



# RISE OF THE MACHINES

A CYBERNETIC HISTORY



THOMAS RID



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## 1. CONTROL AND COMMUNICATION AT WAR

THE EVENING SKY OVER LONDON WAS WIDE AND DARK blue, with only scattered clouds. It was the autumn of 1940. The calm was deceiving. Suddenly the wail of air-raid sirens ripped through the twilight. To Londoners, the sound was as familiar as it was unnerving. Night raids had become the norm. Between August 23, 1940, and New Year's Eve that year, only eight nights were quiet, without German aerial assaults on Britain. The Germans had begun flying at night. That made it harder for the RAF's Fighter Command to hunt the incoming bomber convoys, and it made it harder for London's defenders to shoot them down. But raiding in the dark was also inaccurate. Pilots were still bombing by sight, often using light incendiary bombs to mark targets for subsequent heavy bombardment. The Germans focused on sites of military interest, such as centers of industrial activity and transportation hubs.<sup>1</sup> No light would escape London's blacked-out windows. On moonless nights the Luftwaffe even relaxed the rules of engagement.

That night the moon was rising, illuminating the capital's landscape of red and brown rooftops in a soft and silvery sheen. At 85 Fleet Street, two reporters grabbed their steel helmets and climbed on top of the *Chicago Tribune's* fifth-floor office, next to St. Bride's Church, designed by Sir Christopher Wren in 1672. The two American scribes, Joseph Cerutti and Larry Rue, awaited the coming raid.

They looked up: “The sharp beam of searchlights stabbed the sky.”<sup>2</sup> Then, to the southeast of London, they saw “a glittering chain of tracer bullets mounting skyward.” Next came the crack of antiaircraft batteries, with their shells bursting high in the sky, like shooting stars in reverse. Only then did Cerutti and Rue hear the “remorseless *throb-throb-throb*” of dozens of German bombers, laden with high explosives and incendiary bombs. High over the city the pilots opened the hatches. Their deadly cargo came whistling down, at first invisible, and then the bombs thundered on impact and the incendiaries spread a glaring white flame far and wide. The red glow of fire had become familiar, dimmed at first by clouds of smoke. Flocks of city birds—starlings, sparrows, and pigeons—fluttered into the burning sky. The fire, swiftly taking hold, lit up “in ghastly relief” the huge dome of St. Paul’s, London’s majestic cathedral church.

Only the approaching dawn brought relief. The slowly returning daylight seemed to repel the relentless waves of bombers. “We’re alright now,” said Rue. The *Tribune*’s London bureau chief had seen many raids before: “It’s dead overhead.”<sup>3</sup> Then Cerutti heard the sound of a single plane circling low. A big lone bomb came hurtling down:

It landed on a solid office block in a neighboring street. I stood rivetted behind a low stone parapet. The bomb exploded with an ear-splitting crash and, in the flash of the explosion, I saw the entire façade of the building rise gently into the air, seemingly intact. Windows and cornices stood out clearly as it mounted, perhaps 50 feet, and then disintegrated, raining debris over a wide area.

The famous air battle of Britain unfolded incrementally, starting in June 1940. On August 1, Adolf Hitler issued Führer Directive number 17. It ordered the Luftwaffe to “overpower the English Air Force with all the forces at its command in the shortest possible time.”<sup>4</sup> The bombing raids became more intense during August. After a change of strategy in early September, Hitler chose London as the prime target. On September 15, two hundred German aircraft with a heavy fighter escort took aim at the imperial capital. The pounding continued for months. By day, German bombers and fighters swept across southeast England. By night, they attacked London. The Luftwaffe escalated on the night of October 15–16, sending 235 bombers to the capital. British defenses were dismal: with 8,326 rounds fired, London’s defenders managed to destroy only two planes and damage just two others that night.<sup>5</sup> The year ended with a great fire raid on the city, on the night of December 29–30, which famously engulfed St. Paul’s Cathedral in flames. Only fourteen enemy aircraft were shot down during all of December.

The Battle of Britain was “truly revolutionary,” military historian John Keegan observed.<sup>6</sup> For the first time in history, one state had taken an entire military

campaign to the skies to break another state's will to resist. No land or sea forces were attacking Britain; only the mighty German air force. The need for action and improved air defenses was great. It was acutely felt across the Atlantic. In a curious chain of events, the German bombs that were falling out of London's night sky helped trigger a veritable explosion of scientific and industrial research in the United States. Only four years later, before the war in Europe was over, new thinking machines would be deployed to the English Channel—machines that were capable of fighting each other, and of making autonomous decisions of life and death.



Vannevar Bush was one of his generation's gifted visionaries and a prolific inventor. Since 1932, Bush had been vice president of MIT and dean of the School of Engineering. In 1936, the US Army General Staff had cut half of its research-and-development budget, believing that America's weaponry was adequate and that the money would be better spent on maintenance, repair, and more ordnance.<sup>7</sup> After making inquiries, Bush was dismayed to find a military leadership clueless about how science could be useful in war—and scientists clueless about what the military might need in the event of war.

Bush's service on the National Advisory Committee for Aeronautics (NACA), the organization that preceded NASA, gave him unique insights into cutting-edge aeronautical developments: in 1938, he heard a fellow member, Charles Lindbergh, give a talk after his return from a privileged tour of German munitions and aircraft factories. Lindbergh was impressed by the mighty German war machine, especially by the displays of the seemingly invincible Luftwaffe. And few people understood the power of the flying machines as well as Lindbergh did. Eleven years earlier the aviation pioneer had become the first pilot to fly nonstop from New York to Paris. He later compared his plane, the *Spirit of St. Louis*, to a "living creature." High in the air he, Lindbergh, would find unity with the machine, "each feeling beauty, life, and death as keenly, each dependent on the other's loyalty. We have made this flight across the ocean, not *I* or *it*."<sup>8</sup> Lindbergh feared that when war came, the unity between man and ever faster, bigger, and more powerful machines would no longer be about beauty and life, but about death from above. America should remain uninvolved in the war, the aviator was



convinced.

Bush drew different conclusions. The rugged New Englander had strong views, stamina, and drive.<sup>9</sup> America needed to get ready for war. And that meant that science had to do its bit. In January 1939, Bush, then fifty years old, moved from Boston to Washington to become president of the Carnegie Institution. He was already well connected when he arrived in the District of Columbia that winter: he had chaired a division at the National Research Council, and he had served on NACA. Bush was keen to be involved in the politics of research funding. Carnegie's offices were at the corner of Sixteenth and P Streets, ten blocks north of the White House. With Europe still at peace, in the spring of 1939, Bush became concerned about the "antiaircraft problem," more than a year before the Germans exploited it so devastatingly in the Battle of Britain.

Through his work at NACA, Bush saw that aircraft would grow bigger, faster, and capable of flying at higher altitudes. This evolution, he understood, made it difficult, if not impossible, to bring down the machines with run-of-the-mill gunnery. Hitting the machines directly with artillery shells that exploded on impact was practically impossible. The shells needed to be timed so that they would detonate close enough to the target to bring it down. Yet correctly setting the time fuse became ever harder as speed and distances increased. In October 1939, Bush was elected chairman of NACA, the agency that coordinated research into aeronautics. But NACA's antiagency, an institute coordinating research into air defense, did not exist. Bush proposed to the president that "no similar agency exists for other important fields, notably anti-aircraft devices."<sup>10</sup> On June 27, 1940, Roosevelt established the National Defense Research Committee, better known by the shorthand NDRC.<sup>11</sup> Its purpose was to fund academic research on practical military problems. The NDRC would be spectacularly successful.

Engineers often used duck shooting to explain the challenge of anticipating the position of a target. The experienced hunter sees the flying duck, his eyes send the visual information through nerves to the brain, the hunter's brain computes the appropriate position for the rifle, and his arms adjust the rifle's position, even "leading" the target by predicting the duck's flight path. The split-second process ends with a trigger pull. The shooter's movements mimic an engineered system: the hunter is network, computer, and actuator in one. Replace the bird with a faraway and fast enemy aircraft and the hunter with an antiaircraft battery, and doing the work of eyes, brain, and arms becomes a major engineering challenge.

This engineering challenge would become the foundation of cybernetics. When Norbert Wiener read about the duck-shooting comparison, he instantly fell for it.<sup>12</sup> And he would claim again and again, falsely, that he overcame the related

prediction problem. In reality, one of America's most gifted entrepreneurs had already cracked prediction, and built an entire contracting empire in the process. Wiener's successful theory, although the professor never acknowledged it, stood on the shoulders of an engineering giant.

Elmer Ambrose Sperry's business acumen was extraordinary. He founded Sperry Gyroscope in 1910, at 40 Flatbush Avenue Extension in downtown Brooklyn. Sperry's vision was to build a company that provided control as a separate technology: stabilizing ships, guiding airplanes, and directing guns. Sperry products would make these machines perform at a higher level and with greater reliability than human operators could have achieved unaided.

Sperry understood that air defense problems were not limited to the ground. The Flying Fortresses, America's mighty B-17 bombers, were large and vulnerable to fast, small, and swarming fighters. The large aircraft needed novel defenses. Thomas Morgan, Sperry's president in the early 1940s, explained that the firm's primary value of military products would be that "they extend the physical and mental powers of the men in the armed forces enabling them to hit the enemy before and more often than the enemy can hit them."<sup>13</sup>

Sperry turrets were an example. The turret gunners worked individually. Their .50-caliber guns could be operated by line-of-sight, with visual targeting and relatively close range. An airborne fire control mechanism like a gun director was not necessary to operate the hydraulic turrets. The turret's movement was smoothed and stabilized, enabling the gunner to swing around rapidly in pursuit of enemy fighters. But fending off the attacking planes was not automated, although the machine had fail-safes that prevented gunners from hitting parts of their own planes in the stress of battle. Nevertheless, the turrets were taking man-machine interaction to a new level.

Sperry was looking for a new way to depict how soldiers and workers interacted with machines. The firm's engineering graphics department decided to hire an artist with experience in perspective drawing. They settled for Alfred Crimi, a well-known Sicily-born fresco and mural painter from New York City. After an in-depth security vetting, and after getting used to the Italian sporting oriental silk cravats and a goatee, Sperry gave Crimi a private studio. The company didn't know how to take advantage of the artist properly at first, so he had freedom and time to experiment.

Crimi developed a technique of transparent, overlapping drawing. His best-known paintings show gunners in turrets, with their gun sights visible through the body, "as though seen through an X-ray," Crimi explained.<sup>14</sup> He depicted human-machine interaction both at the fighting front and at the home front, detailing the

company's assembly lines of navy gun sights, female workers working with great focus at a microscope, giant gyrocompasses at sea, and a high-altitude laboratory that simulated an altitude of 72,000 feet.

One of Crimi's most famous pencil drawings shows a gunner lying in a Sperry ball turret. This tiny spherical cabin, with two guns protruding from it, stuck out from the belly of the B-17 Flying Fortress. The turret was kept tiny to reduce drag on the plane. It housed two light-barrel Browning .50-caliber machine guns, with 250 rounds each. An elaborate chute system at the top of the sphere fed ammo down the outer shell to the guns. The guns extended through the entire contraption, on both sides of the gunner. The turret had several triangular windows, with a large, 13-inch-diameter bull's-eye between the gunner's legs. The turret had no space for a parachute.

The gunner rotated the turret hydraulically, with two hand control grips, similar to joysticks. The ball could move nearly 360 degrees vertically and 90 degrees horizontally. This wide range meant that the gunner could either lie on his back or almost stand on his feet while shooting the twin gun. Each joystick had one button to fire. The gunner's right foot operated a push-to-talk intercom system; his left foot operated a reflector sight that superimposed an illuminated pointer on the target. The gunner, usually the smallest crew member, entered the turret when the plane was on course, after the landing gear had been retrieved. The crew pointed both guns toward the ground, and then the gunner pulled open the door, stepped in, placed his feet in the stirrups and curled down into a fetal position between the two Browning guns. After tightening the straps, he had control of the swiveling weapon.

When the gunner tracked an enemy fighter while attacking from below, "hunched upside-down in his little sphere, he looked like the fetus in the womb," in the words of Randall Jarrell, a celebrated American poet.<sup>15</sup> Jarrell served as an officer in the army air forces during the war. In 1945, he published a powerful five-line poem, "The Death of the Ball Turret Gunner." Jarrell's poem wrestled with the consequences of merging man and machine in industrial warfare. The human operator simply became a cog hunched in the belly of the machine, insignificant and disposable, and eventually torn into pieces by enemy fire and "washed out of the turret with a hose."

The same theme, if not as cruelly drawn, defines Crimi's sketches and drawings for Sperry. In true modernist fashion, Crimi's cutaways visually merged man and machine. The sketches made parts of machine casings invisible to reveal human operators strapped inside the turrets as living parts of the machine. Human bodies, in turn, became transparent to reveal dials and levers, or simply disappeared at the waist. Faces were eerily absent. The drawings were



reminiscent of sketches used to teach anatomy to medical students. Crimi and the turrets illustrated how men interacted with machines to increase their muscle power. But the ball turret gunner was still using his own eyes to observe an approaching fighter and his own brain to decide where to aim the guns to destroy it.

Crimi's sketches were intended as "morale builders," for "breaking the monotony endured by the assembly line workers."<sup>16</sup> His drawings were prominently displayed in *Time*, the *Illustrated London News*, *Popular Science*, *Diesel Progress*, and other industry publications.<sup>17</sup> These iconic paintings hit a nerve. The art pieces captured the popular excitement about new forms of human-machine interaction, of "mechanized man"; it was this excitement that Wiener's pathbreaking book tapped into. Crimi, at Sperry, expressed in images what cybernetics would soon express in its own jargon: the relationship between humans and their machine tools was beginning to shift.



Meanwhile, some of the free world's brightest engineers worked on control and communication at war, long before cyberneticists even articulated it as "feedback" loops. Air-to-air combat was difficult enough. But the antiaircraft problem was even more vexing when viewed from the ground. Simply seeing the target could be a challenge. By the time an approaching Junkers Ju 88, a new German bomber used in the Blitz, came into the line of sight, it was probably too late to fire because the aircraft was already too close. Defending against an aircraft from the ground required seeing it before the human eye could. Defense required extending the senses, enhancing perception itself. That trick was accomplished by radar. Existing systems could already be used to guide searchlights in the night sky. But the best radar systems in 1940 were not good enough for automatic fire control against enemy aircraft. The NDRC was determined to overcome this limitation.

The term "radar" originally was an abbreviation, a short form for "radio detection and ranging." The main objective of radar was to determine an object's distance in space from the radar station, its range. By 1940, both the Axis powers and the Allies were starting to use shortwave radar. But neither had yet cracked the design for the much more powerful microwave radar technology. That, however, was about to change. Until the atomic bomb was dropped, the Allies

saw microwave radar as the war's most powerful secret weapon, a crucial new technology that stood between survival and defeat at the hands of the Axis powers.<sup>18</sup>

Radar could “see through the heaviest fog and the blackest night,” in the words of the *New York Times*. The operating principle was simple, a bit like throwing a stone into a dark hole and waiting to see how long it took to hit the ground: the radar station emitted radio waves, the target reflected some of the waves' energy, and an antenna received the echo. The time it took for the echo to return indicated the target's range. The radar's electromagnetic pulse signal traveled at the speed of light, about 186,000 miles per second. If an object was 15 miles away from the radar, its echo would return 0.00016 second later. The detected range and direction would be displayed to the operators on a “scope,” a round screen that resembled the faintly illuminated face of a clock. A number of rings marked the scope, and sometimes a map was superimposed on it. The target would appear on the scope as a small glimmer of light, a “pip.” The pip's distance from the scope's center depended on how long the echo took to return.

Radar also measured precise direction—where the target was, not just how far away it was. The antenna's position indicated the direction: it would rotate and throw out sharply directed pulses, like searchlights of microwaves. The target showed up as a small flickering pip on the operator's round screen when the rotating antenna was pointed straight at the target. The target's altitude was calculated through the antenna's upward-pointing angle. Naturally, radar would pick up noise. Radar manuals in the 1940s often included long sections on “pipology,” or “the study and interpretation of all types of contacts seen on radar indicators,” as one military handbook defined it.<sup>19</sup> It was an art: operators needed a finely trained eye for the size of the pip, its shape, its bobbing and flickering, its fluctuation in height, its movement in range and bearing. Their task was daunting: mistaking noise for a signal could mean firing at a rock, or firing at friendly forces instead of the enemy.

The US Army's first radar system, the SCR-268, was designed in 1937. It was clumsy. The 268 had vast antennas, about 40 feet wide and 10 feet high. It was also inaccurate. The 268's problem was its long wavelength: 5 feet. Using this radar was a bit like using a map in bird's-eye view, without the ability to zoom in and see details. The solution was theoretically simple but practically hard: shorter wavelengths, or *microwaves*. Shorter waves with a higher frequency had a critical advantage. The shorter the wave, the more accurate the beams, and therefore the higher the resolution of the picture that operators could see. Using the new radar, in theory, enabled them to zoom into the map at high resolution. It would be an

incredibly powerful tool. But there was a catch: physicists knew microwaves existed, but nobody had figured out a way to generate and emit microwaves in sufficient power for a useful radar set.<sup>20</sup> German engineers did not even consider microwave radar to be technically possible.<sup>21</sup>

War brought an answer to MIT. It wasn't without irony: by attacking England, Germany helped create one of the most potent weapons that would ultimately bring it down. The fierce German aerial attacks on London and southern England meant that Britain had to focus all her energies on immediate war production. It became harder to continue basic research. So Sir Henry Tizard, then the chair of Britain's Aeronautical Research Committee, set out on a mission to enable US applied research to take advantage of some of England's most prized top secret experiments on microwave technology. Researchers at the University of Birmingham had made a sensational discovery in late 1939 and named it the "cavity magnetron."<sup>22</sup>

The tiny contraption was remarkable: it could produce the coveted shortwaves, below 10 centimeters, even down to 3 centimeters. Even better, aircraft and boats could carry the magnetron's much smaller antennas. The potential was tantalizing for US planners: not only would they be able to see the enemy at high resolution at all times while he was unable to see them, but the technology held even more promise, in that radar could become mobile, enabling aircraft to fly in the blackest of nights and ships to maneuver in the densest of fogs. That still wasn't all: 10-centimeter and 3-centimeter radar sets were much harder to jam than radar with longer wavelength. This meant that the Allies could jam the enemy, blinding him, while enhancing their own perception.

America's radar program changed radically on August 28, 1940. A fierce tropical storm lashed the mid-Atlantic states that Wednesday. Vannevar Bush had dinner with Tizard at the Cosmos Club in Washington, DC. The two got along well and discovered a shared passion for applied civilian research. The dinner set in motion a series of events that led to Bush's NDRC taking control of microwave research. The army and the navy had terminated their own microwave research in 1937 and didn't object. With the magnetron, Bush recalled, "we ran away with the ball."<sup>23</sup>

In October 1940, MIT's Radiation Laboratory was established, initially with a few dozen researchers and just a few rooms. Over the next months, the lab made breathtaking progress. The MIT engineers made another brilliant discovery: they realized that if the reflected radar pulse could be amplified, through feedback, to control the servomechanisms of the radar's antenna, then the same faint signal—now vastly more precise, thanks to the smaller microwaves—could also control a



howitzer. If radar could automatically track a target, then entire guns could automatically track their targets as well.

At the end of May 1941, the Rad Lab demonstrated its experimental automatic angle-tracking radar system at MIT. The engineers hauled a .50-caliber machine gun turret originally designed for the B-29 bomber to the roof of an MIT building and then hooked it up to one of their experimental radar stations. They set up the system so that the gun would automatically point at a tracked aircraft flying by, even when it was behind cloud cover. "It was very impressive," recalled Ivan Getting, who led the demonstration:

You could look through the telescope mounted on the radar mount, and the airplane would go behind a cloud, and you wouldn't see anything but a cloud. When the airplane emerged from behind the cloud, there was the airplane right on the cross hair. It was just like magic.<sup>24</sup>

The engineers knew what to do: take the roof-mounted contraption, redesign it, and mount the automatic antiaircraft gun on a truck. In early December 1941, the Rad Lab took its experimental truck, the XT-1, to the US Army's Signal Corps at Fort Hancock, New Jersey, for demonstration. On Friday evening, December 5, the engineers celebrated the success of their new machine with generous amounts of beer at the fort. Two days later, on Sunday morning, Japan attacked Pearl Harbor.

Over the course of the next four war years, the Rad Lab swelled into a research giant that took over most US radar work, with a \$4 million monthly budget and a staff of about four thousand that included one-fifth of all of the nation's best physicists.<sup>25</sup> The Rad Lab operated its own manufacturing plant, ran its own airport at Bedford, Massachusetts, and had its own field radar stations across the United States and around the world. The lab became the NDRC's largest project and one of the most celebrated scientific institutions of the war. By May 1945, less than five years after the Tizard mission, the army and navy had contracted \$2.7 billion of MIT-inspired radar equipment. This remarkable investment laid the foundation for America's mighty postwar electronics industry.

The lab's most notable achievement was the truck-mounted microwave radar, the XT-1. The army renamed it SCR-584. The machine's name stood for "Signal Corps Radio 584." It was a formidable device. The 584 made nearly all earlier radar systems obsolete. The machine was precise enough to display on its scope the trajectory of a 155-millimeter artillery shell as it approached its target. When the small pip and the large pip converged on screen, both simply disappeared.

Enhancing muscles through gun-pointing hydraulics was impressive. Enhancing perception through radar was even more impressive. Both advances weren't



enough, though. Hitting a German bomber from far away required more than seeing the plane ahead of time and being physically able to point a powerful gun at it. Hitting the enemy bomber required *knowing* where to aim the gun before firing. The shell didn't travel at light speed like the radar pulse from the roof of MIT did: a 155-millimeter shell could be in the air for up to twenty seconds before it reached the German Junkers bombers en route to London, and the targeted plane could fly up to 2½ miles between the moment the enemy antiaircraft gunners fired the shell and the moment the shell hit the plane. Like the hunter shooting ducks on the wing, the gunner had to predict and aim at a point in the future. A separate mechanical brain was needed to make this prediction.

Military units in charge of shooting big guns are called “batteries.” Fire control—accurately aiming the complex artillery guns—was hard. In the early days the different elements of an antiaircraft battery could be several hundred feet apart, depending on terrain and tactics. The battery's independent components were linked by telephone lines. To hit a target, an observer had to relay data to an officer by telephone. The officer would then input the data into a primitive computer and obtain the output variables. He would then telephone the gun installations and read the targeting data to them. The gunners used the data to set the shell's fuse and aim the gun, and then they fired. Lines of communication were half the task. So perhaps it isn't too surprising that a crucial role in the history of fire control fell to a telephone company: Bell Telephone Laboratories, a mighty research institute founded by AT&T and Western Electric based in Manhattan.

Accurately firing a gun at a moving target required two separate calculations: *ballistics* and *prediction*. The ballistic solution is more straightforward: how to fire a shell so that it explodes at a specific point in space and time. To accomplish that task, a gunner needed to provide three values to the gun: azimuth and elevation to determine the direction of fire, and timing for the shell's fuse setting to determine when it would explode. The traditional, nonautomated method for artillery crews was to look these values up in a firing table. These tables had long columns for elevation, azimuth, fuse settings, time of flight, and drift.

As gunnery evolved, the range correction factors became more elaborate: muzzle velocity, headwind, tailwind, air temperature, air pressure, and more. Studying booklets under fire became impractical. In response, mechanical gun directors automated the tables by converting them into strangely shaped metal cones dotted with pins, a bit like the revolving cylinders of an old-fashioned music box that would play a particular melody. These cylinders, so-called Sperry cams, looked like twisted and curved tree trunks. Yet they were manufactured with precision. The tables-turned-cones were the read-only memory—later called ROM—of what, in effect, was a primitive mechanical computer. The machine was

able to look up and combine precalculated values.

Prediction, the second computing task, was more challenging. Calculating how to fire a shell so that it would hit a specific point in space and time was one problem. A harder problem was calculating where that specific point in space and time would be in relation to a fast-flying aircraft. To simplify the situation, engineers made an assumption: the targeted enemy aircraft was flying straight and level, not up and down and curving to evade fire. The gun-directing machine assumed a constant trajectory on a horizontal plane. That assumption was unrealistic, but it wasn't so unrealistic that the prediction became useless.

To reproduce that straight line, Sperry's state-of-the-art gun directors at the start of World War II physically represented the behavior of the approaching bomber in both horizontal and vertical dimensions: "The actual movement of the target is mechanically reproduced on a small scale within the computer," a defense journal reported in 1931. "The desired angles or speeds can be measured directly from the movements of these elements."<sup>26</sup> By 1940, Sperry had been at the bleeding edge of control system engineering for nearly thirty years and was perhaps better equipped than any other company to meet the complex challenge of mechanically predicting a flight path. Sperry's mechanical computer, the M-7, had eleven thousand parts and weighed 850 pounds.

This was the situation before Bell Labs entered the fray. Bell Labs' pitch on gun control started with a dream. In May and June 1940, one of the lab's physicists, David Parkinson, worked on a small project, the automatic "level recorder." Parkinson tried to plot rapidly varying voltage on strip-chart paper. To that end, he simply linked an instrument that measured voltage—a potentiometer—to a pair of magnetic grasps that held a pen. The voltage thus led the pen, drawing curves on paper. When the voltage dropped, the potentiometer dropped the grasps with the pen, so that the curve on the paper dropped.

While Parkinson was working on the level recorder, the Battle of Dunkirk shook Europe. Between May 26 and June 4, 1940, Nazi Germany routed the French, British, and Belgian defenders and forced them to evacuate. The attacks by Stuka dive-bombers were widely reported in the US press and radio. Twenty-nine-year-old Parkinson, troubled by these events, had "the most vivid and peculiar dream" one night.<sup>27</sup> He later recorded his dream in a diary:

I found myself in a gun pit or revetment with an anti-aircraft gun crew. . . . There was a gun there . . . it was firing occasionally, and the impressive thing was that *every shot brought down an airplane!* After three or four shots one of the men in the crew smiled at me and beckoned me to come closer to the gun. When I drew near he pointed to the exposed end of the left trunnion. Mounted there was the control potentiometer of my level recorder!<sup>28</sup>

As he woke up the next morning, Parkinson didn't find it difficult to understand his odd dream: the pen was a gun! If a potentiometer could control motions of a pen fast and precisely, then it could also control the motions of a gun fast and precisely. The signal simply needed to be amplified.

When he arrived at work that day, Parkinson pitched the idea to his boss at Bell, Clarence Lovell. Lovell instantly saw the idea's potential: the Bell machine's core would be a computer. But not a clumsy, creaking mechanical lookup mechanism that didn't actually compute. Bell's electrical computer would really compute, not just look up and combine precalculated values. Lovell and Parkinson's "range computer," as they called their invention, eliminated the trunk-shaped mechanized cones at the heart of Sperry's M-7. Calculating the timing for the fuse required determining the distance from the point of observation to the target by radar. The dream machine represented that distance "in the form of an electrical difference of potential."<sup>29</sup>

Coming up with the idea for electrical calculation, and implementing it in practice, required a range of skills that went beyond what a manufacturing firm had to offer, even one like Sperry. A telecommunications company had what was needed: experience in communications engineering, such as filter design, smoothing and equalization techniques, manufacture of potentiometers, resistors, capacitors, and feedback amplifiers. And the nation's leading telecom lab in 1940 was Bell Labs.

The founder and onetime president of Bell Labs was Frank Jewett. The former instructor in electrical engineering at MIT held a holistic view of communication. In 1935 he had challenged conventional wisdom on electrical signals at a lecture to the National Academy of Sciences: "We are prone to think and, what is worse, to act in terms of telegraphy, telephony, radio broadcasting, telephotography, or television, as though they were things apart."<sup>30</sup>

For Jewett, the electrical signal was the common, universal element. Bush had put him in charge of Division C—communications and transportation—of the newly founded National Defense Research Council. Warren Weaver, a science administrator formerly of the Rockefeller Foundation, led a wide range of the NDRC's projects on automatic controls, including gun directors and radar devices, under the title D-2. Jewett at Bell was keenly aware of the urgency of the fire control project, and inclined to see it as a communication problem. Weaver agreed: "There are surprisingly close and valid analogies between the fire control prediction problem and certain basic problems in communications engineering," he wrote later. Bell Labs got Weaver's second contract. On November 6, 1940, with support from the army's Signal Corps, Weaver's new D-2 shop and Bell



Labs signed the contract for “Project 2.”<sup>31</sup>

Weaver appreciated that the Bell group had deep experience with electronics. On paper, the planned equipment looked too good to be true when compared with existing mechanical gun directors: electrical gun directors required less skill, time, and cost in production—while in operation they afforded higher accuracy, speed, and flexibility. For the first time, the computer (the M-9) would place mathematics inside the feedback loop. Bell’s computer enabled the gun director to calculate simple mathematical functions, such as sine and cosine, through resistors, potentiometers, servomotors, and wipers. The math, amplified, would drive a heavy 90-millimeter antiaircraft gun.

But state-of-the-art gun directors were limited, even when coupled with automated radar tracking. Once the time-fused shell left the gun’s muzzle, it would either hit or miss. Since shells as well as planes were flying faster and higher, setting the fuse precisely enough became ever more difficult, even if done automatically by the gun, not by the gunner by hand. Targeting was open loop: there was no feedback to the shell after it was fired. If only there was a way to tell the shell to explode a little later or earlier than timed, depending on the actual situation up there at an altitude of 10,000 feet.

Johns Hopkins University, also NDRC funded, would come up with an ingenious way to close that feedback loop: the proximity fuse, also known as the “variable-time fuse” or simply “VT fuse.” The shell would be smart, able to sense when it was close to the German bomber and only then explode. The difference was subtle but crucial. Timed fuses were set before being fired; the detonation of proximity fuses was determined by information gathered in flight. The fuse mechanism had to be sensitive yet rugged enough to withstand the shock of being fired by a mighty, 5.8-ton M-114 howitzer. A force twenty thousand times that of gravity would impact the shell in the gun. Worse, the projectile would spin at high speeds in flight. And it had to be safe and not blow up as it left the muzzle.

The new American fuse was a miniature radio station—with a sender, antenna, and receiver—all within the small nose of an artillery shell. When a 155-millimeter shell left the howitzer gun at almost double the speed of sound, its tiny radio station would switch itself on and start emitting a continuous wave. As the projectile approached the German bomber or cruise missile high in the sky, the radio waves would be reflected back by the target, like light in a mirror. The shell would sense the reflection, amplify it, and pass it on to a tiny gas-filled thyatron tube, which would serve as a switch to detonate the charge. The engineering challenge was dizzying. For a decade already, the best German minds had worked in vain on proximity fuses that could be used for air defense.<sup>32</sup>



Closing the final anti-aircraft feedback loop required several inventions. The first problem was building tiny glass vacuum tubes, of the type that had been used in hearing aids. The fragile glass needed to withstand the howitzer. Testing was tough: the Johns Hopkins academics first fortified the hearing-aid tubes with methods they had gleaned from bridge and skyscraper design. Then they dropped them in steel containers, slammed them against lead blocks, whirled them, and fired them with a homemade smooth-bore gun. They found that the glass tube needed to be cushioned in rubber cups and a wax compound. After painstaking testing, they succeeded: the miniature glass tube would survive being fired by the big guns.

The tiny radio station also needed a tiny power plant. This battery, of course, had to pass similar stress tests—but the shock of firing and the spinning in flight could also be opportunities. The Johns Hopkins engineers developed a liquid battery, with two electrolytes separated by a glass ampul. When the gun was fired, the glass broke, effectively switching on the battery. Safety required a short delay, however, so that the shell's radio fuse, upon leaving the muzzle, wouldn't mistake its own artillery battery for the target. The ingenious idea was to utilize the projectile's spin in a mercury switch: when the shell left the muzzle, it took a short moment of spinning around its own axis in order to force the mercury through a porous diaphragm out of the contact chamber, turning the switch on. By the time the mercury was tumbled out, the artillery shell was on its way to the intended target. Now the radio shell was whizzing through the air, armed, on its own, waiting to sense feedback from unsuspecting enemy aircraft.

The radio shell was a breakthrough. "As a secret weapon, it ran second in importance to the atomic bomb only," the *Baltimore Sun* breathlessly reported after the war.<sup>33</sup> The Nazis, unable to design the devices themselves, coveted the highly prized fuses. In June 1942, the FBI captured eight German spies who had been tasked with finding out more about the project. Merle Tuve headed the NDRC's special Division T, which funded the development of the revolutionary device. The shell's mass production was kept secret even from the ten thousand factory workers who built 130 million miniature vacuum tubes over the course of four years. Approved assembly line production started in September 1942. By the end of 1944, 118 plants managed by 87 companies were producing more than forty thousand fuses daily.

Only top managers at about half of these companies knew what they were actually producing. The workers who produced the vacuum tubes were told they would be manufacturing hearing aids. One factory dubbed the device "Madame X." Monthly production eventually reached a peak of two million. So secret was the fuse that its use was permitted only over open water, at least until late 1944.

The sky above the sea was safer for two reasons: it was harder for the enemy to observe antiaircraft firing closely, and it was impossible to pick up a dud from the ground in order to figure out how it worked. The ocean swallowed the secret.

Commanders who used the new technology were ecstatic. George Patton, commander of the Third United States Army, reportedly was so impressed by the device that he expected the very nature of war to change: “I think that when all the armies get this shell we would have to devise some new method of warfare.”<sup>34</sup>



The NDRC’s fire control division under Warren Weaver funded eighty projects over five years, from 1940 to 1945. The contracts practically mapped the world of control systems at the time, as the MIT historian David Mindell pointed out.<sup>35</sup> D-2 awarded fifty-one contracts to companies and laboratories in the private sector, and twenty-nine to academic research institutions. More than sixty projects tackled problems of land-based antiaircraft fire. The average funding volume was \$145,000. Weaver’s largest and possibly most successful contract, at \$1.5 million, was the Bell gun director that resulted in the M-9. D-2’s smallest and possibly most inconsequential contract, at just over two thousand dollars, went to Norbert Wiener, to explore how to predict flight patterns.<sup>36</sup>

As early as February 1940, five months after Nazi Germany had invaded Poland, Wiener joined a subcommittee under the direction of the Princeton mathematician Marston Morse. The scientists discussed how the American Mathematical Society could help during a national emergency that “we hope will never arise.”<sup>37</sup> In July, the Battle of Britain got under way. By late July, shortly after Hitler ordered the invasion of Britain, Wiener learned that the armed forces had received his suggestions on the use of incendiary bombs, and he reiterated his desire to participate in the war effort.<sup>38</sup>

Later, on September 11, Wiener attended a meeting of the American Mathematical Society at Dartmouth College that made computing history. Bell Laboratories had started operating the “Complex Computer” at their old headquarters at 463 West Street in New York a few months earlier. The machine had 450 relays and 10 crossbar switches, as well as remote terminals, each with a keyboard for input and a teletypewriter for output. One was in Dartmouth. Bell’s

George Stibitz was familiar with Wiener's work and invited the participants to challenge the computer with problems involving the addition, subtraction, multiplication, or division of complex numbers. Wiener stepped up to the keyboard, trying to stump the machine. But the New York-based computer outsmarted him. The teletypewriter magically hacked out the correct number. September 1940 was thus Wiener's first encounter with a thinking machine.<sup>39</sup>

Meanwhile, the Germans pounded London. The Battle of Britain was intensifying, with the Royal Air Force bombing launch points for what the British feared would be an imminent German invasion. On September 20, 1940, Wiener wrote to Vannevar Bush, "I . . . hope you can find some corner of activity in which I may be of use during the emergency."<sup>40</sup>

Section D-2 of the newly established NDRC was holding its first meeting also in September. Warren Weaver concluded that the most pressing issue was improving antiaircraft fire control for the army. Two months later, on November 22, Wiener submitted a four-page memorandum for the antiaircraft predictor to Bush's research committee, "to explore the purely mathematical possibility of prediction by an apparatus" and then "to construct the apparatus."<sup>41</sup> Shortly before Christmas 1940, the project was approved: the NDRC awarded \$2,325 to the MIT professor.

Wiener hired a twenty-seven-year-old MIT graduate in electrical engineering and mathematics, Julian Bigelow, as the project's chief engineer. Bigelow was ambitious and valued precision. Always immaculate in suit and tie, Bigelow also was an active amateur aviator, which gave him a skill set that would be useful for his new project. The two academics knew that they were tackling one of the most difficult problems of fire control. The Blitz was at its worst. Just days after Wiener's project got under way, on the evening of December 29, the Luftwaffe strafed the City of London harder than ever. In three hours, 120 tons of explosives and twenty-two thousand incendiaries were dropped. That night, Herbert Mason took the iconic photograph of St. Paul's dome towering over the smoke of London's raging fires.

Never had the antiaircraft problem been more urgent. When under fire, Wiener believed, pilots "will probably zigzag, stunt, or in some other way take evasive action."<sup>42</sup> To illustrate this back in a classroom at MIT, the professor drew a sharp zigzag line on a blackboard. Bigelow pointed out that the pilot's behavior was constrained by the aircraft itself.<sup>43</sup> The pilot did not have complete freedom to maneuver in a fast-moving, inert plane. Zigzag wasn't so easy. Wiener began to understand that human psychological stress and the plane's physical constraints made the man-machine system more predictable. This realization made it easier to



calculate a plane's future flight path from its past behavior. He erased the zigzag line and instead drew a line of smooth curves.

Wiener and Bigelow occupied a former math classroom in MIT Building 2, Room 244, and turned it into a "little laboratory," as they called it. There they experimented with an improvised apparatus. They faced one problem at the outset: they didn't have any data on actual pilot behavior, so they needed to simulate flight under fire. This was a challenge. To replicate the random curves that German pilots were flying over London and elsewhere in wartime Europe, Bigelow installed a motor-driven white spotlight that projected a smooth, circular, but nonuniform flight pattern onto the wall of their makeshift lab. It took about fifteen seconds to traverse the wall.<sup>44</sup>

This was the ideal flight path. To simulate the actual flight path of a stressed pilot, the two researchers installed a second, red spotlight. A mock pilot then had to follow the white curves by pointing this red light at it, chasing the spot on the wall. It was a difficult task, deliberately so. Hunting the light required controlling a "sluggish contrivance," as Wiener called it, which was designed to be complicated and to feel "completely wrong."

The resulting erratic behavior, Wiener believed, would simulate the constrained flight patterns of enemy pilots under stress. Now the two set out to mathematically model pilot-aircraft behavior. Meanwhile, other NDRC projects were making breathtaking progress. By the end of May, the Rad Lab had successfully tested its automated B-17 turret on one of MIT's roofs. Wiener wasn't aware of the Rad Lab research. Days later, on June 4, 1941, Weaver arranged for Wiener and Bigelow to visit a Bell facility in Whippany, New Jersey. On observing Bell's experimental design, Bigelow recalled his surprise at the simplistic assumptions of the engineers: "They had no random variables in them at all and took no account of evasive action or even the natural curvature of the plane's flight path."<sup>45</sup> But Bell had no interest in the abstract math that Wiener presented.

On February 1, 1942, Wiener submitted a lengthy report to Weaver's D-2 section at the NDRC. It had a mouthful of a title: "Interpolation, Extrapolation, and Smoothing of Stationary Time Series." Wiener made an academic contribution to a range of arcane theoretical debates in abstract mathematics. But this work was useless for the war effort; Pearl Harbor had happened only two months earlier, and US auto factories were just switching from commercial production to war production.

Wiener's 124-page paper lacked any sense of urgency. It didn't mention the unsuccessful experiments in the little MIT lab or any mechanical implementation



of his theory. The paper mentioned the antiaircraft problem only two times, buried in a forest of mathematical formulas on page 76. Neither the title nor the introduction or index contained a single reference to the problem that had motivated the project's funding. Instead, Wiener offered a mind-numbing alphabet soup of abstruse mathematics: Brownian motion, Cesàro partial sum, Fourier integral, Hermitian form, Lebesgue measure, Parseval's theorem, Poisson distribution, Schwarz inequality, Stieltjes integral, Weyl's lemma, and many more. When Weaver received the paper, he had it classified and bound in an orange cover. Engineers nicknamed the document "yellow peril," a joking reference to the paper's impenetrable theory and lack of practical relevance.

Five months later, on June 10, 1942, Wiener and Bigelow submitted a brief interim report on their attempts to build the promised apparatus. After playing with lights in darkened Room 244 for several months, they had developed some of the core ideas that would later shape Wiener's cybernetic worldview. They understood that man and machine were forming an entity, a system, a joint mechanism. That combined mechanism would, in effect, behave like a servo, they argued, a device built to autocorrect its performance in response to error:

We realized that the "randomness" or irregularity of an airplane's path is introduced by the pilot; that in attempting to force his dynamic craft to execute a useful manoeuvre, such as straight-line flight, or 180 degree turn, the pilot behaves like a servo-mechanism, attempting to overcome the intrinsic lag due to the dynamics of his plane as a physical system, in response to a stimulus which increases in intensity with the degree to which he has failed to accomplish his task.<sup>46</sup>

These observations, however, were based on only their simulation. "Little information on the nature of the paths of combatant aircraft was accessible either in terms of actual space trajectories, or observational data from the tracking apparatus," they pointed out.<sup>47</sup>

A little more than two weeks later, on July 1, 1942, Stibitz and Weaver visited Wiener's improvised little lab. The visit happened eighteen months into the two-year project. The Germans had just conquered Sebastopol on Crimea, and Rommel's Afrika Korps had invaded Egypt. The United States was about to launch its air offensive against Nazi Germany. The war was even inching closer to New England: just three days before Wiener's meeting, the eight German spies seeking information about the proximity fuse were captured from a boat off Long Island.

The professor boldly told his government sponsors that the equipment he had built at MIT was "one of the closest mechanical approaches ever made to physiological behavior."<sup>48</sup> His theoretical predictor was based on what his sponsors believed were "good behavioristic ideas." Wiener explained the more

general ambitions of his project: he would try to predict future actions of an “organism” by studying the past behavior of that organism, not by studying the structure of that organism.

Stibitz was deeply impressed by Wiener and Bigelow’s presentation of the predictor. “It simply must be agreed that, taking into account the character of the input data, their statistical predictor accomplishes miracles,” he observed. “The behavior of their instrument is positively uncanny,” Stibitz wrote in a report. But Weaver was more skeptical. He wasn’t yet convinced whether Wiener’s machine was “a useful miracle or a useless miracle.” Weaver jokingly told Wiener they would “bring along a hack saw on the next visit and cut through the legs of the table to see if they do not have some hidden wires somewhere.”<sup>49</sup>

Joking aside, the short prediction time, at most about one second, was a very serious limitation. Moreover, the NDRC funders questioned one of the very basic assumptions underpinning Wiener’s model: that enemy pilots under stress would behave in a consistent way. The pilot might not see bursting shells. Individuals might react differently to the same events. Bigelow himself became skeptical. He told Weaver that Wiener’s statistical method had “no practical application to fire control at this time.”<sup>50</sup>

Yet the proud professor could not bring himself to “make this statement,” Bigelow told Weaver. Admitting failure was hard for the former child prodigy. Wiener’s ambition and pride convinced him of the feasibility of statistical prediction. On August 20, 1942, Wiener was still convinced his work would be of the highest significance. The Institute of Mathematical Statistics planned a public workshop that fall. When Wiener heard about the conference program, he sent an urgent note to the organizers: even the titles of presentations could be “a tip-off” to the enemy, he warned, darkly. His work on statistical prediction was “vital and secret in more ways, and in vastly more important ways, than I have been able to tell you,” Wiener told one of the organizers.<sup>51</sup>

Ten days later, Weaver lost patience. On September 1, 1942, Weaver vented in a memo that he was “highly skeptical” of Wiener’s business. In the search for data that they could use for their white-versus-red light experiment on the wall in their improvised lab, Wiener and Bigelow had taken the initiative to visit several army installations, including the Ballistic Research Laboratory of the Army Ordnance Department at Aberdeen Proving Ground, Maryland; the Frankford Arsenal in Philadelphia; and the Antiaircraft Artillery Board at Camp Davis, North Carolina. They also went to Fort Monroe in Virginia. The trip didn’t go well. In Weaver’s words:

[Wiener and Bigelow] have gaily started out on a series of visits to military establishments, without

itinerary, without any authorizations, and without any knowledge as to whether the people they want to see (in case they know whom they want to see) are or are not available.<sup>52</sup>

The army's ordnance officers had other priorities. Germany was pushing into Stalingrad and looked invincible. The American war machine had shifted into high gear. The NDRC also was busy: revolutionary VT proximity fuses started coming off the assembly lines by the tens of thousands. Yet Wiener and Bigelow made little progress and instead appeared to waste others' precious time: "Inside of twenty four hours my office begins to receive telegrams wanting to know where these two infants are," Weaver fumed. "This item should be filed under 'innocents abroad.'"<sup>53</sup> Wiener's \$2,325 contract was terminated after less than two years, in late 1942.

The MIT professor was disappointed. "I still wish that I had been able to produce something to kill a few of the enemy instead merely of showing how not to try to kill them," he cryptically wrote to Weaver on January 28, 1943.<sup>54</sup> As an engineer, Wiener had failed. His antiaircraft predictor never worked as intended, and it was never even close to improving antiaircraft fire. Five years later, Wiener cryptically mentioned the unpleasant episode in the introduction to his landmark book, *Cybernetics*: "It was found that the conditions of anti-aircraft fire did not justify the design of [a] special apparatus for curvilinear prediction."<sup>55</sup> Reality had failed, he believed, not his idea.

Nevertheless, *Cybernetics* centered on the antiaircraft problem, on man-machine interaction, control, and feedback. The hapless professor later implied again and again that he had invented these concepts during the war, single-handedly improving antiaircraft fire. Wiener's work itself represents a fascinating case study of human-machine interaction under stress: the mechanical antiaircraft problem gave Wiener the urgency, the passion, the inspiration, the language, and—most important—a powerful metaphor to articulate cybernetics.

## IV

Meanwhile, Sperry was already selling feedback loops with spectacular success. By 1942, the company had carved out a highly profitable approach to selling control systems. Sperry had created "a whole new field of scientific accessories to extend the functions and the skill of the operator far beyond his own strength,



endurance and abilities,” the company’s history recounts.<sup>56</sup> With the war effort accelerating, demand for its products was exploding. Sperry and its subsidiaries had worked for two decades on product development, and now they were unable to handle the requested staggering quantities: in 1942, Sperry was contracted to produce over a billion dollars worth of control systems.

If anything, this number was understating the significance of Sperry’s contribution to the war, its executives pointed out: “This billion dollars’ worth of technical equipment will fill the vital gap between the one hundred billion dollars’ worth of weapons and the thousands of men who must operate them.” World War II was industrial war at its height, fought with mechanical beasts of steel and iron, clashing on land, at sea, and in the air. Man, unaided, was unfit for war in the machine age. The Sperry Corporation wrote:

His airplanes have become so big and fly so far that he must have automatic pilots instead of flying by hand. The machine gun turrets must be moved by hydraulic controls. The targets of his antiaircraft guns now move so fast in three dimensions that he can no longer calculate his problems and aim his gun. It must all be done automatically else he would never make a hit.<sup>57</sup>

At the beginning of World War I, airplanes flew at altitudes under 2,000 feet, and at a speed of about 70 miles per hour. Antiaircraft weapons were simple: “Those guns that could be trained at high angles were fired the same manner that a hunter would fire at a duck in flight,” wrote Preston Bassett, then president of the Sperry Gyroscope Company, again using the preferred hunting comparison.<sup>58</sup> But the engineers at Sperry understood that shooting down ever-faster objects required ever more automation:

The time factor has now become so small for all operators involved that the human link, which appears to be the only unchangeable factor in the whole problem and which is a very erratic one, has become more and more the weakest link in the chain of operations until it is quite apparent that the human link must be dropped out of the sequence.<sup>59</sup>

During World War I, an air defense battery had about twenty operators who cooperated in the full sequence from searching for the target to firing at it. By 1935, that number was down to eighteen at night and twelve by day. By the beginning of World War II, the number of humans was down to ten. When the war ended, only three to four operators were left. “All that can be said now is that those few remaining must also go,” Bassett observed after the war. “Time has now run out for the slow reaction of a human operator.”<sup>60</sup> Shooting down autonomous machines required autonomous machines.

After Pearl Harbor, “American industry really took its coat off and went to work.” The number of Sperry employees reached its peak of thirty-two thousand



in 1943. Twenty-two subcontractors were building Sperry products during the war; the Ford Motor Company, for instance, produced antiaircraft directors, and Chrysler manufactured gyrocompasses to navigate ships. The total number of employees producing Sperry equipment would swell to well over a hundred thousand during the war.<sup>61</sup> Between 1942 and 1945, the value of shipped Sperry products amounted to over \$1.3 billion.<sup>62</sup> This was at a time when a flight from New York to Chicago with Capital Airlines cost \$18.<sup>63</sup>

Without Sperry's feedback gear, neither machines nor men could operate under fire. Sperry provided the unity, the connective tissue, the man-machine interface. "Without this equipment, neither men nor weapons would be effective," the company knew.<sup>64</sup>

In the early hours of June 13, 1944, General Sir Frederick Pile was awakened "by an unusual uncertainty" on the part of London's air-raid siren.<sup>65</sup> The "Alert" sound went off, that creepy up-and-down howling siren, followed almost immediately by the constant howl of the "All Clear" sound—only to revert back to "Alert" seconds later.<sup>66</sup> It was completely dark in the general's bedroom. Pile was the commander of Britain's Anti-Aircraft Command. A few moments later his telephone rang. The duty intelligence officer reported that "the Diver" had finally arrived. "Diver" was the British code name for the V-1, a terrifying new German weapon: an entire unmanned aircraft that would dive into its target, not simply drop a bomb.

The so-called buzz bomb was the world's first cruise missile, a self-propelled single-use vehicle flying on a nonballistic trajectory at relatively low altitudes. The second Battle of London was about to begin. Seven flying bombs were spotted in this night's opening salvo. One of them was headed straight to East London. It crashed into an elevated railway viaduct at Bethnal Green, blocking all the train lines headed out of Liverpool Street, one of the capital's largest train stations. The public was kept in the dark about the nature of the attack—and about the nature of the defense. The breathtaking engineering achievement that would now creak into action was among the Allies' best-kept secrets. This secret would take many years to come out in clarity. When the first cyberneticists articulated their theories about feedback loops and adaptive machines in the coming years, they had no idea that a spectacular version of this future had already arrived high over the English Channel.

When the German V-1s were finally lobbed from their rail launchers on the Continent toward London, a shrewd, high-tech system lay in wait on the other side of the English Channel, ready to intercept the robot intruders. As the low-flying buzz bombs cruised over the rough waves of the Atlantic toward the coast,

invisible and much faster pulses of microwaves gently touched each drone's skin, 1,707 times per second. These microwaves set in motion a complex feedback loop that would rip many of the approaching unmanned flying vehicles out of the sky.

A tiny amount of the energy waves was reflected by the V-1's skin back to its emitting source, a parabolic antenna on top of an MIT-designed mobile radar station. The antenna would catch the reflection, turn it into a signal, and pass the signal on via cables and vacuum tubes and a series of filters. The signal would then be amplified and fed back to the motors that controlled the antenna. But in reverse: when the signal weakened, the antenna would turn toward the stronger signal, in effect tracing the V-1. The system locked on to what would now become a target. More tiny microwaves bouncing off a drone's skin would enable the watchful system to measure, precisely, the range, bearing, and elevation of the novel German weapon system.<sup>67</sup>

By mid-1943, Allied intelligence services knew from intercepts, photographs, and informants that Germany would soon launch robot bombs against southern England.<sup>68</sup> Pile, an artillery gunner by training, understood that a state-of-the-art gun predictor would make all the difference. "We badly wanted the SCR 584," he recounted.<sup>69</sup> The Air Defense Command also used "radio shells" against the buzz bombs. The new "variable time" proximity fuse autonomously tripped a trigger that detonated the TNT in the shell's body. The fuse had the size of a pint milk bottle. Once it came within 70 feet of the targeted buzz bomb—it blew up, knocking everything within the blast zone out of the sky.

One week after D-day, the Germans started sending robots across the English Channel. The first wave of V-1s was ineffective. Few made it across the sea. The German launch crews, trained as artillerymen, didn't know how to handle this odd and novel "weapon of vengeance," *Vergeltungswaffe*, or simply "V-weapon." They learned fast. Soon the V-1s were being hurled against the capital of the British Empire from about fifty launch sites. More than seven thousand pilotless bombs were fired against London in total. The V-1 was immediately dubbed the "robot bomb" by the press. "Even though Allied troops have cleared the Calais coast of Nazis and their bomb launching platforms, the robot bomb threat is not ended by any means," the *Christian Science Monitor* reported, proudly announcing that Ford would now be building "robombs" for the United States.<sup>70</sup>

By the summer of 1944, about five hundred guns, many of them equipped with the new radio fuses, were in place to counter the incoming buzz bombs. "The result of the advent of VT fuses was truly sensational increases in 'kills,'" an official army report said, in a statement that was widely reported in newspapers

across the United States after the war ended.<sup>71</sup> In the fourth week of July 1944, 79 percent of V-1s flying across the channel were downed. By August, on the last day V-1s were launched in quantity against Britain, the air defenses worked particularly well, Pile recalled: “On a Sunday in August the Germans sent 105 buzz bombs across the Channel but only three arrived.”<sup>72</sup> The new antiaircraft artillery brought down sixty-eight V-1s; the rest were downed by fighters or malfunctioned.

The confrontation in the sky over the English Channel during the late summer of 1944 was remarkable: never before had one autonomous weapon clashed with another autonomous weapon with so little human interference.<sup>73</sup> The future of war had arrived. “Now we saw the beginning of the first battle of the robots,” Pile observed at the time: “Human error was being gradually eliminated from the contest: in the future, the machines would fight it out.”<sup>74</sup> It was automaton against automaton, VT robot against V-1 robot.

The V-1 was both hard and easy to hit at the same time. At first glance, the German cruise missile’s strengths were its size, speed, and altitude. It was small, fast, and low: it was shorter and slimmer than a fighter plane; at 400 miles per hour it was significantly faster than a Spitfire; and it cruised at 2,000–3,000 feet. Worse, the weapon didn’t have a “one-shot stop,” a single point of failure that would bring it down when hit: it didn’t have a pilot, and its engine was highly resilient to damage. But the new weapon had one crucial weakness. The V-1, ironically, lacked precisely the problem that Wiener had tried to solve: an erratic flight path. The *Vergeltungswaffe* flew straight and level. Its flight path was predictable. Any pilot under stress would do the opposite: try to evade enemy fire.