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The Structure of Military-Technical Transformation
William H. McNeill, 1994

We live under an extraordinary cloud of uncertainty. Technological changes alter human experience in far-reaching ways many times over in a single lifetime. I, for instance, can remember when radios were squawking toys boys built at home in hope of hearing broadcasts from Schenectady, and then, a few years later during the Battle of Britain, came the wonder of Edward Murrow's trans-Atlantic voice, clear as a bell, with bomb explosions muffled in the background. More recently, computers began to sprout around me everywhere; and an array of other novelties that did not exist when I was born, or were unavailable to ordinary people, have altered our daily routines- cars, airplanes, frozen food, plastics, TV, E-mail, fax machines, antibiotics and many more.

Because technological change is so pervasive and powerful among us- and not least among the military- we are tempted to assume that restless technological transformation is natural and normal. But the historical record shows that this is not so. In times past, most people lived out their lives in accustomed fashion, using the same things their forefathers had used, and making no deliberate effort to alter or improve them. Human inventive capabilities, however real, came into play only occasionally and exceptionally, whereas we must adjust to an avalanche of innovation, some of it planned and deliberate, some of it unforeseen and unwelcome.

My assignment at this Sixteenth Military History Symposium of the United States Air Force Academy is to ask how and why we find ourselves in such an unusual circumstance, and, in particular, to explore what it was that provoked the extraordinary military-technical transformation of the industrial age that started in the 1840s and, despite some subsequent slowdowns, has spread and accelerated, rather jerkily, ever since.

Let me begin by pointing out that on the face of things, any significant military-technical change is undesirable simply because it makes trouble and increases risk. To use a new weapon effectively, fighting men have to change their habits and learn new skills. This is bothersome in itself; and, in practice, success is never sure ahead of time. In war, sensible persons therefore shy away from compounding the risk and uncertainty created by the enemy, by the weather and by all the other friction of war, and rigorously refrain from trying anything new. Instead, prudent fighting men rely on experience, adhere carefully to time-tested ways, and, in short, behave exactly like Colonel Blimp. He became an object of cartoon ridicule in the 1930s, yet Colonel Blimp's frame of mind constituted the norm of sane military management in past ages. How did he get so out of step with our times?

The changeability of military technology since the 1840s is all the more surprising because this was a time when military men encased themselves in ever thicker layers of bureaucracy. And bureaucracies are not usually inclined to innovation. After all, agreeing with one's bureaucratic superiors is the way to get ahead, while conforming to precedent can keep the unambitious out of trouble. And when an awkward problem arises, it can always be referred to a committee, thereby postponing action indefinitely. Routine is therefore at the heart and core of bureaucratic behavior; yet from the 1880s important segments of the military bureaucracies of the most powerful nations of the world systematically began to encourage radical technical innovation. This occurred in spite of obvious risks and ever mounting costs, as one improved weapon system after another displaced its predecessors in rapid and apparently endless succession. Odd behavior indeed, and all the more so since many expensive innovations were soon scrapped as obsolete and never used in action. Moreover, when new weapons were employed in World Wars I and II, they did not bring easy victory, but instead magnified destruction enormously, hurting winners as well as losers. Why did it happen? How did long-standing national rivalries boil over into such a risky and unsettling arms race?

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An historian is always tempted to look for similar experiences in the deeper past, and plausible historical parallels to the arms races of the industrial era can be found. Two eras in particular occur to me as faint foreshadowings of the modern experience. One came in the Hellenistic age, when rival rulers employed a handful of military engineers to build increasingly powerful siege engines and larger and larger war ships. A second period of rapid and deliberate technological change occurred in China under the Sung dynasty (960-1279) when gunpowder weapons and a galaxy of other military inventions (especially naval) burst upon the scene.

But both these outbreaks of technical instability turned out to be relatively short-lived. Hellenistic engineers quickly reached technical limits of size, strength and resilience set by the wood and fiber available for their catapults and ships; and the political rivalries that had stimulated that arms race disappeared once the Romans established their military supremacy throughout the Mediterranean coastlands. In the Far East the pattern of events was different. Sung officials' efforts to encourage military invention in hope of warding off barbarian assault failed. Instead, after borrowing some high tech, up-to-date weaponry from their enemies, the Mongols were able to complete their conquest of China in 1279; and after the Mongols were driven out of China in 1368, subsequent Chinese regimes regularly preferred diplomacy to war, and were cautious- though never completely inflexible- in investing in new military technology.

But, of course, the Mongol storm was not confined to China; and their conquests spread knowledge of the explosive force of gunpowder throughout Eurasia. Among the peoples whose traditional ways of war were thus affected, the European response was by far the most radical and persistent. As a result, China's initial flirtation with systematic pursuit of technological improvement under the Sung dynasty was soon overshadowed by Europeans' enduring enthusiasm for more and better guns, large and small.

In a sense, the modern arms race dates back to the reckless way rival European rulers set out to build wall-destroying artillery in the 14th and 15th centuries. To begin with, critical skills for casting large metal objects were narrowly circumscribed around the city of Liege, but just as guns were becoming really powerful and comparatively mobile, the breakup of the Burgundian lands after Charles the Bold's death in 1477 divided Europe's gun-casting capabilities between French Valois and German Hapsburg rulers. As a result of this happenstance of dynastic politics, no single monarch or state was ever able to monopolize big guns in Western Europe, whereas in all the other civilized lands of Eurasia, when effective artillery arrived on the scene it was swiftly monopolized by a single ruler. Comparatively vast empires resulted-Ottoman, Safavid, Mughal, Muscovite, and, of course, the Chinese, where, however, big guns were less important than elsewhere simply because the Chinese rulers had no wish to destroy walls their soldiers defended against the continuing nomad danger.

Thereafter, Western Europe remained technologically innovative, largely because state rivalries persisted in nourishing deliberate efforts to improve weaponry and military organization. Any new practice or supenor weapons design spread very rapidly from one army to another. This had the effect of maintaining an ever-shifting and ever-precarious balance of power within Europe; whereas in all the rest of Eurasia, once rulers succeeded in monopolizing heavy guns, they saw no reason to tinker with a weapons system that enabled them to break into the stronghold of any defiant local potentate or potential rival who lived within range of their artillery and field army.

The modern history of Japan offers a particularly vivid and convincing example of how dispersed access to guns accelerated military-technical change for about half a century, until a single victor emerged whose policy of restricting access to guns stabilized Japan's new political-military order for the ensuing two hundred years.

Samurai swordsmen and archers found nothing to admire in clumsy guns when this Chinese invention first came to their attention, and the success with which the Japanese repelled massive Mongol invasions in 1274 and 1281 confirmed Japanese warriors in their disdain for newfangled weaponry from abroad. But these attitudes changed abruptly after 1542, when local military leaders realized that the (by then much improved) guns, large and small, that European sailors carried on shipboard as a matter of course offered enormous advantages in the local feuds that had long simmered among them. Japanese craftsmen quickly learned to produce muskets and larger guns as those Europeans employed, and when military rivals hurried to acquire these new weapons in ever larger numbers, the scale and decisiveness of warfare escalated very quickly. Commoners armed with muskets proved able to overwhelm the most expert swordsmen, and within half a century, a low-born warlord, Toyotomi Hideyoshi (d. 1598), was able to crush all rivals and establish his authority throughout the country.

His successors, the Tokugawa Shoguns, sought to maintain their sovereign power and stabilize Japanese society by weaving a complex network of alliances and agreements with local clan leaders throughout the country. All concerned were eager to reaffirm the prestige and privileges of samurai swordsmen whose traditional role in society had been seriously compromised by the sudden importance of musketeers. Accordingly, after repressing a serious revolt (1637-38), the Tokugawa Shoguns proceeded to disarm commoners by confiscating guns and prohibiting their manufacture. In addition, by cutting off contact with the outside world, except for a single Dutch ship permitted to anchor off an island in Nagasaki harbor once a year, the Shoguns made sure that unauthorized weapons and other subversive novelties (like Christianity) could not be smuggled into the country.

These measures allowed samurai swordsmen to retain their traditional primacy in Japanese society for the next two hundred years, even though a lasting peace deprived them of their function as fighting men. This paradoxical situation was eventually upset when in 1854 Commodore Oliver Perry, largely on the strength of his naval guns, compelled the Japanese government to change its policy of excluding foreigners, thus inaugurating a new era of tumultuous military-political upheaval that climaxed in World War II.

Japan's fluctuation between extremely rapid, violent accommodation to new weapons and a no less remarkable, deliberately contrived stability exaggerated a parallel fluctuation in European accommodation to gunpowder weapons. For the radical political-military upheaval that prevailed in Europe, when guns were new, slowed down very perceptibly after 1648, when comparatively well consolidated states and bureaucratically organized standing armies emerged from the Thirty Years' War. Political rivalries did not disappear, and military-technical change did not come to a complete halt. But the uniformity of equipment and training that made large standing armies more efficient also increased the cost of introducing new weapons very sharply, since many thousands of any new model were required if the benefits of uniformity were not to be lost. This became a very persuasive consideration for all European military administrators. As a result, the small, successive changes of design (cumulatively important, though often trifling in themselves) that had come very quickly in earlier centuries slowed almost to a halt. The fact that the British army used the same musket from 1690 to 1840 aptly illustrates the resulting stabilization of Old Regime armies, for during all those years unchanging muzzle-loading muskets were the principal infantry weapon, and infantry remained the undisputed queen of battles.

Naval design also attained remarkable stability during these decades, and international rivalries simmered down as well. When the ideological fires fed by Protestant-Catholic controversy subsided, war became little more than the sport of kings, reinforced by the rivalries of merchants along Europe's Atlantic face. By 1750 or so it certainly looked as though Europe too, like Japan after 1636, had adjusted to the shock of gunpowder weaponry and was settling down towards comparative stability in matters of military technology and political structure.

But, as we all know, that was not the way things went. Instead, international rivalries intensified, beginning with the Seven Years' War, 1756-63, followed by the wars of the American Revolution, 1776-83 and rose to a notable crescendo with the wars of the French Revolution and Napoleon, 1791-1815. This succession of wars, in turn, provoked unprecedented efforts to mobilize human and material resources, transforming the economy and society of Europe and inaugurating the industrial age in which we live.

Nonetheless, although all the years of war between 1756 and 1815 stretched Old Regime military-political management to the limit, they did not alter weapons in any notable fashion. To be sure, the French had responded to their defeats in the Seven Years' War by improving the design of their field artillery, and enjoyed perceptible advantages at Valmy against the Prussians (1792) and at Toulon (1793) against the British as a result. But other armies soon caught up, while other innovations of the war years, such as rockets, observation balloons, and field telegraph, had only marginal importance. The same was true of navies, although the British resort to larger caliber guns, the so-called carronades, prefigured what was later to happen to naval armament, without, however, transgressing the limits set by sails, muzzle-loading cannon, solid shot, and wooden ships.

Despite the Revolution, an almost unbending technological conservatism prevailed in the French armed forces as well as among their politically conservative enemies. This is nicely symbolized by the fact that Napoleon disbanded the balloon observation corps that civilian initiatives had introduced to the French army in the revolutionary year of 1793; and Wellington, after witnessing a trial rocket-firing during which the missiles' erratic course endangered him and other observers, refused to have anything more to do with weapons that, when all went well, doubled the range of existing artillery. (Nevertheless, as the Star Spangled Banner may remind us, the British navy and several continental armies continued to employ rockets, abandoning them only in the 1840s when radically improved guns had begun to match the range and improve upon the accuracy of rocket fire.)

What eventually upset military-technological conservatism was nevertheless an indirect effect of the mounting intensity of warfare that distracted Europe between 1756 and 1815. Demand for iron, uniform cloth and other commodities assumed unprecedented scale when millions of men were mobilized into armies and navies and had to be equipped. When war ended, this demand suddenly ceased, facing the mills, factories and artisan shops that had supplied Europe's armed forces with a crisis of survival. Many closed down, especially on the continent, where state arsenals had played the principal part in war production. In Great Britain, however, a host of civilian enterprises had supplied both British and continental forces with iron, cloth and other materials on an unprecedented scale; and many of the forges and factories that had sprouted luxuriantly during the war years succeeded in finding new civilian markets for their products after 1815, though not without undergoing a difficult post-war depression.

The fate of the iron industry was especially important, for the cheapening of iron, thanks to efficient new furnaces built to supply the British navy's voracious appetite for cannon and other hardware (anchors, chains and the like), permitted the rapid development of new civilian markets. In particular, steam engines, steamships and railroads soon were constructed largely of iron; while bridges and new forms of heavy machinery also expanded the civilian demand. What we have learned to call the first industrial revolution, based principally on coal and iron, thus moved into high gear; and with it dawned the industrial age with which this conference is concerned.

At first, the military market was noticeably absent. After 1815, demobilization and military cut-backs everywhere prevailed. Military men were not inclined to experiment with novelty of any kind, and civil administrators were interested mainly in reducing the cost of the armies and navies that each government chose to maintain. For a while, efforts at making the Concert of Europe into a Holy Alliance against revolution affected diplomacy and perhaps helped to dampen the rivalries that had emerged from the peace settlement. At any rate, peace and stability were widely wished for after the storms and strains of revolutionary war, and no responsible authority entertained the notion of trying to upset the balance of power by trying to improve upon existing weapons systems.

This post-war era ended abruptly in 1841 when key figures in the French navy came to feel that their nation and service had been humiliated by failure to support the French protege, Mehmed Ali of Egypt, in his collision with the Ottoman Sultan and the British navy. Mehmed Ali (1769-1848) was an Albanian soldier of fortune, who seized control of the Ottoman province of Egypt in 1805, and then relied mainly on French advisers to help him modernize the country. His army, trained and equipped along European lines, soon proved far superior to any rivals in the eastern Mediterranean; and when the Ottoman Sultan imprudently attacked his over-mighty subject in 1838, Egyptian victories quickly threatened to topple the Ottoman regime. But the British were unwilling to see a French protege' installed in Constantinople, and by using their Mediterranean fleet to blockade Egypt made it impossible for Mehmed Ali to supply his army by sea. Land communications were inadequate, so the Egyptian army had to withdraw and submit to a settlement dictated by the European powers. French assent to this upshot was very grudging, and came only after King Louis Philippe refused to risk war in support of Mehmed Ali, thereby provoking the angry resignation of his fiery, patriotic prime minister, Adolph Theirs.

Memory of this humiliation rankled, and one of Louis Philippe's sons backed French naval officers when they proposed a simple way to counter Great Britain's galling naval preponderance. Their plan was to install steam engines in French warships, thus allowing them to move against the wind without having to tack. The British immediately felt exposed to cross-Channel invasion, since by choosing a time when the direction of the wind would prevent sailing vessels from matching the mobility of steam-powered ships, even a few of the remodeled French ships could neutralize the Royal Navy's numerical superiority. With this, the fat was in the fire. Not surprisingly, the British Admiralty swiftly matched the French by installing steam engines of their own; and the superior industrial base and political tradition that Britain had inherited from the Napoleonic Wars made it comparatively easy for them to maintain superiority at sea despite a succession of other French efforts to renew the challenge by launching further technical innovations one after another.

Until the 1880s, British responses to French initiatives remained reluctant. Any significant change in naval technology meant that the Royal Navy's existing stock of battle ships, and the skills of sailing and fighting them, lost part of their value. Change was troublesome and costly. It was also distasteful. Spic and span sailing vessels had to take dirty coal on board so that nasty steam engines could spew the sails with even dirtier smoke. Equally distressing was that aristocratic naval officers had to accept uncouth mechanics as colleagues in managing their ships.

But despite heart-felt regret, by the 1840s Britain's traditional reliance on wooden walls was no longer possible. Another French technical invention made that evident to all concerned. As early as 1822 a French army officer, Henri J. Paixhans, succeeded in designing a gun that could fire explosive shells safely, and published a book explaining how his shell guns could easily destroy any wooden warship. In a trial firing two years afterwards Paixhans' guns did indeed destroy an old hulk, just as he had predicted. Thereupon, after appropriate deliberation lasting some thirteen years, the French navy decided in 1837 (just before the humiliation of 1841) to install the new shell-firing guns on shipboard. The Royal Navy and other European navies, including the Russian, swiftly followed suit.

From that time onwards, naval officers realized that sea battles, as they had known them, were a thing of the past. Lying yard arm to yard arm in the approved Nelsonian fashion, and firing broadsides of solid iron shot until the less efficient (or merely unlucky) ship was pounded into submission had become impossible. One or two hits from exploding shells sufficed to cripple any ship, (and set it on fire) as the Russians demonstrated at Sinope in 1853 by shelling the Turkish navy into oblivion in a few hours. That meant, all of a sudden, that the Russian navy could sail to Constantinople unopposed; and it was this prospect that persuaded the French and British governments to cooperate in sending ships and soldiers to help the Turks, thus launching what became known as the Crimean War (1854-56).

From many points of view, this short and half-forgotten war marks the point in European history when the systematic technological conservatism that had dominated military management since 1648 broke down. The French and British navies both accepted the premise that wooden ships had become obsolete, and competed in building steam-powered, armored vessels of wildly diverse designs, intended to carry enormous mortars and other heavy artillery for attacking the Russians' fortified naval base of Sevastopol. But existing steam engines were comparatively weak and consumed a great deal of coal so that naval vessels still had to rely on sails for long distance cruising. Awkward hybrids therefore prevailed in naval design for the next thirty years before sails could be abandoned.

On land the technological impact of the Crimean War was rather more significant. In the first place, acute problems in meeting sudden increases in the demand for hand guns provoked Europeans to imitate what came to be known as the American system of manufacture for small arms, thus introducing mass production methods to the armaments industry on a really large scale. This was, I suppose, the most fundamental step yet taken in the industrial arms race, liberating an important segment of military supply and design from the shackles of artisan modes of production. Thereafter, it became comparatively cheap and easy to modify small arms while still retaining the benefits of uniformity even when supplying hundreds of thousands or even millions of men. In addition, the Crimean War brought civilian entrepreneurs to the forefront of artillery design and manufacture. Thereafter, private pursuit of profit began to reinforce national rivalries in encouraging technological change in armaments, thus assimilating military technology to the competitive model that already prevailed in the civilian marketplace.

Details of these transformations demonstrate vividly the indirect and unpredictable paths of change in human affairs. Mass production, for instance, began with the War of 1812 when the American government found itself desperately short of muskets, largely because the French had supplied American forces in the Revolutionary War from across the Atlantic. A corps of artisans able to turn out standard muskets therefore did not exist in the United States when war with Britain in 1812 created a sudden need for such weapons. Ingenious Yankees in the Connecticut river valley eventually responded by inventing automatic and semi-automatic machines- the so-called American System of Manufacture- that could make gun parts accurately enough to allow a workable weapon to be assembled from interchangeable parts. Invention and installation of such machinery took a while, and assembly lines were not fully operational until about 1850. The new machines were costly and often wasted material, but turned out gun parts far faster than had previously been possible. Moreover, workers tending the machines needed no special skill. European gun smiths, by contrast, used simple hand tools- hammer and file for the most part- and were economical of raw materials; but since hand-made parts were never exactly the same, each gun had to be carefully fitted together with delicate filing and other time-consuming adjustments.

American gun makers, of course, had only a relatively modest market for their standardized products at home. Hoping to expand his sales, one of them, Samuel Colt, brought his wares to the London Exhibition of 1851, where he astonished the public by disassembling revolvers, scrambling the parts and then reassembling and firing his pistols. The possibility of mass production of standardized gun parts was therefore familiar in Western Europe when the Crimean War provoked a sudden surge in demand for small arms. But established artisan methods set sharp limits on how quickly production could be increased, since training skilled gunsmiths took time. On top of that, both English and French armies were experimenting with muzzle-loading rifles, using a new bullet invented by another Frenchman, Captain Claude Minie, in the mid- 1840s. Rifles were more accurate and carried more than smooth-bore muskets, but to attain these advantages existing smooth-bore muskets had to be rifled- another exacting task for the limited number of gun smiths who could do the job. Under these circumstances, British gun smiths tried to take advantage of their situation by raising prices, with the resulting public controversy delaying instead of accelerating output.

This experience persuaded the British government to mechanize small arms manufacture by importing milling machines from the United States. Accordingly, a new arsenal to manufacture military rifles was set up at Enfield in 1855 and became fully operational four years later, after the war was over. Other forms of mass production were easier to organize, so that, for instance, a machine set up for the purpose in the Woolwich arsenal began to turn out 250,000 Minie bullets a day and a second machine combined bullet and cartridge into a single package at a comparable rate. The advantages of mass production were just as obvious to other governments so that within a decade of the time mechanized rifle production at the new Enfield Arsenal came on line, similar establishments arose in all the other leading countries of Europe and spread to Turkey and Egypt as well.

Increased rates of manufacture made the introduction of new designs for small arms feasible again. The difference was enormous, for when first France (1866), and then Prussia (1869), decided to re-equip their armies with modern up-to-date rifles, it took only four years to provide every soldier with the improved weapons. By contrast, when in 1840 the Prussians had decided to re-equip their army with an older design of breech-loading rifle- the so-called needle gun, invented by Johann Nicholas von Dreyse- it took twenty-six years to complete the changeover. The artisans Dreyse employed to manufacture the new weapons could not produce more than 10,000 a year; and even when the resources of the state arsenals were brought to bear, production only increased to about 22,000 per annum. By comparison, in 1863, when the Prussians were still straining to complete their 1840 program, the new Enfield arsenal turned out 100,370 rifles in a single year, routinely and without any exceptional emergency to spur extra effort.

Long-standing obstacles to technological change of small arms were thus swept away, and inventors rapidly developed increasingly effective rifle (soon, also, machine gun) designs so that, from time to time, European armies continued to re-equip their infantrymen- by the millions. Each such change required new drill, new tactics, and new logistics to match the guns' increasing appetite for ammunition. Under the circumstances, familiar routines began to blur and established rules for the conduct of battle became obsolete as the experience of World War I eventually showed. But until 1914 most army officers refused to admit that anything had happened to upset their battle plans. Instead they left technological change to a handful of specialists and assumed that radically improved infantry weapons would have no important effect on how soldiers would have to behave in battle.

But military men were not left to their own devices when it came to changes in artillery design. Instead, the yawning gap between what they expected and what turned out the be the case in 1914-18 widened even further because the manufacture of artillery and other heavy weapons became inextricably entangled with the pursuit of private profit.

This began when individual industrialists decided to apply civilian skills to the manufacture of guns, believing that it would be easy to produce a better weapon than the muzzle-loading cannon that government arsenals turned out. On the continent, it was Alfred Krupp of Essen who pioneered the manufacture of technically superior breech-loading steel artillery. Like Samuel Colt, he announced his technological prowess by exhibiting a few samples at the London Exhibition of 1851. But at first he had difficulty persuading governments to buy his product, partly because steel guns were expensive, partly because they sometimes suffered from casting flaws and fractured unexpectedly, and mostly because military procurement officers were accustomed to acquiring artillery from state arsenals and distrusted the crass and selfish motives of an upstart manufacturer like Alfred Krupp who, after all, expected to make money from selling his guns. Egypt was his first customer (1855); Prussia rather reluctantly followed with a trial batch of 300 guns; but only when the Russians placed far larger orders after 1863 did breech-loading steel artillery really begin to displace bronze muzzle-loaders. Range and rate of fire for field artillery began to increase accordingly; and a long series of improvements came very rapidly thereafter as private firms and state arsenals competed with one another in introducing new designs.

But field artillery was limited by the fact that guns had to be light enough for horses to pull them cross country. No comparable limit affected naval artillery; and the race between ship's armor and big guns therefore became more technologically significant than anything happening to field artillery. The pace of naval change was enormously enhanced by the fact that during the Crimean War two venturesome private manufacturers in England, William Armstrong and Joseph Whitworth, decided it was time to bring military engineering up to the level of civil engineering by showing the government's arsenal how to make bigger and better guns. They both had the resources at their command to design and build prototypes that were in fact superior to existing arsenal products. But persuading military procurement officers to buy newfangled weapons was another matter. Armstrong and Whitworth trumpeted rival claims for the superiority of their guns; and public tests of armor-piercing capability showed both strengths and weaknesses in their competing designs. Intense controversy arose between Whitworth and Armstrong; as well as between those who preferred to entrust the manufacture of big guns to state employees and those who argued that private manufacturers, tainted though they might be by greed, ought to be preferred if their products were indeed superior. Official policy waffled, and, after a brief flirtation with William Armstrong, (persuading Whitworth to give up gun making) the British armed services reverted in 1864 to arsenal production. Thereupon, thanks initially to vigorous sales in the United States, where the Civil War created sudden demand for his big guns, Armstrong developed an international market for his wares, rivaling (and ere long also collaborating with) Alfred Krupp's parallel enterprise.

After his dismissal from official appointment as Engineer of Rifled Ordnance, Armstrong's relation with the Admiralty became intensely ambivalent. He always nourished the hope of selling guns, turrets and other heavy equipment to the Lords of the Admiralty once again, yet more than once he whipsawed the Royal Navy into unwelcome new expenditures in the Arsenal by equipping foreign navies with guns (or complete warships) that out-performed existing British models. From the point of view of the managers of the Royal Navy, he thus matched at home the continued challenge from the French, who from time to time invested in new weapons that promised to make the existing British fleet obsolete.

By the 1880s, resulting uncertainty had become acute. British arsenal designs and production persistently lagged behind innovation originating privately or in French arsenals In particular, two technical changes- one French, one German- made the latest 80-ton muzzle-loading monster guns that British battleships were carrying hopelessly obsolete. First, between 1881 and 1887 the French chose to challenge British naval preponderance by concentrating their naval construction entirely on fast, long-range cruisers, designed for commerce raiding, supplemented by even faster torpedo boats for short-range operations. British ships were too slow to catch the new French cruisers on the high seas; and British naval guns fired too slowly to be able to hit an approaching high speed boat before it came into torpedo range. Thus, in spite of all its expensive efforts at technological modernization, the Royal Navy once again faced the prospect of being unable to safeguard the Channel or to protect British commerce from the French.

The second problem was equally intractable. In 1878-79 Krupp introduced a new line of big steel artillery pieces, suitable for naval use, and designed to take advantage of slow-burning smokeless propellants that had recently been perfected. Demonstration firings showed military observers from all the leading countries of the world that Krupp's new guns completely outclassed muzzle-loaders like those Woolwich arsenal was producing. Obviously, from a British point of view, something drastic had to be done and quickly to preserve the Royal Navy's power and effectiveness.

This was the setting in which the naval arms race assumed a new character, becoming far more expensive, far more radical, and far more important for the national economy of Great Britain and for other countries that chose to challenge British naval preponderance. In a word, what happened was that the modern military-industrial complex came to birth when a small group of technically minded British naval officers, of whom Captain John Arbuthnot Fisher was the ringleader, began to foment and hasten technological changes, believing that if official funds and policy actively promoted improvement in weapon systems, British skill and industrial capacity would suffice to keep the Royal Navy ahead of all rivals indefinitely.

The effect was drastic. Instead of responding sluggishly and regretfully to innovations arising privately or in French arsenals, the Admiralty began to challenge inventors and manufacturers to come up with appropriate new devices, and, before long, helped them to meet development costs for particularly promising innovations. In a sense this was no great departure from established routines. The Admiralty had long been accustomed to specify the size, shape and other characteristics of warships constructed in official dockyards, and the Woolwich arsenal built naval guns to specification as well. Ever since iron and steam had begun to supplant wood and sails, specification for new ships involved departure from former patterns-sometimes very drastic. But by and large, before the 1880s specified innovation merely transferred (with adjustments) existing civilian technologies to naval construction. Naval technology had consistently lagged behind, largely because those in charge were so loathe to abandon old ways and accustomed routines.

But a reckless new spirit, welcoming and accelerating innovation, took root in the 1880s, when Fisher and others like him inaugurated what may be called ‘command technology’ and soon applied it across the entire spectrum of naval purchases. In effect they reversed older relationships between inventors and military procurement officers. Instead of waiting until someone came along with a new device, as army and navy officers had been accustomed to do, and challenging the innovator to prove that the cost and trouble of change over was worth it, the British Admiralty began to define what it wanted in the way of new performance characteristics, and then required arsenal personnel to compete with private manufacturers to see who could most nearly match their desires. Invention thus became deliberate and organized, with the result that innovation in naval technologies soon outstripped civilian engineering in important fields like the development of hydraulic machinery, steam turbines, diesel engines, optical glass, radio communications and electrical control systems- not to mention more obvious matters like steel metallurgy and the chemistry of explosives.

In 1886, when the Admiralty was first authorized to buy materiel from private manufacturers whenever the arsenal could not provide an equivalent item, no one foresaw that the Royal Navy would become as intimately intertwined with heavy industry as it did. But in fact, the arsenal was critically handicapped after 1886 because the massive investment needed to go over to using steel as raw material for guns and ships was never made. Krupp had shown in 1887 that long-barreled, breech-loading steel guns were indisputably superior. Armstrong and the French-both a new private firm, Schneider-Creusot, and arsenal gun makers-responded by investing in steel-making and gun-manufacturing plant; but the Woolwich arsenal was never granted the necessary funds for this radical change over, so that naval procurement increasingly went to private sources.

Naval officers were not prepared to buy abroad nor to depend solely on Armstrong for supplying steel guns and other heavy equipment for their ships. They solved that problem by inducing England's leading steel maker, Vickers, to enter the armaments market in 1888, and sought to play one firm off against the other thenceforth. As the scale of successive naval building programs increased-and increase they did thanks to foreign competition, first from the French, then from Germany, the United States and Japan- price ceased to be decisive in more and more instances. Often only one supplier had the capability of making a particular item. Oftener still, decision of which contracts to award to which firm became an overtly political act. Naval building became a recognized way to counteract the business cycle by keeping men at work in periods of depression. Even more telling, naval contracts exempted English steel makers and other heavy engineering firms from having to compete on world markets with cheaper American and German producers. Navy expenditures (supplemented, but on a comparatively modest scale, by army purchases) became a critical balance wheel for the entire national economy. Indeed, according to Arthur Marder, on the eve of World War I as much as a sixth of the male workforce of Great Britain was employed by the Navy or by prime contractors for the Navy.

Similarly powerful military-industrial complexes swiftly formed in France and Germany, and emerged in the United States as well, without, however, attaining comparable weight in the economic-political life of our nation until during and after World War II. In Japan, on the contrary, the military-industrial complex had been of prime importance for the national economy and for politics ever since the Meiji restoration in 1868. But before World War I, the Japanese were still catching up with European technology; and their version of command technology therefore involved less outright invention and more borrowing (with minor adaptation) than was the case in England, Germany, and France.

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I will not attempt to deal with more recent perturbations and turning points in the history of the wars, arms races and recurrent military-technical transformations that have followed. Other papers at this symposium will shed light on diverse aspects of that vast subject. Instead I wish to conclude with some brief reflections on the process as a whole, aimed at addressing the theme assigned to me: the structure, or perhaps better structures, of society and politics that provoked and sustained the radical changes of the past hundred and fifty years.

First and most obvious: rivalries among sovereign states were an essential ingredient, and when such rivalries provoked actual warfare, the pace of technical change regularly intensified. This needs no argument. Without the French-British rivalry, the naval history of the 19th century, with which I have been mainly concerned in this lecture, would be inconceivable; and this rivalry was what created the world's first self-transforming military-industrial complexes- on both sides of the Channel. The French always relied more on technologically proficient engineers in state service, and never gave their successive naval building programs the consistent political support the Navy enjoyed in Britain, largely because the French army, with far less technologically varied demands on industrial production, always came first. But despite these differences, military purchasing also played a critical role in the development of the French economy in the 19th century, and by the 1890s, the French, like the Germans, had brought private industry into an increasingly close partnership with the state.

At the same time, the actual expression of the state rivalries of Europe depended on what a few key personalities decided at particular times and places. Thus, the almost whimsical way William Armstrong decided to use the resources of his engineering firm to build better guns after reading a newspaper report about how a single field artillery piece had affected the outcome of the Battle of Inkerman had consequences far beyond anything he conceived of when he first sketched how he proposed to build bigger and better gun barrels by sweating layers of wrought iron around one another. Similarly, if Fisher had been more scrupulous in obeying his naval superiors, the public outcry that arose when he secretly primed a well-known journalist with facts about the sorry state of the Royal Navy's armaments in 1884 would not have resulted in the passage of an expanded naval budget- the first of a series of escalating budgets, each supported by a carefully contrived publicity campaign in which newspapermen, naval officers, industrialists, politicians and other interested parties soon learned to cooperate.

Were all these interested parties pre-ordained to coalesce into Great Britain's military-industrial complex? And was that complex pre-ordained to provoke parallel structures in France, Europe, and other countries, including our own? Or did individual decisions and the happenstance of particular response to specific situations have the unintended and unforeseen effect of bringing them together? No one can answer that question with certainty. What happened, happened; but it seems to me that personal decisions, with a heavy freight of unforeseen consequences, were what drove the process as a whole. If key personalities had been different, the course of events would surely have been different too-perhaps diverging only slightly, perhaps fundamentally. For instance, would Germany have set out to rival England's navy without Admiral Alfred von Tirpitz, Kaiser Wilhelm II and the writings of Captain Alfred Thayer Mahan? Would World War I have been fought had the policies of the Kaiser's government not persuaded France, England and Russia to bury their differences and form the Triple Entente? Or would we have atomic warheads today if refugees from Europe had not persuaded Albert Einstein to sign a letter that alarmed President Franklin Roosevelt in 1939? These and many other accidents of human encounter have sustained the arms race ever since it took on its modern form in the 1880s. Would things have turned out approximately the same anyway?

I find it impossible to believe that personal decisions in critical situations did not alter outcomes in detail and, through the cumulation and conjunction of details, shape and reshape the arms race fundamentally. I also find it obvious that what key individuals hoped and expected to achieve by their decisions seldom or never matched up with what happened. Instead, unexpected and unforeseen responses to particular decisions prevailed- universally and perpetually. The reactive process was enormously complex, limited only by the diffusion of information (and misinformation) among participants. Purposes were essential inasmuch as they governed everyone's actual decisions. But results were always surprising- sometimes radically, embarrassingly different from what had been intended. After all, the Kaiser lost his throne, the Royal Navy bungled the Battle of Jutland; and we find ourselves burdened by nuclear warheads and afraid what others may do if and when they acquire access to these almost unimaginably powerful explosives.

The effect so far has been to make international relations more dangerous and unpredictable than they were when wars were fought with weapons long familiar to all concerned. In addition, costs have escalated sporadically but ineluctably-matched in our time only by the escalation of medical costs. Eventually, limits to both forms of extravagance will surely assert themselves. Conscious policy is likely to remain ineffective in shaping long term results, as hitherto. Changes in the process itself will have to occur, perhaps through the involvement of competing interests and groups that are now largely inert, or, alternatively, by some sort of (presumably atomic) catastrophe that might end human life entirely, or merely end the industrialized arms race by establishing a world monopoly of capital weapons.

As I said at the beginning, we live in an exceptionally uneasy age and need to reflect on how the process of weapons development became so unmanageable exactly when deliberate invention of specific improvements of particular weapons became routine. We need to confront the irony whereby the rational triumphs of deliberate, organized invention became increasingly irrational in their aggregate effect. We even need to wonder about unending technical change and our capacity to endure it-individually, collectively, and ecologically.

I therefore leave you with much to think about and no ready answers. Time will tell, as always. That is mildly comforting to an elderly historian like me. I fear it will merely irritate technically proficient, can-do officers and cadets of my audience, trained, as you are, to take command of the situation and to solve most of your problems by ordering up new, more powerful machines.

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