfare and Total War: A War of Innovation?

Of course each nation entered the war with arsenals, powder factories, proving grounds, and military testing facilities for weaponry staffed by trained professionals including some scientists and engineers. Although in these secrecy had always reigned, in fact by 1914 the leading experts in all nations understood the same fundamental principles of explosives, propellants, and shell manufacture, which had been established since the 1880s with the obsolescence of black powder, which had powered weapons for centuries, and its replacement by more stable and powerful compounds based on the 19th-century science of organic chemistry. Similarly, the long-known principles of ballistics had to be updated with the design of far more powerful and accurate firearms and artillery based on the new chemicals. All national armies had modern machine guns and modern artillery.[13] Here the key invention had come in 1897 with the French 75-mm field gun and its hydraulic recoil-damping system, allowing a much higher rate of accurate fire. Despite French efforts to keep this a secret, all other nations had developed comparable and competing systems, in some cases with significant differences, although many armies still retained many older, obsolescent designs not yet fully replaced by the new models. The Germans in particular recognized the need for weapons that could attack fortifications and had developed and built large numbers of modern light and heavy howitzers, as well as even heavier but relatively mobile siege artillery, which could fire high-explosive shells at a steep angle. In this way the Germans entered the war far better prepared for the trench warfare that was to come than were their opponents whose modern artillery primarily consisted of field guns firing shrapnel shells at a relatively flat angle, which was devastating to troops in the open but would be less effective against them when entrenched.[14] All in all, it was not so much scientific or technological factors as the political and institutional contexts in the various countries that accounted for the quantitative and qualitative differences in their military hardware by 1914.

In any case, the first few months of war quickly demonstrated that all the pre-war expectations and mobilization plans were woefully inadequate for the scale of what was rightly being called the “Great War” – a war that consumed human and material resources at a horrendous rate. As the war descended into the mire of static trench warfare toward the end of 1914 (albeit mainly on the Western Front – the Eastern Front was always far more mobile), the military and political leaders in all the major powers were confronted with unexpected problems and challenges for which their previous training had provided little preparation, forcing them to mobilize expertise on an unprecedented level. Each side of the Western Front rapidly became a vast and complex technological system, ultimately incorporating almost all branches of the civilian economy, much of the infrastructure, and significant elements of civilian scientific and technical institutions as well.[15]

The war became notoriously dominated by the power of defensive technology, featuring the machine gun situated in a trench or ultimately a concrete pillbox to protect the gunners from artillery fire, and further protected by coils of barbed wire that could become deathtraps for attacking infantry. Trenches and dugouts themselves became increasingly elaborate, buttressed with sandbags, lumber, metal, and reinforced concrete, and using duckboard flooring in muddy conditions. Mechanical digging machines occasionally supplemented human labor (which often meant non-white or colonial labor among the French and British). Elaborate light-rail networks using small cars and locomotives developed, especially from around 1916, to replace horse or human transportation in supplying the trenches. New weapon systems emerged specifically for the trenches, such as small, short-range trench mortars hurling lightweight shells in a high arc.

Battles now revolved around the problem of breaking through the trench lines, which became an obsession – repeatedly planned, almost never achieved. In the west, mobile warfare would not return until 1918; in the intervening years the lines moved no more than a few miles either way. Hence much of the expertise to be surveyed in the rest of this article was focused on developing technologies that could achieve a breakthrough and restore “normal” warfare, i.e. the attacking style that the generals on each side had learned in their youth and had expected in August 1914, with glorious cavalry charges pursuing a fleeing enemy.[16]

Artillery, Explosives, and Chemical Warfare: The Chemists’ and Physicists’ War

The most effective weapon of the war, in terms of casualties produced, was artillery.[17] The basic types of artillery all existed in 1914, but the war saw both qualitative and quantitative changes. The British and French ultimately had to rely far less on field artillery, like the 75s, firing smaller shrapnel shells (which released myriads of bullets in midair to mow down unprotected infantry). Instead, they followed the Germans in emphasizing higher calibers and pieces (especially howitzers) that could fire much larger high-explosive shells in high arcs. Thus the numbers and scale of such cannon and shells increased exponentially, especially after the expansion of capacities for munitions production from 1916 on.[18] The Germans produced perhaps the two most famous types of artillery used in the war: first, the 420 mm “Big Bertha” used effectively to break the resistance of Belgian fortresses around Liège in August 1914, though it proved to be ineffective against the better-designed French fortresses around Verdun in 1916. Second was the ultra-long-range “Paris gun” of 1918, which was however neither especially accurate nor effective as a military weapon; its most notorious hit was on a church filled with worshippers.[19] In the final year of the war, with the return to a more mobile style, field artillery again came into its own, though the classic shrapnel shell never again dominated the battlefield (they were perhaps only about ten percent of the total used in 1918).

Heavy artillery and high explosive shells required huge quantities of metal shell-casings and explosives, along with the materials required to produce them. This became a huge problem early in the war, as all the armies encountered shell shortages and had to find or build new productive capacities. The Germans in particular faced serious shortages of nitrates in 1914-15, which became a primary motivation for the establishment of the KRA.[20] Nor were other critical materials such as cellulose, glycerin, and toluene in sufficient supply for a long, large-scale artillery war. This led early on to efforts to find various types of effective substitutes.

From this perspective, as noted in the previous section, the Germans first used poisonous chlorine gas in clouds as a substitute for artillery; this was Fritz Haber's proposal in December 1914, in response to the request of the Chief of the General Staff and War Minister, Erich von Falkenhayn (1861-1922), for an agent that would permanently disable Allied soldiers.[21] Moreover, though the French began the shift in 1916 from clouds back to artillery shells as the principal means of delivering gas, the Germans used a considerably higher percentage of gas shells than did the Allies. This was due as much to the continuing shortages of high explosives for shell-filling on the German side, as to the fact that Fritz Haber's institute in collaboration with the research-intensive dye companies ensured that the Germans maintained the initiative in chemical warfare until late in 1918. Their last critical innovations occurred however in the summer of 1917, with the introduction of so-called mustard gas and arsenicals. The former was an insidious blister agent, very persistent and producing a delayed reaction that could cause temporary blindness or severe burns, more rarely death. Arsenicals were intended to be "mask-breakers," severe irritants that would cause soldiers to tear off their masks and expose themselves to more toxic agents; but the Germans could not solve the problem of dispersing these agents in fine enough particles to make them effective in combat.[22] In contrast, the problem for the Germans with mustard gas was that it was in a sense too effective. As they never solved the problem of decontamination, they had no defense once the Allies had achieved large-scale production by the late summer of 1918. The Americans in particular were preparing to deluge the Germans not only with mustard gas but also with Lewisite, an agent that combined the properties of both mustard gas and arsenicals. Lewisite never reached the battlefield, as the first shipment was still on its way to France when the Germans signed the Armistice.[23]

Cartography and reconnaissance

Maps were vitally needed for charting the detailed trench networks. Existing pre-war maps were simply not precise enough (1:84000 on the French side, 1:100000 on the German side); they needed to have at least four times the resolution, and in some cases much finer detail. Thus by early 1915 both sides had organized field cartographic sections and both used aerial photography provided by aircraft to enhance their maps. Overall, it appears that the French and British ultimately produced better maps than did the Germans, largely because they had better pre-war maps to work with.

Perhaps the most crucial reason for having detailed maps was to provide better direction to long-range artillery. Yet, locating the enemy's artillery raised other problems. Initially both sides tried to pinpoint muzzle flashes by sight, but this was not especially effective in most cases. Eventually the alternative of triangulating by sound proved to be far more effective, whereby physicists had to distinguish between the sound of the shell passing and that of the cannon firing. Both sides used somewhat different approaches. The Allies relied on a system developed by the French astrophysicist Lucien Bull (1876-1972) beginning in the fall of 1914, with sets of microphones that could record the amplitudes of sounds on moving strips of paper. Other Allied physicists, particularly Lawrence Bragg (1890-1971) and Charles G. Darwin (1887-1962), made additional improvements to the technique, which the Americans further refined in 1918. By then, under ideal weather conditions, trained observers could use the graphical data to pinpoint the location of German artillery within a couple of minutes. This would make it possible in an offense (as first tried at the battle of Cambrai in November 1917) to direct the initial bombardment not at the German trenches, but to silence their artillery. At Cambrai, of course, the British were relying on another innovation, the tank (see below), to lead the infantry across barb-wire entanglements and trenches. Americans were so impressed that an image of a sound-ranging tape recording the last shots of the war became the frontispiece to the official report on munitions production.[24] On the German side, a group of physicists including Max Born (1882-1970), Ferdinand Kurlbaum (1857-1927), and several others also developed a comparable sound-ranging system using oscillographs, but the General Staff considered it too expensive to be deployed. Instead, they relied on trained men with stop-watches, which ultimately proved to be less accurate and much slower.[25]

Birth of the Modern Aircraft as a Tactical and Strategic Weapons System

Despite experiments during the 19th century, powered flight either with dirigible hydrogen-filled airships or airplanes was essentially born in the first decade of the 20th century. Yet the airplanes of 1914 were still highly fragile and experimental in nature, despite more than a decade of development. Both sides had military and naval aircraft in 1914, essentially for reconnaissance (see previous section); indeed, without military support it is doubtful whether Germany would have had an aircraft industry at all before the war.[26] Germany's pre-war efforts largely went toward dirigibles, as pioneered by Graf Ferdinand von Zeppelin (1938-1917). But the war greatly accelerated the development of the modern airplane, transforming it into a recognizably modern form as compared with the primitive types of the first decade. Most of the wartime developmental work came from inventors and engineers in aviation companies working on a largely trial-and-error basis, with little input from scientific research such as that done on wing design by Ludwig Prandtl (1875-1953) at the University of Göttingen Institute for Technical Physics. In any case, he did not publish his experimental and theoretical work on wing design until the end of the war in 1918-1919. In the absence of effective scientific research, a characteristic innovation resulting from empirical methods was a means for pilots to fire machine guns mounted on the front fuselage of an aircraft through a front-mounted propeller, without shooting it off. The first effective solution came in the Fokker E.1 monoplane introduced in mid-1915 with mechanically synchronized propeller and machine gun. The ensuing “Fokker scourge” brought the Germans temporary air supremacy until the French and British responded with even more effective versions in 1916, leading in turn to further German innovations, in a pattern typical of wartime innovation.[27]

The main problem with all early aircraft was the lack of powerful engines, so that only extremely lightweight materials could be used (initially cloth-covered airframes frames of light wood, gradually shifting to light metals such as aluminum). Primarily biplanes were used to maximize lift, but these were relatively slow – not a serious problem for reconnaissance until the development of fighter airplanes in 1915 led to a pattern of steady technical improvements by both sides in an effort to win control of the air. These were of course primarily tactical aircraft, used over the fighting fronts. It might be thought that strategic aerial bombing was impractical with the aircraft then available. Nevertheless, in 1915 both sides inaugurated strategic aerial bombardment of enemy cities, which required aircraft capable of carrying heavy loads of bombs. The Allies used airplanes to attack German industrial cities on the Rhine, while as early as January 1915 the Germans sent naval airships to bomb British coastal towns, followed by unsuccessful efforts to reach London in February and an attack by an army airship on Paris in March; many more followed, but with little military impact. Aside from the poor mechanical reliability of the aircraft and their vulnerability to weather conditions, there were as yet no accurate navigational equipment, precision bombsights, or bomb racks, far less any means of guiding the bombs, so that such bombing had little strategic significance and could serve only as a terror weapon. As the Allies developed more effective anti-aircraft guns and incendiary bullets to use in fighters that could climb high enough to attack them, the airships became too vulnerable and the Germans switched to twin-engine Gotha bombers in 1918. By the end of the war, however, both sides had constructed even “giant” bombers. The British Handley Page V/1500 four-engine bomber was capable of reaching Berlin from airfields in England carrying a 3,000 lb. (1,400 kg) bombload, which could have included gas bombs. Its first bombing mission was delayed several times, then canceled by the Armistice.[28]

Infantry Weapons and Body Armor

The soldiers who went to war in 1914 and those who participated in the great offensives of 1918 carried dramatically different equipment. Aside from the standard rifle, which remained essentially the same, the war saw the development of various types of portable automatic infantry weapons and especially hand grenades, which became crucial offensive weapons for assaulting trenches and machine gun nests. Perhaps the most obvious innovation was the reintroduction of armor in the form of the steel helmet, absent from European battlefields for centuries. The reason was of course that in trench warfare the principal cause of death was by head wounds, often not from bullets but from shell fragments (later inaccurately termed shrapnel, see above). The French were the first to issue such helmets in 1915, but their Adrien model, based on the fireman’s helmet, was not strong enough, so that soldiers still suffered many head wounds from fragments. Nevertheless, even a reduction of 2-5 percent in casualties was enough to persuade others to follow with their own models in 1916, the British “tin hat” (which could be easily mass-produced by cold-pressing circular sheets of manganese-alloy steel, but was uncomfortable and did not offer the best protection for the head) and the German "coal scuttle," both inspired by different types of medieval helmets. When the Americans entered the war in 1917, their top designers Bashford Dean (1867-1928) and Daniel Tachaux (1857-1928) (experts in medieval armor from the Metropolitan Museum in New York) produced several possible models and concluded that the best variation would be one that was better shaped to protect the soldier's head; as this looked too similar to the German helmet, which was widely admitted to be the best helmet of the war, it was of course rejected by military authorities. Americans thus wore British-style helmets (albeit with a different type of lining for greater comfort) throughout the war and the 1930s, developed their own characteristic helmet in the Second World War, and finally in the 1980s returned to a modern version of the originally-favored design, but using Kevlar rather than steel. Because some 70 percent of casualties resulted from shell fragments, light-weight steel body armor was another possibility explored by the contending nations, but apparently only the Germans produced sets as standard issue; the weight of some twenty pounds a set restricted their use.[29]

Armored Vehicles

The development of armored vehicles might have seemed a logical consequence of the advent of trench warfare; nevertheless, it was two years before the first British "tanks" appeared on the Somme battlefield in September 1916, and even longer before the French introduced them during the Nivelle offensive of April 1917. In neither case were the initial models especially robust or reliable, with frequent breakdowns and negligible impact, leaving the Germans with the false impression that tanks were not worth developing. In November 1917 British tanks finally demonstrated the possibility of achieving a breakthrough at the battle of Cambrai, but this first qualified success, like so many other innovations during the war, was nullified by other factors. Only in July-August 1918 did French and British tanks, used in large numbers (about 1,500 each) in cooperation with infantry and under conditions conducive to their operations, have a significant impact on turning the tide against the Germans (who developed only a handful of their own tanks and never had much success with them).

The development of the British tank has traditionally (and not entirely incorrectly) been ascribed to the pioneering efforts of engineering officers who received little support from higher authorities until Winston Churchill (1874-1965) took over at the Ministry of Munitions in July 1917. Churchill became a great proponent of mechanized warfare in general, which he saw as an effective alternative to massed infantry assaults following massive (but often ineffective) artillery bombardments. On the French side, the simultaneous development of the *char d'assaut*, initially promoted by Col. J.B.E. Estienne (1860-1936), has received less attention from English-language historians, though in fact the French ultimately used more tanks (in part in cooperation with the Americans) than did the British. However, the French tended to favor lighter and smaller but also faster and more maneuverable vehicles, mainly the Renault FT, which could be produced in larger numbers to make up for massive losses due to breakdown and destruction by German artillery and heavy antitank rifles or machine guns. Thus the French were using 2,000 "tanks of victory" by November 1918.

These early Allied tanks were mechanically unreliable and often ineffective, with a failure rate of around 50 percent. Yet Churchill later eloquently lamented with some justice that the Allies might have put more effort into developing them earlier and on a far larger scale, “if only the Generals had not been content to fight machine-gun bullets with the breasts of gallant men, and think that that was waging war.”[30]

Communications: Telephone and Wireless

Field communications was a major problem during the war. All trenches were wired for using field telephones, but the wires were easily cut by bombardments, even if buried. The problem became even more intractable during an offensive, as laying down wires from a reel while crossing no-man’s-land was not a very practical solution. Visual signaling exposed the signaler and could be very dangerous, as was the traditional method of sending runners. As a result, one of the most common means of communication, albeit an unreliable one, remained the carrier pigeon. The uncertain communications typically left senior officers in the rear with no clear idea of the status and location of their forward units during an offensive, and thus reinforcements, supplies, and artillery barrages might be misdirected or mistimed.

The obvious solution was wireless communication, i.e. radio telegraphy or telephony, which however presented many problems of its own, especially for the field units for transmitting and receiving. By this time it was possible to transmit voices using a continuous wave with amplitude modulation (AM), which was far superior to the older spark-coil systems. In 1914 AM sets were not yet sufficiently lightweight and reliable (due to the need for fragile vacuum tubes) to be easily portable in themselves, aside from the need for an external antenna to achieve any real range as well as a portable power source in the form of batteries (either too heavy or too short-lived/underpowered) or a generator (requiring fuel or human power). It must be recalled that commercial radio broadcasting scarcely existed, so the needs of the war greatly intensified work on these problems. All sides made considerable progress during the war, setting the stage for commercial radio in the early 1920s. Although many portable field sets were produced, the most practical types were mounted in vehicles (making tanks especially useful for field communications during the 1918 Allied offensives) and in aircraft.[31]

Related to military communications is of course the field of cryptography, a very ancient art that took new forms as a result of radio communications during the war. In the early stages, the ability to read enemy messages greatly assisted military intelligence on both sides, figuring in the German victory at the Battle of Tannenberg and possibly also the French victory on the Marne.[32] The war made it obvious that every army had to pay special attention to secrecy in communications, and in the interwar period the development of coding/decoding equipment became a particular priority for technical experts in all nations.

Naval War: Surface Ships and Submarines

The most complex, sophisticated, and above all expensive weapons system of the war was the super-dreadnought battleship, the product of major technological innovations in design led by the British in an intensely competitive pre-war naval arms race with Germany.[33] These innovations culminated in the Scott-Vickers gun director and the Dreyer fire control table (a mechanical computer), which made possible highly accurate and synchronized salvos at sea. Thus in 1914 everyone expected surface ships to play a major role in the Great War, with the British and German battle fleets slugging it out for supremacy on the high seas, yet in actuality there was only one (and indecisive) major battle, Jutland.

The key dimension of the naval war was under water, whereby the Germans countered the effective British blockade of the North Sea by a submarine campaign against shipping to the British Isles. The submarine was a true product of the Second Industrial Revolution, driven by internal combustion and electricity, and its torpedo weapons were ingeniously designed missiles propelled by compressed-air motors and guided by gyroscopes. German submarines repeatedly violated international conventions and produced enormous controversies by sinking passenger liners without warning, most notoriously the *Lusitania* in May 1915.[34] On the other hand, the Germans also briefly experimented in 1916 with the use of large, ocean-going commercial submarines as blockade-runners, shipping stocks of dyes and pharmaceuticals to the United States.[35] The British undertook a variety of counter-measures against the submarine during the war, including the depth charge and massive minefields, which together destroyed seventy submarines by the end of the war, as well as the defensive use of aircraft and convoys (introduced after the United States entered the war and provided sufficient destroyers as convoy guards). But the most significant innovation to come out of the war was "asdic" (which the Americans later called sonar) a method of detecting submarines underwater based on the ultrasound research of the French physicist Paul Langevin (1872-1946); however, effective asdic devices were only deployed after the war's end.[36]

Conclusion: Science, Technology and the Birth of Total War

Was the Great War of 1914-1918 a "modern" war? As the foregoing essay has shown, the armed forces on both sides utilized some of the most modern technologies of the day, products of the Second Industrial Revolution: rapid-fire weapons (cannon and machine guns) with recoil-damping devices that permitted far more accurate fire, chemicals (in particular explosives, but also pharmaceuticals, photochemicals, and chemical warfare agents), electronic communications (radio, telephones, and microphones for sound ranging), photographic and optical technologies, and self-propelled machines driven by electricity or internal combustion which expanded the mobility, scale, and scope of warfare to include the air and under the seas. Moreover, the industries that produced these technologies and products included highly efficient factories and inventing laboratories staffed by scientifically-trained chemists, physicists, and engineers. From a medical perspective, this war was also notable as the first in which disease did not produce the majority of casualties (at least on the Western Front).

Yet modern as it may appear, the Great War also continued to exhibit many old-fashioned traits, particularly given the 19th-century mindsets of the top military leaders. The generals on both sides wasted millions of lives in infantry charges against prepared positions while continuing to dream of unleashing massed cavalry charges after breakthroughs that, on the Western Front at least, never came. Given the rather conservative outlook of most of the leaders, it is not surprising that they were slow to recognize the full potential and implications of the technologies at their command, and it thus took several years before the war took on most of its most modern features. This also meant that, despite the national loyalties and enthusiastic willingness of most scientists to participate, the military authorities were slow to find the most effective means of mobilizing them for war work. The military-related innovations that emerged from this work did not, on the whole, arise from scientific research during the war. Instead, they primarily made use of previously known scientific or technical knowledge utilized in new ways, or on a far greater scale and sophistication than previously experienced. The most significant impact of the war on fundamental scientific innovation was negative, diverting human and material resources from disinterested research to short-term, destructive purposes that made it possible to take 20th-century warfare to a new level of totality and horror.

Ultimately, therefore, the most significant scientific consequence of the war was that it militarized modern science, if only by demonstrating unmistakably that even ostensibly innocuous civilian scientific work could produce indispensable tools for modern warfare. Moreover, warfare itself had become more dependent upon such scientific innovation. The “chemists’ war” taught this lesson most clearly by publicizing the “dual-use” characteristics of such peacetime products as synthetic dyes and ammonia. As the British General Harold Hartley (1878-1972) wrote in reporting on an Allied inspection tour of German chemical factories in February 1919, “In the future...every chemical factory must be regarded as a potential arsenal.”[37] But the same principle would apply to a host of disciplines, including physics, engineering, even biology. The widespread perception of the militarization of science, and the fear that German science might emerge even stronger to fight a victorious “war after the war,” helps to explain the Allied scientific leaders’ insistence on excluding the Germans from the international scientific community at the end of the war. Henceforth it would no longer be possible to draw a convenient dividing line between civilian and military technologies, a factor that helped to undermine the Allied efforts to disarm Germany through the Versailles Treaty and ultimately shaped planning for the Second World War. But this blurring of the distinction between the civilian and the military, already advanced in the First World War, came to tragic fruition in the Second, the epitome of modern “total war.”

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Notes

1. ↑ See especially Chickering, Roger/Förster, Stig (eds.): Great War, Total War. Combat and Mobilization on the Western Front, 1914-1918, Cambridge 2000.
2. ↑ Edgerton, David: The Shock of the Old. Technology and Global History since 1900, New York 2007, pp. 143, 158-159.
3. ↑ For logistics see Brown, Ian M.: Transportation and Logistics, in: Daniel, Ute / Gatrell, Peter/Janz, Oliver/Jones, Heather et. al. (eds.): 1914-1918-online. International Encyclopedia of the First World War, issued by Freie Universität Berlin, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10454 (Brown also discusses the special logistical issues of non-European fronts); for military medicine in general, see Bergen, Leo van: Medicine and Medical Service. In: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10221; for the influenza epidemic, see Phillips, Howard: Influenza Pandemic. In: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10148; for psychiatry and shell shock, see: Reid, Fiona: War Psychiatry. In: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10288. For the humanities and social sciences in an academic context, see Donson, Andrew: Schools and Universities. In: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10346; see also selected articles on science and technology in individual countries.
4. ↑ Cf. Forman, Paul/Heilbron, John L./Weart, Spencer: Physics Circa 1900. Personnel, Funding, and Productivity of the Academic Establishments, in: Historical studies in the physical sciences 5 (1975); Kern, Stephen: The Culture of Time and Space 1880-1918. With a New Preface, Cambridge, MA 2003.
5. ↑ Vom Brocke, Bernhard: Wissenschaft und Militarismus. Der Aufruf der 93 „An die Kulturwelt!“ und der Zusammenbruch der internationalen Gelehrtenrepublik im Ersten Weltkrieg, in: Calder, William M./Flashar, Hellmut/Lindken, Theodor (eds.): Wilamowitz nach 50 Jahren, Darmstadt 1985; Nicolai, Georg Friedrich: Die Biologie des Krieges. Betrachtungen eines Naturforschers, den Deutschen zur Besinnung, Zürich 1919.
6. ↑ Levenson, Thomas: Einstein in Berlin. New York 2003, pp. 84-86, 110-114, 129.
7. ↑ Cited in Heilbron, John L.: H. G. J. Moseley. The Life and Letters of an English Physicist, 1887-1915, Berkeley 1974, p. 124.
8. ↑ Fordham, Elizabeth: Universities, in: Winter, Jay M./Robert, Jean-Louis (eds.): Capital Cities at War. Paris, London, Berlin, 1914-1919, vol. II: A Cultural History, Cambridge 2007, pp. 235-79; Irish, Tomás: The University at War, 1914-25. Britain, France, and the United States, Basingstoke 2015.
9. ↑ Cf. Johnson, Jeffrey Allan: Women in the Chemical Industry in the First Half of the 20th Century, in: Tobies, Renate/Vogt, Annette (eds.): Women in Industrial Research, Stuttgart 2014, pp. 119-144. On Curie see Quinn, Susan: Marie Curie. A Life, New York 1995, pp. 361-371.
10. ↑ Lepick, Olivier: La Grande Guerre chimique. 1914-1918, Paris 1998, pp. 54-56, 93-119.

11. ↑ Chancerel, Pierre: Raw Materials. In: 1914-1918-online, Berlin 2015-07-16. DOI: http://dx.doi.org/10.1546333/ie1418.10686; Schwarz, Angela: Science and Technology (Germany). In: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10413; Marsch, Ulrich: Zwischen Wissenschaft und Wirtschaft. Industrieforschung in Deutschland und Grossbritannien, 1880-1936, Paderborn et al. 2000, pp. 293-338; Szöllösi-Janze, Margit: Fritz Haber, 1868-1934. Eine Biographie, Munich 1998, pp. 256-408. The best discussion of German war corporations is in Roth, Regina: Staat und Wirtschaft im Ersten Weltkrieg. Kriegsgesellschaften als kriegswirtschaftliche Steuerungsinstrumente, Berlin 1997.
12. ↑ MacLeod, Roy M.: L'Entente chimique, in: Aubin, David/Bret, Patrice (eds.): Le sabre et l'éprouvette. L'invention d'une science de guerre, 1914-1939, in: 14-18 Aujourd'hui-today-heute (2003), pp. 135-152; Schroeder-Gudehus, Brigitte: Les scientifiques et la paix. La communauté scientifique internationale au cours des années vingt, Montréal 1978. Greenaway, Frank: Science International. A History of the International Council of Scientific Unions, Cambridge 1996.
13. ↑ For weapons overall see Audoin-Rouzeau, Stéphane: Weapons, in: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10417. Translated by: De Schaepdrijver, Sophie; also Cornish, Paul: Machine Gun, in: 1914-1918-online, Berlin 2015-12-02. DOI: http://dx.doi.org/10.1546333/ie1418.10779.
14. ↑ Storz, Dieter: Artillery, in: 1914-1918-online, Berlin 2014-12-16. DOI: http://dx.doi.org/10.1546333/ie1418.10510. Translated by: Reid, Christopher.
15. ↑ For the tactical and strategic context of these developments see Philpott, William: Warfare 1914-1918. In: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10172.
16. ↑ Palazzo, Albert: Seeking Victory on the Western Front. The British Army and Chemical Warfare in World War I, Lincoln 2000, pp. 40 and 90.
17. ↑ Storz, Dieter: Artillery, in: 1914-1918-online, Berlin 2014-12-16. DOI: http://dx.doi.org/10.1546333/ie1418.10510.
18. ↑ As shown in Figure 1 of Brown, Transportation and Logistics 2014.
19. ↑ Dutrône, Christophe: Paris Guns. In: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10335.
20. ↑ Travis, Anthony S.: The Synthetic Nitrogen Industry in World War I. Its Emergence and Expansion, Cham 2015.
21. ↑ Baumann, Timo: Giftgas und Salpeter. Chemische Industrie, Naturwissenschaft und Militär von 1906 bis zum ersten Munitionsprogramm 1914/15, Düsseldorf 2011.
22. ↑ Still the best general work is Haber, L. F.: The Poisonous Cloud. Chemical Warfare in the First World War, Oxford, UK 1986; see also Lepick, Olivier: La Grande Guerre chimique. 1914-1918, 2d ed., Paris 1998; Martinetz, Dieter: Der Gaskrieg 1914/18. Bonn 1996; and Girard, Marion: A Strange and Formidable Weapon. British Responses to World War I Poison Gas, Lincoln 2008.
23. ↑ Steen, Kathryn: The American Synthetic Organic Chemicals Industry. War and Politics, 1910 – 1930, Chapel Hill 2014, pp. 95-112. On US chemical warfare development in general see Heller, Charles E.: Science and Technology (USA). In: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10292.
24. ↑ Crowell, Benedict: America's Munitions 1917-1918, Washington, DC 1919.

25. ↑ Eckert, Michael: The Dawn of Fluid Dynamics: A Discipline Between Science and Technology, Hoboken 2006, pp. 57-82; Ortner, M. Christian: The Austro-Hungarian Artillery from 1867 to 1918. Technology, Organization and Tactics, Vienna 2007.
26. ↑ As argued in Morrow, John H.: The Great War in the Air. Military Aviation from 1909 to 1921, Washington, DC 1993.
27. ↑ Woodman, Harry: Early Aircraft Armament, London, 1989.
28. ↑ Bowyer, Chaz: Handley Page Bombers of the First World War, Bourne End, Bucks 1992.
29. ↑ Details in Crowell, America's Munitions 1919, pp. 221-226; ;"); see also Arnold, Chris: Steel Pots: The History of America's Steel Combat Helmets, San Jose 1997; Baer, Ludwig: The History of the German Steel Helmet, 1916-1945, San Jose 1985.
30. ↑ Churchill, Winston: The World Crisis. New York 1931, p. 745; for British tank development see Hartcup, Guy: The War of Invention. Scientific Developments, 1914-18, London 1988; on the French see Audoin-Rouzeau, Weapons 2014.
31. ↑ Tworek, Heidi J.S.: Wireless Telegraphy. In: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10347.
32. ↑ Showalter, Dennis E.: Tannenberg. Clash of Empires, 1914, Washington, DC et al. 2004.
33. ↑ Brose, Eric: Arms Race prior to 1914, Armament Policy, in: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10219; see also Soubiran, Sébastien: in Aubin/Bret, Le sabre et l'éprouvette 2003, pp. 153-166.
34. ↑ Medlock, Chelsea Autumn: Lusitania, Sinking of, in: 1914-1918-online, Berlin 2014-10-08. DOI: http://dx.doi.org/10.1546333/ie1418.10051.
35. ↑ Steen, American 2014, pp. 1-2.
36. ↑ Hackmann, Willem D.: Seek & Strike. Sonar, Anti-Submarine Warfare, and the Royal Navy, 1914-54, London 1984.
37. ↑ Cited in Johnson, Jeffrey Allan/MacLeod, Roy M.: The War the Victors Lost. The Dilemmas of Chemical Disarmament, 1919-1926, in: MacLeod, Roy M./Johnson, Jeffrey Allan (eds.): Frontline and Factory. Comparative Perspectives on the Chemical Industry at War, 1914-1924, Dordrecht 2006, pp. 222.

Selected Bibliography

Aubin, David / Bret, Patrice (eds.): **Le sabre et l'éprouvette. L'invention d'une science de guerre, 1914-1939**, 14-18 Aujourd'hui-today-heute, Paris 2003: Agnès Viénot.

Baumann, Timo: **Giftgas und Salpeter. Chemische Industrie, Naturwissenschaft und Militär von 1906 bis zum ersten Munitionsprogramm 1914/15**, Düsseldorf 2011: Universitäts- und Landesbibliothek der Heinrich-Heine-Universität Düsseldorf.

Brocke, Bernhard vom: **Wissenschaft und Militarismus. Der Aufruf der 93 'An die Kulturwelt!' und der Zusammenbruch der internationalen Gelehrtenrepublik im Ersten Weltkrieg**, in: Calder, William M. / Flashar, Hellmut / Lindken, Theodor (eds.): Wilamowitz nach 50 Jahren, Darmstadt 1985: Wissenschaftliche Buchgesellschaft, pp. 649-719.

Chickering, Roger / Förster, Stig (eds.): **Great War, total war. Combat and mobilization on the Western Front, 1914-1918**, Washington; Cambridge; New York 2000: German Historical Institute; Cambridge University Press.

Eckert, Michael: **The dawn of fluid dynamics. A discipline between science and technology**, Weinheim 2006: Wiley-VCH.

Edgerton, David: **The shock of the old. Technology and global history since 1900**, Oxford; New York 2007: Oxford University Press.

Fordham, Elizabeth: **Universities**, in: Robert, Jean-Louis / Winter, Jay Murray (eds.): Capital cities at war. Paris, London, Berlin 1914-1919, volume 2, Cambridge et al. 2007: Cambridge University Press, pp. 235–279.

Freemantle, Michael: **The chemists' war, 1914-1918**, Cambridge 2015: Royal Society of Chemistry.

Galison, Peter / Roland, Alex (eds.): **Atmospheric flight in the twentieth century**, Dordrecht; Boston 2000: Kluwer.

Greenaway, Frank: **Science international. A history of the International Council of Scientific Unions**, Cambridge; New York 1996: Cambridge University Press.

Haber, Ludwig Fritz: **The poisonous cloud. Chemical warfare in the First World War**, Oxford; New York 1986: Clarendon Press ; Oxford University Press.

Hackmann, Willem Dirk: **Seek and strike. Sonar, anti-submarine warfare, and the Royal Navy, 1914-54**, London 1984: H.M.S.O..

Hartcup, Guy: **The war of invention. Scientific developments, 1914-18**, London; Washington 1988: Brassey's Defence Publishers.

Irish, Tomás: **The university at war, 1914-25. Britain, France, and the United States**, Basingstoke; New York 2015: Palgrave Macmillan.

Lepick, Olivier / Chaunu, Pierre: **La grande guerre chimique, 1914-1918** (2 ed.), Paris 1998: Presses universitaires de France.

MacLeod, Roy: **Sight and sound on the Western Front. Surveyors, scientists, and the ‘battlefield laboratory’, 1915-1918**, in: War & Society 18/1, 2000, pp. 23-46, **doi**:**10.1179/072924700791201405**.

MacLeod, Roy / Johnson, Jeffrey Allan (eds.): **Frontline and factory. Comparative perspectives on the chemical industry at war, 1914-1924**, Archimedes, 16, Dordrecht 2006: Springer.

Marsch, Ulrich: **Zwischen Wissenschaft und Wirtschaft. Industrieforschung in Deutschland und Grossbritannien, 1880-1936**, Paderborn 2000: Schöningh.

Martinetz, Dieter: **Der Gaskrieg 1914/18. Entwicklung, Herstellung und Einsatz chemischer Kampfstoffe. Das Zusammenwirken von militärischer Führung, Wissenschaft und Industrie**, Bonn 1996: Bernard & Graefe.

Mendelsohn, Everett: **Science, scientists, and the military**, in: Krige, John / Pestre, Dominique (eds.): Companion to science in the twentieth century, London 2003: Routledge, pp. 175-202.

Morrow, John Howard: **The Great War in the air. Military aviation from 1909 to 1921**, Washington, D.C. 1993: Smithsonian Institution Press.

Steen, Kathryn: **The American synthetic organic chemicals industry. War and politics, 1910-1930**, Chapel Hill 2014: The University of North Carolina Press.

Steinhauser, Thomas: **Hundert Jahre an der Schnittstelle von Chemie und Physik. Das Fritz-Haber-Institut der Max-Planck-Gesellschaft zwischen 1911 und 2011**, Berlin; Boston 2011: De Gruyter.

Szöllösi-Janze, Margit: **Fritz Haber, 1868-1934. Eine Biographie**, Munich 1998: C. H. Beck.

Tobies, Renate / Vogt, Annette (eds.): **Women in industrial research**, Stuttgart 2014: Franz Steiner.

Travis, Anthony S.: **The synthetic nitrogen industry in World War I. Its emergence and expansion**, Cham 2015: Springer.

Woodman, Harry: **Early aircraft armament. The aeroplane and the gun up to 1918**, London 1989: Arms and Armour.

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