Archimedes the Military Engineer

23 Centuries of Defense-in-Depth, from 213 BCE to 2013 CE

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Introduction

Archimedes was not the first engineer to apply the principles of defense-in-depth to a military campaign, but his unique and systematic approach to the problem caught the attention of his contemporaries as well as that of future generations. Indeed, David Lane, historian of operations research, cites Archimedes' defense of Syracuse as a precursor to the systems approach to military operations, 23 centuries before the term was even invented.

Archimedes was far ahead of his time in other ways, as well. His carefully thought-out defensive approach suggests that he understood and followed the maxim later expressed by the great Prussian strategist Carl von Clausewitz in 1832: *War is the continuation of politics by other means*. Moreover, he saw that engineering was also the continuation of politics by other means, in that he developed his engineering approach to serve the political and military strategies. It was a clear demonstration that military and engineering strategies are most effective when they serve clear political goals.

Archimedes' chosen strategy to counter the Roman siege of Syracuse is today known as defense-in-depth. This is more than merely a layered defensive system. *Defense-in-depth* acknowledges that no single line of defense is foolproof against an attack. Instead, a series of multiple, layered defenses cause an attack to lose momentum, often by exploiting different weaknesses that make it harder for the enemy to develop a set of countermeasures. An example from biology is the human body's system of defense against infectious diseases, which consists of:

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- A physical barrier (skin) against infection entering the body
- An innate immune system (e.g., white blood cells) that provides immediate defense against any infection
- An adaptive immune system (e.g., antibodies) that "remembers" the body's response to an infection and prepares itself for subsequent encounters with that same infection

This chapter examines four examples of defense-in-depth, from Archimedes' time to the twenty-first century.

213 BCE: Archimedes and the Defense-in-Depth of Syracuse Against the Romans

Archimedes (c. 287 BCE–212 BCE) lived his life while Syracuse was generally at peace. Syracuse was one of the several Greek city-states on the island of Sicily. At the beginning of the third century BC, the Mediterranean basin was controlled by the Carthaginians in the west and the Greeks in the east. The Romans controlled most of the Italian peninsula and looked to expand its control over Carthaginian territory.

The beginning of the First Punic War (264 BCE–241 BCE) between Rome and Carthage was marked by Syracuse's King Hiero II attacking and laying siege to the rival city to the north, Messana. Archimedes, a member of Hiero's family who was just 23 at the time, may have witnessed this siege, though from the attacker's point of view. During the siege, Hiero aligned himself with Carthage, but after the Romans landed in Sicily, he switched his allegiance to Rome and thus avoided a costly battle. Hiero would hold the peace for the next half-century, until his death in 215 BCE.

During the long peace, Hiero built up his city and called upon Archimedes to oversee the defensive works against future sieges. Archimedes presumably spent much of the next five decades directing the extension and erection of walls on both the landward seaward sides, as well as incorporating a series of "engines" (machines) with varying ranges and capabilities to repel attacks "to any distance." During this time, he apparently traveled at least once to Egypt, where he was reputed to have invented the water screw (Archimedes screw) for irrigation (Figure 1).

The Second Punic War (there would be three Punic Wars, at roughly 50-year intervals) began in 218 BCE. The first phase of the war was marked by Carthaginian attacks against Roman lands, including Hannibal's famed crossing of the Alps with elephants and the Battle of Cannae. Hiero died during the conflict, and the next leader, his grandson Hieronymus, was assassinated after he tried to make peace with Carthage. The ruling faction that succeeded him was strongly pro-Carthaginian. Syracuse's strategic position between the Roman and Carthaginian empires (Figure 2) led Rome to dispatch its general Marcus Claudius Marcellus to bring Syracuse to its side.

Marcellus began his siege on Syracuse in 213 BCE, when Archimedes was about 74 years old. His defensive works had been untested since he began them, many

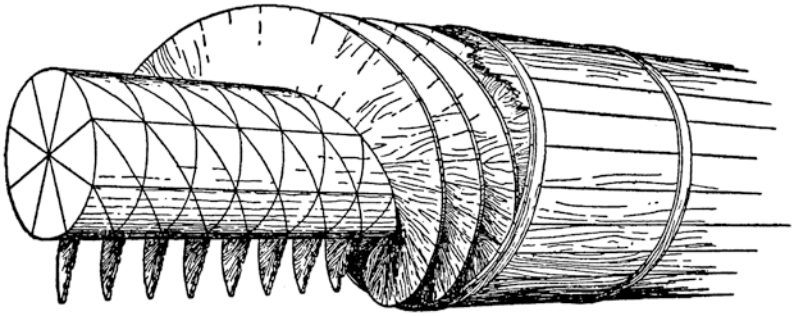


Figure 1 Archimedes' screw



Figure 2 Rome and Carthage. Note Syracuse's strategic position between them

decades before. He had, however, thought meticulously about the Roman modes of attack and where to place his strongest defenses. The city-state was ringed on the landward side by a defensive wall built atop steep cliffs and crags, almost impossible to climb opposed. On the seaward side, a line of tall cliffs to the north provided similar protection from amphibious landings. The main harbor was protected by the island of Ortygia, which provided clear lines of fire and permitted a chain to be drawn across the harbor mouth to prevent incursions. The only accessible part of the city was therefore a thousand-yard stretch of seawall at Achradina, which was

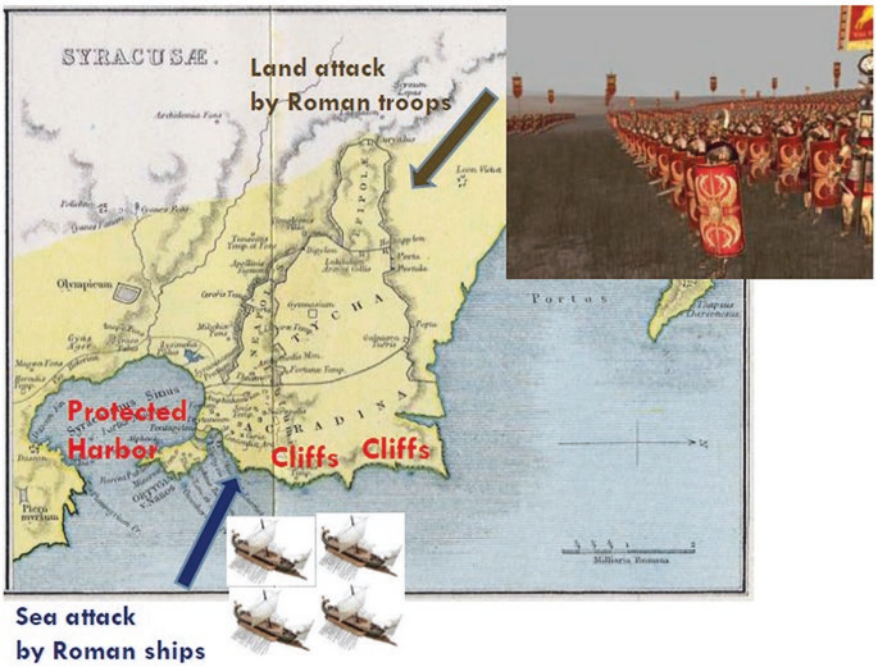


Figure 3 Syracuse under assault

fronted by a shallow and rocky coast. Archimedes carefully used the natural defenses of the terrain to concentrate his defensive forces at the vulnerable points, so that, according to the historian Polybius, "that there was no need for the defenders to busy themselves with improvisations; instead they would have everything ready to hand, and could respond to any attack by the enemy with a counter-move."

The Roman assault force consisted of both naval and army elements. Marcellus commanded a fleet of Roman ships that would attack the city-state at Achradina. At the same time, his joint commander Appius Claudius Pulcher brought troops with scaling ladders and towers to assault the north gate (Figure 3). Marcellus and Appius evidently expected that a quick siege would avoid more costly, time-consuming war by attrition. They were soon disabused of this by Archimedes' defenses.

Polybius, writing almost 70 years after the siege, focused his narrative on the naval assault at Achradina. His sources were apparently particularly impressed by Archimedes' system of defense-in-depth. In fact, Marcellus' attacking force was only lightly armed, which greatly contributed to his being stymied by Archimedes' superior firepower. Marcellus' naval force consisted of 60 quinqueremes, which were oared, ram-equipped warships similar to the more famous triremes, but larger and with five rowers per tier of oars instead of three. The ram bows were of course useless against a seawall, so the actual assault was conducted using four sambucae ("harps"), each of which consisted of two quinqueremes lashed together side by side for stability, with a large scaling ladder mounted to the decks. These sambucae

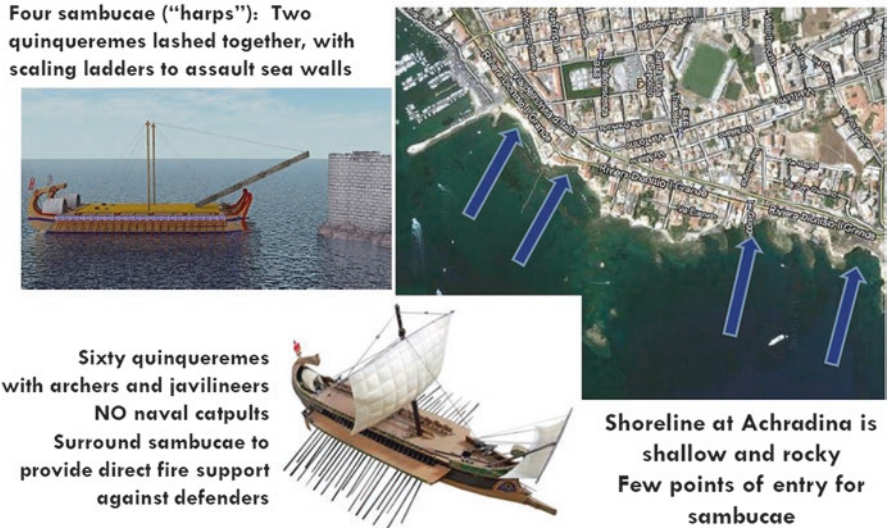


Figure 4 A Rome's naval siege at Achradina

would only be able to attack where the rocky coast was deep enough to allow it to come right up to the seawall, so that they could lean their ladders against the wall, allowing Roman troops to assault by escalade. Surrounding the sambucae were the quinqueremes with archers and javelineers on deck, who would provide fire support against the defending Syracusians (Figure 4). Marcellus followed standard Roman practice of the time, which relied heavily on massed troops, and did not employ siege artillery such as stone launchers, catapults, and crossbows. Archimedes, by contrast, had amassed a large, integrated arsenal of these weapons, plus one of his own design. For many months, this would render the Roman siege impotent.

Archimedes had developed a system of defense-in-depth that took advantage of Rome's inherent weakness in artillery and dependence on massed troops. The assaulting troops were massed against the city walls, and with javelineers throwing their spears upwards against defending troops, their effective range was about 15–20 yards. Archers could fire at ranges up to 60–80 yards. Not only were these weapons relatively short-ranged, but their throw weight and penetrating power against shields and armor were quite limited. Against this, Archimedes had arrayed multiple layers of defense with greater range, throw weight and capabilities. Rome's naval assault may have been doomed before it began (Figure 5).

Archimedes, by contrast, used a number of well-known Greek weapons to counter the Roman siege, one of which, the catapult, had been developed in Syracuse a century before his birth (Figure 6). At very short distances, he deployed cranes to drop large stones on the attacking sambucae and any quinquereme which happened to be just below the ramparts. Those ramparts would also (presumably) be lined with archers and javelineers whose height gave them a distinct advantage against the Romans in the ships below. At medium range and long ranges, a variety of stone

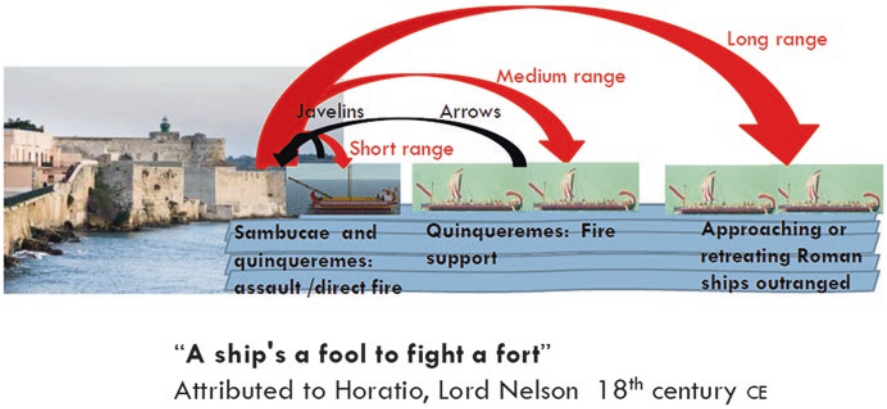


Figure 5 Archimedes' system of defense-in-depth

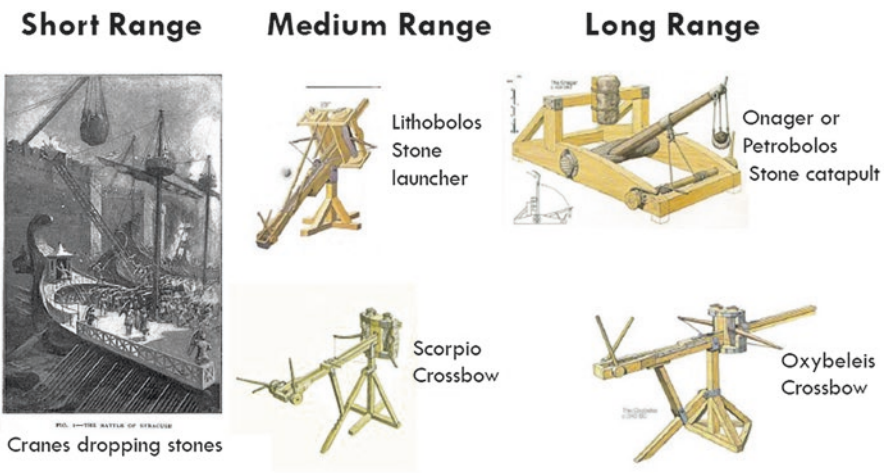


Figure 6 Well-known weapons used by Archimedes in the siege of Syracuse

launchers, catapults, and crossbows, powered by twisted animal sinews that provided the requisite torque, hurled rocks and bolts at high speed with great penetrating force. The largest weapons, such as the petrobolos and oxybeleis, could hurl heavy artillery out to several hundred yards, far outranging the Roman archers. This not only allowed the Syracusians to begin attriting Marcellus' shipborne troops long before they got into bow range but also denied them safe refuge upon retreat until they were far offshore. On the landward side, similar engines in a layered defensive array wreaked havoc on Appius' soldiers.

Polybius made note of one unusual weapon, invented by Archimedes, which caught Marcellus by surprise:



Figure 7 Archimedes' claw

> *A grappling-iron attached to a chain would be let down, and with this the man controlling the beam would clutch at the ship. As soon as the bow was securely gripped, the lever of the machine inside the wall would be pressed down. When the operator had lifted up the ship's bow in this way and made her stand on her stern, he made fast the lower parts of the machine, so that they would not move, and finally by means of a rope and pulley suddenly slackened the grappling-iron and the chain. The result was that some of the vessels heeled over and fell on the sides, and others capsized, while the majority when their bows were let fall from a height plunged under water and filled, and thus threw all into confusion.*

Historians have argued endlessly over whether "Archimedes' claw" ever existed. The description certainly appears fanciful in some parts: a fully laden quinquereme displaced around 100 tonnes, far greater than could be "lifted up by the bow" and which would certainly break the supporting beams. However, in 1999 and 2005, BBC and Discovery Channel (Figure 7) sponsored model and full-scale trials of a similar device and found that it could, conceivably, tip over such a vessel. (It should be noted that in 2010, the Discovery Channel's show *Mythbusters* was "directed" by President Barack Obama to determine whether the legend of Archimedes using burning mirrors to destroy the Roman fleet was plausible. It was not.)

As Polybius noted, *Marcellus' operations were thus completely frustrated by these inventions of Archimedes*. The system of defense-in-depth, with a mix of weapons and defenses that could protect the city at various ranges, made it impossible for the Romans to develop any systematic means of counterattack. This did not, however, spell victory for Syracuse. Marcellus and Appius settled on a protracted siege that would starve out the inhabitants. Though Carthage was able to occasionally break through the Roman blockade, supplies soon dwindled. After a stalemate that lasted almost a year, in 212 BCE, Appius' troops were able to breach the walls when they were left unguarded during a festival. Though Marcellus gave

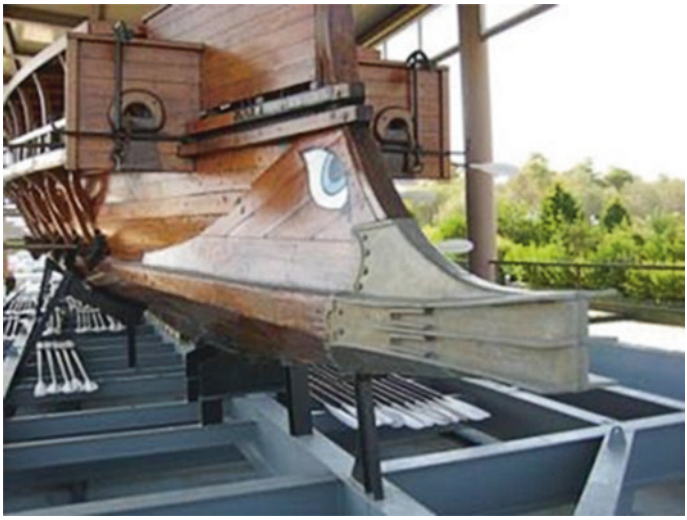


Figure 8 Ram bow of *Olympias*, a modern replica of a Greek trireme

strict orders to take Archimedes alive, he/Archimedes was killed by a soldier who apparently did not recognize him. Another 8 months of siege against the interior citadel starved the population into submission. Syracuse and the rest of Sicily fell under Roman rule. Ten years later, the Second Punic War ended with a Roman victory over Carthage. Rome now dominated the Western Mediterranean and was set firmly on the path to becoming the world's greatest and most influential empire.

1866: The Screw Propeller and the Ram: Naval Defense-in-Depth

Archimedes would have been familiar with the many varieties of oared warships of his age—triremes, quadriremes, and quinqueremes—distinguished by the number of rowers in each tier of oars. The navies of Greece, Rome, and Carthage maintained fleets of these warships to fight for dominance of the Mediterranean. They were all equipped with the same weapon—a massive bronze ram, sturdily fixed to the keel structure, which would hole the enemy ship by breaking apart hull timbers (Figure 8). Fleets would face head to head and execute complex maneuvers in order to ram the enemy. For a thousand years, from 500 BCE until 1500 CE, the oared ram galley was the primary maritime weapon of the Mediterranean.

The introduction of naval artillery in the 1500s vaulted the sailing warship to primacy. For almost three centuries, the sailing ship of the line, equipped between 60 and 120 cannon that could devastate an enemy's hull and rigging, became the symbol and reality of maritime power (Figure 9). Naval battles were no longer



Figure 9 How battles were fought before steam: French and British ships of the line at the Battle of Chesapeake Capes, September 5, 1781

fought head to head, as in the day of the ram, but in long, parallel lines of battle where opposing fleets would sail side by side, pounding each other in hours-long gun duels.

Steam power began to take the place of sail by the middle of the nineteenth century. At first, steam engines drove paddlewheels, a well-understood technology derived from the waterwheels which dotted every nation's countryside. Steam power was soon adopted by navies, as it gave the advantage of not being reliant on the fickle wind. Steam came at a price; the massive propulsion machinery (boilers, pistons, and coal bunkers) demanded considerable volume and manpower, paddlewheels were vulnerable to being destroyed by gunfire, and the paddlewheel boxes took up valuable real estate in the center of the gun deck. This considerably reduced the firepower available. For example, a 3000 tonne sailing warship might carry 74 guns, but a comparably sized steam warship would have just 20 guns (Figure 10).

The invention of the screw propeller, claimed by dozens of individuals from the 1820s to the 1840s, solved many of these problems when it was adopted. The most influential inventor was a British farmer named Francis Pettit Smith, who was inspired by the Archimedes screw to develop a screw-shaped propulsion device for ships. Over several years, he refined his device from an elongated screw with several turns that resembled Archimedes' original device, to a screw with two turns. Smith even dubbed his test ship for the screw propeller SS *Archimedes*, which was launched in 1839. Based on their experiences, Smith and others further refined the idea to a propeller with a single turn and multiple blades. The fact that the screw could be located below the waterline both reduced propulsion vulnerability to

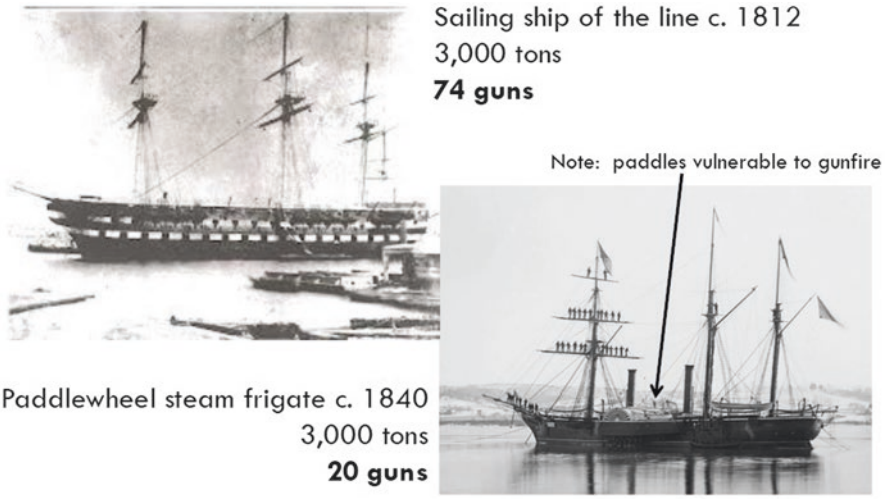


Figure 10 The problem with steam paddlewheel ships—lack of firepower

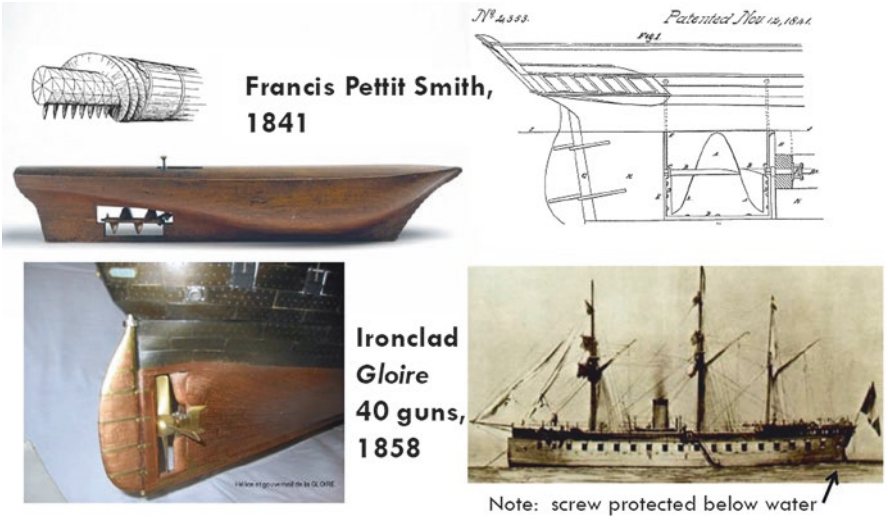


Figure 11 Screw propulsion comes of age

gunfire and freed up deck space for weaponry, often doubling of the number of guns that could be carried by a warship, though still fewer than the older sailing ships of the line (Figure 11).

As steam propulsion was coming of age, iron was adopted over wood as the shipbuilding material of choice. For warship builders, this presented both a great advantage and a serious problem. On the defensive side, iron was stronger than wood and more resistant to damage, but on the offensive side, it was far more

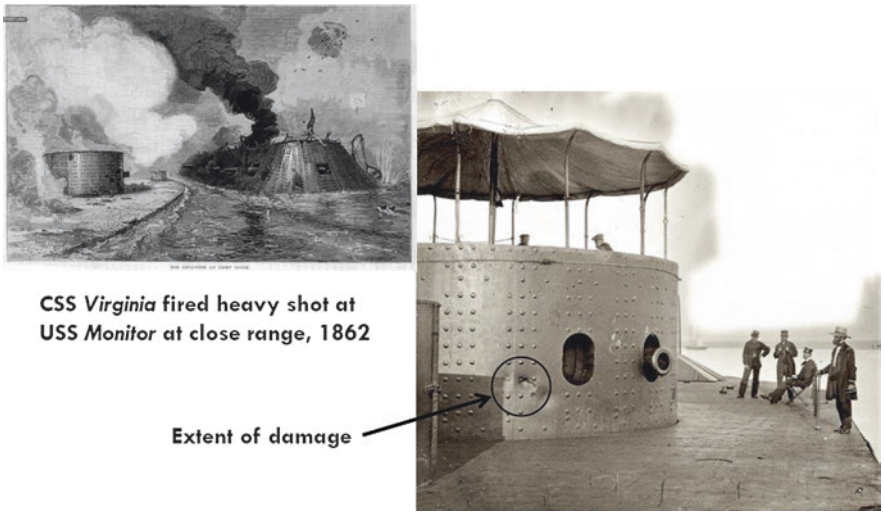


Figure 12 The problem with iron ships—protection

difficult for naval artillery to damage an enemy ship. During the 1862 Battle of Hampton Roads between the Confederate and Union ironclads CSS *Virginia* and USS *Monitor*, shot bounced off the ships' hulls and turrets even though they were firing at point-blank range (Figure 12).

The French navy had been the first to understand this problem and develop a solution that would provide the needed defense-in-depth. Just as the newfangled screw propeller hearkened back to the Age of Archimedes, its newest weapon, the ram, came from the same era and was, in fact, inspired by the Archimedes screw. Nicolas-Hippolyte Labrousse was a brilliant 22-year-old lieutenant in the French navy when in 1839 he witnessed the trials of Smith's screw-propelled SS *Archimedes*. He quickly realized that the screw could be harnessed to turn the ship into a ram like the Greek and Roman galleys and overcome the numerical advantage of the British navy. Labrousse drafted his idea the following year in a memorandum that argued for the "absolute" combat of ramming: … *as in Rome, the ram will re-establish equilibrium in favor of courage, and diminish superiority founded on greater numbers*. The idea was widely discussed and even tested over the next 20, but it was not until French industry had advanced sufficiently that the ironclad warship *Solferino* with a heavy, pointed ram could be built (Figure 13). As its constructor Dupuy de Lôme said, the warship … *could rip open by the shock, at even a moderate speed, any armored ship it attacked*. The British navy responded by constructing its own ram-equipped warship. The idea spread quickly; within months, navies around the world were ordering ram-equipped warships. Even the aforementioned CSS *Virginia* was built with a ram.

The combination of iron, screw, and ram provided a novel system of defense-in-depth that navies quickly adopted (Figure 14). First, the protection afforded by iron hulls and underwater screw propulsion allowed a ship to approach the gun-firing



Figure 13 The ram is introduced to iron warships: French ironclad *Solferino*, 1861

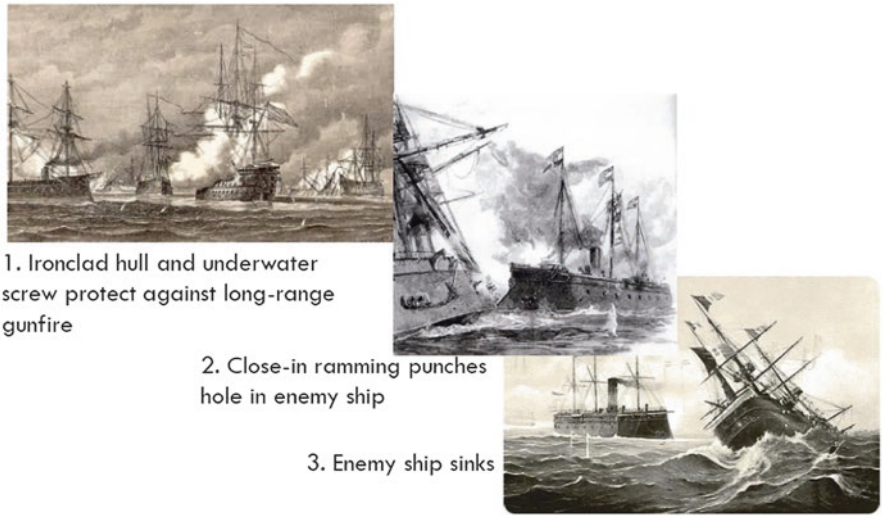
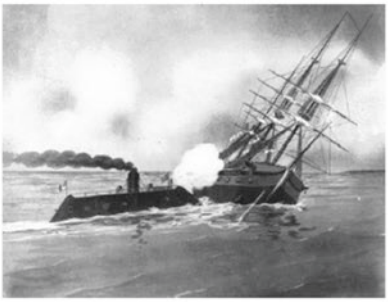
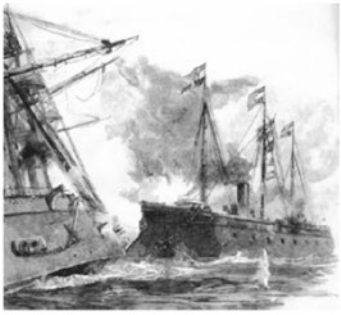


Figure 14 Screw and ram create defense-in-depth



CSS *Virginia* rams USS *Cumberland*
Battle of Hampton Roads,, 1862



Ferdinand Max rams *Re d'Italia*
Battle of Lissa, 1866



Huáscar rams *Esmeralda*
Battle of Iquique, 1872

Figure 15 Screw and ram in action

enemy vessel with relative impunity. Though the exchange of fire would likely cause superficial damage to both ships, the mortal wound would be inflicted when the ramming ship closed within striking distance and punched a hole in the enemy ship. The enemy vessel would immediately begin flooding as the ram was withdrawn, causing it to sink rapidly.

This system of naval defense-in-depth saw widespread usage in the 1860s and 1870s. The day before the ironclad duel during the aforementioned battle of Hampton Roads, CSS *Virginia* rammed and sank the Union frigate USS *Cumberland*. During the Third War of Italian Independence, the Austrian navy defeated the larger Italian navy at the Battle of Lissa (in the Adriatic) on July 20, 1866, in part because the Austrian flagship *Erzherzog Ferdinand Max* rammed and sank the Italian flagship *Re d'Italia*. On May 21, 1879, in the Battle of Iquique during the War of the Pacific, the Peruvian ironclad monitor *Huáscar* rammed and sank the Chilean corvette *Esmeralda* (Figure 15).

Thus, the Archimedes screw and the ram from antiquity combined to create a system of defense-in-depth that dominated naval thinking for several decades during the late nineteenth century. However, technological developments in the form of

underwater torpedo and improvements in artillery were already changing the nature of naval warfare. Torpedoes now allowed a ship to hole and sink an enemy vessel at long distances without ramming. At the same time, more powerful guns, larger exploding shells, and improved gunfire control made naval artillery more deadly against even well-armored ships. By the turn of the twentieth century, ramming had become the equivalent of the bayonet charge against machine guns and was quickly dropped.

1940: The Maginot Line: A Case of Failure of Defense-in-Depth

The twentieth century ushered in more than just improvements to artillery and gunfire control. Warfare itself became industrialized, with revolutionary developments in communication, transportation, and weapon technologies that fundamentally altered the conduct of war. The World War I saw these elements brought together in devastating ways. The aftermath was staggering: 16 million dead, 21 million wounded or missing, and hundreds of billions of dollars in destruction. The effect upon France was shattering. Five percent of its population was killed outright—higher than any other major power—and one person in ten was wounded. The national birth rate plummeted. By 1930, France had just 40 million inhabitants compared with 70 million in Germany, on top of which there was a widespread shortage of military-aged men.

War planners knew that static defenses required fewer troops, so they carefully planned a large-scale system of defense-in-depth that would ensure the limited number of soldiers would be placed in the most advantageous positions (Figure 16). The primary defense, known as the Maginot Line, was directly along the French-German border. Its purpose was to greatly slow down any German advance, attriting those forces and buying time for French troops to be mobilized to meet the onslaught. Further north, the planners assumed that the Ardennes Forest along the borders with Luxembourg and Belgium were too dense and rugged to permit large-scale mechanized assault (tanks and mobile artillery) to cross. The region between the Ardennes and the English Channel would see the largest concentration of French troops to face down the anticipated German "right hook" through Belgium. At the same time, French planners anticipated that Britain would come in on their side if Belgian neutrality were violated.

The Maginot Line was built at enormous cost between 1930 and 1940. It was not a single barrier but rather a large-scale system of defense-in-depth (15–20 miles deep) that relied on a number of systems, tactics, and technologies to slow down and weaken the enemy (Figure 17). At the front was a series of antitank barricades to slow down tanks and other heavy vehicles, making them susceptible to counterfire. Behind those, blockhouses and strong houses, often camouflaged as residential homes, housed troops and antitank batteries to "sound the alarm" and provide


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Brussels
Cologne
Liège
Liège
Namur
BELGIUM
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Troops
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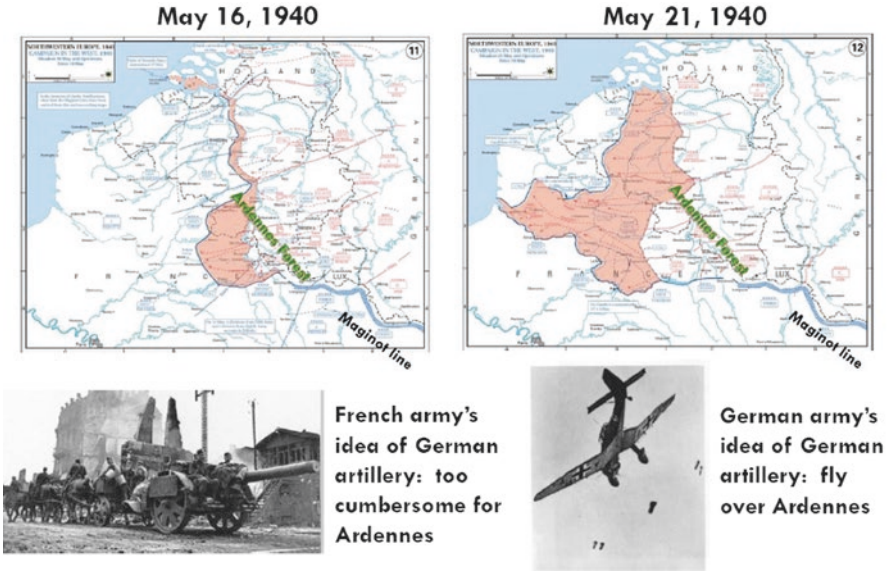


Figure 18 German forces bypass the Maginot Line and advance through Ardennes

principal line of resistance were additional defenses, including rail artillery, which could be quickly moved to different zones to destroy German troops that had broken through the principal line of defense. Behind the Maginot Line, masses of French troops would mop up the remaining German forces.

The German invasion plan of France was designed to deal with the Maginot Line. The heart of its strategy was to avoid attacking the Line head-on, instead relying on a flanking attack through the Ardennes Forest. The French planners considered the forest too dense to allow tanks and heavy artillery to pass and only lightly defended the line opposite. The German army, in a stunning display of what is today called "asymmetrical warfare," did not send tanks through the Ardennes but instead relied on the Luftwaffe (notably its JU 87 Stuka dive bombers) for fire support.

Germany first deployed a decoy force in front of the Maginot Line to draw off French forces from the main line of attack. On May 10, 1940, the German army invaded the Low Countries and crossed them in 2 days. As the army began invading France, the Luftwaffe flew over the Ardennes and destroyed French emplacements and army positions, paving the way for German troops to advance. German forces were well into France by May 16, reaching the Channel on May 21 (Figure 18). A month later, all resistance had collapsed and France signed an armistice with Germany, beginning a 4-year long occupation.

Though Maginot Line was, in fact, a well thought-out system of defense-in-depth, it ultimately failed in its purpose to protect France from a German invasion. When the German army did attack the Line directly head-on, the French defenders were generally able to repel the attack. On the larger scale, however, advances in technology and tactics—notably the employment of air power—allowed the

invading army to simply bypass the fortifications, surround them from the rear, and cut them off. In the face of these changes, the Maginot Line had simply become irrelevant to modern maneuver warfare.

2013: Cyber Defense-in-Depth for the Twenty-First Century

Defense-in-depth in the twenty-first century is increasingly focused on protecting against "cyberattacks" on the software elements of key systems. This goes well beyond the military. Critical infrastructure is increasingly software-driven: power plants, electrical grids, oil rigs, chemical factories, etc. each requires millions of lines of code to operate. Malicious code (viruses, worms, etc.) can be stealthily inserted by an attacker, which can lie dormant and unseen for long periods before wreaking havoc on a system.

Such attacks are becoming more prevalent as both corporations and governments increasingly connect their computer systems via the Internet and other networks and store information in vast third-party systems known as "the cloud." Cyberattacks can come from both state and non-state actors, and it is not easy to identify the source. In August 2012, Saudi Aramco, the largest oil production company in the world, was attacked by a virus which shut down most of its computers, causing the company to spend a week and many millions of dollars restoring services. Though a group of computer hackers claimed responsibility, suspicion also fell on rival companies and even the Iranian government. In March 2013, several South Korean TV stations and banks were attacked and their computer terminals shut down. Though some evidence pointed to North Korea as the source, a "hacktivist" attack has not been ruled out.

Cyberattacks have increased in both frequency and sophistication. Not only are the number of computer systems and users increasing almost exponentially, but the cyberattack tools available are also multiplying. Many of these tools are being offered as turnkey packages, which require little in the way of direct software skills and knowledge by a potential attacker (Figure 19).

Cyber defense, the deployment and use of systems and tactics against software attacks, has also grown more sophisticated, including the important realization that some attacks will get through any system of defense and to plan for recovery afterwards. Defense-in-depth against cyberattacks now includes the following diverse elements:

- Intelligence: understanding the threat.
- Passive defense: antivirus, firewalls, etc. known to most computer users
- Active defense and offense: using intelligence to create preemptive attacks against intruders and developing rapid retaliation and response
- Redundancy and separation: avoiding single points of vulnerability, for example, having multiple software types across critical systems
- Resilience: the ability to restore services after an attack

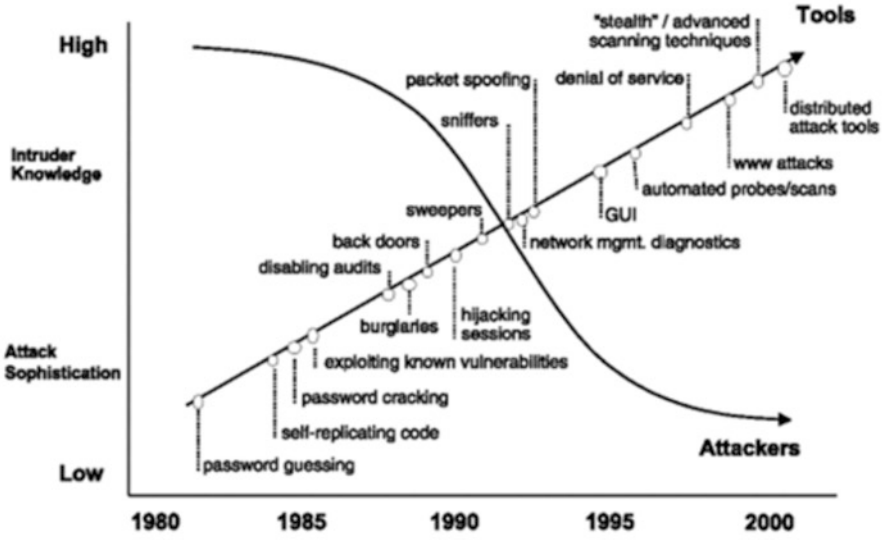


Figure 19 Cyberattacks are becoming more sophisticated, yet require less skill by intruders

Conclusions

Archimedes was one of the influential pioneers of defense-in-depth, which has proven to be a useful military and engineering strategy to meet varied political goals. The defense of Syracuse and the employment of the ram and screw showed how multiple, layered technical and tactical systems can prove effective in slowing down and countering an attack. However, even the best defense can be overcome; the Maginot Line was outflanked by rapid, unanticipated advances in technology and tactics, and the defenders were unable to recover from the assault when their carefully prepared protective works were simply bypassed.

The current generation of cyberwarfare planners is using lessons learned from these and other examples to create appropriate defense-in-depth for the modern era, especially in understanding that some attacks will get through, and provide acceptable levels of operations after attack. As cyber defense continues to evolve, the lessons from Archimedes will continue to be relevant in the twenty-first century.

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