Alex Roland

WAR AND TECHNOLOGY

A Very Short Introduction

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Chapter 1
Introduction

Humans were born armed. Protohumans had fashioned and used purpose-built weapons before *Homo sapiens* first walked the Earth. These weapons were surely used for hunting and probably for warfare. To make and use weapons and other military technologies is part of what it means to be human. The goal of this book is to trace the coevolution of technology and warfare from the earliest human experience to the present.

Technology and warfare are essentially material. They are communal processes for manipulating the physical world to serve human purposes. Technology seeks to bend the material world in pursuit of human goals. Warfare seeks to bend human behavior by the threat or application of physical force. The two phenomena share a physical and material affinity. A second goal of this book is to trace the evolution of that affinity.

A central thesis runs through the book. Technology has changed warfare more than any other variable. Politics, economics, ideology, culture, strategy, tactics, leadership, philosophy, psychology, and a host of other factors have all shaped warfare. But none of these variables explains the transition from prehistoric to modern warfare as completely as technology. From the Stone Age to the nuclear age, technology has driven the evolution of warfare.

A brief thought experiment might help to crystalize this generalization. Imagine that Alexander the Great came back to life in the second decade of the twenty-first century and found himself assigned to conquer Afghanistan. Might he be up to the task? He conquered that territory in 330 BCE, during one leg of a thirteen-year campaign that took him from his home in Macedonia through what is today Greece, Turkey, Syria, the Levant, Egypt, Iraq, Pakistan, Afghanistan, and beyond. Along the way he met and defeated the best armies of his time, fought through deserts and mountains, carried all the supplies he could not buy or steal along the way, and left relative peace and political stability in his wake. That campaign certifies him as one of the great captains of all time, an obvious master of the art of warfare.

He clearly understood and applied what students of warfare have called the "principles of war." Lists of these principles vary, but all look something like the nine codified in the *U.S. Army Field Manual 3–0* (2011): objective, offensive, mass, economy of force, maneuver, unity of command, security, surprise, and simplicity. These principles are not really rules of warfare, but rather categories of analysis organized as a checklist. Still, experts have viewed them as the keys to success in battle. Antoine-Henri, Baron Jomini (the subordinate and student of Napoleon), said that the "principles are unchangeable; they are independent of the nature of the arms employed, of times and places." If Alexander mastered them in the fourth century BCE, he could surely deploy them to equally good effect in the twenty-first century. In no instance would the principles tell him what to think, but they would always tell him what to think about. There is no reason to believe that he would weigh them any less astutely in the modern world than he did in the ancient world.

No reason, that is, except technology. The one thing that our reborn Alexander would not know and could not learn would be technology. What would he make of explosives, airplanes, satellites, radios, computers, or precision-guided munitions? Citizens of the modern, developed world carry around in their minds tacit knowledge of these technologies, an unconscious understanding of how planes and helicopters remain aloft, why satellites move in orbit, how things blow up, what capabilities reside in the electromagnetic spectrum. Alexander's war in Afghanistan would be over before he could get his mind around such wonders. Everything else about modern warfare would be known or knowable to him. Technology alone would make modern warfare incomprehensibly different from the warfare he knew in his lifetime. As Jomini discerned, the fundamentals of warfare are timeless and immutable. The technology, however, changes incessantly, and transforms warfare in the process. It is the primary driver of change in warfare. It is the variable that would render Alexander impotent. This book will attempt to reveal how and why those changes took the forms they did over the course of human history.

Some arbitrary—but hopefully useful—conventions govern the narrative that follows. First, it is heavily front-loaded. That is, it concentrates on premodern warfare. In that distant past, a set of concepts took root in human practice. One premise of this book is that those concepts—collected in the glossary—offer a key to understanding the kaleidoscopic world of modern military technology. Second, a subordinate thesis highlights one of the most striking, and seemingly contradictory, consequences of changing military technology. While superior technology has generally favored victory throughout history, it has not guaranteed it. "New" and "better" military technologies are not necessarily winners. Technology in warfare does not exist on some absolute scale of effectiveness. Rather, its value is relative to the enemy's capabilities. Think of warfare as a duel, but one in which each party gets to choose his or her weapon. For each side, the choice of weapons will shape the preferred rules of engagement (including no rules at all) and the strategy, tactics, politics, diplomacy, environment, and other conditions of the fight. If, for example, one party chooses a pistol and the other chooses a sword, the outcome is virtually preordained. So too is the likely outcome reversed if the second party chooses a rifle instead of a sword. The technology of the pistol is unchanged, but its relative effectiveness is trumped.

This book also notes that technology and warfare have interacted reciprocally through history. Warfare has changed technology almost as much as technology has changed warfare. This dialectic will be explored within a conventional but slightly simplified chronological periodization, beginning with prehistoric warfare and proceeding through Neolithic, ancient, classical, medieval, early modern, and modern periods. Crossing these basic chronological divides will be periodizations peculiar to the military technologies themselves. One will trace the forms of energy driving military technologies, from muscle and wind to carbon-based chemical reactions to nuclear power. The physical realms in which warfare has been conducted also impose their own chronologies. Land warfare, the oldest and most complex form, has the longest history. Its story is subdivided in a traditional periodization, and further delineated by two "Combined-Arms Paradigms" and two of the three "military revolutions" highlighted in this book. War at sea, in the air, and in space appeared at later times, ending with the convergence of all four realms of warfare in World War II. Finally, there are three topical perspectives on the nature of change in military technology: research and development, dual-use technologies, and military revolutions.

"Warfare," as used in this book, is the conduct of war against an enemy. It is the application or threat of force to kill, capture, or coerce an enemy to do one's will. As such, warfare is generally an activity conducted within a state of war. "War," in Max Weber's classic definition, is organized, armed conflict between states. States are those political entities that claim a monopoly of armed force within their territory. It has become fashionable of late to define war as a condition existing between communities, since so many nonstate actors now appear to be engaging in something like war. But for the purposes of this history, Weber's definition will do. War is a condition; warfare is an activity.

The meaning of "technology" is less clear. In this book, technology is purposeful, human manipulation of the material world. It entails changing some material by the application of power through some tool or machine by some technique. In essence, technology is a process of altering the material world to serve some human purpose. Manipulating ideas, concepts, feelings, relationships, beliefs, emotions, or other human dispositions may be a second-order consequence of some technologies. But it is not technology unless the material world is transformed. Technology, in short, is among the most material of human activities. So is warfare. Indeed, warfare and technology can both shape—even determine—the outcome of war. But they are not war. War may be, as Clausewitz declared, a continuation of politics by other means. But so too is warfare—and its technologies—a continuation of war by other means. Those means are profoundly and inescapably material.

Some activities that fly under the banner of warfare may or may not deserve that title. Cyber warfare, for example, which will be discussed later, certainly uses technology to alter the material world, but it has not yet risen to the level of warfare. Terrorism is not a form of war; it is a technique that may be employed in war or may be an instrument of personal rage or dementia. One may declare war on terrorists, but not on terror. Psychological warfare manipulates ideas more than material; technology may be used but is not essential.

One final definition requires attention. Artifacts of technology are often referred to casually as being themselves technologies. Think of aircraft carriers, tanks, and bombers. These artifacts of technology may be parts of technological systems that sail, shoot, and bomb, but they are not themselves technologies. This distinction is significant for this book, because fortifications and roads are among the most important technological artifacts in the history of warfare. Artifacts such as these, and the technologies that produced them, will appear often in the pages that follow.

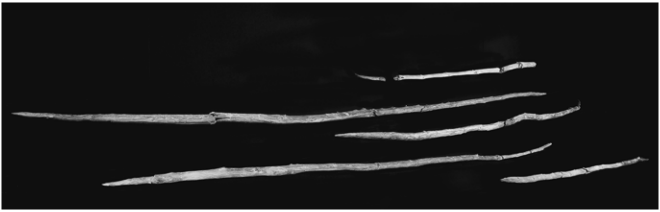
The historical record illuminated in this text is primarily Western. This is the history most familiar to the author and richest in evidence. A premise of the book, however, is that the arguments and concepts presented here are universal.

Chapter 2
Land warfare

Prehistoric warfare

We can say very little with confidence about technology and warfare before the dawn of civilization, but we can nonetheless identify some patterns emerging out of the mists of prehistory. One stunning clue arose in the 1990s out of an opencast lignite mine in Helmstedt, Germany. Project Schöningen, named for the mine, unearthed as many as eleven wooden throwing spears that had been preserved for three hundred thousand years in a layer of sediment from a former lake. Spruce stems and pinewood had been crafted into irregular, pointed shafts ranging in length from 5.9 feet to 8.2 feet. Most remarkably, the bodies of the spears are tapered like a modern javelin, weighted forward to fly true. If *Homo heidelbergenses* could throw overhand, they might have launched these spears 35 meters.

These artifacts tell us many important things about prehistoric weapons technology. First, proto-humans were improving upon nature one or two hundred thousand years before *Homo sapiens* emerged. Abundant artifactual evidence has suggested that humans used stones and bones as weapons and that in the Mesolithic and Neolithic periods the stones were being worked artificially into useful shapes. It is reasonable to assume that wood was similarly being crafted, though most of the resulting artifacts



1. The oldest weapon artifacts yet found, the Schöningen spears were dual-use technological artifacts, useful for hunting and warfare. Used by *Homo heidelbergensis* in central Europe three hundred thousand years ago, they prove that humans were born armed.

have long since decomposed. The Schöningen spears establish beyond all doubt that much more sophisticated work was being done on wood much earlier. The spears provide an evidentiary base for inferring wooden spears, pikes (stabbing spears), clubs—even knives—in the intervening millennia. We cannot know for sure if the spears and other weapons were used for hunting or warfare or both, but we can surmise more confidently now than ever before: *Homo sapiens* was born armed.

The next biggest question unanswered by the archeological record is whether Stone Age weapons were for hunting or warfare or both. Most of the remaining reliable evidence—bones, stones, and cave paintings—comes from the late Mesolithic or the Neolithic periods, between roughly twenty thousand and six thousand years ago. By that time, the existing weapons were clearly being used for both hunting and warfare. And there is no reason to believe that a weapon used for one did not find its way to the other. Perhaps poisoned arrows, for which there is some evidence, were reserved for targets that the predator did not intend to eat. But the vast majority of prehistoric weapons—slings, spears, pikes, clubs, knives, axes, maces, atlatls, woomeras—were early instances of what we would now call dual-use technologies. These are technologies that can serve either military or civilian purposes. It is as easy to imagine that some of these weapons were invented for warfare and transferred to hunting as it is to imagine the opposite.

This generalization holds true as well for the greatest of all prehistoric military technologies: the bow and arrow. Invented in the Paleolithic era, more than forty thousand years ago, the bow and arrow has remained in continuous use, in hunting and warfare, up to the present day. While other prehistoric weapons were tools, the bow and arrow is a machine. It has moving component parts and it stores energy. While other prehistoric weapons were intuitive, the bow and arrow required a leap of imagination, an ability to visualize something that did not exist in the natural world. We cannot know if this marvel of creativity developed just once, to be spread by osmosis through the worldwide human community, or if the bow and arrow was reinvented over and over by local geniuses. When the Greeks and Romans conjured a god of arms-making—Hephaestus for the Greeks, Vulcan for the Romans—he was a smith, a metalworker. But the real god of arms-makers was the Paleolithic Edison who invented the bow and arrow.

While many of the secrets of prehistoric weaponry remain hidden to us, the little that we know allows us to make some generalizations about the roots of technology and warfare. First, as already mentioned, most of these technologies of death were probably dual-use. Second, they included both missile and shock weapons, a distinction that continues to the present day. Missile weapons work at a distance, helping to keep the hunter/warrior out of harm's way. Shock weapons—instruments of hitting and stabbing—are more deadly, but they require their wielders to come into contact with their targets. If the target happened to be a large animal—prehistoric man's preferred prey—or another warrior, the encounter could be dangerous. This dilemma runs through all of human history, from Shaka Zulu, "the black Napoleon," who changed the assegai from a throwing spear to a stabbing weapon, to the modern soldiers who mounted bayonets on the ends of their small arms for hand-to-hand fighting when the ammunition ran out.

The contrast between missile and shock weapons also illuminates a third characteristic of prehistoric hunting and warfare. We may infer from studies of nineteenth- and twentieth-century societies fighting with prehistoric weapons that the tactic of choice has usually been pounce and flee. Because big animals and enemy warriors are dangerous, the best way to kill them is by ambush, to attack them by surprise and inflict what damage you can—through missile or shock—and then run like hell. If the attack was successful, you could return later to recover the corpses or dispatch the wounded. If the attack failed, you would live to fight another day. Throughout human history, the ambush has been the preferred technique in asymmetrical warfare, when a relatively weak fighter must attack a stronger foe. In the twenty-first century, the improvised explosive device (IED) has become the new Schöningen spear—the instrument of ambush.

Ancient warfare

The Neolithic Revolution came to the Levant—the land around the eastern Mediterranean—in the tenth millennium BCE, running its course in the region by the middle of the fourth millennium BCE. In those six thousand years, residents of the area learned to domesticate plants and animals and settle in river valleys. They built villages that grew into cities. Some of the early villagers, domesticators of animals, moved out of the river valleys into the surrounding highlands, tending their flocks in a middle ground between the agriculturalists and the hunter-gatherers who continued to roam beyond the pale. All three of these human groupings—foragers, pastoralists, and farmers—developed military technologies for fighting within and between their communities.

The sedentary farmers of the nascent civilizations produced the most important military technology of the ancient world:

fortification-building. While other military technologies helped to determine who won or lost battles and wars, fortification helped to determine if a war or battle would take place at all. As agriculturalists formed sedentary communities to domesticate plants and animals, they found themselves accumulating property beyond the bare necessities. Agricultural surplus, clothing, jewelry, tools of food preparation and consumption, and furniture began to fill up simple shelters. Houses got bigger. Predators—animal and human—roaming the countryside raided these concentrations of food and loot. The simplest defense was wooden poles, set in the ground side by side and strapped together. As mud and stone replaced the wood in these simple houses and walls, new building technologies appeared. Those technologies grew into monumental architecture, the foundation of the city-state. It is a nice question whether the technology evolved first to build the city walls and was then adapted to homes and public buildings or whether the evolutionary arrow pointed in the other direction: perhaps they built the altar and the temple first and then used the same materials and techniques to fortify their enclave. In any event, the dual-use technology of massive, permanent public building became the symbol of the first great civilizations. Indeed, our word for civilization comes from the Roman word for city.

The earliest exemplar is an outlier, geographically and chronologically. Jericho presumably began like other settlements of the Neolithic Revolution, experimenting with the domestication of plants and animals. Unlike the others, however, it fortified its position, an oasis in the Jordan River valley just north of the Dead Sea. By 8000 BCE, a town of perhaps 40,000 square meters, occupied by perhaps two to three thousand people, enjoyed the protection of stone walls 5 feet thick and 12 to 15 feet high. Along one of the walls a tower rose 28 feet above ground level, with an internal staircase that allowed lookouts to climb to the top and survey the countryside for miles around. The Stone Age residents of Jericho left no written record to explain who they were or how and why they came to build such unprecedented defensive works.

2. Rising above the plain north of the Dead Sea, the ancient city of Jericho, today Tell es-Sultan, is one of the earliest exemplars of prehistoric fortified cities, artifacts of non-weapons technologies that shaped war and warfare throughout human history. This photo reveals part of the walls of Jericho and the top of the 12-foot-high tower that once looked out across the plain.

Their location at the intersection of multiple trade routes suggests that travelers might have preyed upon the town, but we cannot know. Archeological research does, however, establish that these walls did not come tumbling down until the sixteenth or fifteen century BCE, though still before the time of the Biblical account. In short, the walls of Jericho worked for more than six thousand years. The settlement seems to have changed inhabitants twice in that time, but not by violent conquest.

The ancient city-state of Uruk, on the Euphrates River, offers far more insight than Jericho into early monumental fortification. Uruk flourished around 2900 BCE, in the middle of the Bronze Age. Modern archeology has provided reliable artifactual evidence about this truly monumental city, which we can correlate with a written foundation myth. These two sources of information illuminate both the technology of monumental building and the role it played in society.

The *Epic of Gilgamesh*, like Homer's *Iliad*, circulated as oral tradition until it was captured in various written forms by authors with no firsthand experience of the events they reported. Decades of scholarly study have yielded widespread consensus on the original myth and produced volumes of speculation on what it might mean. We know with a high degree of certainty that Gilgamesh, a real person, ruled the Mesopotamian kingdom of Uruk in the first half of the third millennium BCE. The discerning reader must sift the rest of his story to separate the wheat of historical plausibility from the chaff of apocryphal legend, but even legend is instructive. Two-thirds god and one-third man, Gilgamesh ruled Uruk for 126 years. His epic tells of a series of heroic quests in pursuit of fame and immortality. One quest takes him to the cedar forest ruled by Humbaba, a fallen god who also controlled the underground river that led to hell. This cedar forest was most likely in the Nur Mountains of modern Turkey, on the upper Euphrates River. Accompanying Gilgamesh on his quest is Enkidu, a barbarian seduced by civilization. When they meet

Humbaba, Gilgamesh slays him with magic weapons forged for him by a good deity, but not before Enkidu falls victim to Humbaba's deadly gaze. Gilgamesh travels to hell and back in search of immortality, but returns knowing that he will eventually follow Enkidu to the grave.

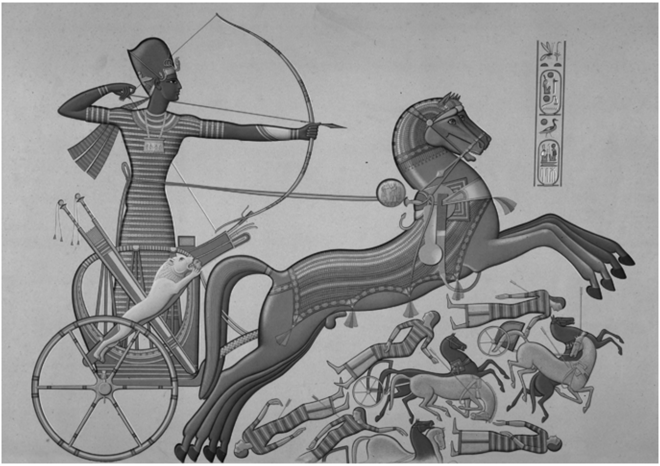
While the *Epic of Gilgamesh* explores love, life, and death, it also sheds light on the more material world of Bronze Age Mesopotamia. Gilgamesh went to the cedar forest to get wood for the city gates of Uruk and perhaps also for the ovens that baked the mud clay bricks with which Uruk and its walls were built. Gilgamesh boasts often of the hard-baked bricks of his city, a luxury available only to those with the wealth and courage to acquire the necessary firewood. In Gilgamesh's day, his city boasted a wall about 3.4 miles around, enclosing 2.3 square miles, roughly 220 times the size of Jericho. Its population surpassed eighty thousand in Gilgamesh's time, making it the largest city in the world. A moat surrounding the city provided an extra barrier against invaders and threatened to drown those who might attempt to dig under the city walls. Within the 25-foot-thick walls, the city had its share of monumental civilian architecture, temples and other public buildings designed both to house community functions and to awe the observer. Gilgamesh cherished above all else the title of "Builder of Walls." He was master of the technology that guaranteed the security and prosperity of his city. Even more than the military prowess afforded by his magic weapons, Gilgamesh staked his reputation on the fortifications he built, "Uruk of the strong walls." By this time, of course, prehistoric warfare had clearly turned into Max Weber's organized armed conflict between states.

While monumental fortification was transforming conflict around other urban centers such as Babylon and Nineveh, two other military technologies were changing field warfare. The metal that gave the Bronze Age its name soon replaced the stones in arrowheads, spears, knives, and other instruments designed to penetrate human and animal flesh. Furthermore, bronze made possible an entirely new weapon: the sword. Earlier stabbing weapons were limited in length by the weight and brittleness of stones and bones. Bronze—a mixture of copper and tin—could be worked into blades of several feet in length, edged on both sides and sharpened to facilitate stabbing and cutting. The very earliest writings from the new civilizations reveal apparently well-developed foundation myths in which heroes with godlike qualities deploy weapons endowed by the gods with supernatural powers. Gilgamesh, for example, carried a bow of prized Anshan wood and an ax—“the Might of Heroes”—fashioned for him by gods. His weapons, we are told, weighed 600 pounds, obviously instruments that only the demigod Gilgamesh could lift, let alone wield to effect. More than any other military technology around the world, the sword quickly took on symbolic meaning in legend, folklore, and mythology. From King Arthur’s Excalibur to the very real Japanese Honjo Masamune, swords have romanticized warfare more than any other technology. Soldiers around the world still wear them in dress parades as reminders of a time when warriors believed—or wanted to believe—that certain instruments of warfare could transmute virtue, justice, honor, or even godliness into military victory. Or perhaps it was the other way around; perhaps magical swords were a sign of a god’s grace. Modern warriors still give their weapons names like Zeus, Patriot, Crusader, and Peacemaker.

The greatest of all Bronze Age weapons did not arise from the new civilizations, nor was it made of bronze. The wooden chariot evolved on the Eurasian steppe and burst into the Levant in the seventeenth century BCE, unbidden and unanticipated. There had been war wagons in Mesopotamia in the fourth millennium BCE, but these heavy trucks, riding on four fixed, solid wheels and pulled by asses or oxen, likely carried warriors and their equipment at a lumbering pace to the site of battle. The chariot, in contrast, sped across the battlefield on two spoked wheels behind two or four horses, faster than soldiers could get out of their way. They appear to have swept all before them, running circles around or through infantry armies and forcing their enemies to surrender or arm themselves in kind. For almost six hundred years, these "superweapons" of the ancient world, as historian William McNeill has called them, forced the great powers or would-be great powers into an unprecedented arms race. To compete, states had to develop fine woodworking skills in territories with little wood, amass horses in horseless regions, and build arsenals, stables, and repair facilities for both home defense and operations abroad. So great was the demand for these exotic machines of war that an international mercenary class appeared—the *maryannu*—to sell their services and equipment to those states that could not master the technology or afford their own standing fleet. King Solomon reportedly amassed 1,400 chariots.

By some accounts, the greatest chariot battle of all time occurred at the beginning of the thirteenth century BCE, when the Egyptian chariot forces of King Ramses II of Egypt met the chariots of the Hittite king Muwatallis, outside the city of Kadesh, on the Orontes River in modern Syria. Mystery and controversy surround the battle, but there is little doubt that a campaign involving thousands of chariots and tens of thousands of soldiers reached a climax that imperiled Ramses and forced his withdrawal to Egypt. The decisive battle of the era went to the quasi-civilized Hittites.

Remarkably, for one of the most important weapons in all of world history, we do not know for certain how the chariot was used in battle. Majority opinion favors a weapon platform. One charioteer drove the vehicle into range of the enemy forces while one or two passengers shot missile weapons—arrows or spears—at the enemy formation. Another candidate is the jeep, a vehicle that takes warrior elites to the site of the combat, where they dismount to fight on foot. This use is portrayed in the *Iliad*, at the end of the Bronze Age, when Achilles, for example, is carried to the walls of Troy to call out Hector for hand-to-hand combat. When Achilles slays the Trojan champion, he drags the body around the city walls



3. The chariot revolutionized warfare in the second millennium BCE. This depiction of the pharaoh Ramses II at the battle of Kadesh (c. 1274 BCE) shows him riding over the bodies of Hittite soldiers slain by his arrows. The chariot, a dual-use technology, was the world's first weapon platform on land.

behind his chariot. The third possible use for chariots is shock: driving the vehicle directly into the enemy infantry formations with the archers and spearmen on board firing into the ranks as the chariot passes through.

However it was used, the chariot receded from the Levant even more quickly than it had appeared. After about 1200 BCE, the chariot lost its dominance of the Levantine battlefield, never to be recovered. The technology migrated both east and west, seeing use in India, China, Greece, Rome, mainland Europe, and even England and Ireland in succeeding centuries. But eventually it disappeared from these battlefields as well, retiring to uses of hunting, ceremony, transportation, and sport, such as racing. What could have caused such a dramatic and rapid eclipse of such a powerful weapon system? Because 1200 BCE was about the time when the Bronze Age gave way to the Iron Age, some scholars have conjectured that new iron weapons allowed infantry to stand up to chariots. But this interpretation has fallen out of favor. Alternatively, the explanation might be economic—that the chariot arms race was ruinously expensive on all the participants, finally exhausting their ability to finance it. Others have identified an event known as "the Catastrophe" as the agent of change. Around 1200 BCE, waves of barbarian warriors from the Eurasian steppes, impelled perhaps by environmental or climatological forces, moved into the lands of southwest Asia surrounding the Black Sea, the Aegean Sea, and the eastern Mediterranean. As they advanced, they drove before them the residents of these regions, who in turn fell upon their neighbors to the south, creating a cascade of forced migrations and invasions that climaxed in the waves of "Sea Peoples" that washed ashore in Egypt in the thirteenth century BCE. Ramses III met these amphibious invaders in his chariot, something of a last hurrah for this superweapon in the Levant.

One explanation for the eclipse of the chariot that seems to fit with all the evidence is the possibility of new infantry tactics, perhaps introduced by the steppe warriors who launched the Catastrophe. Being horsemen themselves, they perhaps knew that horses would not charge into a wall or a solid line of men holding their positions. If the chariot really was being used in shock, and if the infantry armies of the day learned that they could stop them by simply holding their ground—perhaps stiffened in their resolve by new iron weapons—then it might be that the chariot suddenly lost its menace. Perhaps it was a terror weapon all along, exerting more of a psychological than a material impact.

In any event, the chariot lost its preeminence in Levantine warfare, retiring to supporting roles behind the lines, on the roads or the parade ground, or in the circus or on the hunt. But the chariot's brief, dramatic reign over Western combat effected a military revolution, the first of three that will be highlighted in this book. "Military revolutions," as used here, are transformations of warfare so profound and sweeping that they not only redefine the nature of warfare but also change the course of history by shifting the relationship between states and access to coercive power. As William McNeill said of the chariot, it "transformed the entire social balance of Eurasia." While bringing about such a transition, the chariot also introduced a number of issues that were to recur often in the history of technology and warfare.

First, it was a truly revolutionary weapon. It forced all states within its reach to adopt it, counter it, or make peace with its masters. In the terminology of this book, the fighting options were for symmetrical or asymmetrical warfare. The asymmetrical option required a counter technology or technique. For six hundred years, no one appears to have been able to stop it. Instead, they adopted it—one measure of a true revolution. That is, they chose symmetrical warfare, like the Cold War arms race of the twentieth century. Second, chariots were invented not by civilizations but by barbarians. The whole history of innovation in military technology has been centered on civilization and has usually given civilized states leverage over the primitive. In this case, however, the barbarians of the Eurasian steppe initiated the revolution—first by domesticating horses and then by harnessing them to combat vehicles. Once the civilizations encountered this new technology, they all embraced it or succumbed to it.

And that is the third point. Until 1200 BCE, when the chariot's impact waned, there seems to have been no counter technology. Maybe some armies sought terrain on which the chariot could not function, but there appears to have been no anti-chariot. Chariot fleets fought chariot fleets symmetrically. Fourth, this technology diffused with great comparative speed, from the steppe to the Levant and then to most of civilized Eurasia. The chariot seems to have instilled in military leaders an imperative to adopt or surrender. Fifth, this technology was arrested either by its own inherent limitations or by innovative countermeasures. Either the chariot collapsed because of its own cost or warriors developed a technique to stop it.

Sixth, like the sword, the chariot took on transcultural symbolic value. Egyptian pharaohs sought to be portrayed in their chariots, either on the hunt or in war. The chariot became the vehicle of choice for civilian or military leaders who wanted to create a popular aura of command, power, and triumph. Seventh, the chariot began a cavalry-infantry cycle that has persisted into the twenty-first century. Through long epics of recorded history, especially in the West, warfare has been dominated alternatively by mounted or infantry warriors, each employing alternating weapons systems that commanded the battlefields of their day. The chariot roaring down from the steppes launched the first mounted cycle; the eclipse of the chariot returned the Levant to an infantry cycle. In the pages that follow, this book will explore and try to explain the forces—especially technology—that moved history from one of those cycles to the next. Eighth, along the same lines, the chariot became not just a dual-use technology but rather a quintuple-use technology: it was used for war, transportation, hunting, ceremony, and sport. The steppe nomads probably developed it for hunting; others found different uses. Ninth, and finally, the chariot was the first ground-warfare weapon platform. Nothing on a par with it would appear in land warfare before the tank in the twentieth century. But in its social and military function, it was the forerunner of the naval ship, the military airplane, and the spacecraft. Like those platforms in other realms, the chariot required one part of the crew to operate the vehicle and one part to operate the weapons. It was way ahead of its time.

The first combined-arms paradigm

The Catastrophe, c. 1200 BCE, plunged the Levant into a "dark age" of economic, political, military, and technological stagnation. The eclipse of the chariot left land warfare in a Combined-Arms

Paradigm unrelieved by military innovation. Until late in the Middle Ages, field armies of the civilized states built their military power around a phalanx of foot soldiers, supported by mounted warriors and light infantry auxiliaries. For a thousand years, all of these soldiers deployed basically the same arsenals. The heavy infantry of the phalanx carried spears and swords. The spears ranged from missile weapons like the Roman *pilum* (really a javelin) to the Macedonian *sarissa*—a heavy pike more than 20 feet long. Swords varied from the short, stabbing Roman *gladius* to the long, slashing swords of the Sasanids. A variety of other stabbing and clubbing weapons also might be carried for close-in fighting. These heavy infantry were armored as well. All carried a shield supplemented by various kinds of body armor. Most wore helmets and some sort of breastplate or mail, complemented perhaps by greaves (to protect the shins from kicking in hand-to-hand combat) and other specialty guards.

Light infantry might support the heavy by providing missile barrages from the flank or front (skirmishing). They usually shot bows and arrows, javelins, or slings. Because they relied on mobility for protection, they wore far less armor—if any. Mounted warriors rode chariots, horses, or camels. The few scythed chariots documented in this time were clearly used for shock, riding into enemy infantry formations, but chariots may also have been used as missile platforms and for flanking, screening, and scouting. Cavalry performed the same functions.

Infantry dominated the Combined-Arms Paradigm until the waning days of the Roman Empire. Then a new cavalry cycle began to emerge, lasting until the gunpowder revolution. Assyrians, Persians, Greeks, Macedonians, Romans, Scythians, barbarians from the forests and the steppes, and Muslims from the desert fought differently from one another, but the differences were in organization, tactics, strategy, and culture. Through both infantry and cavalry cycles, the technology of classical and medieval land warfare remained fundamentally the same, locked in a static paradigm of field combat. All states adapted the existing repertoire of arms and armor to suit their budgets, their natural resources, their labor and conscript pools, and their ways of war.

The Neo-Assyrian Empire

One apparent exception to this pattern illuminates the larger phenomenon. The Neo-Assyrian Empire (911–612 BCE) was a fully formed militarized state, the first recorded predator state in world history. Over the course of three centuries, the Neo-Assyrians set the world standard for continuous, rapacious, remorseless, and expansionist warfare, distinguished by self-conscious innovation in field and especially siege warfare. They built warships while still a landlocked state. They are depicted fording rivers in combat gear floated by air-filled animal bladders. They built roads to connect the ever-expanding bounds of their empire. And they armed and equipped their soldiers with the most modern, high-quality uniforms, armor, and weapons they could produce. They resurrected the chariot as a heavier vehicle, riding on thick wheels with as many as a dozen spokes. This new machine allowed them to carry a crew of four and perhaps even ride into the rough terrain of the foothills and mountains around the Mesopotamian valley. The heavier chariots may also have facilitated shock tactics, driving directly into enemy infantry ranks. There is even some evidence that the Assyrians pioneered the introduction of the scythed chariot, designed to cut down enemy foot soldiers in formation. All of these chariot innovations suited the aggressive, bloody, horrific style of war practiced by the Neo-Assyrians.

Neo-Assyrian innovations in siege warfare proved even more dramatic. To the traditional tool for attacking fortifications—ladders—they added siege towers on wheels, giving their soldiers direct access to the defenders atop the city walls. They introduced a kind of ram for battering city gates and another for the walls themselves. These wall rams came in two versions, one to batter the walls and another to pick at the mud clay bricks of most

Mesopotamian fortifications. The Assyrians even dug mines beneath city walls and perhaps built catapults to fire over them.

In the end, however, the Neo-Assyrian florescence in military technology failed to end the technological stasis that settled on Western warfare—both field and siege—after the Catastrophe. Not even their ingenious siege devices could alter the preponderance of power enjoyed by sophisticated fortifications. Armies at the gates of robust fortifications could surround and starve out the population within the fortress. They could poison the water supply. They could slaughter the inhabitants of conquered cities in order to terrorize the defenders of other fortresses into capitulation. Or they could gain entry by betrayal or trick—as the Achaeans did with the Trojan Horse. Though Sargon II (r. 721–705 BCE) and other Assyrian kings fancied themselves destroyers of walls—perhaps a counter to Gilgamesh's pride in being a builder of walls—there is little evidence that their siege technology conquered many cities. The greatest destroyer of walls in the ancient world, "Demetrius the Besieger" of Macedonia, failed to take Rhodes in a year-long siege in 305–304 BCE that fielded the largest siege engine of the age, a nine-story mobile siege tower bristling with catapults at multiple levels. Even that engineering marvel, however, succumbed to Rhodian assault and defensive catapults. As historian Paul Bentley Kern observed of this campaign, "Ancient siege warfare had reached a technological dead end that was not escaped until the introduction of gunpowder a millennium and a half later." Most urban conquests by the Assyrians and their successors followed time-honored traditions of barbarians, weaker powers, and even great empires down to the Middle Ages—surround and squeeze. Siege technology would not upset this balance until the walls of Constantinople fell in 1453.

Still, there is no gainsaying the inventiveness and the effectiveness of the Neo-Assyrian Empire. What could account for this effervescence of technological innovation? Were the Neo-Assyrians simply more intellectually curious than their contemporaries—a hypothesis reinforced by the unparalleled library of their king Ashurbanipal (668–627 BCE)? Was their population smaller than their ambition, sending them in search of labor-saving machinery that might leverage their military power? Or are all militaristic states ever vigilant in the pursuit of new arms and equipment? Whatever the reason, the Neo-Assyrians introduced a raft of new military technologies.

These innovations did not, however, ensure success. Rather, they introduced a pattern of dueling technologies in siege warfare that continued unabated into the modern world. Defenders build strong walls. Attackers develop a siege tower to scale the walls. The first side sets the siege towers on fire. The second side covers its siege towers with wet animal skins to retard the flames. One side develops siege artillery to breach the walls, and the other side emplaces comparable machines on its walls to shoot at the besieger's machines. And so it goes. More than simply counter technology, dueling technologies entail an ongoing, machine-like, reciprocal pattern of innovation. Through most of the First Combined-Arms Paradigm, defensive fortifications succeeded more often than sieges, Neo-Assyrian boasts to the contrary notwithstanding.

Classical warfare

Shortly after the fall of the Assyrian Empire in 612 BCE, Western civilization left what I call its ancient period (3500 to 500 BCE) and entered the classical era (roughly 500 BCE to 500 CE), the age of Greece and Rome. Still operating within the First Combined-Arms Paradigm, the Greeks and Romans improved upon the siege engines and other military technologies of the Assyrians, and they also refined written records, bureaucracies, roads, and fortifications. In the process they pioneered engineering in a decidedly modern form. It is entirely possible that the Assyrians had their own military engineers; the images and artifacts they left behind suggest as much. But only with the Greeks and Romans does the literary record confirm such engineering carried to high levels of refinement.

As with so much in Western civilization, this story begins in Greece in the middle centuries of the first millennium BCE. Residents of the Greek city-states began to fashion a civilization more prone than its contemporaries to interpreting the natural world rationally and to cultivating philosophy, science, politics, culture, and art as ornaments of the state. Some students of Western civilization have found its roots in what they call the "Greek miracle." In the military realm, one historian has gone so far as to claim that the classical Greeks even invented a "Western way of war." Most scholars find that assertion unconvincing, but there is nonetheless widespread agreement that classical Greek civilization introduced the world to many of the concepts, beliefs, and patterns of thought and feeling that have come to make up the Western worldview.

In the realm of military technology, the most important Greek contribution was what we would now call science-based engineering—that is, the design, construction, and use of machines and structures based on mathematics and, in modern parlance, "science." Hellenistic Greeks proved especially adept at siege technology and its reciprocal, its dueling twin, the refinement of fortification. Greek ideas and engines spread around the Mediterranean world, along with the rest of their cultural legacy, taking root most spectacularly in the Roman Republic and Empire. There, military technology achieved a transcendent importance, in many ways outshining the field warfare of the vaunted Roman army.

Between them, the Greeks and Romans bequeathed to the world a panoply of siege engines. In addition to rams and mobile armed towers, they developed multiple forms of artillery: catapults, ballistae, onagers, scorpions, etc. These latter throwing engines, forerunners of modern artillery, all stored and released energy from one of three sources: tension, torsion, and gravity. (Tension and torsion machines, respectively, stretched or twisted organic materials such as rope, wood, or animal hair or sinew.) The hurling machines, which launched their projectiles in curving ballistic arcs, might have thrown incendiaries, animal carcasses, snakes, or other unpleasant missiles into the enemy fortress, but it is hard to imagine them doing much harm to the walls. The direct-fire weapons might have chipped away at the walls and perhaps opened some breaches around gates or other weak points, but they lacked the power to readily force a breach even in the mud brick walls of Mesopotamian fortifications. Towers to go over the walls and mines to collapse them held out more promise, but moats and fire could limit their effectiveness. It is entirely possible that the major impact of these ingenious machines was psychological. It is likely that nontechnological means remained the most effective forms of siege warfare—negotiation, starvation, terror, ruse, and betrayal.

Still, the military engineers of the classical world made many other contributions besides clever siege engines. First of all, they instilled in kings the belief that technology could deliver military advantage. Some engineers held positions at court, and others moved about the Mediterranean selling their services. Dionysius I of Syracuse went so far as to establish a center for military research and development, producing, by one account, the catapult. Archimedes, the greatest mathematician of his age, died in the futile defense of Syracuse against Roman attack, but not before inventing a system of mirrors to burn an invading fleet with concentrated sun rays. He may even have invented a highly leveraged crane to capsize enemy ships, though it is always hard to know how much of the classical war stories to believe. His contrivances and those of his Greek colleagues may have been more clever than effective.

The engineers' contributions to what we would now call civil engineering were even more impressive and verifiable. The Romans laid down 55,000 miles of primary and secondary paved roads that circled the Mediterranean and sped the Roman legions to duty assignments around the empire. Brilliantly engineered, these roads adapted standard plans to local materials and terrain, producing remarkably straight roads of various depths, widths, and cohesion along elevation contours that minimized rising or falling grades. Bridges of wood and stone complemented the roads. A classic dual-use technological artifact, the Roman roads served the military and strategic goals of the state, while promoting government, commercial, and personal travel that bound the empire together. The Persians, Assyrians, and Chinese built comparable state roads for commerce, war, and government communication, as did the Incas and others in later centuries, but not until the German autobahn and the US interstate highway system did any state road network rival that of Rome.

Soldiers of the Roman army built many of those main roads and applied the same skills and knowledge on campaign. The army forded rivers with pontoon bridges, and Caesar twice built wooden bridges across the Rhine in the face of the Germanic tribes, demonstrating that resistance to Rome was futile. The same mentality fueled the Roman army's preferred siege technology, earthen ramps built up to the top of the enemy's wall. This was an ancient siege technique raised to high art by the Romans. The Roman ramp at Masada is still in place, and the footprint of one of the camps that protected the army while it was under construction is clearly visible nearby. Roman republican and imperial armies lost more than their share of battles, often due to poor leadership. Hannibal, for example, dealt them some of their most devastating defeats on their home territory. But always the Romans came back, fighting relentlessly and doggedly until they won. It may be said that they won more victories by engineering than by fighting. For them, military engineering was not just an instrument of state power; it was an ethos, a way of war. Eschewing the elegant, mathematics-based engineering of the Greeks, the Romans embraced a pragmatic, cut-and-try engineering, much of it no doubt learned on campaign and passed on in doctrine. Many enemies came to terms with Rome not because they were defeated but because they were weary.

In spite of Rome's achievements in engineering, however, field warfare in the classical period remained bound within the technological stasis of the First Combined-Arms Paradigm. The most remarkable innovations were simply variations on static technological forms. The *gladius hispaniensis* is a case in point. The gladius was the generic sword of the Roman legionnaire, shorter than most swords before and since but also varying greatly over time in length, blade style, hilt, and especially material. Its history illustrates a penchant for assimilating innovations in military technology. The Romans were unsurpassed, said Polybius, "in the readiness to adopt new fashions from other people, and to imitate what they see is better in others than themselves." The Romans already had a short sword of wrought iron when they discovered the special qualities of Iberian swords during the Second Punic War. Hannibal Barca launched his invasion of Rome from his family's Carthaginian colony on the Iberian Peninsula. The Romans soon discovered that the swords from Spain were stronger than theirs and held their point and edge much longer. They could, in fact, be honed to a razor edge, magnifying their effectiveness and durability in battle. The Romans studied the Iberian technique of sword-making and took it home. They did not, however, take home the Iberian iron ore that gave Toledo steel many of its special qualities. Seldom, therefore, did Roman knockoffs achieve the attributes of the authentic *gladius hispaniensis*. In time the Romans moved on to lesser gladii named for their manufacture in Mainz or Pompeii. But the *gladius hispaniensis* entered Roman folklore in the same way as previous legendary weapons, such as Gilgamesh's ax and the arms forged by the gods Hephaestus and Vulcan. The very existence of such weapons, to say nothing of their supernatural powers, suggested that the warriors who wielded them were doing God's—or the gods'—work.

The second most instructive and influential variation on the First Combined-Arms Paradigm of the classical age was the composite recurve bow, the weapon of choice for light cavalry. Like the chariot before it, this military instrument was invented by barbarians, probably on the Eurasian steppe. It was a short bow, with ends turned away from the archer, ideally suiting it to firing from horseback or chariot. The rider could easily move his weapon over the horse's neck or the chariot rail to fire from side to side. Like the *gladius hispaniensis*, it took its special qualities from the materials and the technique of manufacture. Its laminate construction—usually sinew in front, wood in the middle, and horn in back—maximized overall strength and power. These laminates were glued together, and then the whole bow was bent and steamed to impart its characteristic curve and wrapped to reinforce the structure. Short when unstrung and even shorter when strung, it was easy to carry and to maneuver when shooting. In the hands of experienced bowmen, it delivered enormous hitting power and high rates of accurate fire.

Thus it was that technologies within the First Combined-Arms Paradigm changed in significant ways while the paradigm itself stagnated. New variations on the basic arms and armor appeared and disappeared on the Eurasian battlefield, favoring now one combination of military force, now another. Through the rise and fall of classical Greece, the Macedonian Empire, and the Roman Republic, heavy infantry formed the center of gravity of Western armies. These phalangeal paladins, hoplites and their descendants, were collectively the queen of battle, the most powerful force on the chessboard of land warfare. Both Greeks and Romans encountered enemies in southwest Asia whose military formations were based on light or heavy cavalry, or both. Seleucids, Parthians, Armenians, Scythians, Sasanids, and others fielded swarms of lightly armored mounted warriors firing recurved bows, or troops of cataphracts (as the Greeks called them), armored warriors on heavy, sometimes armored horses, attacking with lance and shock.

Often the heavy horsemen were nobles or aristocrats, the members of society able to afford their combat panoply. In the heyday of the phalanx, disciplined heavy infantry had been proof against mounted attack. But, as the Western Roman military establishment deteriorated in the fourth and fifth centuries, the disciplined infantry formations of Rome's zenith gave way to more disordered European battlefields in which the mounted warrior rose in importance. The First Combined-Arms Paradigm abided—swords, spears, bows and arrows, shields, armor—but the center of gravity was changing sides. In the last centuries of the Roman Empire and first centuries of the Middle Ages, the infantry-cavalry cycle reversed itself once more. Mounted warriors became relatively more powerful, while infantry receded to supporting roles. As with the chariot, the imperative to change had come not so much from the technology of mounted warfare as from the waning discipline and training of infantry warfare.

Medieval warfare

In the fifth century CE, a dark age settled on Europe comparable to the dark age following the Catastrophe of 1200 BCE. Roman taxation and administration collapsed while authority, military force, economic networks, and political organization deteriorated. The First Combined-Arms Paradigm survived, but the transition from an infantry to a cavalry cycle slowed to a crawl. Three components of the new mounted weapon system emerged slowly between the fifth and the fourteenth centuries. First, the knight's armor transitioned in the late Middle Ages from the mail (garments woven from interlocking metal rings) of the late classical period into the plate armor of the Hundred Years War and finally full body armor for horse and rider in the sixteenth century. Second, the weight of this armor spawned horse breeding from the eleventh through the thirteenth centuries, leading to what historian R. H. C. Davis called "the age of the 'great horse'" in the fourteenth and fifteenth centuries. Targeted breeding in this period was accompanied by inclusion of more oats and other grains in the horses' diets, a change with logistic implications. While the lightly armed and armored mounted bowman of the Eurasian steppe could feed his smaller horse entirely on grass, giving the rider virtually unlimited mobility and range, the heavy mounted knight of the West was tethered more closely to his magazine and wagon train.

The third technical innovation behind the medieval mounted knight was the stirrup. This simple device, really a technological artifact, found its way from Asia to eastern Europe in the seventh century and western Europe in the eighth. One medieval historian, Lynn White, Jr., used its appearance in the West to complement a long-standing theory of the origins of feudalism in the West. German historian Heinrich Brunner had argued in 1887 that feudalism was in essence a social/political system based on a military relationship. The lord or king of a territory parceled out land to vassals (and they, perhaps, to subvassals) so that they could use the income from the property to pay for the expensive arms and equipment necessary to be a mounted knight. In return for this land and income, these vassals swore allegiance to their lord and promised forty days (or thereabouts) of military service each year. But why, asked critics of the theory, did European feudalism begin early in the eighth century? Because, White said, that was when the stirrup first appeared in the West, empowering the heavily armed and armored mounted knight to grow into the dominant force on the European battlefield. The stirrup allowed the knight to become a shock weapon, leaning into his lance and grounding infantry and mounted soldiers alike with crushing force. Lords gave mounted knights land, the revenue from which could pay for their expensive equipment and retinue, and the knights gave military service in return. The knight, in essence, was the nucleus of the feudal system, an ingenious and unparalleled concordance of political, military, economic, social, and judicial power. The stirrup made the mounted knight irresistible on the battlefield, and the mounted knight enforced the feudal system.

Critics of the Brunner/White thesis have dominated the literature for the last half century, noting that the mounted knight was already a dominant force before the stirrup, that the distribution of land to vassals was well under way when Charles Martel supposedly hit upon this formula after the battle of Poitiers (732 CE), that European feudalism was never the neat, uniform social system that the stirrup hypothesis envisioned, and that the saddle was more important for shock cavalry than the stirrup. Some scholars accused Lynn White of technological determinism, that is, of claiming that the stirrup produced feudalism. In fact, White explicitly rejected such a claim, proposing only that the stirrup, which seems to have appeared in the West at almost exactly the time of Poitiers, provided the final catalyst for medieval society to precipitate feudalism out of the political, military, economic, social, and judicial stew that was eighth-century Europe. The interpretive controversy over the impact of the stirrup offers a poignant reminder that "technological determinism" is usually a rhetorical flourish, never a historical reality. Historians accuse their colleagues of being technological determinists, but no respectable historian ever practices that interpretation. Instead, the judicious historian seeks understanding in context, drawing upon all those categories of analysis that promise explanatory power. The stirrup was a dual-use technology that helps explain—but did not cause—feudalism.

Historiographical controversies notwithstanding, there is no gainsaying that the heavily armed and armored mounted knight bestrode the European battlefield for half a millennium or more, from the early eighth century to the end of the twelfth century. The reason for his success was not so much the irresistibility of his military force as the psychological impact of his presence on the battlefield in the face of the motley, ill-equipped, and disorganized mobs that passed for infantry after Rome's collapse. In other words, this cavalry cycle appears to have imitated the chariot cycle that preceded it, enjoying dominance for half a millennium over infantry formations beset by disarray and fear.

The heavily armed and armored mounted knight began to experience serious reverses in the thirteenth and fourteenth centuries, before gunpowder finally dismounted him for good. First came the confederation of Mongol tribes that Genghis Khan (1162?–1227) molded into an imperial army. Genghis oversaw the conquest of northern China and central Eurasia to the Caspian Sea. His son and successor carried the Mongol conquest through Russia and the steppes all the way to modern Budapest, from which they threatened the land defended by the European feudal array. This Mongol army, barbarians all, simply outclassed the Europeans in every dimension of warfare. They had their own intelligence service; a sophisticated system of communication; a logistic train that supplemented their modest needs for human and horse food; an experienced light cavalry of mounted warriors who had spent their adult lives shooting animals and humans with composite recurve bows from horseback; a doctrine that blended dispersed strategic movement with tactical convergence to meet the enemy; a ruthless, bloodthirsty, and terrifying fighting ethic; and a leadership that traveled with the army and directed it brilliantly. What is more, the Mongols probably introduced Europeans to the most revolutionary of all military technologies: gunpowder. These invaders from the steppe brushed aside the West's mounted knights in Hungary and Poland in 1241 and seemed poised to extend the largest contiguous empire in all of human history from the Pacific to the Atlantic oceans. But then, in 1242, they suddenly turned around and retired to Mongolia. This civilization-saving reversal owed nothing to European resistance. Rather, the great khan had died, and all the tribes returned to the convocation that would choose his successor. Later Mongol attacks in Europe proved less effective, in part because of enhanced Western fortifications. Still, the Mongols of 1241 left the reputation of the European feudal array in shambles.

Nor did foreign invaders offer the only challenge to the European knight in the High Middle Ages. The Hundred Years War (1337–1453) pitted the English form of the feudal array against the

French form. The center of gravity in both systems remained the heavily armed and armored mounted knight. The English knights, however, enjoyed the support of a unique auxiliary: longbowmen. These lightly armed and armored foot soldiers wielded a bow of extraordinary proportions: about 6 to 7 feet in length at a time when the average Englishman stood perhaps 5 feet 6 inches. Their yew bows required prodigious strength and great skill to string, pull, and shoot with accuracy. But they could generate more than 100 pounds of force, enough to bring down any horse and penetrate all but steel breastplates. Furthermore, he could fire as fast as battle conditions required. To keep from being overwhelmed on the battlefield by swarming cavalry, the longbowmen of the fifteenth and sixteenth centuries sometimes planted stakes in front of their position, a barricade that could keep the enemy knights from running them down. Repeatedly, these bowmen proved to be the difference in battles with the French nobility in the Hundred Years War—most notably at Crecy (1346), Poitiers (1356), and Agincourt (1415). The French at times facilitated their own defeat by rushing the bowmen directly, without supporting missile fire and in tactical disarray. But it was the longbow that made the difference and allowed outnumbered English armies to roam the French countryside with impunity.

The continental feudal array met similar reversals when it tried to invade the provinces of Switzerland in the fourteenth and fifteenth centuries. There, militias met the mounted knights in highly disciplined and cohesive squares, bristling on all sides with pikes to arrest cavalry charges. Usually, the horses pulled up before impaling themselves on the pikes. All that was required was the courage and resolve of the soldiers to stand their ground. When the momentum of the cavalry charge was exhausted, soldiers armed with halberds, Lucerne hammers, morning stars, and other deadly polearms swarmed the milling cavalrymen. The hooks of their halberds could pull the knight from his mount. Once on the ground in plate armor, the knight could be dispatched easily with a knife through the eye-slit of his helmet or an ax through a vulnerable joint. Polearms with ax blades could cut through a leg of the knight's horse, bringing both to the ground and certain death or capture. In some battles, the feudal array outnumbered the Swiss pikemen enough to overcome them. But more often than not, the Swiss got the better of such encounters. When the mounted knight of the feudal array finally went out of fashion, many of the Swiss halberdiers, trading on their reputation, sold their services as mercenaries, most famously guarding the pope, as they still do today. While other royal bodyguards wear swords to evoke their historical lineage, the pope's Swiss guards still bear the murderous halberds that made them famous.

The European knight was thus defeated by three different counter technologies over the course of two hundred years before finally yielding pride of place once more to infantry during the sixteenth century. Why did this latest revolution of the infantry-cavalry cycle take so long to complete? Among the many answers are two directly related to the technology of European warfare in the High Middle Ages. First, the feudal system embodied a convergence of military, political, economic, cultural, and social power that gave it a robust institutional inertia. The mounted knight was the centerpiece of the system, with multiple levers of power at his disposal. Second, when the mounted knight could not dominate the battlefield, he could retire within his castle walls, to withhold feudal service to his lord, repel military challenges from his peers, and even withstand the Mongol invader. Medieval siege technology, hardly improved from its classical precursors, could overcome the fortifications of many towns and cities, but it failed more often than not against well-designed and well-defended castles. Furthermore, many feudal agreements limited the vassal's military service to forty days a year, hardly enough time to conduct the campaigns of starvation into which so many medieval sieges devolved. Perhaps the European knight of the High Middle Ages could not win all his battles, but he could always retreat to his inviolable castle.

The gunpowder revolution

Thus it was that gunpowder proved so devastating, not only to the individual knight but also to the whole feudal order. On the battlefield, individual firearms achieved more cheaply and routinely what the English longbow, the Swiss pikeman, and the Mongol mounted warrior did with their special weapon systems. And when the knight retreated to the safety of his castle, cannons blasted through the walls. These castles often had high, thin, curtain walls, testaments to the stagnation and ineffectiveness of siege technology since the time of the Assyrians. The walls were built high to deter ladders, but they were not built thick. When siege artillery rolled up before them, it easily opened gaps through which infantry could rush. Lords used artillery to bring their vassals to heel, to strip them of their exclusive hold on military power, and to convert their obligation for service in the feudal array into a tax. These lords could then use the tax revenue to raise their own infantry armies, buy more artillery, and subordinate more of the warrior nobility. Along the way, feudalism gave way to monarchy on its way to absolutism. Historian Clifford Rogers counts this as one of the most significant military revolutions in Western history.

This political and military transformation of Europe was but one of many changes wrought by gunpowder—the second of the three great military revolutions highlighted in this book, and one of the most important inventions of all time. At least eight other momentous consequences flowed from the gunpowder revolution. First, it inaugurated, in both warfare and society in general, an age of chemical power—what I call the Carbon Age. The cannon was the first internal combustion engine, powered, like most of its successors, by carbon-based fuels—wood (or charcoal, one of the ingredients of gunpowder) and fossil fuels (coal, oil, and natural gas). It revealed retrospectively that the technological ceiling capping the First Combined-Arms Paradigm was muscle—and to a lesser extent wind—power. In the future, the scale of warfare would expand to the limits of chemical power. Once weapons and other military technologies harnessed the power of chemical reactions—fire, for example—then a riot of death-dealing innovation ensued with world-changing speed. The scale of death and destruction unleashed by war through the remainder of the second millennium CE still beggars the human imagination. Though prehistoric warfare and warfare within the First Combined-Arms Paradigm killed more people per capita than warfare in the Second Combined-Arms Paradigm, most of those deaths had resulted from disease and famine brought on by war. Chemical energy unleashed on the world a killing power that climaxed in World War II with a "storm of steel" on the battlefields and the firebombings of Dresden and Tokyo in the urban centers of civilization.

Second, gunpowder changed the dynamic of fortification. Siege engines in the ancient and classical worlds had never been terribly efficient or effective. In Europe, at least, walls grew higher and thinner. Even the incomparable city walls of Constantinople gave way before the new firepower, contributing to the fall of the city in 1453. As the new guns became more powerful, the old walls became more vulnerable. Fortification had to change or fail. At the end of the Middle Ages, northern Italian city states pioneered a new form of fortification, the *trace italienne*, reigniting a contest of dueling technologies that had begun with the Neo-Assyrians and would continue into the twentieth century.

Third, missile weapons became deadlier than stabbing, cutting, or clubbing weapons. Though the bow and arrow had surely killed more humans than any weapon before the gun, it was still an instrument of pounce-and-flee tactics, disdained by the Greeks and associated with barbarians and the "light" auxiliaries of classical and medieval warfare. Now most of the killing on the world's battlefields would be done at a distance by firearms and artillery, a shift that appalled the likes of Miguel Cervantes—horribly wounded at the naval battle of Lepanto—and his fictional knight errant, Don Quixote. The strength and skill of the warrior might now succumb to the pull of a trigger finger. Courage and honor were forfeit to death at a distance.

Fourth, gunpowder dethroned the mounted knight while elevating the gunner. The cavalry of the Middle Ages gave way to a new infantry cycle. As Don Quixote feared, gunpowder put in the hands of any unwashed, unskilled commoner an instrument that could kill a noble knight. The shift in military power shook not just the warrior class but the whole society, putting commoners on top and the nobility at risk. Cavalry would not disappear until the twentieth century, but it would recede into the supporting role formerly occupied by the irritating but unmanly slingers, bowmen, and skirmishers of old. Not even the diabolical and deadly crossbow had had such an impact.

4. This painting depicts soldiers and contractors for the Polish army manhandling a primitive cannon over a pontoon bridge during the battle of Orsha (1514). Perhaps this was one of the weapons that surprised and turned back the Muscovite forces, handing the Polish-Lithuanian alliance an upset victory over superior numbers.

Fifth, a Second Combined-Arms Paradigm displaced the model that had dominated field warfare since the Catastrophe of the twelfth century BCE. The new paradigm added field artillery to the infantry and cavalry duo of old. From the seventeenth century until the end of World War II, commanders would juggle variations on three combat arms—infantry, cavalry, and artillery—all of them empowered by chemical energy and saturating the battlefield with firepower.

Sixth, the ammunition to fuel this firepower imposed on armies a logistical burden greater even than the demands of feeding heavy horses on campaign. One might find oats and other grains while traversing the countryside, but seldom would caches of arms, spare parts, fuel, and ammunition be found outside defended arsenals and magazines. Furthermore, the logistical tail following armies on campaign offered a vulnerability upon which a weaker enemy might pounce and flee.

Seventh, for the first time since the human community had divided itself into civilized, pastoral, and barbarian segments, the civilized states eliminated the existential threat posed by barbarians. Repeatedly in recorded history, supposedly primitive barbarian warriors had descended from the steppes of Eurasia or the deserts of North Africa to conquer great civilizations. Persians, Romans, Byzantines, Harappans, and Chinese had all succumbed at one time or another. Even Western civilization as a whole stood on the precipice of barbarian conquest in 1242. But never again. After the gunpowder revolution, barbarians might resist incursions by civilized states. They might even turn gunpowder weapons on their civilized enemies. But absent industrial know-how and infrastructure, they could never produce their own arms and ammunition. And lacking those, they could no longer threaten to conquer civilized states that had built up a gunpowder infrastructure. This asymmetry tempted many Western states into the imperial adventures accompanying the "rise of the West." Though many of those adventures ended badly for the Western imperialists, they never again faced extinction by barbarians at the gate.

Eighth, gunpowder transformed naval warfare with equally momentous consequences, as will be seen below. Ninth, and finally, gunpowder proved to be just the first phase of a larger, two-stage revolution of even greater impact. Gunpowder released the chemical power of carbon compounds explosively, sending projectiles flying at high speeds from the mouths of cannons, the barrels of small arms, and the shells of exploding devices. A second wave of carbon combustion would sweep over warfare in the nineteenth century, harnessing the chemical power of carbon compounds to drive machines of war. Those machines would achieve new heights of killing and destruction in the world wars of the twentieth century. That second revolution-within-a-revolution itself occurred in two phases, one in the nineteenth century and a second, more powerful phase in the twentieth century. That second half of the Carbon Age will be explored later.

But before turning to other realms of warfare, it is well to ask why it was that China, where gunpowder was invented, failed to develop its potential, while the West, which imported the concept, used it to such great effect. Historian William H. McNeill says that Westerners are simply a very warlike people. Kenneth Chase disagrees. Instead, he says, early firearms were too heavy and awkward to use effectively against the nomadic warriors of what he calls the “Arid Zone”—the Eurasian steppe and the North African desert. These are the people I call the barbarians. Instead, gunpowder technology favored those states facing the new infantry cycle—western Europe, Japan, and the Ottoman Empire. Thus, in his view, gunpowder fueled the infantry cycle and reacted to it. Robert O’Connell thinks artisanal entrepreneurs and capitalists gave the West its gunpowder edge. And there is no escaping the simultaneous origins of the scientific and gunpowder revolutions in the West, followed in many quarters by a riot of technological innovation. The West, after all, was the culture that came to view nature as something to be conquered.

Land warfare will be left at this juncture, at the beginning of the Second Combined-Arms Paradigm. The gunpowder revolution swept Europe in roughly century-long stages. Guns appeared in the fourteenth century. Siege guns toppled existing fortifications in the fifteenth century. Small arms sparked a new infantry cycle in the sixteenth century, dethroning the mounted knight. And mobile field artillery added a third combat arm to field warfare in the seventeenth century. A straight line led from that new paradigm to total warfare in the first half of the twentieth century.

Chapter 3
Naval, air, space, and modern warfare

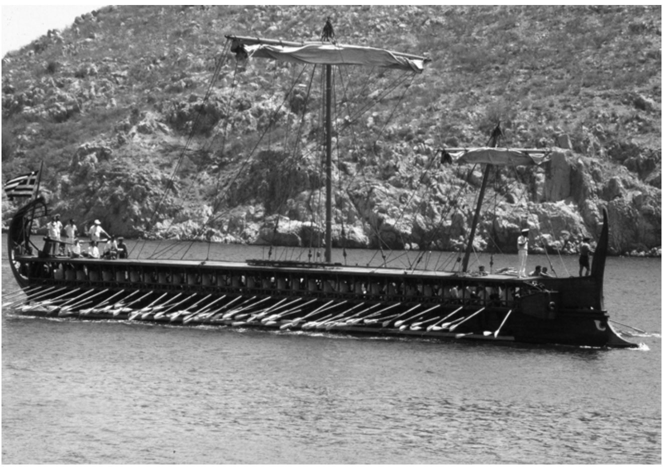
Naval warfare

When naval warfare emerged from the mists of ancient history in the second millennium BCE, it was conducted in galleys, oared vessels fitted with auxiliary sails. As with warfare in the air and in space, and unlike most land warfare, naval warfare is defined by the platform carrying the naval warriors and their weapons. Naval warfare has been conducted on three classes of platforms defined by their systems of propulsion—galleys, sail, and steam—each with its own characteristic technologies and ways of warfare. One technology always governed the platform itself, the vehicle in which the warriors and their weapons rode to combat on an inhospitable sea, and one technology defined how the naval warriors fought. Their weapons might target the enemy ship or the enemy crew. But always the technology of the platform had to complement the technology of the fight. In land warfare, the chariot, and perhaps even the mounted warrior, might be seen as comparable marriages of platform and weapons. But before the twentieth century, the naval vessel was the most complex of military technologies—a system of systems.

Commerce called navies into being, both to attack it and protect it, and commerce has been a primary *casus belli navalis* ever since. Before there were naval vessels, civilian boats and ships carried people and cargo across the seas. The Mediterranean Sea, a laboratory of early naval warfare and an archive of its evolution, developed a particular kind of commercial ship, out of which naval vessels would evolve. These ships were frame-built; that is, the shell of the hull was built first, and then ribs and other stiffening infrastructure were added. This construction method worked in the comparatively calm seas of the Mediterranean, but it produced fragile ships reinforced with a keel external to the shell of the hull. The lightness and fragility made Mediterranean naval galleys fast and weak.

No doubt, piracy gave rise to naval vessels. Slow, unarmed merchant ships were vulnerable to faster raiding vessels that could overtake, grapple, and board a cargo-laden vessel. Pirates, in short, could pounce and flee. Adding soldiers to the merchant ships would have slowed them further and increased the cost of shipping without guaranteeing that they could stand up to maritime predators. Therefore, by the eighth or ninth centuries BCE, maritime states such as Assyria and Phoenicia were launching purpose-built naval vessels to protect their own commercial fleets and perhaps also to prey on the fleets of others. Soon these purpose-built vessels took on distinctive characteristics. For speed, they lengthened their hulls, decreased their draft, added more rowers, and converted the round bow of cargo ships into a ram. The tactic of choice was to ram an enemy vessel—civilian or naval—and then row backward to leave the victim holed and disabled. In time, the pointed and metal-sheathed prow—the Romans called it a *rostrum*—gave way to a blunt ram, meant to cave in the enemy hull instead of piercing it. Too often, the pointed ram could become wedged in the foundering hull of the enemy, disabling the attacking ship and allowing soldiers from the stricken ship to board and capture it.

As multiple states built up naval fleets in the classical era (500 BCE to 500 CE), an arms race settled on the Mediterranean. Speed was the main determinant of victory in this contest, and the structure of the Mediterranean galley dictated one way to achieve it: more rowers. Naval vessels grew longer, until they mounted fifty rowers to a vessel, twenty-five on each side. After that, the lengthening of vessels slowed, constrained perhaps by the scarcity of tall trees to serve as keels. Instead, rowers came to be stacked on multiple split levels in polyremes (Greek for “many oars”). Phoenicians and Assyrians floated biremes. The Athenians built the most perfect of all polyremes, the trireme, which brilliantly stacked three rowers in barely more than the fore-and-aft space normally taken by one. Thereafter, successor naval powers, such as Carthage and Rome, fought in quadriremes, quinquiremes, and even larger elaborations on the Athenian theme. Much doubt surrounds the arrangement of rowers on the monster vessels, but many scholars believe that the higher numbers simply meant they added more rowers per oar, rather than more oars per vessel.



5. *Olympias*, a reproduction of a Greek trireme built in the 1980s, enters the harbor of Tolon, Greece, in 1990. The galley was a weapon platform designed to ram enemy vessels with its underwater prow, but more often its crews disabled and boarded enemy warships for hand-to-hand fighting.

Whatever the propulsion scheme, these oared battleships surely exhibited the appeals and hazards of gigantism. If a weapon is effective, it seems, a bigger version will be more effective. This proved true for galleys—up to a point. The bigger galleys were built stronger to carry the additional weight of more rowers, possibly even big enough to mount siege engines for use against harbor fortifications. Their size also made them less vulnerable to holing by lighter galleys. And the larger polyremes also had more freeboard above the waterline, allowing their soldiers to fire missile weapons down on the main deck of enemy vessels and to jump down to board them. At some point, of course, the monster ships could be outmaneuvered by smaller, nimbler vessels, and the big ships could not chase pirates and other lesser craft into shallow water. Still, the galley battleship was a piece of monumental architecture, the most complex moving technological system of its day, useful for astonishing and intimidating those who might contest control of the sea.

As the ships evolved, their characteristics dictated tactical evolution as well. Ramming was always the ideal, but was seldom achieved. Alternatively, fast and nimble vessels rowed and steered by trained veterans might run the bow of their ship down the side of the enemy's vessel before he could ship his oars—that is, pull them inboard. The disabled warship could then be rammed, boarded, or bypassed while it tried to redistribute its unbroken oars. Often, however, even this tactic was beyond the capabilities of ships maneuvering in cramped quarters, and naval combat devolved into opposing fleets crashing into each other en masse in lines abreast. Then missile weapons and boarding parties would decide the issue. The Romans, who were primarily land warriors before coming into naval conflict with the Carthaginians in the First Punic War (264–261 BCE), found themselves at a disadvantage in both ships and seamanship. One mechanism they adapted from eastern Mediterranean naval warfare to cope with this asymmetry was the *corvus*, or beak, a pivoting gangplank that could project over the bow of their galleys. The device stood vertically on its pivot next to the forward mast, to be dropped onto the deck of an enemy vessel that came within range. Then Roman soldiers—the heart of Rome's military strength—could plunge across the gangway and take the foe in hand-to-hand combat. In short, they reduced naval warfare to land warfare on a floating platform—most famously at the critical battles of Mylae and Ecnomus. After building and losing three galley fleets, the Romans finally defeated the Carthaginians at sea and established what naval theorist Alfred Thayer Mahan would later call control of the sea.

Like other sea powers, however, the Romans discovered that control of the sea could be ruinously expensive. Galleys had a life expectancy of twenty to twenty-five years, and they consumed huge quantities of naval stores and rowers. Thalassocracies, dominant sea powers such as Athens and Carthage, might find the money to build and support standing navies—Athens devoted most of the revenue from a rich silver mine to pay for its fleet—but land powers such as Rome wearied of maintaining an army to secure its empire and a fleet to secure the Mediterranean, especially in the absence of a significant naval threat. Other states in subsequent centuries would struggle to find the proper balance between land and naval power.

After the fall of the Roman Empire, sea power in the Mediterranean fragmented among contending states and empires. The Byzantines came closer than anyone to controlling at least some parts of the Mediterranean. And they also defended their empire against challenges at sea with the only truly secret weapon of the ancient world. So-called "Greek fire" was an incendiary with many of the characteristics of modern napalm. As used on Byzantine *dromons*—small, fast galleys—it was preheated below decks and then shot under pressure from a nozzle in the bow. A flame at the tip of the nozzle ignited the fluid as it took flight. It reportedly stuck to anything it touched and continued to burn even underwater. Appearing in combat around 677 CE, during the first Muslim siege of Constantinople, it drove off the enemy ships and helped to secure the survival of the city and the empire. The formula for the incendiary was guarded jealously by the imperial family and their confidants, reserved exclusively for the defense of Constantinople until it disappeared, perhaps, in the riot of palace intrigues that passed for Byzantine government. No one then or since has been able to reproduce its reported effects. Even if those reports were exaggerated, enough people appear to have believed them to make this an unparalleled terror weapon.

Gigantism weighed upon galley warfare to the end. The Roman liburnian and the Byzantine *dromon* bucked the pattern, but the Venetian *gallia sotil* of the sixteenth century had about the same dimensions and twice the displacement of a Roman quinquereme. When the last great galley battle in Mediterranean history took place at Lepanto in 1571, the four participating navies tried to adapt cannons to their oared vessels. The Christian naval forces, averaging about five guns per ship, defeated the larger Muslim fleet, which averaged fewer than three guns per ship, but none of the participants found a convincing way to exploit the potential of shipboard cannons. The galley was going extinct in a new naval environment for which it was ill adapted. The gunpowder revolution that was transforming not just land warfare but all of world history had enormous potential to alter naval warfare as well. But it demanded a different platform. The biggest galleys at Lepanto could mount a large cannon facing forward on the centerline, but most of its gunpowder weapons were small antipersonnel guns. The casualties they could inflict seldom won battles. Cannon had the potential to kill ships, not just their crews. And in warfare on platforms, the platform is more important than the crew—John Paul Jones notwithstanding.

Two major and several minor technological innovations converged in the early modern era (1500–1800) to produce the Western side-gunned sailing ship, the most complex technological artifact of early modern history. First, the gunpowder revolution introduced a whole suite of weapons that worked as well at sea as on land. Second, the northern Atlantic sailing cog evolved in the late Middle Ages into a fighting platform, much as early rowed vessels had turned first into armed merchantmen and then into purpose-built naval vessels. The cog was a squat, rotund, slow, stable, seaworthy cargo vessel that had been carrying goods and some passengers about the Baltic and North Seas and up and down the Atlantic coast of Europe since the early Middle Ages. As this trade grew after the European commercial revolution of the fourteenth century, it attracted ever more piracy. The pirates attacked in similar vessels, carrying fighters armed with missile weapons and personal arms for boarding and hand-to-hand combat. The merchantmen naturally armed themselves in like manner, fueling a minor symmetrical arms race. To gain advantage in the resulting engagements, both sides built "castles" on the decks of their ships, structures from which their archers could fire down at the personnel on the decks of enemy ships. By the fifteenth century, individual firearms were being used from these castles, and it was not long before cannons were added to the ships' armaments.

But here the process hit a technological ceiling. Putting heavy cannon in the castles high above the waterline made the small ships unstable. And when the cannons fired, the recoil could tip the vessel precariously. So, only small antipersonnel weapons could be mounted thus. At some point a collateral innovation broke through this ceiling. Merchant shippers introduced ports in the sides of their vessels to facilitate loading and unloading of cargo. These ports were developed to be watertight when closed for sailing, to keep water from flooding in when the vessel heeled over under sail. Such ports, of course, could also be used for firing cannons. Once cannons could be moved from the castles above the main deck to the lower decks of the ship, then the firepower that a vessel might carry was limited only by the size of the vessel. A new race toward gigantism was on. From the hundred-ton cogs of the twelfth century mounting a few archers on primitive castles fore and aft there emerged by 1700 hundred-gun ships displacing almost two thousand tons. Cogs had targeted enemy crews. These floating batteries targeted other ships.

The full potential of the side-gunned sailing ship would never have been reached, however, were it not for a number of additional innovations. The steering oars that had maneuvered all galleys known to history gave way late in the twelfth century to a sternpost rudder, connected to a wheel or tiller on deck. This mechanism proved indispensable for controlling the large sailing vessels, whose handling characteristics in heavy weather put enormous stress on the helmsman. The compass had appeared in Europe around the turn of the thirteenth century. With it, sailors could venture farther from shore, eventually hazarding exploration of the Atlantic Ocean. In the eighteenth century the modern sextant replaced the more primitive astrolabe or cross-staff of previous centuries, giving mariners reliable estimates of latitude—distance north or south of the equator—when out of sight of land. And finally, also in the eighteenth century, Britain's John Harrison produced an exquisitely conceived and crafted maritime chronometer that could keep accurate time indefinitely, even on a rolling, pitching ship. With it, sailors could determine longitude, their position east or west of a fixed reference. Latitude and longitude gave the mariner an exact location in the middle of the ocean.

The capabilities of side-gunned sailing ships were unprecedented. Because they were powered by wind, a renewable energy source, their range was limited only by food and water for the crew. Since these were readily available worldwide, the sailing ship knew no bounds. As it roamed the world's oceans, it proved invulnerable to any other ship afloat, from Mediterranean galleys to Chinese junks to South Asian dhows. Indeed, so powerful were these ships that their only military competition on the high seas came from each other. An arms race of would-be European naval powers drove the size of vessels to staggering proportions, creating in the process a hierarchy of power. Fleets were dominated by "ships of the line," vessels of sixty guns or more that were big enough and powerful enough to survive duels with the largest vessels afloat. So expensive were these floating fortresses that only the wealthiest of states could afford to compete. Like the chariot, the ship of the line forced would-be naval powers to contend in kind, that is, symmetrically, or retire from the field.

The competition offered untold rewards and great hazard. Not only did sea power allow states to protect their own commerce and prey on the commerce of their enemies, as galleys had done, but it also allowed European navies to project power ashore. Thalassocracies such as the Dutch and the British prospered by concentrating their resources on naval power. States such as Spain and France tried to be great powers on both land and sea, like the Romans before them. They failed, suffering financial exhaustion and finally military ruin. At the end of the early modern competition for sea power and empire, Horatio Nelson, the greatest commander of the age of sail, defeated a combined French and Spanish fleet at the battle of Trafalgar in 1805. Though Nelson died of his wounds in the battle, Britain emerged as the unquestioned mistress of the seas, beginning a Pax Britannica that would last until World War I.

Nelson's flagship at that climactic battle of the age of sail was HMS *Victory*—a weapon system of one hundred guns, displacing 3,500 tons and requiring a crew of eight hundred to sail and fight. She descended directly from the North Sea cog that first put portals in her side to load and unload cargo. But *Victory* and her sister ships of the line existed under a technological ceiling that would constrain their operation and ultimately spell their doom. Like the galleys they succeeded, they were ruinously expensive. Building and maintaining them drove countries to denude their countrysides of trees and sweep their streets and taverns in search of destitute men who might be pressed into service as sailors and gunners. Their dependence on the wind for power limited their speed and direction of movement. They could go anywhere—but slowly, tacking back and forth to reach destinations upwind.

6. In the bittersweet, decisive battle of Trafalgar (1805), HMS *Victory*, the flagship of Horatio Nelson, was an icon for British command of the sea. The Irish artist Daniel Maclise depicted *Victory* as both the center of gravity for the battle and the idealized site of Nelson's death from sniper fire.

Furthermore, when they engaged in battle, they had to bring their guns to bear on the enemy by maneuvering the ship itself. In other words, their weapon platform was also their aiming mechanism. So they tended to fight in "line ahead" formation, with entire fleets sailing single-file parallel to the enemy fleet. Such tactics led to horrific exchanges of cannon fire, often at close range, often indecisively. Indeed, it was Nelson's willingness to attack the enemy line at right angles that brought about his greatest triumph.

By the time of Trafalgar, however, the age of sail was already in eclipse. The American artist/engineer Robert Fulton had built his first steamboat in Paris, and he would launch his first commercial model—the *Old North River*—less than two years after Nelson's death. Neither of these Fulton boats nor the others that sprang up in imitation and competition on the coastal and inland waters of the United States posed much threat to HMS *Victory*. The *North River* measured just 150 feet in length, and the weight of its chugging, vibrating engines threatened to shake it apart even in calm waters. The wooden paddle wheels driving all of these early steamboats through the water would disintegrate catastrophically under cannon fire. A battery of guns would stress them further, and high seas would sunder them before the enemy fired a shot. But they nonetheless began a technological evolution that produced within a century HMS *Dreadnought*, the first all-big-gun battleship. Just forty years after *Dreadnought*, the Japanese battleship *Musashi* turned turtle under fire and carried about a thousand of its 2,400-man crew to their deaths at the bottom of the Sibuyan Sea—the largest and most futile dinosaur in this particular race to gigantism.

The first phase of this story, from the *Old North River* to the *Dreadnought*, unfolded in the technologically fecund decades of the nineteenth century. The steamboat, a dual-use technology first developed for commercial purposes, proceeded on a single trajectory before specialized naval vessels were introduced. First the engines were made more powerful and more efficient by the introduction of double-acting pistons and high-pressure steam. The first steamboat made it across the Atlantic in 1819, but naval officers resisted the new technology as unreliable and aesthetically offensive. When steam entered naval ranks, it appeared mostly in the form of auxiliary engines mounted on traditional side-gunned sailing vessels of the line—a hybrid reminiscent of galleys with sails. Of course naval guns were improving at the same time, leading to experiments with iron armor mounted on traditional wooden hulls. In 1862, two armored vessels powered entirely by steam—one (the *Monitor*) purpose-built entirely of metal and mounting two guns in a rotating turret and the other (the *Merrimac*) an ironclad, side-gunned wooden vessel—met in the American Civil War to announce the arrival of the age of steam in naval warfare. Thereafter, developments proceeded rapidly: iron and then steel hulls, rifled guns mounted on centerline turrets, armored hulls and decks turning battleships into floating fortifications, turbine engines that converted steam into speeds of twenty knots or more, radios to communicate within and between fleets, gyroscopes to stabilize vessels and their guns, and range finders to allow one of these juggernauts of the sea to strike another 10 miles or more away.

Meanwhile, a new line of carbon-based heat engines transformed the nineteenth-century naval arms race and made possible the riot of power and destruction unleashed in the world wars. Nicolaus Otto pioneered the modern four-cycle, liquid-fuel, internal combustion engine in the 1860s, another dual-use technology. Now, for the first time, the stored power of carbon compounds—this time in the form of liquid fossil fuels—could be harnessed within the engine cylinder itself. Steamships would remain steamships, powered by water vaporized in a boiler immersed in a coal or oil fire. But the true internal combustion engine meant that much smaller machines could now be driven anywhere above the surface of the water and below the upper limits of the atmosphere with a compact engine running on liquid fuel. The applications included two technologies that would slay the mighty battleship.

One such application was the submarine. Attempts had been under way for centuries to build underwater weapons. Steamboat inventor Robert Fulton actually built one for Napoleon in 1800 and captained it and a crew of three into the English Channel in a failed attempt to blow up blockading British naval vessels. The Confederate States Ship *Hunley* succeeded in sinking a Union warship in the American Civil War, though it too sank in the operation. These ingenious devices were driven by human muscles turning cranks, hopelessly underpowered until internal combustion engines and storage batteries made them seaworthy and potent. American John Philip Holland pioneered the first modern prototype in 1897, just seventeen years before potent submarines began commerce raiding in World War I.

The internal combustion engine also powered the airplane, another dual-use technology invented for civilian purposes and quickly conscripted for military service. The Wright brothers taught the world to fly in a series of demonstrations in 1908. Within a few years, their invention raised human conflict into a third dimension and transformed the battlefields of World War I. In that same war, the tank harnessed the internal combustion engine to initiate a new cavalry cycle that would dominate land warfare through much of the twentieth century.

The internal combustion engine, and the machines it powered, transformed warfare more completely than its predecessor in the Carbon Age—the steam engine. Nowhere was the change more dramatic than in naval warfare. The steam battleship, like its predecessors of oars and sail, the polyreme and the ship of the line, swelled in its first century of existence from the diminutive, single-turret USS *Monitor* of Civil War fame to the unprecedented *Yamato* and her sister ship, *Musashi*. Both Japanese vessels displaced 72,800 long tons fully loaded—18 times the weight of Nelson's *Victory*. Their nine main guns, of more than 18-inch caliber, threw 3,200-pound shells 26 miles—100 times the weight and 26 times the range of Nelson's largest gun. Yet *Yamato* was sunk by carrier-based dive-bombers and torpedo planes that weighed about one-hundredth of one percent of their prey.

Gigantism had once again seduced warriors with a dinosaur. Repeatedly through human history, the allure of brute force had masked the potential of maneuver and aimed fire. In all realms of warfare, big and small were inherently neither good nor bad. Rather, technology magnified the brute force of big while enhancing the mobility of small. Technologies such as the internal combustion engine were great levelers and force multipliers. In the twentieth century and beyond, war became in many ways a contest to find the most appropriate technology for a given mission. Quality might or might not trump quantity. Big might or might not trump small. New might or might not trump old. The full arc of the Carbon Age was manifest in naval warfare, where change was sparked by technology push. That is, technologies developed elsewhere transformed naval warfare. Gunpowder had called into being the side-gunned sailing ship. The steam engine had called into being the steamship. And the internal combustion engine had powered the airplanes that sank the most monstrous of steamships.

So too did naval warfare figure prominently in the transition beyond the Carbon Age and into the Nuclear Age. Atomic or nuclear power was a dual-use technology of a rare sort: its inventors immediately appreciated its dual uses. As the atom gave up its secrets with accelerating speed in the 1920s and 1930s, physicists saw the possibility of destabilizing and splitting the atoms of certain heavy elements. If they could be split, the process would give off astronomical amounts of energy. If the neutrons released in the splitting of one atom could go on to split other atoms, the process might create a chain reaction. Theoretically, chain reactions could be controlled to release the energy slowly or explosively—one technique for power generation and one for bombs. When German scientists Otto Hahn and Fritz Strassman, with help from exiled colleague Lise Meitner, split an atom in 1938 by bombarding it with neutrons, scientists around the world quickly grasped the implications. With World War II looming in Europe, a race began to produce an atomic bomb. The resulting Manhattan Project in the United States, with collaboration from British and Canadian researchers, outpaced its rivals during the course of World War II and displayed its handiwork at Hiroshima and Nagasaki in 1945.

US Navy captain Hyman Rickover saw more clearly than most at the end of World War II that atomic power—what he came to call nuclear power—had military potential beyond the bomb. If the chain reaction could be harnessed, nuclear fission might power naval vessels, solving two problems that had shadowed the age of steam since its inception. First, a nuclear-powered ship could go years between refuelings, eliminating the need for frequent stops at coaling or oil stations. Second, a nuclear reactor could provide power without oxygen, making possible a true submarine, one that could remain beneath the waves for weeks, even months, on end. Rickover convinced the navy to let him find out if these possibilities could be realized.

After educating himself on the technology of nuclear reactors at the Manhattan Project's Oak Ridge National Laboratory, Rickover won approval for a pilot program to develop nuclear power for ships—beginning with a submarine power plant. The basics of the technology posed several pivotal questions from the outset. He would have to choose the fuel, a moderator to slow the speed of released neutrons, a coolant to maintain core temperature, a heat exchanger to transfer the energy from the pile to a water supply for steam to run the ship's turbines, a cladding material to reflect neutrons back into the pile and prevent the escape of radiation, and finally control rods to speed up or shut down the chain reaction. With the cramped quarters of a submarine in mind, Rickover chose a light water reactor. The pressurized water in this design performed cooling and moderating, while a different water supply provided heat transfer. For aircraft carriers, he would choose a similar but slightly larger boiling-water reactor.

It was the prototype light water reactor, built at Shippingport, Pennsylvania, that had the largest impact. Successfully developed for nuclear submarines, it powered the USS *Nautilus* on its maiden voyage in 1955. Thereafter, nuclear reactors powered two lines of American submarines, attack subs and so-called boomers, launching platforms for strategic ballistic missiles armed with nuclear warheads. When the missiles aboard these submarines scaled up to intercontinental range, the submarine-launched ballistic missile (SLBM) became the third and least vulnerable leg of the American strategic triad—bombers, land-based missiles, and SLBMs. Soviet weapons might strike American intercontinental bombers on the ground at their home bases or intercontinental ballistic missiles (ICBMs) on their launch pads, but never in the Cold War did the Soviet Union develop the capability to find and destroy the boomers hiding in the ocean's depths. The SLBM was the ultima ratio of Cold War deterrence.

Rickover's management of the Navy's nuclear reactor program had consequences beyond strategic deterrence. His choice of the light water reactor early in the program and the contract with Westinghouse Electric Corporation to build the first submarine reactors created a cascading effect. Economists often speak of this effect as "lock-in," a cultural or institutional commitment to one technological trajectory over another. Social scientists who study the history of technology call it "closure," by which they mean the end of a period of competing technological trajectories, when one is chosen and the others fade from prominence. Historian Thomas Hughes has called this phenomenon "technological momentum," to distinguish it from that hobgoblin of technology studies, the dreaded technological determinism. All of these analogies are meant to suggest that there is never anything "inevitable" about the technological choices communities make. Seldom is there one "best" technology for doing any particular job. Rather, different communities at different times and places find one technology better suited to their needs, resources, and temperament. But once those communities express a preference for one over the others, they create momentum behind that choice; they tend to close out further development of alternatives; and they lock the community into the investment they have made in their selection.

Thus it was with the light water reactor. Encouraged by the administration of President Dwight D. Eisenhower and its "atoms for peace" program, Westinghouse designed a light water reactor for commercial power applications. Many other combinations of fuels, moderators, coolants, cladding, control rods, and heat transfer mechanisms presented themselves, but Westinghouse capitalized on the technology it already knew. Thus it was that the United States launched its commercial nuclear power industry on a trajectory that helped determine its future. Economists call the resulting line of development path-dependent, meaning that the field is not free to find its own end point but is constrained by the path it started down early on. The further it goes down that path, the less likely it is to backtrack to the road not taken. First steps in path dependence are especially weighty, and Rickover made those fateful early commitments. For a multitude of reasons, America's love affair with nuclear power soured in the late 1970s, and the so-called second generation has yet to find much traction. One of the reasons was the choice made early on to suit military purposes.

Of course, the major factor behind the atrophy of the first generation of nuclear power in the United States was safety. The Three Mile Island accident of 1979 sounded the death knell of an industrial boom that was already struggling to maintain momentum. Rickover always insisted that nuclear power, properly managed, was safe. When he finally relinquished control of the Navy's nuclear power program in 1982, Rickover noted that, as he had promised, no US Navy ship was ever lost or even ever seriously damaged by a nuclear accident. The attack submarine USS *Thresher* sank in 1963, carrying her entire crew to the bottom of the Atlantic Ocean, but this was a mechanical failure not directly related to the ship's reactor. The navy's nuclear vessels avoided accidents through rigorous education, training, and discipline, overseen personally by Rickover. His whole career was a testament to human agency, to the power of people to limit the dangers seemingly inherent in certain kinds of technology. Modern complex technological systems can sometimes seem "autonomous" or "out of control," as political scientist Langdon Winner has suggested. But Rickover proved that humans could manage risk much more successfully than they typically do.

Air warfare

The airplane was a dual-use technology invented by two bicycle mechanics. It took the military a while to figure out what to do with it. Beginning in 1899, Wilbur and Orville Wright systematically scoured the existing literature on human flight. Then they designed and tested their own airfoils, developing lift tables to inform their design of both wings and propellers. To control themselves in flight, as birds did, they invented wing warping, an ingenious mechanism for achieving differential lift on their wings. From the ground they maneuvered a tethered version of their airframe in the wind until they understood control, then they mounted the big kite and glided in free flight from hilltops. By then, they knew how to fly. To power their airplane they commissioned a mechanic to design and build an engine to their specifications, and they designed their own propeller. They put all the components together in the winter of 1903 and flew a distance of 852 feet under their own power. Never before or since have two independent, untutored inventors read, thought, observed, theorized, experimented, and designed a new technology in such a short time with such staggering consequences. While their patent application awaited approval, they practiced flying for five years in a field near their bicycle shop. In 1908, they demonstrated their achievement in Paris and Washington, convincing all impartial observers that they had by themselves solved the problems that individual researchers, institutions, and governments had been attacking for years.

What did the world make of this gift of flight? Some used the airplane to look at the world from above. Civilians took pictures. Soldiers surveyed the battlefield. The U.S. Army Signal Corps, in charge of reconnaissance, purchased the first Wright Flyers. The possibility that this fragile platform of sticks and cloth could one day carry cargo and passengers, guns and bombs, beggared their imaginations.

Soon, however, researchers in Europe found themselves competing to launch faster and more maneuverable aircraft, part of a general arms race that accelerated Europe's descent into World War I. When new, fast airplanes rose above the battlefields of France, they encountered each other and quickly began fighting for what came to be called "air superiority." Observation planes morphed into fighter aircraft, mounting machine guns and reviving memories of chivalric knights engaged in one-on-one duels of honor. Since the death and destruction they inflicted in this air combat was limited to each other, the world took little note of the ominous implications for the future. The Germans experimented with bombing Britain from two huge, multiwing behemoths named *Gotha* and *Giant*. But the pilots over the battlefield dropped on the enemy troops little more than hand grenades and detritus from the floor of their open cockpits. The airplane of World War I was still primarily a vehicle, a platform for observing and driving off other observers. Only in the years between the world wars would this new platform find the military and civilian applications that eventually altered life on earth.

Two main military uses suggested themselves. Continental Europeans focused on fighter aircraft, driven by high-powered, liquid cooled in-line engines for speed and advanced aerodynamics for maneuverability. They sought to win control of the air over the battlefield to conduct reconnaissance and attack the enemy's ground forces. The United States and Britain, however, followed the lead of Italian air-power theorist Giulio Douhet, specializing in strategic bombing. This mission required an entirely different aerial platform, a larger vehicle powered by radial air-cooled engines to achieve great range. It was no coincidence that both these countries also needed commercial aircraft with the same capabilities: airliners to carry passengers across the United States and around the world to Britain's far-flung empire. The Germans, drawing on their experience in the Spanish Civil War (1936–1939), foresaw a greater scope for air power and developed a suite of aircraft for everything from air superiority, to long-range and medium-range bombing, to air assault by paratroopers. Eventually, the British had to complement their strategic bombers with fighters for home defense, and the United States had to add fighter escorts to protect their bombers on missions over enemy territory. Both

Britain and the United States experimented with fighter-attack aircraft for duty at sea. Unlike galleys and sailing ships, airplanes as platforms were all custom-designed from the outset for the particular weapons they were to carry and missions they were to perform.

An icon of dual-use aircraft between the world wars appeared in 1935, when the DC-3 took to the air. This passenger liner, the third iteration of a commercial design by the American Douglas Aircraft Company, featured cantilevered wings; cowled, air-cooled, rotary engines; variable-pitch propellers; retractable landing gear; wing flaps; a streamlined, stress-skinned monocoque fuselage; and flush riveting. It was the state of the art. Douglas built more than six hundred of the planes for commercial use before suspending production in 1942 to concentrate on military applications. It built more than ten thousand of the military derivatives—the C(argo)-47 and C-53—during the war and licensed the Soviets and the Japanese to build more than five thousand of their own national versions in the 1930s, aircraft which were converted to military purposes during the war. No airplane in history has matched the utility or longevity of the DC-3, which is still flying in some parts of the world.

The timeless qualities of the DC-3 contrast markedly with the hothouse evolution of purpose-built military aircraft. Air races and prizes, such as the one that lured Charles Lindbergh into his historic transatlantic flight in 1927, spurred technological innovation between the wars. Fighter, escort, reconnaissance, transport, and attack aircraft became more effective over both land and sea, as demand pull from the armed forces dragged technological capability into realms that airpower enthusiasts had barely imagined. During World War II, Americans moved up from the B-17 bomber with which they started the war—a plane capable of flying 287 miles per hour at 35,000 feet for a range of 2,000 miles with a bomb load of 6,000 pounds—to the incomparable B-29 of Hiroshima and Nagasaki, a behemoth flying 357 miles per hour at 32,000 feet for 3,250 miles with a bomb load of 20,000 pounds. But these marvels of military invention could not match all the predictions made by the early air enthusiasts. Strategic bombing never attained the decisiveness its prophets had predicted, and other forms of air power found their capabilities bent to practical purposes on the ground and on the sea. Close air support, for example, shaped land warfare more decisively than most had predicted, and air transport moved people and material around the world more quickly and safely than ships could do. Paratroopers jumping out of airplanes added a strategic mobility to ground warfare that no previous mounted warriors had ever achieved.

Additionally, suites of supporting technology arose to aid or counteract the rapid evolution of air power. Long-wave radar

7. This grainy action photo captures American B-29s dropping incendiary bombs over Yokohama, Japan, in May 1945. These "Superfortresses" could carry a bomb load of 20,000 pounds to a range of 3,250 miles and achieve a top speed of 350 miles per hour at 30,000 feet, above the altitudes that fighter aircraft could reach. Two of these planes, nicknamed *Enola Gay* and *Bockscar*, dropped the atomic bombs on Japan in August 1945. The B-29 was the ultimate weapon platform of its day.

along the United Kingdom's east coast gave critical early warning to British fighter-interceptors in the 1940 Battle of Britain. Shortwave radar, one of the most critical and fecund inventions of the war years, spawned more than one hundred applications, including airborne radar and proximity fuses. Improved radios allowed ground commanders to communicate directly with the close air support flying above them. New bombsights made possible what the Americans liked to call precision bombing—though it was never as precise in battle as on the test range. Long-range navigation systems (later called LORAN) guided bombers to distant targets. Antiaircraft weapons offered some ground defense against air attack. And, finally, atomic weapons debuted at the very end of the war, helping to spare the Allies and the Japanese alike the carnage of an amphibious invasion and giving the air power enthusiasts a patina of respectability for the frayed doctrine of decisiveness.

After World War II, radars merged with computers to form air defense systems that automated defensive responses while also promoting the dual-use technology of computer networking. Early experiments in pilotless aircraft laid the groundwork for unmanned aerial vehicles—sometimes called drones. Aerodynamic advances such as swept wings and wasp waists promoted supersonic flight. Guns and missiles vied for superiority in air combat. Aerial refueling extended the range of military aircraft.

Finally, aviation bequeathed to the world an institutional model of how to routinize and institutionalize innovations in military technology. Because flight posed more technological challenges than warfare on either land or sea, air power pioneered scheduled obsolescence on a cycle shorter than navies had yet anticipated. Even before one generation of airplanes was operational, its replacement was under development. Every new platform had to fly higher, faster, and farther than its predecessor; its weapon systems had to be more accurate, powerful, and irresistible; and its supporting technology had to improve safety, reliability, and efficiency. What one historian has called “capability greed” settled upon air forces sooner than other services and drove them into qualitative arms races of ruinous expense and intensity. And where they went, the other services followed, leading in short order to what President Dwight Eisenhower labeled a military-industrial complex.

Space warfare

The origins of space warfare paralleled aviation in many ways. Both were first invented by inspired amateurs as ends in themselves, without any attention to military applications. Soon, however, the military possibilities became apparent. Airplanes and spacecraft soon began serving as platforms for military activity, exemplars of dual-use technologies that found applications from both demand pull and technology push. The difference with spacecraft is that they never became the weapon platforms that early advocates of space warfare envisioned.

Spaceflight technology took off, so to speak, in the 1920s, spurred by theorists and visionaries who predicted that humans could and would travel to the moon, to Mars, and perhaps beyond. Reducing those visions to reality was the life’s work of two remarkable communities: Wernher von Braun’s Spaceflight Society in Germany and Robert Goddard’s much smaller research team in the United States. Both experimented with early designs of small liquid-fuel rockets. Achieving some success, they sought outside funding for the more expensive proposition of building larger rockets that could carry significant payloads to very high altitudes. Von Braun and his colleagues turned to the Wehrmacht. Goddard solicited support from a wider variety of public and private patrons: the Smithsonian Institution, the United States Navy, and the Guggenheim family. The accelerating pace of military research and development in Germany and the United States in the years leading up to World War II carried rocket research toward weaponry rather than toward the civilian spaceflight that Goddard and von Braun had first intended. By the end of the war, von Braun’s team had developed the V-1 (V for *Vergeltungswaffe*—vengeance weapon) "buzz bomb," a kind of cruise missile, and the even more famous and deadly V-2 ballistic missile, capable of carrying a 1,000-kilogram warhead about 200 miles. Germany launched more than three thousand V-2s at Allied targets in the closing years of World War II, but owing in part to the shortcomings of its guidance system, the Germans killed more of their own people in forced-labor camps building the rockets than they did bombarding enemies.

At the end of World War II, the United States and the Soviet Union captured most of the hardware and personnel from the V-2 program and put the people to work on their respective missile-development programs. The Soviets had greater need for long-range missiles, so they began an ambitious program in 1947 to build an ICBM capable of carrying an atomic bomb (which they had not yet perfected) from Soviet territory to the United States. The United States, in contrast, began its ICBM program in earnest only when it learned of Soviet progress. This particular race to develop symmetrical weapon systems was won by the Soviets, who displayed their achievement to the entire world on October 4, 1957, when they used their new ICBM to launch *Sputnik I*, a civilian, scientific satellite, into earth orbit. In spite of President Eisenhower's reluctance to militarize space, a hybrid military-civilian space race ensued.

The space race ran on parallel tracks, each relying on the dual-use technology of ICBMs. Configured as launch vehicles, they put the first satellites and then the first humans in space. At the same time, the military versions of these liquid-fuel rockets mounted nuclear warheads to join manned bombers as the second leg of a "triad" of the strategic weapon systems with which the United States and the Soviet Union fought their "Cold War" of deterrence from the 1950s through the 1980s. The third leg of the triad joined the suite in the 1960s, when the US Navy perfected a solid-fuel ballistic missile that could be carried safely aboard the

8. *Mercury-Atlas 6*, an American Atlas intercontinental ballistic missile configured as a space launch vehicle, lifts off from Cape Canaveral Air Force Station in Florida on February 20, 1962, carrying astronaut John Glenn in his *Friendship 7* space capsule on the first American orbital flight. The Atlas rocket is still in service, a dual-use technology supporting both military and civilian functions.

nuclear-powered submarines that Admiral Rickover had brought into being.

The United States won the civilian version of the space race in 1969, when it landed the first men on the moon. Those astronauts flew the Apollo launch vehicle, a civilian, purpose-built rocket masterminded by that chameleon of spaceflight, Wernher von Braun. He had been recruited by the National Aeronautics and Space Administration (NASA) to build launch vehicles for civilian, as opposed to military, masters. Thus, the cycle had come full circle, and the spaceflight enthusiast who wanted to go to the moon was freed from military service to pursue that goal.

The dual-use technology von Braun helped to pioneer had been advanced through World War II and the early Cold War by demand pull from the military, only to turn around in the 1950s and serve as a technology push for the US civilian space program. Turning his great talents and boundless ambition to civilian spaceflight, von Braun imprinted on the late twentieth century what one historian has called the von Braun paradigm. This model envisioned liquid-fueled rockets (descendants of his V-2) lifting people and material to low-earth orbit. There, astronauts would build space stations as bases for manned flights to the moon, Mars, and beyond. In the second decade of the twenty-first century, this model still guides the long-range planning of NASA.

Historian Walter McDougall has made clear that NASA and the civilian space program were really continuations of the Cold War by other means, but the United States at least tried to keep military and civilian space activities separate. Their Soviet counterparts organized their military space activities in the "rocket forces," creating a fourth branch of the military establishment on a nominally equal footing with the army, navy, and air force. The Soviet civilian space program was divided among a set of competing design bureaus, managed directly by the central government. This institutional arrangement in the Soviet Union contributed to the perception that space must surely become another arena of warfare—just as war had spread historically from land to sea and air, only in space, the platforms to carry military weapons would be more complicated, more expensive, and potentially more dangerous than anywhere on earth.

As it happened, however, warfare did not spill into space. President Eisenhower resisted domestic pressures arising from the "red scare" of the 1950s, the rampant alarmism of Joseph McCarthy and his fellow true believers, and dire warnings from the military-industrial complex that the militarization of space was inevitable. His immediate Democratic successors, John Kennedy and Lyndon Johnson, reversed the bombastic rhetoric of the 1960 presidential campaign to institutionalize the Eisenhower caution in a series of agreements and policies that slowed the American enthusiasm for arming the heavens. By the time the Outer Space Treaty was signed in 1967, both superpowers and most other industrialized states in the world had agreed not to put weapons of mass destruction in space, not to make national claims on extraterrestrial bodies, and not to interfere with the orbital platforms of other states. The high cost of spaceflight, the vulnerability of spacecraft in orbit, and the difficulty of using orbiting spacecraft as platforms for earth-directed weapons had convinced virtually everyone that weapons in space were a bad idea. Not until Ronald Reagan suggested a partially space-based antiballistic missile program in 1983—his Strategic Defense Initiative, quickly labeled by the press "Star Wars" after a contemporary science fiction film series—did a major power seriously consider placing strategic weapons in space. Twenty years later, President George W. Bush took that failed proposition one step further by withdrawing the United States from the Anti-Ballistic Missile (ABM) Treaty (1972), but by then the dismal cost-effectiveness of a space-based ABM system was already manifest.

Though weapons were not going to play a prominent role in space activity, earth orbit nonetheless became a site of critical military activity. Nonweapons technologies, ranging from reconnaissance satellites to global positioning systems (GPSs), grew in importance through the Cold War and into the twenty-first century. By the time of the Iraq and Afghanistan wars of the 2000s and 2010s, the United States military had come to believe that its dependence upon space-based assets for communication, intelligence, navigation, and weather monitoring had become so acute on the ground and at sea that the vulnerability of those assets posed a risk to American security. Through the turn of the twenty-first century, therefore, spacefaring states were developing new technologies to protect their assets in orbit and to threaten those of potential enemies. This new arms race reached a zenith—or nadir—of sorts in 2007, when China destroyed one of its own obsolescent satellites in orbit in an apparent effort to demonstrate its own technological prowess. The result was a scattering of space debris that threatened to set off a cascade of collisions with other orbiting spacecraft of the kind captured so brilliantly in the 2013 movie *Gravity*. China was chastened by the experience, and all spacefaring states were reminded of the power and vulnerability of their space-based assets. The episode reinforced the taboo against weapons in orbit. Space warfare may one day break out, but it is unlikely to appear until the technology of the von Braun paradigm is superseded.

Modern warfare

The American humorist Will Rogers observed, "You can't say civilization don't advance…, for in every war they kill you in a new way." This pithy insight resonates in the early twenty-first century as poignantly as it did between the world wars when Rogers voiced it. As this book has been at pains to emphasize, however, it was not true through most of human history. For thousands of years, the means and instruments of warfare evolved at a glacial pace. The gunpowder revolution in the western Middle Ages launched an epoch of accelerating change by adding chemical power to warfare. Modern warfare sped up the process and distributed it across four physical realms—land, sea, air, and space.

Historians conventionally divide the modern epoch into two phases. "Early modern" is usually associated with the period between the Middle Ages and the French Revolution, roughly 1500 to 1789. "Modern" is everything since, though some historians discern a postmodern period beginning sometime in the second half of the twentieth century. But postmodern warfare is not a concept with much explanatory power, so "modern warfare" will be treated here as a single epoch that is still running its course.

Some humanists and social scientists ascribe to modern history a set of characteristics they call "modernity." Among the most important features are Enlightenment rationality, secularization, the dominance of the nation-state, industrial capitalism, scientific and technological progress, and a particularly lethal and destructive form of warfare that targets both military and civilian sectors. In the twentieth century especially, the carnage of the world wars and the apocalyptic possibility of nuclear war cast upon "modernity" a shadow of ennui and foreboding, an apprehension that the human race might just disappear in a cataclysm of its own making.

In the nineteenth century, however, the benefits of modernity still seemed to greatly outweigh its hazards, especially in the Western states where "progress" was being made most rapidly. At its heart that progress was fundamentally material, an increasing understanding and mastery of the physical world that seemed to promise ever more wealth, comfort, safety, and health—at least for the Western states that were creating and defining modernity. Philosopher of science Alfred North Whitehead said, "The greatest invention of the nineteenth century was the invention of the method of invention." He meant that the Western phenomenon of the scientific revolution followed by the industrial revolution had given rise to a technique of applying scientific method to technical invention. Problems were broken into their component parts, and each part was subjected to research in the existing literature, observation, hypothesis, experimentation, testing, innovation, and production. When all the pieces of the puzzle were in hand, they were integrated into a system of systems, and the whole was subjected to the same process. The Wright brothers' development of the airplane is a classic example. Of course this system of innovation worked as well for military technology as for civilian, but the Pax Britannica from 1815 to 1914 and the general absence of great-power war masked the murderous potential of the industrialization of warfare in the countries where it was taking shape. The colonized world and a handful of prescient observers saw what was coming, but most Westerners viewed the modernization of warfare as one more indicator of their superior civilization.

The transition in naval warfare from an age of sail to an age of steam, already discussed, offers something of a case study in nineteenth-century innovation. From the first successful steamboat—Robert Fulton's *Old North River* in 1807—to the British *Majestic*-class battleships of the 1890s, the guns, hulls, armor, propulsion, and size of warships had undergone a transition requiring an industrial, technological, financial, and administrative infrastructure that only the most developed nations could afford. Even mighty France essentially dropped out of the naval arms race at the turn of the twentieth century, leaving only Britain, Germany, Japan, and the United States as realistic contenders for sea power. Ambitious Russia thought that its antiquated fleet could compete; instead, it suffered at the battle of Tsushima in 1905 one of the most total naval defeats in all of history. Auxiliary technologies, such as automotive torpedoes, radios, gyroscopes, and high-pressure turbines further enhanced the war-fighting capabilities of the great navies.

Weapons driven by gunpowder, that most revolutionary of military technologies, also were experiencing dramatic change. On both land and sea, externally ignited, smoothbore, single-shot cannons and small arms gave way to self-actuating, repeating, rifled guns. In all cases, rifled barrels imparted greater range and accuracy than smoothbores, and prepackaged shells (or powder bags) with their own igniters allowed electrical or percussion detonation. In handguns, revolvers delivered multiple shots from pistols without reloading, followed before 1900 by magazine-fed pistols. Magazines did the same for rifles, either through human-powered reloading—bolt or lever actions—or through automatic gas or recoil mechanisms. Machine guns—fully automatic firearms—appeared by the end of the nineteenth century, ranging from the hand-cranked, proto-modern Gatling gun of the American Civil War to the Maxim gun, deployed to such great effect in the Boer War of 1899–1902. Americans, masters of laborsaving technologies, pioneered this mass production of death.

The technological transformation of ground warfare in the nineteenth century differed significantly from the change set in motion in the late Middle Ages by the introduction of gunpowder. Firepower was the key to victory in both eras, but increases in firepower resulted from different processes. In the late Middle Ages and early modern epoch, individual firearms and artillery were bulky, awkward devices, slow and difficult to reload in the face of the enemy. The barrel had to be swabbed clean after each discharge, loaded with powder, packed with wadding, and finally topped off by jamming a tight-fitting projectile down the barrel. Then a fuse or priming powder had to be ignited from an external source, vulnerable to wind and rain.

The key to firepower with such machines lay in training the gunners. Reloading small arms in the sixteenth century could require ninety steps or more. A unit of infantry hoping to achieve simultaneous volley fire could reload only as fast as the slowest gunner. Enemy cavalry could wait beyond the range of the guns and then cross the battlefield at a gallop to fall on the gunners before they were all reloaded. Infantry formations in the sixteenth century often posted pikemen in front of the gunners to protect them while reloading. The best-trained and choreographed gunners produced the highest rates of fire.

In the nineteenth century, increasing rates of fire flowed from the guns, not the gunners. Two hallmarks of modern technology—mechanization and automation—combined to saturate the battlefield with bullets. The soldiers actually were deskilled by the evolving technology. They needed only to aim and shoot, and volume of fire mattered more than accuracy. The Achilles heel limiting this torrent of projectiles was the logistics of providing ammunition to feed these shooting machines.

Chemists, mostly Europeans, introduced a variety of new propellants in the nineteenth century—the Americans called them smokeless powder—for both small arms and artillery. Gunpowder, or black powder, had always burned imperfectly, leaving solid residue to clog guns and thick smoke to blanket the battlefields of land warfare and the gun decks and turrets of naval warfare. Most of the new propellants pioneered in the nineteenth century were based on nitrated cellulose (gun cotton) combined with other ingredients to enhance stability and increase explosive power. The new propellants reduced smoke and residue and increased the power, range, and reliability of the guns. Standardized charges also allowed for the computation of more reliable firing tables, making it possible to site and range artillery more quickly and to "fire for effect" more efficiently. Predictably, these improvements in guns also spurred gigantism, both in siege weapons and naval guns. Indeed, the modern battleship taking shape at the end of the nineteenth century soon found itself in a race of dueling technologies—guns and armor—that would continue through World War II.

Non-weapons military technologies also contributed to the transformation of warfare in the nineteenth century. The steamboat, it must be remembered, began as a civilian, commercial technology, finding its way onto naval vessels slowly over the course of the century. More than half a century separated Robert Fulton's maiden voyage in 1807 from the first naval battle between steamships, the engagement of the *Monitor* and the *Merrimac* in Hampton Roads in 1862. The same pattern of civilian innovation was true of railroads, which originated hauling coal from mines. By the American Civil War they were moving troops and supplies within and between theaters of operation. Railway networks installed before the war favored the North, with lines running between eastern and western theaters, while the lines in the South, designed to connect the center with the periphery, provided avenues of assault for Northern invaders. In the wars of German unification, 1864–1871, a rail network intentionally designed to support military strategy sped Prussian forces and their gear to the frontiers and brought the wounded home.

Communication in the nineteenth century also served military and civilian purposes. The telegraph magnified command and control across and between theaters of operation, and furthermore empowered both military and civilian leaders to direct their subordinates in the field. The laying of submarine cables in the late nineteenth century extended the commander's reach internationally and also precluded tragedies such as the Battle of New Orleans in 1815, in which an estimated 336 British and American fighters were killed after the signing of the peace treaty in Ghent, Belgium, ending the War of 1812.

Countless other nonmilitary innovations arose in the fecund nineteenth century. Napoleon's army experimented with interchangeable parts, a technology that American inventor Eli Whitney claimed to have perfected in the first decade of the nineteenth century. In fact, Whitney's parts needed hand filing to make them truly interchangeable, but his example spurred successive innovators to perfect the technique. Humans had been manufacturing steel for more than three thousand years when a series of discoveries in metallurgy and innovations in manufacture made possible the mechanization and industrialization of made-to-order steel in large quantities and many forms. Captains of industry in the late nineteenth century—Krupp, Carnegie, and others—made fortunes manufacturing the steel for locomotives, skyscrapers, battleships, and artillery. Indeed, the industrial infrastructure of steel manufacture became a hallmark of both economic and military might. More mundane, but also transformative in its way, the quotidian tin can brought dietary variety and economy to people around the world and nutrition to soldiers on the march. The marvelous Montgolfier brothers of France even introduced the world of manned balloons, which quickly assumed military importance as reconnaissance platforms. Could the airplane be far behind?

The changes in warfare brought on by these rapidly evolving technologies had their greatest impact on imperial wars, where they gave Western powers an asymmetrical advantage over indigenous populations. Of course, the Western powers had enjoyed just such an advantage during the first wave of Western imperialism, beginning in the fifteenth century. The Spanish conquistador Hernando Cortés, for example, had projected Western power to the shores of Mexico on side-gunned sailing ships, and then conquered the entire Aztec Empire by capturing its capital with an invading army of a few hundred men equipped with gunpowder weapons, horses, and gunboats they built on site. In reality, Cortés owed as much to his indigenous allies as he did to his military technology, but the Aztecs were not the last natives to be awed and surprised by a gunpowder army.

Historian Daniel Headrick has noted that this first wave of Western imperialism put European powers in control of 35 percent of the world's land mass by 1800, the beginning of the modern era. Over the course of the long nineteenth century, those same Western powers used new technology to increase that control to 84 percent. The key to conquering half the earth's land mass in the course of one century, says Headrick, was power projection inland. Cortés's conquest of Mexico in the sixteenth century had been an exception. Most European conquest in the early modern era had been based on the side-gunned sailing ship. This instrument could sail into the ports of the major trading states in the nonindustrial world and seize control of the traffic in imports and exports. Appointment of viceroys, supported by an armed contingent with cannons and small arms, ensured that local rulers channeled wealth and commerce into and out of the ports in accordance with the mercantilist interests of the colonial power. The imperial power did not have to occupy the colonized state to make it serve the capitalist purpose.

Technological change, says Headrick, transformed this model in the nineteenth century. Steamboats allowed the Western colonizers to project naval power up the navigable rivers to the interior. The telegraph allowed the viceroys in the port cities and capitals to remain in touch with their inland outposts. The enhanced firepower of modern artillery and small arms ensured that small Western armies could prevail over large native forces armed with only the muscle-powered weapons of antiquity. Railroads carried those Western armies to inland entrepôts that the rivers did not reach. The Suez Canal shortened the lines of communication between the European states and their colonies in the east and south of Africa and Asia. Submarine cables put viceroys in touch with their home governments. And quinine—not really a technology—insulated the colonizers from some of the most debilitating indigenous diseases. In short, nineteenth-century technologies allowed the European imperialists to exercise control over entire territories and populations.

Technology's decisive impact on imperial wars in the nineteenth century proved less influential in great-power war. In part this was because the great powers—mostly European states plus the United States and, toward the end of the century, Japan—kept pace with technological change. The armies and navies of the industrialized states were armed symmetrically. They did not, in general, experience the asymmetry that dominated imperial wars. Even more importantly, there was simply not that much great-power war in the nineteenth century. The Pax Britannica that settled on the world between Napoleon's defeat at Waterloo in 1815 and the outbreak of World War I in 1914 reflected Great Britain's dominance of the world's oceans and Europe's exhaustion after a quarter century of the wars of the French Revolution and Napoleon. Two great exceptions to this pattern foreshadowed the ways in which technology would transform warfare between industrialized states, though many observers failed to appreciate just how complete the transformation would be.

The American Civil War (1861–1865) introduced many firsts. The North's industrial advantages over the agricultural South ranged from it superior transportation and communication networks to its manufacturing infrastructure, which could be converted to war production long before the Confederate states could build capacity from scratch. The North had a navy, along with the industry and shore establishment to support it; the South countered with innovative but inadequate experiments in blockade running, commerce raiding, mines, torpedoes, and submarines. The North countered or imitated these innovations, while adding armored riverine gunboats to its arsenal. Both sides revealed their entrepreneurial enthusiasm in the first year of the war by fielding steam-powered armored warships—the *Monitor* and the *Merrimac*—for a battle in Hampton Roads that is often taken as the transition point in the evolution from sail to steam navies. The North always had the overwhelming advantages of population and wealth, but these were amplified by its technological superiority, providing, in modern parlance, a "force multiplier."

The wars of German unification (1864–1871) provided another laboratory for changing military technology. In successive wars with Denmark, Austria, and France, Prussia shocked the world with the celerity and decisiveness of its victories. As with most great historical events, many causes lay behind the Prussian success—not least the militarization of the Prussian state, the poor preparation of its enemies, the professionalization of the Prussian army, and the ruthless geopolitical maneuvering of Otto von Bismarck (1815–1898), the minister president of Prussia, who isolated rivals and blocked outside interference. Technology played an operational role, especially in the strategic use of railroads and the high quality of the Prussian Dreyse needle gun, which allowed soldiers to reload in a prone position. By the time of the Franco-Prussian War (1870–1871), however, another emergent feature of modern industrialized warfare trumped this Prussian advantage—the clash of dueling technological developments. The French chassepot rifle proved just as effective as the Dreyse, pitting symmetrical small arms against each other and nullifying, to some extent, the advantage that each side had hoped to achieve with its innovation.

Most observers marveled at the power on display in these midcentury great-power wars in America and Europe. They fit neatly into a larger narrative of human dominion over the forces of nature and the peoples of the undeveloped world. In the closing decades of the nineteenth century, Westerners treated themselves to dozens of international fairs celebrating their technological prowess. The London exposition of 1851 established the model, and imitators proliferated as the century wore on. In historian Michael Adas's phrase, Europeans came to see "machines as the measure of men," proof of the superiority of their civilization and also justification to take over and make over the rest of the world in their image.

Late in the nineteenth century, concern about the growing lethality of modern weaponry sparked an interest in arms control that would continue through the twentieth century and into the twenty-first. Since the beginning of history, and perhaps before, human societies had agreed to limit their use of some military technologies and techniques when fighting against others they considered to be like them. Usually, however, war against strangers or barbarians or "the other" was without constraint. The famous Christian sanction of the crossbow at the Second Lateran Council in 1139, for example, condemned the use of the weapon against other Christians while allowing it against Muslims. The Hague Conventions of 1899 and 1907 limited the use of poison gases, bullets that expanded on impact, projectiles dropped from balloons, arming of merchant ships, and laying of automatic contact submarine mines. The effectiveness of such prohibitions has always been limited by the assertion that the laws of war may be overridden by "military necessity." Arms controls have always worked best when the participating states have seen it as in their best interest to comply.

At the turn of the twentieth century, however, only the most astute monitors of contemporary history saw clearly where the evolution of military technology might lead. The best of these, Jan Bloch (1836–1902), a Polish banker and financier, predicted in a multivolume analysis of nineteenth-century warfare that war was bound to lose its decisiveness. Escalating firepower, both small arms and artillery, would drive combatants to ground and eliminate maneuver on the battlefield. Armies would grow in size and power. The field of battle would expand beyond the ability of the commander to see or comprehend. And industry would feed the huge armies with endless supplies of food and ammunition. The result, said Bloch, was bound to be static wars of attrition, ending not in victory but in mutual exhaustion, both moral and economic. At the heart of the stalemate was technology.

Total warfare

Bloch's ominous prophecy unfolded much as he had anticipated in the trenches of the Western Front in World War I (1914–1918). There the combatants of the great powers saturated the battlefield with shrapnel and bullets, driving the soldiers underground in lines of excavation that zigzagged from Switzerland to the sea. Both sides tried innovations in strategy, tactics, techniques, and technologies to break the standoff: artillery barrages, chemical weapons, commerce warfare at sea, strategic bombing, strategic misdirection at Gallipoli, pioneering tactics of fire and movement, and even primitive tanks. Nothing worked. Just as Bloch had predicted, moral and economic attrition finally determined the outcome.

World War II (1939–1945), sometimes viewed as the second phase of a single great-power world war, proved even more titanic and transformative, a watershed in human history. To begin with, both conflicts were humanity's first and only total wars. Second, they were wars of industrial production, won by the alliances that produced the most stuff. Third, World War II was the first war conducted in all four realms of human warfare: land, sea, air, and space. Fourth, World War II was the first war in human history in which the weapons in play at war's end differed significantly from those at the outset. Fifth, World War II was the last great-power war. And sixth, World War II ended with the nuclear revolution, a turning point in the technology of warfare and the history of humankind.

Journalist/historian Walter Millis (1899–1968) argued that "total war" is best thought of as a culmination of three great historic revolutions. The French Revolution had introduced the *levée en masse*, the nation in arms. The industrial revolution had shown how to produce enough war materials to arm, equip, and move those mass armies; Fordism and mass production of the twentieth century had only improved upon the speed and efficiency of industrialization. And the Prussian general staff had introduced a managerial revolution equal to the task of marshaling those forces in time and space. Only when these capabilities were in place would five thousand years of evolving military technology climax in the carnage and destruction of the world wars.

Both of the world wars were contests of industrial production, a convergence of modernity with industrialization and twentieth-century mass production. Along the way, each side tried to use its vast arsenal to destroy not just the arsenal of the enemy but also the enemy's will and material resources. Inescapably, the enemy's population became a target, for it embodied both the national will and the productive capacity of the state. Never before had so much material been mobilized for warfare, and never before had so much been destroyed. Most wars in human history have killed more by disease, famine, and dislocation than by direct assault, but the world wars were different. Killing and destruction had themselves been industrialized, laying waste combatant states on a scale never before seen. The Axis powers finally ran out of stuff before they exhausted the will of their populations.

For most of history, humans fought only on land. Not until the late ancient or early classical periods did interstate conflict go to sea. Another two millennia of technological development passed before humans flew for the first time, but it took hardly more than a decade to pass from the first flight to the first air warfare. Space warfare followed in just a few decades: the V-2 rocket could and did fly into space, though its wartime trajectories kept it within earth's atmosphere. The world wars introduced two new realms of warfare in just half a century, fueling human foreboding that technology was out of control. Some students of modern military technology classify cyber warfare as yet a fifth realm, but it is as old as electromagnetic control mechanisms, which were also at work in World War II.

World War II witnessed the development and introduction of significant new weapons that did not exist before 1939. The list includes microwave radar, jet propulsion, proximity fuses, guided missiles, cruise missiles, "precision" bomb sights, acoustic torpedoes, computerized code breaking, and, of course, the atomic bomb. The important point to note here is the appearance of systematic, institutionalized military research and development in World War II.

World War II was the last great-power war. Indeed, there has been very little interstate war of any kind since 1945. Most war has been intrastate: rebellions, insurrections, civil wars, and anarchy within failed states. Seldom in these conflicts are the total resources of the state mobilized, as they were in total war. The technology of this kind of warfare is generally "conventional," sometimes ad hoc. That is, it deploys the same Combined-Arms Paradigm as in World War II: infantry, artillery, and mounted warfare (tanks, personnel carriers, and later helicopters) supplemented by tactical rockets and missiles and close air support. The absence of great-power warfare since 1945 has contributed to this new technological stasis, as has the most revolutionary of modern military technologies: nuclear weapons. Appearing at the very end of World War II, nuclear weapons ushered in a "long peace" (John Lewis Gaddis's name for the absence of great power war) that abides in the second decade of the twenty-first century. Many factors contributed to this long peace: the destructiveness of conventional, industrialized warfare, the creation of new international institutions such as the United Nations, a growing commitment to the rule of law, the increasing interconnectedness of the community of nations, acceleration of communication and transportation, and growing appreciation that modern war was no longer winnable.

But none of these factors had the clarity, immediacy, and materiality of Hiroshima and Nagasaki. As the Cold War incited an arms race in the two decades after World War II, as the superpowers moved from atomic bombs to thermonuclear bombs—an order of magnitude lighter, cheaper, and more powerful—and the weapons proliferated to other states, a taboo against nuclear war settled on the human community. Mankind had finally developed a weapon too horrendous to use. If the illusion of winning modern war had not been clear before the world wars, Hiroshima and Nagasaki revealed it starkly. Even as the two superpowers amassed a combined nuclear arsenal of seventy thousand warheads, a consensus coalesced around never using them again.

Seventy years into the nuclear age, the consensus holds. Nuclear weapons still exist, and they proliferate slowly. But they have served so far as guarantors of interstate peace. There have been no great-power wars and only a handful of interstate wars in the last seven decades, wars that have been limited by international cooperation. Of course, the long peace could end at any time, and the nuclear taboo could fail. Ideologues bent on suicidal terrorism might one day acquire an atomic or thermonuclear device—or some other weapon of mass destruction. But if they ever detonate such a weapon in anger, they will no doubt discover that nuclear weapons offer deterrence and retaliation, but they serve no useful offensive purpose. For now, at least, the nuclear revolution has produced a more peaceful age than any mankind has ever known, the daily carnage on the evening news notwithstanding.

Chapter 4
Technological change

Research and development

In addition to generating new weapons, World War II ushered in two momentous transformations in the world's relationship with military technology. The nuclear revolution, already mentioned, will be addressed again later. The second great transformation of military technology was modern, institutionalized, routinized research and development.

World War I saw some mobilization of scientific and technical research, but it was nonetheless a war of industrial production. In many ways, World War II followed the same pattern, with the United States serving as the great arsenal of democracy. Its gross domestic product (GDP) exceeded the combined output of all its major allies—Britain, France, and the Soviet Union—plus all the other states that comprised the United Nations. By the end of the war, those states had a collective GDP five times the size of the collective output of the Axis powers. The war in the North Atlantic finally shifted in favor of the Allies in the first half of 1943, when they produced ships and cargo faster than German submarines could sink them. The Germans lost the pivotal Battle of the Bulge in the winter of 1944–1945 when they had to abandon their tanks on the battlefield for want of fuel, while the Allies had already run a fuel pipe across the bottom of the English Channel to power the armada of tanks and trucks that would motor to Berlin. Napoleon's army may have traveled on its stomach, but military forces in the middle of the twentieth century traveled in ships, planes, and motor vehicles powered by internal combustion engines and fueled by petroleum. Their logistical tail stretched behind them in a never-ending umbilical back to Roosevelt's arsenal.

This multiheaded juggernaut, powered by Allied—especially American—industrial capacity, did not, however, always bring to bear the best war materiel. American naval aircraft and torpedoes, for example, were inferior to those of the Japanese. American tanks were inferior to both German and Soviet tanks. Both Germany and Great Britain flew jet aircraft before the end of the war; the United States did not. German long-range submarines were every bit as good as American ones. And late in the war, as Germany collapsed under the weight of Allied stuff, Hitler channeled his dwindling resources into secret weapons, new technologies that might yet turn the tide. His jet aircraft, especially the ME-262, had the potential to deny the Allies air superiority over the battlefield, but there were too many bugs, too little fuel, and not enough airplanes for them to pose a serious threat. Wernher von Braun's rockets could reach targets in Britain, but they were not sufficiently accurate or numerous to cow the British. Still, the potential of these new weapons demonstrated that the Allies did not have a monopoly on military invention and innovation. When the atomic bombs exploded over Hiroshima and Nagasaki to end the war in the Pacific, they confirmed the decisive impact of research and development on warfare.

The United States came away from this experience chastened by the many instances in which its military technology proved inferior to the enemy's. For all the remarkable achievements of its scientific and technical establishment during the war, including the incomparable Manhattan Project, military leaders nonetheless concluded that they could not return to the prewar mechanisms for developing new military technologies. Quantity had been the main determinant of victory in the world wars, but quality could determine the outcome of the next war.

The leader of America's wartime mobilization of science and technology was Vannevar Bush, head of the wartime Office of Scientific Research and Development and de facto science advisor to President Franklin Roosevelt. At the end of World War II, he wrote for the president *Science: The Endless Frontier* (1945), a blueprint for government support of American research and development for military, medical, and economic innovation. Bush's experience during World War II had convinced him that scientists knew best. The government should fund a "National Research Establishment" and let the scientists set the agenda. The American government, unwilling to give any group such carte blanche, rejected his plan, opting instead for a National Science Foundation (NSF) and the National Institutes of Health (NIH) for basic research in science and medicine, respectively. Most other government-funded research and development was left to the mission agencies, such as the newly formed Department of Defense. The NSF and NIH would do "basic research" in pursuit of general understanding—a kind of technology push—while the mission agencies would apply demand pull to bend the potentials of science and technology to their specific needs.

Within the Department of Defense, each of the three main services—army, navy, and the newly independent air force—quickly developed their own idiosyncratic mechanisms for promoting technological innovation suited to their institutional goals and doctrines. The army, the least technological of the services, elected to continue its support of wartime contractors, such as the Moore School at the University of Pennsylvania, working on computer development. It also created some internal infrastructure—first a Research and Development Division and then an Office of the Chief of Research and Development—to oversee its activities. But otherwise it continued to rely on its time-honored arsenal system to provide innovation.

The navy proved to be the most progressive of the three services, exploiting the ties it had long since established with universities and other institutions of basic research. It continued and enlarged its wartime Office of Naval Research and expanded the operations of its fabled Naval Research Laboratory in Washington, DC. These complemented the navy's established programs of ship design and development, which evolved into the Naval Sea Systems Command.

The air force, successor to the wartime Army Air Forces, took the most dramatic steps toward a new model of government-supported innovation. Continuing the wartime pattern of relying on contracts, it first recruited Theodore von Kármán, the legendary aerodynamicist at the California Institute of Technology, to chair a scientific advisory board and produce a twelve-volume study of the future of aviation. The title of volume 1, written by von Kármán, said it all: *Science: The Key to Air Supremacy*. The air force went on to buy innovation by contract, even sponsoring the RAND (Research and Development) Corporation, the first of the think tanks that would become mainstays of US military research and development. The air force also continued its army tradition of arsenals, expanding its in-house research and development (R&D) program at Wright Field in Dayton, Ohio, and opening new laboratories such as the Arnold Engineering Development Center in Tullahoma, Tennessee.

So great was the enthusiasm of the military services for new technology that the secretary of defense felt compelled to place institutional constraints on reckless innovation. A Research and Development Board, called for by the National Security Act of 1947, which created both the air force and the new Office of the Secretary of Defense, evolved in the Eisenhower administration to become an assistant secretary of defense for research and development. This office, under varying names, has been in existence since 1953. After *Sputnik I* and the riot of space proposals made by the different services, President Eisenhower concluded that another agency was required just to sort out the competing schemes for technological one-upmanship. The Advanced Research Projects Agency (ARPA) came into existence in 1958 to screen the half-baked proposals coming from the services, but it too developed a life of its own and took on the additional role of seeking out and promoting new technologies deemed to be in the national interest.

With this sort of institutional promotion, defense research and development grew like Topsy during the Cold War, producing some monstrosities of technological excess. After *Sputnik I*, the army proposed building a base on the moon, because it was a staple of military theory always to take the "high ground." The army and air force in the 1950s found themselves embroiled in the so-called Thor-Jupiter controversy, each one spending lavishly to build its own version of the same intermediate-range ballistic missile. Interservice rivalry over defense dollars spurred technological innovation as a bureaucratic technique for capturing roles and missions and the budgets that went with them. The marine corps insisted on building vertical-takeoff-and-landing aircraft—the Harrier and the Osprey—that proved to be more expensive than useful. The navy insisted on pursuing a nuclear-powered fleet even though this form of propulsion proved too costly for most ships other than submarines and perhaps aircraft carriers. The air force tried to develop a piloted, reusable space plane; unfortunately, they chose to name it "Dynasoar," for "dynamic soaring," and a dinosaur it was. The air force's twenty-first-century extravagance, the F-35 multipurpose fighter, threatens to bankrupt the service.

This hothouse environment of technological enthusiasm and development was labeled by President Eisenhower in his 1961 farewell address the "military-industrial complex." By this he meant that defense contractors and the military services had fallen into a liaison built around their shared interest in exaggerating the dangers of the Cold War and promising security through expensive, cutting-edge technology. Many observers since have noted that Congress and America's universities were also complicit in this "complex." Members of Congress found it useful to promote military R&D and production in their states or districts, and universities found it useful to accept research funding from the military services. Nor was the United States unique in this regard. One historian has seen in Britain during the Cold War a "warfare state," and a Berkeley political scientist noted in the depths of the Cold War that the United States might *have* a military-industrial complex, but the Soviet Union *was* a military-industrial complex.

In short, the competition for new and winning military technologies drove the great powers to institutionalize military innovation. At times this entailed beginning work on a next-generation weapon system as soon as the new generation went operational. This planned obsolescence mirrors the annual design changes promoted by the American automobile industry in the 1950s and 1960s. "Capability greed" became a staple of weapon systems specifications, driving costs up and reliability down. The military establishments of the industrialized states found themselves racing not so much against each other as against themselves. Some incentive was provided by the international arms market, which had a seemingly insatiable appetite for the newest military technology. Most of the incentive, however, bubbled up within each state's self-reinforcing military-industrial complex.

The passage of time resolved some of these disputes. The Cold War ran its course without triggering the third world war that many had feared. Indeed, the world backed into John Lewis Gaddis's 'long peace.' In war or peace, however, the military captured most US government spending on research and development. This pattern is controversial on many counts. Costly development of questionable technologies starves basic research that might produce more long-term, fundamental innovation. Many economists feel that military R&D tends to produce less economic growth than investments in civilian realms such as energy, transportation, and infrastructure. Civilian R&D is more likely to spin off military applications than vice versa. And military R&D tends to be gold-plated, because the contracting parties are operating in a marketplace that is simultaneously monopsonistic and oligopolistic: there is one buyer given to "capability greed" and a small number of sellers given to nonprice competition.

Dual-use technologies

In addition to having both military and civilian applications, some technologies are dual-use in another sense: the military may use them in both weapons and non-weapons roles. Some examples already have appeared in this book: fortifications, roads, chariots, steam engines, transport aircraft, and nuclear power—to name a few. But this category of military technology warrants closer examination, for it places the technology of warfare in the larger context of technology in general, and it illuminates one important dimension of the timeless dialectic between the military and civil society. Just as societies get the armies they deserve, they also get the military technology they deserve. Furthermore, many civilian technologies arise from military sources, shaping civil societies in ways seldom explored.

Non-weapons dual-use technologies

Non-weapons military technologies are the most obvious candidates for dual-use. They support warfare without attacking people or things. One inexorable trend in warfare has been the growth in number and significance of non-weapons military technologies. The earliest warfare no doubt began with the simplest of instruments—spears, knives, clubs, stones, and bows and arrows—all weapons. Very little support was needed. Over time, however, communities found that warriors were more successful when supported with armor, logistics, intelligence, communication, medical treatment, transportation, and the like.

As these services and supplies multiplied, warriors came to be seen as the "tip of the spear." In time the shaft came to outweigh the point until, in the twenty-first century, support personnel and material can account for 90 percent or more of a military force. In modern parlance, this is called the tooth-to-tail ratio—the balance between fighters and enablers. Though military culture continues to extol the primacy of the warrior who delivers the kinetic impact to the target, the truth is that non-weapons technologies outnumber and outweigh those at the tip of the spear. A few examples will make the point.

Fortifications, the most influential of non-weapons technologies, have already appeared in this story. They did not so much determine who won or lost a war—though they sometimes had that effect—as they determined when some wars would happen and, more importantly, not happen. As states and civilizations separated themselves from the barbarians and pastoralists who continued to live beyond the pale, they built cities dominated by monumental architecture—including walls. The walls, of course, were artifacts, not technologies. But they shared with the temples and ziggurats and public forums building technologies of large structures. Whether made with stones (Jericho) or dried bricks (Uruk) or concrete (Rome), these cities almost always had walls to hold the barbarian at bay. The walls, like those that protected Constantinople for more than 1,100 years, were designed both to repel and to intimidate would-be attackers. They announced that the residents of the city had power and resources equal to any challenge. They were, in short, a deterrent to war, a promise of futility and defeat to any who dared assail them. And as civilizations grew in military power and sought to conquer each other, they strengthened their walls all the more, to send the same message to their peer states.

Some states chose to fortify not only their cities but also vulnerable portions of their borders. The Great Wall of China, erected over the course of a thousand years or more, extended in various overlapping segments more than 13,000 miles along the northwest frontier of China. The Romans erected their own border walls, called *limites*, across the natural boundaries and invasion routes into the empire. Originally roads punctuated by defensive watchtowers and forts, the *limites* were sometimes elaborated with palisades and occasionally stone or earthen walls, like Hadrian's Wall in Britain. Like the Chinese, the Romans did not expect to stop invaders so much as deflect and slow them down, so that armies could be dispatched to the frontier to confront them. This is not so different from the purpose of the infamous Maginot Line, built by France between the world wars. Though the Maginot Line gave static defenses a bad name when it was circumvented by invading German armies in 1940, it actually did what it was meant to do—slowed and deflected the invader until reinforcements could arrive. Unfortunately for the French, their army still could not hold.

Fortifications in history have given the civilizations that built them an added benefit. They have allowed their states to reduce the standing armies that they would otherwise have needed to defend themselves. The walls served, in short, as a peacetime investment in security that paid dividends in all the years beyond their period of construction. States capable of extracting sufficient revenue or labor from their citizens could build defensive public works while holding down the much higher cost of keeping expensive soldiers under arms in the absence of a threat. And because fortifications had little offensive power, they were an investment in peace—that is, in military technology that did not directly threaten their neighbors.

Perhaps the second oldest and most important non-weapons military technology is roads. Like fortifications, roads are not technologies but artifacts of technology. Indeed, the first roads were not even that, but simply the routes, like the Silk Road, that humans and animals traversed with enough regularity to leave a trace. In time, civilizations began improving these natural thoroughfares. When those improvements reached the level of using tools and machines in a conscious technique to produce a solid and durable roadbed, then a technology of roads was in place. Archeological evidence of such roads comes down to us from Persia, China, Peru, and other empires. The Romans raised this technology to high art, disposing the same practical engineering that marked the Colosseum, the aqueducts, and the purely military technologies of field fortifications, sieges, and bridges. They stitched together their empire with hard-surface roads, some of them so well founded and paved that they have survived into the twenty-first century, roughly two millennia after their construction. What these roads all have in common with modern variants such as the German autobahn and the American interstate highway system is that they served civilian purposes of commerce and government administration while at the same time allowing states to mobilize and move their armies to sites of external threat. Unfortunately for many states through history, they also provided avenues of invasion, undermining their military purpose in the most disastrous way.

A more recent example of non-weapons dual-use military technology is the steam engine. A classic instance of technology push, the steam engine was first a scientific curiosity—appearing from ancient times through the seventeenth century—and then a commercial tool to pump groundwater out of coal mines. Those first steam engines of the eighteenth century were so inefficient that they made economic sense only when operating at the mouths of those coal mines, where fuel was cheap. Not until 1769, when James Watt invented the separate condenser, did the steam engine begin to realize its potential. Working with business partner and cannon manufacturer John Wilkinson, the company of Boulton and Watt provided the Wilkinson ironworks with power for its drills, while Wilkinson provided Boulton and Watt with a boring technology that made possible precision cylinders for their engines. It was a civil-military technological synergy seldom matched by any military-industrial complex. Soon steam engines were powering not only the factories of Britain's industrial revolution but also railroads to move armies in the American Civil War and the wars of German unification, and steam warships powerful enough to overcome wind and tide. Even the most modern major warships, fueled by oil or nuclear power, are steamships that drive themselves and their auxiliary equipment by passing steam through modern turbines.

Equally important in both warfare and civil society is the internal combustion engine. The first internal combustion engine was the cannon, an instrument for harnessing to human purposes the energy given off by rapid burning of a carbon compound in an enclosed space. The steam engine, an external combustion engine, used an external fire to heat water in a confined space. Not until the late nineteenth century did practical machines appear that transformed the energy of fire directly into mechanical power. Over the course of the nineteenth century, a series of experiments with internal combustion engines, accelerated by the commercial availability of petroleum distillates, produced practical machines operating on both spark and compression ignition.

By World War I, internal combustion engines were powering military aircraft, submarines, land vehicles for passengers and cargo, tanks, and even auxiliary electrical power. Wherever internal combustion engines and fuel could go, electricity could go, for lighting, heating, radios, telegraphs, machine shops, hospitals, kitchens, refrigerators, and the innumerable electrical appliances that support military operations. Huge, fixed generating plants had been powering cities since late in the nineteenth century. With the development of portable generators powered by internal combustion engines, armies could now campaign with all the appliances of modern warfare. And airplanes could carry aloft the radios, instruments, and auxiliary equipment that supported aircrews in their missions of fighting, bombing, and reconnoitering. The warfare of total war was empowered by the internal combustion engine.

Another non-weapons dual-use military technology that is also a mainstay of civil society is electric and electronic communication. This category includes everything from the first electric telegraph to the more modern telephone, radio, television, and Internet. These latest means of communication can carry analog and digital signals of codes, voices, and images at or near the speed of light. Of course smoke and flag signals had traveled at the speed of light throughout history, but they were limited to line of sight. (Sound certainly traveled at its own speed, but that was much slower than light.) Beginning in the nineteenth century, military personnel could communicate with each other near the speed of light if they were connected by powered wires; the introduction of radio sped the communication and eliminated the wires, though its range was constrained by a variety of technical and environmental factors.

In modern digital communications, all content is digitized—converted to binary form—and then transmitted on an appropriate electromagnetic wave, to be converted into data, voice, or visual form at the receiver. It travels at the speed of light in line of sight or broadcast, depending on the nature of the receiver. Because warfare has always been a zero-sum game, in which one side's advantage was the other side's disadvantage, the commander who learned of his enemy's actions or movements before his own were known to them, and who could deliver his orders to his subordinates faster than his adversary could, had an overwhelming battlefield edge. Today's military commander has at his disposal—for better or worse—almost instantaneous, worldwide communication of all forms of information up and down his chain of command and real-time contact with his subordinates in combat. It is a nice question whether this has cleared Clausewitz's "fog of war" or thickened it.

The first "computers" were women, civilians calculating ballistic trajectories for the army in the years leading up to World War II. During that war, computers, another non-weapons dual-use technology, became machines. The rise of these machines to their twenty-first-century ubiquity can be classed as neither military nor civilian. Both realms of society made indispensable contributions to the evolution of computers, no matter how one defines "computer." It is a commonplace of twenty-first-century life that a computer revolution has taken place—or is still taking place—but there is no consensus on what changed. Has it been a revolution in communications, information, computation, artificial intelligence, or simply entertainment? It may be best to think of it in technological terms as a refinement of solid-state electronic devices that has made possible significant transformations in all those fields of human activity.

From that perspective, the military made important contributions to early analog and digital computers for such purposes as ballistic firing tables, encryption and decryption of communications, simulation of nuclear reactions, and integration of radar networks. The first transistor emerged from civilian work on telephone switching, but one of the first two inventors of microprocessors, Jack Kilby, made his discovery while working for the US Air Force on the electronics of missiles. The military also played a critical role in the first networking of computers, and has made its share of contributions to subsequent developments as well. Now solid-state electronic devices of unimaginable complexity and capability empower military instruments ranging from the newest night-vision goggles to interceptor missiles that can achieve the mythical goal of hitting a bullet with a bullet. The so-called net-centric battlefield of the twenty-first century is awash in microcomputers and connected almost instantaneously to macrocomputers of superhuman calculating power. Ships, aircraft, spacecraft, and their payloads—including weapons—are systems capable of near-autonomous operation.

Isaac Newton illustrated his theory of gravity by hypothesizing an object propelled horizontally from a mountaintop in such a way that at some point the force of its movement tangential to the earth's atmosphere would exactly match the gravitational pull of earth. Such an object, he explained, would become a satellite of earth, balanced between escape velocity and the gravity well that is planet earth. It would take almost three centuries for humans to devise the launch vehicle necessary to test Newton's theory, but the military implications of the capability were obvious all along. Not only could a satellite—also an artifact of a non-weapons dual-use technology—observe the earth from space, but it could also de-orbit all or part of itself to strike a target on the earth's surface. The first human satellite, *Sputnik I*, entered orbit on October 4, 1957. Though its mission was nominally scientific, an experiment in the International Geophysical Year, its true impact was military. For, as Newton had explained, the force that could put a body in orbit also could fly it to a target on the other side of the world, where deceleration could bring it down upon a predetermined point. The launch vehicle was, by definition, an intercontinental ballistic missile. Defense intellectuals immediately prophesized the militarization—indeed the weaponization—of space, extrapolating from human experience on the sea and in the air that warfare would go wherever humans went.

As it turned out, the great powers have indeed militarized space, but so far they have by and large refrained from weaponizing it. So-called near-earth orbit, ranging from hardly more than 100 miles up to geostationary orbit more than 22,000 miles above the earth's surface, is awash with military satellites conducting communications, reconnaissance, signals interception, meteorology, and global positioning. In the Outer Space Treaty of 1967, the two superpowers, followed in subsequent years by most of the other nations of the world, forswore the placement of weapons of mass destruction in space. And the technology of satellites and their orbits has made it clear to most that conventional weapons circling the earth make no more sense than nuclear weapons. So satellites have become indispensable to military activities and operations on earth, but humans so far have seen fit to keep their weapons within the atmosphere.

This list of non-weapons dual-use technologies could be expanded easily. It might, for example, include canning of food, tracked vehicles, transport aircraft, helicopters, gyroscopes, radar, GPSs, and digital fly-by-wire for movement of aircraft control surfaces. But the principal significance and implication of these technologies remains the same. Beginning in prehistoric times, humans have developed non-weapons military technologies. Many were first developed for civilian purposes and then adapted to military functions; the Schöningen spears come to mind. But sometimes, as with computers and fortifications, the military played the leading role. In the modern world, some civilians are uncomfortable using technologies of war, even if they do not kill or destroy.

By the same token, militaries often believe that technologies developed for civilian purposes require extensive modification to make them adequate to the demands of warfare. More often, however, people are unaware of where these technologies came from and what purposes called them into existence. Few civilians worry that their automobile engines also power airplanes and submarines and tanks. Few e-mailers worry that their mode of communication evolved out of personal messages exchanged between researchers for the US Defense Advanced Research Projects Agency interacting on a network designed to share research results. Furthermore, the growing importance of non-weapons technologies in modern warfare demonstrates the accelerating trend toward conflicts spilling off the battlefield and into the civilian communities, transportation networks, economic markets, medical facilities, and industrial arenas of modern life.

Weapons dual-use technologies

Even weapons can be dual-use. Not all instruments of force in society are military. The state has—or claims—a monopoly of armed force within the territory it purports to control, but the state may license citizens outside the military to use force in certain prescribed circumstances, such as policing, self-protection, security, hunting, and the like. As with nonweapons technologies, these instruments may have military or civilian origins before migrating to the other realm. Also as with non-weapons technologies, a few examples will clarify the topic.

Pride of place among dual-use weapons goes to the Schöningen spear and its prehistoric cousin, the bow and arrow. From hunting animals to hunting people, these technologies proved equally effective in war and peace. Of course, the similarities between hunting and warfare included much more than technology. Both pursuits exploited intelligence, stealth, teamwork, communication, and courage, in addition to knowledge of terrain, weather, and behavior of the prey. Humans, in addition to being hunters, also could be the hunted, needing technologies of defense against both two-legged and four-legged predators. The primary tactic of the prehistoric hunt, as best we can surmise, was pounce and flee, the same tactic still used by relatively weak military forces against their stronger foes. We may think of it now as ambush, or what that great military strategist Mao Zedong called "mobile warfare," but the principles are the same. Use surprise to attack the prey unawares, but save an escape route to run away and fight another day if need be. Thus it was that the first dual-use weapons were missile weapons, inflicting wounds at a distance while allowing the attacker avenues of flight.

The chariot is another dual-use weapons technology that has already been discussed. It is important to note, however, that it always had both weapons and non-weapons functions in the military. In this sense, it was like ships, planes, rockets and other weapon platforms. More than a weapon, it was part of a weapon system, whose parts could be disaggregated into categories of weapons and platforms. Indeed, the chariot was a quintuple-use technology, dominating combat in the Levant through much of the second millennium BCE and then taking up noncombat roles such as transport, hunting, racing, and ceremony. As with ships, airplanes, and spacecraft, its military version combined a moving platform with an onboard weapon system. It was this basic configuration that made it a natural dual-use technology, for the platform always held out the promise of alternative uses, just as ships and planes can serve civilian functions. When the chariot was used as a jeep in its transportation role, carrying Achilles to his showdown with Hector, for example, it functioned the same as dragoons and modern infantry riding to battle in armored personnel carriers—almost, but not quite, a weapon system. But the chariot in its other roles was strictly civilian. No doubt many of the ceremonial uses of the chariot—Roman triumphs come to mind—sought to bestow an aura of military prowess on the returning champion, but this use was no more military than the Constantinople chariot races between competing political parties in the Byzantine Empire.

Nuclear power is another dual-use technology. This one gave the military both weapons (bombs) and non-weapons (ship propulsion) uses. A science-based technology, it arose from rapid advances in theoretical and experimental physics in the 1930s. It was physicists in the United States, some of them refugees from Nazi Germany, who first brought to the attention of President Franklin Roosevelt the possibility of an atomic bomb. The crash program of the Manhattan Project during World War II resulted in the only use of atomic weapons in warfare in human history. Nuclear weapons went on to have a profound impact on war, but only a secondary effect on warfare—for these weapons have never again been detonated in anger. Rather, they contributed to the "Long Peace," the absence of great-power war since 1945. Like fortification, the nuclear revolution has been as important for the wars that did not happen as for the ones that did. All warfare since 1945 has been shaped by the nuclear umbrella under which it has operated.

Meanwhile, peaceful uses of nuclear power have proliferated. These have been most prominent in the generation of electricity and in medicine. Attempts have been made to use nuclear propulsion for ships—and even airplanes—but the only widespread application has been in military submarines and capital ships—mostly American aircraft carriers. The first use of this technology to destroy the Japanese cities of Hiroshima and Nagasaki, along with the accidents, both civilian and military, that have occurred from time to time in the ensuing decades, have cast a pall of danger and fear over nuclear power. Yet Admiral Rickover and others demonstrated that it could be used safely when handled with care.

Equally ironic in its suspension between military and civilian uses is chemical weaponry. These wicked instruments of death and disability rose to prominence in World War I, when the German chemist Fritz Haber bent his Nobel Prize–winning talents to the development of chlorine gas and other deadly gases. Haber's postwar defense that death was death by any means ignored the horrendous suffering and disability inflicted by some chemical weapons, such as mustard gas. But Haber might have made a different argument for chemical weapons, as others have done: they could put soldiers out of action without killing them. Indeed, by this standard, mustard was a more humane agent than the deadlier chlorine and phosgene, because it was less lethal. But even if advocates of gas warfare had been able to overcome the world's moral revulsion at these weapons, they still faced intractable problems of delivery. Neither exploding shells nor canisters, let alone aerial bombs, could ensure that the released gas would not carry on the wind onto friendly forces or innocent civilians. Thus it was that the technology of distribution posed a greater challenge than the agents themselves, leading to post–World War I reaffirmations of the 1907 Geneva Convention against gas warfare. That taboo held over the ensuing century, with a few horrible and frightening exceptions—mostly against civilians.

The primary civilian analog of gas warfare is the release of chemicals that attack human pain receptors. Tear gas and pepper spray are the most common. Ironically, tear gas is classified as a chemical weapon by the Geneva Convention, and therefore banned from warfare. But most states use it against their own citizens for subduing criminals and controlling crowds. Both agents have the potential to kill, though exposure to them seldom results in death. Still, their continued use points to the blurring of distinctions between civil and military realms in the modern world.

Another dual-use weapons technology—explosives—may seem at first blush to be so exclusively military as to disqualify itself. But explosives appear to have originated in China as fireworks, and their civilian uses continue to shadow their more familiar combat roles. All conventional nonnuclear explosives share the same physical profile: they derive their power from a chemical reaction that takes the form of rapid and confined burning. Gunpowder, the first and most revolutionary of explosives, underwent constant research and development from the time of its introduction in the West by the Mongols in the thirteenth century. All varieties combined carbon, sulfur, and saltpeter (potassium nitrate). The trick was finding the right proportions, which varied depending on the purity of the ingredients. By the nineteenth century, researchers were exploring variations to achieve greater power, smaller bulk, and less smoke. The results included TNT, smokeless powder, gun cotton, nitroglycerin, dynamite, and various plastic explosives. The military sponsored much of the research behind these developments, but the results found countless civilian applications. Of course, fireworks continue to amuse and entertain, but explosives also aid mining, civil engineering, demolition, avalanche control, and other constructive pursuits. Military explosives also power the small arms used by hunters, sportsmen, and peace officers, and nitroglycerine ameliorates some heart conditions.

Missiles and rockets have varying, overlapping, and confusing definitions that invite misunderstanding. For purposes of this discussion, it is best to think of rockets as self-propelled projectiles driven by the rearward thrust of hot gases produced in the combustion of fuel and oxidizer carried within the vehicle.

A missile may be any projectile, but here the term will refer to those rockets that are actively guided in flight. Rockets have flown since the first Chinese fireworks, but the first applications of propulsive combustion in the West were not in rockets but in guns, where the propellant burns explosively and throws the projectiles without further application of force after leaving the gun. The first military rockets in the West appeared in the late eighteenth century and received some lasting fame in the attack on Fort McHenry in the War of 1812, when Francis Scott Key immortalized their red glare. But because early rockets were unguided, they remained area weapons of limited effectiveness until the middle of the twentieth century.

Then Wernher von Braun and his colleagues combined a rocket flying a ballistic trajectory with a crude inertial navigation system to direct their V-2s hundreds of miles and land them in a circular error probable (the circle within which 50 percent of the rockets could be expected to fall) of 4.5 kilometers. Guided missiles went on to become a cornerstone of the strategic arms race between the United States and the Soviet Union and even now are a guarantor of great-power peace. But those same rockets that maintained the balance of terror between the superpowers also served as the launch vehicles of the space age. Virtually all spacecraft that have left the earth's atmosphere since the flight of *Sputnik I* in 1957 have ridden on the technology of ballistic missiles, both solid- and liquid-fueled. The core technologies were developed by the military for military purposes. And Wernher von Braun again represents the military-civilian dynamic. He began in civilian pursuit of spaceflight, migrated to military work for the Wehrmacht and the US Army, and returned to civilian pursuits to build the Apollo launch vehicle to carry Americans to the moon. The von Braun paradigm still empowers and constrains human spaceflight.

The final dual-use technology in this compilation is automatic firearms, or machine guns. These instruments are individual or crew-served weapons that employ mechanisms for clearing the chamber, inserting a new round from a belt or magazine, and firing that round without any discrete input from the gunner beyond constant pressure on the trigger. Since the first gunner stepped onto a battlefield, his rate of fire has been a main determinant of success. Indeed, the first gunners took so long to reload that they had to be protected by pikemen lest enemy cavalry fall upon them between shots. A series of innovations from the seventeenth century to the twentieth increased rates of fire by replacing matchlocks with flintlocks, combining shot and explosive in a single cartridge, loading in the breech instead of the muzzle, and employing bullets with percussion caps and extractable shells, muscle-powered mechanisms to expel shells and insert new bullets and cock the weapon, and finally gas-powered reloading mechanisms that used the power of the bullet's explosion to perform the same functions. After that, it was just a matter of improved design to produce ever faster, lighter, and more reliable automatic weapons. Americans had a special knack for this line of development, perhaps because of their national preoccupation with the right to bear arms. Not only did Americans lead the development of the machine gun for military purposes, but they also led the world in introducing automatic weapons in hunting, sport, and personal security. At the time of this writing there are more personal firearms in America than there are Americans, many times more than the number maintained by the United States military. And most of these weapons were developed in the first instance for military purposes. It is difficult to think of a military technology that has permeated civil society more fully than the individual firearm in America.

What, then, might we say about dual-use technologies, both weapons and non-weapons? First of all, they illuminate the fundamental question of whether or not military research and development and production benefit society. Is there a redeeming civilian spin-off from research devoted to purposes of warfare? In some cases, there surely has been, though any such redemption must be discounted for the opportunity costs of what those researchers might have contributed to society had they worked on civilian technologies directly. In the same vein, have the economies of modern, industrialized states become dependent on government spending for military research and development? Have the world's major free-enterprise democracies become, in William McNeill's terms, command economies, channeling their resources into state purposes and starving the free market? Or have these democracies become "national security states," in the language of Michael Hogan and other historians? The military-industrial complex of the Cold War has loosened its grip on most developed states, but it has not disappeared. Furthermore, we might wonder if modern military technology, like war itself, is spreading throughout human societies, blurring the former distinctions between military and civilian, combatant and noncombatant, war and peace. If military technologies pervade civilian life, and if civilian technologies are appropriated to military purposes, then the militarization of the modern world may well run more deeply in the fabric of modern society than we are wont to admit. Dual-use technologies shed light on all these questions.

Military revolutions

As soldiers and scholars contemplated technological changes in warfare in the 1990s, two arcs of analysis intersected without really having much impact on each other, passing instead like proverbial ships in the night. But the similarities and differences in their trajectories speak volumes about our understanding of the technology of warfare at the beginning of the twenty-first century. They also highlight the risks inherent in thinking superficially about this topic. And they illuminate the ways in which military technology has evolved since World War II.

Military historians described one arc of analysis, the role of military revolutions in history. Historian Clifford Rogers has shown that the term "military revolution" had been a trope of military commentary and analysis in the West through the eighteenth and nineteenth centuries. But the term gained purchase on the historical imagination only when scholars began to think of it in the same way they thought about the momentous Western revolutions that altered the course of history—most prominently the American, French, Russian, scientific, and industrial revolutions. Historian Michael Roberts intimated just such a comparison in his 1955 lecture "The Military Revolution, 1560–1660." Roberts described a transformation of ground warfare in Europe prompted by the introduction of individual firearms and field artillery on the battlefield in the early modern period (roughly 1500–1789). The transformation was characterized by new tactics integrating firearms and pikes, large and sustained campaigns, bigger armies, and a greater impact of warfare on society. The historiography of Europe between the Renaissance and the French Revolution was then in what one historian has called the "early modern muddle," and Roberts's thesis added salience and gravitas to the discourse. It also highlighted the contributions of Swedish king Gustavus Adolphus (1594–1632), whose biography Roberts was writing.

Historian Geoffrey Parker endorsed Roberts's thesis in 1976, while revising it significantly. Then, in 1988, Parker completely reformulated the thesis in his landmark book, *The Military Revolution: Military Innovation and the Rise of the West, 1500–1800*. By this time, Roberts's thesis was hardly recognizable. The only component that remained intact was an increase in army size, but this Parker attributed to the introduction of the *trace italienne*, a new style of fortification developed as a counter technology to siege artillery. Parker added two entirely new components to the early modern military revolution: the extension of its temporal boundaries to cover the entire early modern period and the projection of European power overseas in the first great wave of Western imperialism. Expanded in this way, Parker said, the military revolution explained, at least in part, the rise of the West. This larger and more potent military revolution certainly bore comparison with the great political and material revolutions of the Western historical canon. Parker's argument had been anticipated by other historians, but his book nonetheless took the military history community by storm, becoming one of the two most influential works of the last fifty years, along with John Keegan's *The Face of Battle*. It set off a tsunami of scholarship criticizing the Parker model, finding other examples, and theorizing the phenomenon of military revolution. Since historians usually find what they go looking for, the literature began to fill up with histories of military revolutions. They were found in the Middle Ages, in Asia, in the American Civil War, in the naval arms race at the turn of the twentieth century, and in the wars of German unification, to name just a few instances. Almost all of these examples generated their own definitions of what constituted a military revolution, expanding and diluting the concept at the same time.

Meanwhile, another scholarly trajectory was rising out of a different intellectual community: American soldiers and defense analysts. It came to be called the "revolution in military affairs" (RMA). The American defense intellectuals had the concept from Soviet military analysts, who had theorized a "military-technical revolution" in the 1950s. At first the Soviets focused on the impact nuclear weapons might have on the conduct of conventional warfare. In the 1960s and 1970s, those concerns evolved into a related unease about the growing gap between Soviet and American conventional military technology. The post–World War II enthusiasm for technological innovation within the American armed services was producing rapid technological change with which the Soviet Union simply could not keep pace. In realms such as computers, high-performance aircraft, stealthy submarines, satellite reconnaissance, and many other cutting-edge "high" technologies, the United States seemed to be moving into a realm by itself, a first among equals that might soon achieve unassailable preeminence over Soviet—and all other—military forces.

As Americans read this Soviet literature, they developed a new appreciation for their own ascendancy. Did it not make sense to concentrate on this asymmetric advantage over the enemy? Was not the Soviet concern proof of the efficacy of American research and development?

Thus was born in the American defense community a campaign to feed and strengthen the “revolution in military affairs.” Precision-guided munitions, a pet project since the disappointments of Vietnam, were achieving unprecedented accuracies. Talk abounded of an “electronic battlefield” of the future. Air power theorist John Boyd preached “OODA loops,” a doctrine using American technological sophistication to allow its forces to observe, orient, decide, and attack faster than the enemy. Visionaries spoke of “net-centric warfare,” in which electronically networked forces would reconnoiter, communicate, and coordinate on the battlefield faster than their foes.

The revolution in military affairs emerged in various forms, but all had certain characteristics. None of the interpretations of the RMA were about nuclear warfare, either strategic or tactical. They *were* about America’s qualitative edge in conventional military technology, a hedge against Soviet/Russian numerical superiority in land forces in Europe. And they all predicted that the United States might reach an unassailable plateau of military capability on which it would be invincible to all, including the Soviets/Russians. The movement accelerated in the 1990s. The capability was demonstrated to the satisfaction of its advocates in the first Gulf War (1990–1991). Andrew Marshall, guru of the Pentagon’s Office of Net Assessment, sponsored a formal study of the phenomenon. And the administration of President Bill Clinton (1993–2001) considered it a way to cut defense spending without reducing American security. Part of the irresistible allure of the revolution in military affairs was that it seemed to offer more bang for the buck.

The RMA also attracted the attention of former secretary of defense Donald Rumsfeld. When Rumsfeld returned to the post of defense secretary in the administration of George W. Bush in 2001, he announced two major goals: to field an operational ballistic missile defense system (which had been under development since it was announced by Ronald Reagan in 1983) and to use the RMA to reform the military. In Rumsfeld's view, the Pentagon—especially the army—remained wedded to a Cold War paradigm of conventional war, which would be fought against larger Russian forces on the plains of Europe. This mindset was captured in the army's devotion to a next generation of mobile field artillery. The *Crusader*, six years into development when Rumsfeld re-entered office, was a tracked, self-propelled, automatic-loading 155-millimeter gun able to throw a 100-pound projectile 14 miles. Weighing 43 tons and towing a 40-ton resupply vehicle for fuel and ammunition, the gun could be airlifted on C-5A and C-17 transport aircraft to any crisis scene with a 3,500-foot runway. But Rumsfeld believed the army was preparing to fight the last war against a Soviet empire that no longer existed. He wanted a lean, nimble army to fight small wars. He canceled the *Crusader* soon after the attacks of September 11, 2001, on New York and Washington.

Rumsfeld relied on the capabilities attributed to the revolution in military affairs to respond to September 11. In Afghanistan, where the attacks had been orchestrated, the American military put a handful of "boots on the ground" to direct air strikes against the al-Qaeda enemy and its Taliban hosts. In a matter of weeks, American firepower had driven al-Qaeda into Pakistan and the Taliban into hiding. Then the Bush administration turned its sights on Iraq. Ignoring the advice of his army chief of staff, Secretary Rumsfeld invaded Iraq with a preliminary airpower campaign of "shock and awe," supported by about 150,000 American troops on the ground. This juggernaut rolled over the army of Saddam Hussein (weakened by the 1990–1991 Gulf War), drove Hussein into hiding, and "liberated" the country to face the Sisyphean task of building a stable and just state in a chaotic corner of the world. When President Bush appeared on a US

9. An F/A-18F Super Hornet prepares to launch into the night from the deck of the aircraft carrier USS *Harry S Truman*. The system of systems embodied in such nuclear-powered carriers is the most complex military artifact so far in the twenty-first century.

aircraft carrier in the Persian Gulf on May 1, 2003, under a banner reading "Mission Accomplished," it was a testament to the revolution in military affairs. The United States did indeed seem to have an irresistible military prowess.

Soon, however, American ground forces revealed their own Achilles heel. One by one, the vehicles of the new, modern, mounted warfare succumbed to ambush by IEDs—improvised explosive devices. These simple bombs, detonated by contact, timing, or command, soon infested the Iraqi roads and bridges on which American military vehicles traveled. The detonating instruments were as simple as a cell phone. The explosives ranged from hand grenades and small mortar and artillery rounds (many captured from Americans or from Iraqi army ammunition depots abandoned when the regime collapsed) to massive unexploded bombs and homemade charges. US trucks, armored personnel carriers, and even tanks were unprepared for this weaponry. They

10. The improvised explosive device (IED) is the ultimate counter technology. This ordinance was captured by coalition forces in Baghdad during the war in Iraq (2003–2013). Mines and artillery shells such as these were hooked to simple detonators, such as cell phones, and planted in the path of coalition forces.

were put out of action at alarming rates, and their crews and passengers were subjected to horrendous physical and psychological injuries. It would be years before the revolution in military affairs produced counter technologies equal to the challenge. Al-Qaeda even distributed online propaganda films of their IED attacks on the Americans, yet another dual-use technology turned against the industrialized West.

This was not the first time that high-tech, industrialized, Western-style armies had met setbacks imposed by low-tech, preindustrial, non-Western partisans. Mao Zedong had introduced what he called “people’s war” in the civil war for China against the Western-style army of Chiang Kai-shek. Ambush, which he called “mobile warfare,” loomed large in his scheme. His tactics were used by Ho Chi Minh’s forces in Vietnam to capture the French garrison at Dien Bien Phu and then to defeat the American military in the final phase of the Vietnamese war of national liberation. Other wars in the years since World War II have pitted poorly armed partisans against the military establishments of industrialized states with equally surprising results. For example, Israel has twice struggled to win the battle against intifadas without losing the war of world public opinion. The terrorists who attacked the United States in 2001 inflicted more casualties on American soil than the Japanese attack on Pearl Harbor in 1941 using no weapon more sophisticated than a box cutter. Ironically, the weapon of choice for these partisans and terrorists has usually been the very weapon that marginalized the barbarians since the introduction of gunpowder: gunpowder.

What, then might be said about the state of military revolution in the early twenty-first century? First and most important is a caution: belief in technology—even high technology—as a military panacea is misplaced and dangerous. Technology does indeed favor victory, but it does not guarantee it. In studying revolutionary military technology, historians did better than the defense analysts, in part because the historians were retrospectively analytical and the RMA was prospectively prescriptive. While historians have shown themselves to be just as cavalier when invoking revolutions, they have at least had the insight to understand that revolutions can be identified only after the fact. Not all change turns out to be fast enough and great enough to warrant the label "revolutionary."

Furthermore, the RMA and the trope of "military revolutions" both involved a certain amount of professional gamesmanship. Historians could have more impact on the existing scholarship and sell more books by claiming that their studies revealed revolutionary change. And advocates of the RMA could exert more influence on policymakers by promising transformational change at low cost. This is not to say that claims of revolution were disingenuous, only that the rhetoric of revolution often proved irresistible to advocates and audience alike. Both experiences suggest that talk of revolution should always be received skeptically.

The final point of comparison between the two movements confirms all of these trends. The RMA group often invoked the historical literature on military revolutions because it seemed to add scholarly gravitas to the current phenomenon they were espousing. But students of historic military revolutions paid little attention to the discourse on the revolution in military affairs. The historians, after all, were mostly academics, swimming in a scholarly sea of left-leaning, antimilitary sentiment. Indeed, for reasons of theoretical and scholarly integrity, it behooved them to eschew practical, contemporary applications of their findings. Enthusiasm for the RMA and for military revolutions rose to prominence in the 1990s and 2000s, before fading in the 2010s.

Conclusion

Only a few words can or need be said about the future of technology and warfare. The increasing pace of technological change became a cliché of the twentieth century, and so it remains. But the kernel of truth behind the platitude is that the pace really is accelerating and is likely to continue doing so. This is especially true for military technology, which is still subject to widespread, self-conscious, institutionalized research and development. On the horizon as this book goes to press are true drones (not remotely piloted), robotic (preprogrammed) weapon systems, further microminiaturization, nanotechnologies of warfare, and, perhaps most alarming of all, autonomous weapon systems (capable of some degree of independent response to environmental and situational inputs). These will enter a world that is paradoxically more dangerous and less lethal than at any time in human history. That is, the technologies of warfare are more effective than ever before, but there is less warfare in the world, based on casualties as a percentage of population, than ever before. Where all this will lead is impossible to predict.

If this book suggests any answers, they probably lie in an understanding of the terms in the glossary. Military technologies will surely change in the future, but the principles behind these terms, like the venerable "principles of war," will probably abide. They appear to transcend peculiarities of time and place. No doubt other principles from other realms of human activity will also shape the future of warfare, but the glossary nonetheless provides a beginner's set of tools—a primer for our reborn Alexander—for thinking about the very particular realm of technology and warfare. The heavy emphasis in this book on early warfare makes the point that the concepts guiding the evolution of technology and warfare emerged early and remain potent.

Dual-use technologies, for example, have thrived across all of human experience, from the Schöningen spear to remotely piloted aircraft. It is reasonable to expect that civilian technologies will continue to find military applications and vice versa. And we can expect that attempts to limit the transfer of military technologies will be confounded by the dual natures of some. Cold War constraints on export of computer technologies, for example, proved difficult to enforce. Dual-use technologies also illuminate another truism of world history, that military power mirrors economic power. So true is this that economic competition in the world is increasingly seen as a kind of moral equivalent of military might.

So long as the world remains divided between developed states and those without industrial infrastructure, armed conflict between the two divisions will be predominantly asymmetric. Beyond this, it is impossible to predict what technological marvels the developed states will bring to bear or what low-tech innovations—IEDs, sabotage, purloined weapons of mass destruction, etc.—the have-nots will deploy. Symmetrical arsenals among the developed states will likely deter interstate war indefinitely, barring some technological breakthrough.

Cyber warfare offers one example currently gripping the public imagination. It seems at first to pose an unprecedented threat to developed states with complex networked infrastructures, who find themselves vulnerable to hackers—the new barbarians at the gates—with stealthy and irresistible siege technology at their disposal. Some of the concepts developed in this book can help to demystify the phenomenon and set it in historical context. First of all, cyber attacks so far have been for normative purposes of espionage, sabotage, and subversion—not warfare. Even the most serious cyber attack to date, the Stuxnet incursion into Iran's nuclear program in 2009 and 2010, failed to produce war. Cyber attacks constitute a dual-use technology that can target both military and civilian targets. They can be both symmetrical (e.g., between state actors) and asymmetrical (between state and nonstate actors). Cyber attacks operate in the tradition of missile weapons, working at a distance and allowing the attacker to escape direct retaliation; this recommends them to weaker adversaries, but states with superior cyber resources also have superior offensive potential. It was reportedly the United States and Israel that attacked Iran with Stuxnet. And, as with satellites, the gigantism of the Internet is a source of its vulnerability. North Korea reportedly escaped attack by a pre-Stuxnet virus by insulating most of its national computers from the Internet. All of this suggests that cyber attacks are simply a new form of technologies that the world has dealt with for millennia. No doubt cyber warfare will play a role in future conflicts, but the powerful state actors will have at their disposal superior resources, both to protect themselves and to retaliate against abusers of the system. Cyber warfare may well end up in the same category as poison gas and antisatellite weapons, in which the most powerful states will abstain from attacking each other and weaker states will attack to little effect.

The asymmetry of modern warfare seems to be producing a reversal of the classic preferences for missile and shock weapons. Historically, weaker powers have chosen missile weapons to ambush stronger enemies, while powerful states have tried to close with their weaker enemies and crush them. While many weaker combatants continue to use missile weapons to pounce and flee, those embracing suicidal warfare seem to be turning increasingly to shock attack—closing with the enemy to kill all within reach, including themselves. The world has seen suicidal warriors before—the Japanese kamikazes of World War II come quickly to mind—and the tactic has yet to prove sustainable. One reason, of course, is that this method uses up one's reserves of manpower. But technology alone cannot reveal whether the current instance will be different. Meanwhile, developed states find themselves turning increasingly to missile weapons, the old favorites of the barbarians. In modern warfare, these instruments are now called "standoff weapons," the drones and other tools of air power that avoid the risks of putting "boots on the ground." As with the automated weapon systems now being developed for future warfare, these attempts to win battles without putting military personnel in harm's way are without precedent in human history.

Dueling technologies will no doubt continue to evolve, so long as one side or another fields new technologies that are perceived by their adversaries as threats. The recent contest between IEDs and armored vehicles in Iraq and Afghanistan provides one example, as does the continuing refinement of ballistic missiles and antiballistic missile systems. In the latter case, however, if any community wanted to nuke a US city, for example, it would likely opt for a low-tech delivery platform: a ship in New York's East River or a container moving through the Los Angeles/Long Beach Seaport. In 2014, these two West Coast ports handled about 40 percent of the cargo entering the United States, on the order of seven million containers, each one a potential bomb carrier. A low-tech Trojan Horse can still be a better choice than a high-tech siege engine.

In the same vein, gigantism will probably continue the slow decline it has experienced in the nuclear age. Technological determinism will remain an empty epithet. Humans will retain the agency to harness their military technologies until human nature itself changes. And military revolutions, to say nothing of revolutions in military affairs, will remain rare. If Alexander returns, he will have a lot to learn, but the concepts explored here might provide a starting point.

Glossary

ambush (also **pounce and flee**): A tactic, often employed by the weak against the strong, using missile weapons. The attacker, often in a group, surprises the prey and inflicts as much damage as possible without getting in harm's way, then retires before the enemy can respond or be rescued by reinforcements.

appropriate technology: Few technologies are universal. To be successful, most must be appropriate, that is, suited to the time, environment, conditions, and applications in which they are applied. Galleys, for example, worked well in coastal waters but could not venture far out to sea.

asymmetrical technologies: A situational condition in which two sides engage in armed conflict with significantly different instruments of warfare, both weapons and non-weapons technologies. Since World War II, for example, aircraft carriers have enjoyed an asymmetrical advantage over conventional capital ships: the ability to attack them before coming within range of their guns.

capability greed: Historian Blair Hayworth's name for the propensity of military organizations to gold-plate their arms and equipment and to add unnecessary features.

Carbon Age: The second age measured by sources of military power. It ran from roughly 1400 to 1945, in between an age of muscle and wind power and the age of nuclear power. In the **Carbon Age**, firepower and machines driven by internal combustion engines dominated all realms of warfare.

cavalry-infantry cycle: Alternating dominance of mounted and infantry forces in land warfare.

closure (see also **lock-in, momentum**): A term from the social studies of science and technology identifying the point at which one of several possible technological pathways achieves such dominance of the marketplace as to virtually extinguish competition.

Combined-Arms Paradigms: Periods of land warfare in which all combatants fought with the same combinations of types of weapons, even though individual weapons and fighting styles varied greatly from state to state. After the chariot revolution, field warfare was conducted by combining mounted warriors and infantry. After the gunpowder revolution, field artillery added a third arm to the paradigm.

counter technology: A military technology designed to negate or reverse the effect of another technology.

demand pull (see also **technology push**): Technological development impelled by demand for some capability. Necessity is the mother of invention.

dual-use: Those technologies with both military and civilian applications.

dueling technologies: Technologies developed dialectically in response to each other's evolving capabilities. One example is fortifications versus siege technologies.

gigantism: Increasing the size or power of a technology in the belief that more is better.

lock-in: A term from economics marking the point at which producers of a commodity have invested so much (sunk costs) in a technological choice that it is considered impractical to backtrack to another path. See also **closure** and **momentum**.

military revolution: A transformation of warfare so profound and sweeping that it not only redefines armed conflict between states but also changes the course of history, shifting the relationship between states and access to coercive power. This book identifies three: chariot, gunpowder, and atomic/nuclear weapons.

missile weapons (see also **shock weapons**): Weapons that strike from a distance without requiring contact with the enemy. Also known as "standoff weapons."

momentum: Historian Thomas P. Hughes's alternative to **technological determinism**. It allows that some technologies acquire permanence over time as infrastructure adapts to them in their present form, making it difficult for human agency to change the technological paradigm. The United States' embrace of light water nuclear reactors is an example.

non-weapons technologies: Military technologies that support warfare without directly attacking people or things.

path dependence: A technology is **path-dependent** when its mature form is shaped significantly by the course of its development. To be **path-independent** suggests that there is one best technological solution to a problem and that it would be realized no matter what course the development process took. This flirts with **technological determinism**.

pounce and flee: See **ambush**.

revolution in military affairs: An American military theory of the 1990s and 2000s. It maintains that improvements in US conventional military technologies, especially high technologies such as computers and computer networking, would give the United States unassailable dominance of the battlefield. It fell out of favor in the 2010s.

shock weapons (see also **missile weapons**): Those weapons, such as sword, pike, and bayonet, that required closing with the enemy. At sea, ramming and boarding are **shock** tactics.

symmetrical technologies: Weapons and non-weapons military technologies that mirror the enemy's.

system of systems: Multiple technologies or artifacts gathered in an integrated combination with capabilities greater than those of the components. The most basic steamship, for example, requires a steam generator, a machine to convert heat to mechanical energy, and a propeller of some sort to turn mechanical energy into propulsion.

technological ceiling: A limit imposed on a technology or system by the inadequacies of one or more components. True submarines were impossible before nuclear power.

technological determinism: A rhetorical label used in two ways. First, it suggests that technology independently and decisively controls historical outcomes. Second, it can suggest that technology is **path-independent**, following an inexorable course of development to some single, best configuration.

technological stasis: A condition of static technological development with little significant innovation.

technology push (see **demand pull**): This occurs when a technological capability spurs development of applications. The availability of steam propulsion, for example, transformed naval vessels.

weapon platform: A vehicle carrying a weapon or weapon system. Chariots, tanks, ships, airplanes, and spacecraft can all be weapon platforms.

weapon system: A technology of attack or defense that consists of several component technologies or technological artifacts. All **weapon platforms**, for example, are weapon systems, as was the mounted knight and mobile field artillery.

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