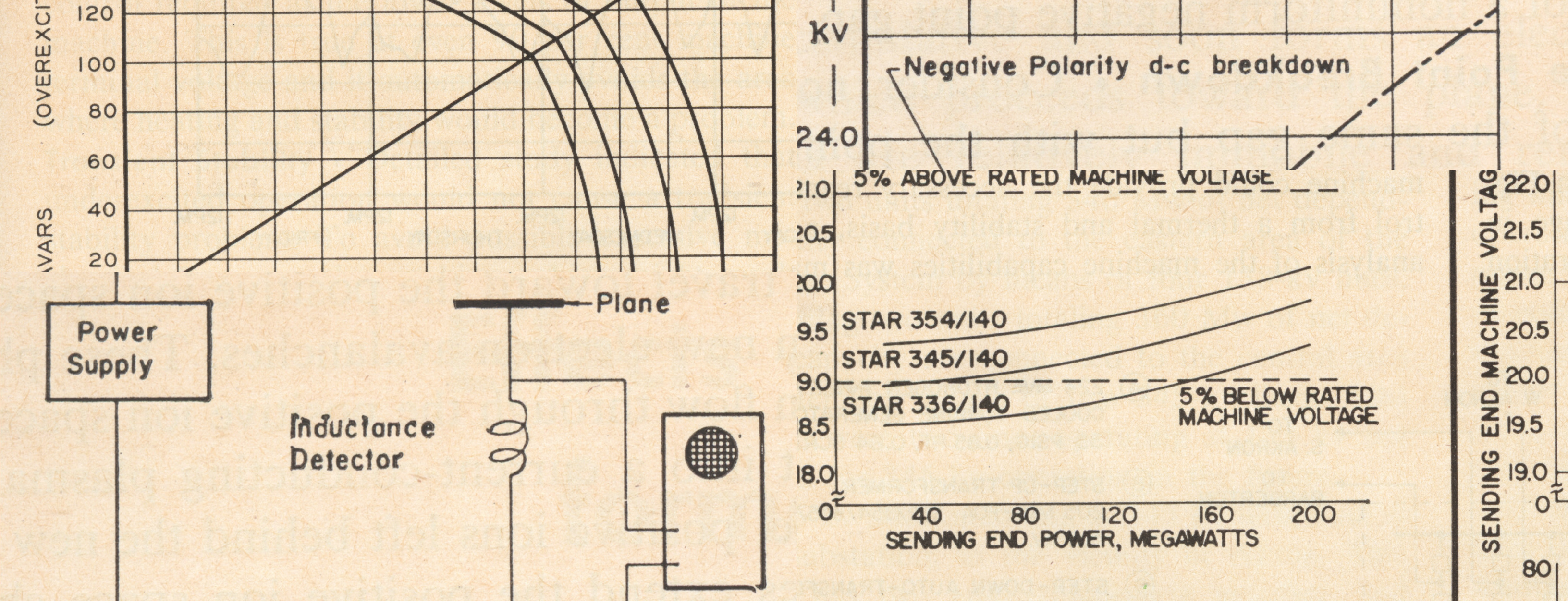

INSPIRING TECHNOLOGY

34

BREAKTHROUGHS

CELEBRATING 140 YEARS OF
ADVANCING TECHNOLOGY FOR
THE BENEFIT OF HUMANITY

IEEE

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IEEE

Inspiring Technology: 34 Breakthroughs
Celebrating 140 years of advancing technology for the benefit of humanity

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EDITOR’S NOTE

In choosing the 34 breakthroughs described in this book, we leaned heavily on the IEEE’s own list of official milestones. Twenty-three of the milestones selected are on that IEEE list. The IEEE list, however, is a living document. Someday most, if not all, of the unofficial milestones might be on it.

There are more people to thank for their work on this book than I have space to identify. But here goes. First, the idea to publish a handsome volume to mark the 140th anniversary of the IEEE came from 2023 IEEE President and CEO Saifur Rahman. Without his advocacy, you would not be holding a book right now. Next, there's Michael Winkleman and his team at Leverage Media, including reporter-writers John Morell, Peter Haapaniemi, Michael Abrams, Polina Schultz, Gary Stern, and Amy Freed Stalzer; as well as James Van Fleteren for the design and layouts.

I had help in editing this book from Brian Santo and Michael Winkleman. In addition, I thank my colleagues at *IEEE Spectrum*, especially the *IEEE Spectrum* art department under the direction of Mark Montgomery, for their expert contributions. Special thanks to Randi Klett, *IEEE Spectrum*’s photography director, who worked tirelessly to find most of the outstanding images you’ll see in these pages, and to production specialist Sylvana Meneses for her excellent work.

I was fortunate to have the advice of historians and others who generously donated their time reading drafts. Staff members at the IEEE History Center, directed by Michael Geselowitz, offered helpful suggestions and corrections. Among them, special thanks are due to Alex Magoun and Daniel Mitchell. Other historians and experts weighed in on some chapters; here I must thank Benjamin Gross of the Linda Hall Library, W. Bernard Carlson at the University of Galway, Stefano Selleri of the University of Florence, James V. Stone at Sheffield University, and James Rautio, founder of Sonnet Software.

GLENN ZORPETTE
Fellow, IEEE

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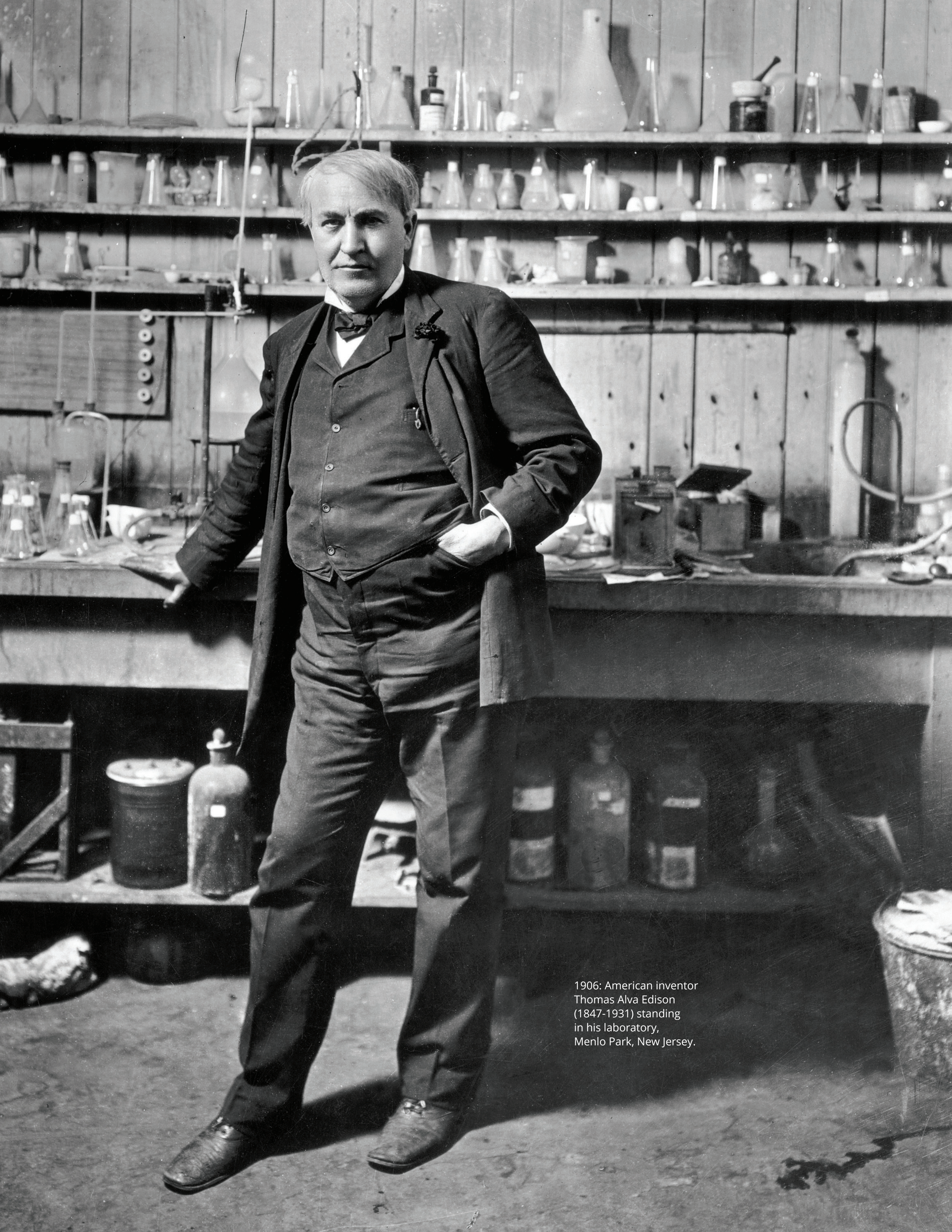

1906: American inventor Thomas Alva Edison (1847-1931) standing in his laboratory, Menlo Park, New Jersey.

INTRODUCTION

The Global Organization that Inspires Innovation

The field of electrical engineering has fundamentally changed the way humans communicate, the way we work, the way we move, learn, heal, create—in short, the way we live. This transformation came in bursts of inspiration, yes, but more often than not, in the slow steady march of tireless experimentation, careful work, and collegial collaboration.

But regardless of their genesis, these advancements didn't happen in a vacuum. Both creative inspiration and diligent endeavor require context, memory, and support. Throughout the past 140 years, the IEEE has been there to provide those ingredients—that fertile ground from which these achievements could flourish. Our various technical communities have brought the best minds in engineering together; created the spaces where they can share their work; and cultivated innovators, entrepreneurs, teachers, and leaders to advance technology for the benefit of humanity.

Ancient peoples had long observed natural electrostatic and magnetic effects. As modern science emerged in the Enlightenment of the 17th and 18th centuries, scientists began to study and try to understand these phenomena, producing and capturing static electricity in the laboratory. A major breakthrough occurred in 1752, when Benjamin Franklin, with his famous kite experiment, demonstrated that lightning was actually electricity. This led to the first "electrical engineering" invention, Franklin's lightning rod.

The next great breakthrough occurred in 1799, when Alessandro Volta invented a way to convert chemical energy in an electric current—the battery. This development enabled further scientific research that led to an understanding that electricity and magnetism were related phenomena, which then led to the invention of electric generators and motors and, ultimately, the telegraph, the first telecommunication technology, with Samuel F. B. Morse introducing the first commercially practical telegraph in 1838.

In the mid-19th century, electricity traveled through conductive wires. From 1860 to 1871, James Clerk Maxwell worked on a theory to unify everything that was known about electricity and magnetism, and in 1873 published his famous treatise doing just that. To everyone's surprise, he suggested that invisible electromagnetic waves were traveling through the air. This was eventually proven by Heinrich Hertz in 1886.

But even while Maxwell was struggling with the theoretical underpinning of electrical science, working electrical engineers were not standing still. The techniques for generating electricity continued to improve, and more applications were found, notably to use electricity to produce light. By 1882, Thomas Edison and others had begun to open central power stations selling electricity to businesses and later the public. In parallel, on the communications side, telegraph engineers worked out how to connect the whole world by undersea cables.

And Alexander Graham Bell developed a way to send voice, rather than Morse code, over wire, patenting his telephone in 1876.

Against this background of increasing technological importance, electrical engineers in Europe began to organize themselves into associations, the first, in 1871, being the Institute of Electrical Engineers in the UK. A popular activity in the late 19th century, beginning with the Great Exhibition in London in 1851, was holding technology-based world's fairs. In 1881, the French government decided it was time for an international exhibition focusing just on electrical technology. The British followed in 1882.

The electrical engineers of the United States realized that their colleagues from around the world who belonged to professional associations would be attending these events and decided to create their own association to welcome them officially. In October 1884, at the Franklin Institute in Philadelphia, Thomas Edison, Alexander Graham Bell, and other telegraph, telephone, and power industry leaders welcomed their American colleagues and foreign visitors to the International Electrical Exhibition, the first technical meeting of what they called the American Institute of Electrical Engineers (AIEE), the organization that would become today's IEEE.

In the 140 years since, IEEE members and their colleagues, supported by IEEE conferences, publications, standards, recognitions, and professional communities, have produced innumerable discoveries and inventions that have led to the world we live in. From humble beginnings, the IEEE has grown into a global institution, the world's largest technical professional organization dedicated to advancing technology for the benefit of humanity, with 440,000 members in more than 190 countries.

The following pages offer just a selection of the milestones to which the past century and a half have been witness. I hope you find these stories both a fitting celebration of our community's successes and an inspiration for the IEEE's next 140 years.

S Rahman

SAIFUR RAHMAN,
IEEE Life Fellow
2023 IEEE President & CEO

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PHYSICS | 1860-1873

Let There Be Light

Many important breakthroughs happened in the 19th century. None, arguably, was more important than Maxwell's Equations.

By the early 19th century, scientists had developed a useful empirical understanding of electricity and magnetism. In the 1820s and 1830s, work by Hans Christian Oersted, André-Marie Ampère, Carl Friedrich Gauss, and Michael Faraday established experimentally that electricity, magnetism, and optics were all linked. But the precise details of these linkages, and an overarching theory describing them, remained elusive. That changed with the work of James Clerk Maxwell.

Between 1860 and 1873, Maxwell developed a unified theory of electricity, magnetism, and light, which is now summarized in four partial differential equations. The four describe the relationship among moving electric charges, magnetic fields, and electric fields, indicating mathematically how they give rise to each other and to electromagnetic waves. His work became the cornerstone of classical electromagnetism and the foundation for almost all of the categories of the emerging discipline that would come to be known as electrical engineering.

Although hardly anyone grasped it at the time—not even Maxwell—his discoveries ushered in an era in which the universe could only be understood in terms of intangible fields, rather than mechanical objects. "Since Maxwell's time, physical reality has been thought of as represented by continuous fields, and not capable of any mechanical interpretation," Albert Einstein wrote in a 1931 essay. "This change in the conception of reality is the most profound and the most fruitful that physics has experienced since the time of Newton."

EXPLAINING ELECTROMAGNETISM

Born in 1831 in Edinburgh, Scotland, Maxwell began his scientific work at the age of 14, publishing a paper on the mathematics of oval curves. Many other papers followed throughout his life, exploring topics includ-

James Clerk Maxwell, pictured here around age 22 at Trinity College, Cambridge University, held a color wheel that he used in experiments to show that a mixture of red, green, and blue light would result in white light.

BETTMANN/GETTY IMAGES

ing polarized light, the design of optical instruments, how the eye perceives color, the motion of molecules in a gas, the compressibility of water, the stability of Saturn's rings, and statistical mechanics.

While in his mid-teens, Maxwell began studying at the University of Edinburgh, going on to the University of Cambridge in 1854. Named a fellow shortly after graduating, he turned his attention to electromagnetism by trying to frame mathematically Faraday's qualitative, spatial ideas about lines of force. This work led to a paper called "On Faraday's Lines of Force," in which Maxwell drew an analogy between the flow of a hypothetical incompressible fluid and electrical and magnetic force distributions.

In 1856, at age 25, he became a professor at Marischal College in Aberdeen, and in 1860 he began teaching at Kings College, London. That move marked the beginning of a period in which he did the most important work on his theory of electromagnetism, publishing two more key papers on the topic.

The first was his four-part "On Physical Lines of Force" (1861), which extended Ampère's circuital law and laid out the equations of electromagnetism. Oersted had noticed, in 1820, that an electric current flowing through a wire would deflect the magnetic needle of a nearby compass. Ampère then constructed a force law that he used to explain the forces that would deflect, for example, parallel wires that were conducting currents flowing in opposite directions.

These observations led, in 1826, to Ampère's circuital law. Imagine current flowing in one or more wires going through a randomly drawn closed loop. The circuital law related the total current going through the wires to the magnetic field at each point along that same loop.

But there was a problem. Let's say you have a circuit that includes a capacitor and that the current flowing in the circuit is time varying (for example, an alternating current). In this case, Ampère's circuital law does not hold; a current will be measured in the wires connecting the capacitor, but not in the gap between the capacitor plates. So suppose, in attempting to apply the circuital law to this circuit, you put your imaginary closed loop in the middle of, and parallel to, the plates of the capacitor. You will have zero current flowing through your closed loop, but you will nevertheless have a magnetic field ringing that loop and associated with that current.

The reason is that there is a time-varying electric field in the gap between the capacitor plates, linked to the charge accumulation on the plates. This electric field in the gap behaves much as an actual current would—notably, causing the same circuital magnetic field around the gap that a conductive current would. Maxwell accounted for this phenomenon by inventing a concept called displacement current, and using it to modify the formulation of the circuital law. This insight produced one of the four Maxwell's Equations, sometimes referred to as Ampère's law with Maxwell's addition.

Maxwell's second breakthrough paper was "A Dynamical Theory of the Electromagnetic Field" (1865). Here, Maxwell set aside the mechanical model and approached the problem of the interactions between electricity and magnetism by considering the energy exchanges

Michael Pupin and the Gospel of Maxwell

In 1883, Michael Pupin, a newly minted physics graduate of Columbia University, arrived at the University of Cambridge to study under the great James Clerk Maxwell. Alas, Maxwell had died four years earlier.

Pupin stayed on at Cambridge nevertheless, but was soon disenchanted to learn "how few were the physicists who had caught the meaning of the theory, even 20 years after it was stated by Maxwell in 1865." Transferring to the University of Berlin in 1885, he earned a Ph.D. under the great Hermann von Helmholtz, who did understand Maxwell's achievements and taught Pupin all he knew about them.

Pupin returned to Columbia, where he became the second faculty member in the department of electrical engineering. In addition to spreading the gospel of Maxwell to his students, the young engineer began accumulating a portfolio of patents. For the emerging technology of telephony, he invented coils that made possible inductively loaded transmission lines, which made him rich. Later on, Pupin became a mentor to radio pioneers Edwin Armstrong and Alfred Goldsmith.

He was also active in both the Institute of Radio Engineers (IRE) and the American Institute of Electrical Engineers (AIEE), serving as president of the IRE in 1917 and of the AIEE in 1925. Among the accolades he won later in life were the IRE Medal of Honor, in 1924, the AIEE's Edison Medal, in 1920, and the Pulitzer Prize, in 1924, for his best-selling autobiography, *From Immigrant to Inventor.*

between the two, using a technique called Lagrangian dynamics. He reached an astonishing conclusion: the existence of electromagnetic waves. He did this by deriving a wave equation describing the propagation of these waves.

For example, according to his interpretation of Ampère's circuital law, a time-varying electric field gives rise to a time-varying magnetic field. And according to his formulation of Faraday's law (more precisely known as the Faraday-Lenz law), a time-varying magnetic field gives rise to a time-varying electric field. Maxwell's mathematical exploration of this linkage indicated that it was therefore possible to create time-varying, coupled, electric and magnetic fields that would travel through space. The electric field would produce a magnetic field, the magnetic field would produce an electric field, and so on, endlessly. In this electromagnetic wave, the electric field and the magnetic field would be perpendicular to each other and also to the wave's direction of propagation. Maxwell did not specify how this wave could be created, although the equations indicated that it could be created simply by time-changing current.

Maxwell also calculated the speed of propagation of this electromagnetic wave, which turned out to be very close to the speed of light, which had been established as early as 1676 by the Danish astronomer Ole Roemer. To Maxwell, the implication was clear. "The agreement of the results seems to show that light and magnetism are affections of the same substance and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws," he wrote. In other words, light is an electromagnetic wave.

This insight was arguably Maxwell's greatest achievement. By considering all that was known about electricity and magnetism at the time and demonstrating that the equations governing electrical and magnetic interaction permitted the propagation of electromagnetic waves at the speed of light, he arrived at a conclusion, and a series of equations, that would underpin the entire early enterprise of electrical engineering: electric generators, induction motors, synchronous motors, and radio. And although scientists did not realize it at the time, his work revealed that there is a vast spectrum of invisible, electromagnetic waves in the universe.

Decades later, other theoreticians used Maxwell's Equations to show that the speed of light was invariant, which was inconsistent with Isaac Newton's physics. One result of that, said Einstein, was that "the special theory of relativity owes its origins to Maxwell's Equations of the electromagnetic field."

Einstein, who kept a photograph of Maxwell on the wall of his study, had a stock answer when he was asked if he stood on the shoulders of Newton. "No," he would respond. "On the shoulders of Maxwell."

"PRODIGIOUS POSSIBILITIES"

Maxwell's work on electromagnetism did not immediately gain widespread notice, and among those who did notice it there was considerable skepticism. Nevertheless, in the years following the publication of Maxwell's 1873 Treatise on Electricity and Magnetism, a small group of physicists took it upon themselves to continue Maxwell's work by clarifying it and providing experimental proof of his ideas. For example, Maxwell"s theoretical work produced 20 equations. Oliver Heaviside, a British telegrapher and self-taught physicist and mathematician, read Maxwell's writings and said, "I saw that it was great, greater, and greatest, with prodigious possibilities in its power." Working independently, he applied the conventions of the brand new discipline of vector calculus to simplify those 20 equations into four—the Maxwell's Equations that are still taught today.

In 1888, German physicist Heinrich Rudolph Hertz produced radio waves, and the fact that a new type of electromagnetic radiation could be produced directly via oscillating charge did a great deal to bolster the credibility of Maxwell's field theory of electromagnetism. By the mid-1890s, Maxwell's Equations were widely accepted and beginning to open the door to the countless remarkable conveniences we now mostly take for granted. Maxwell, himself, however, missed all that, having died of abdominal cancer in 1879 at the age of 48.

And yet, he lives on. In his collected Lectures on Physics, Richard Feynman wrote, "From a long view of the history of mankind, seen from, say, ten thousand years from now, there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics." ■

COMMUNICATIONS | 1866

Laying It Down

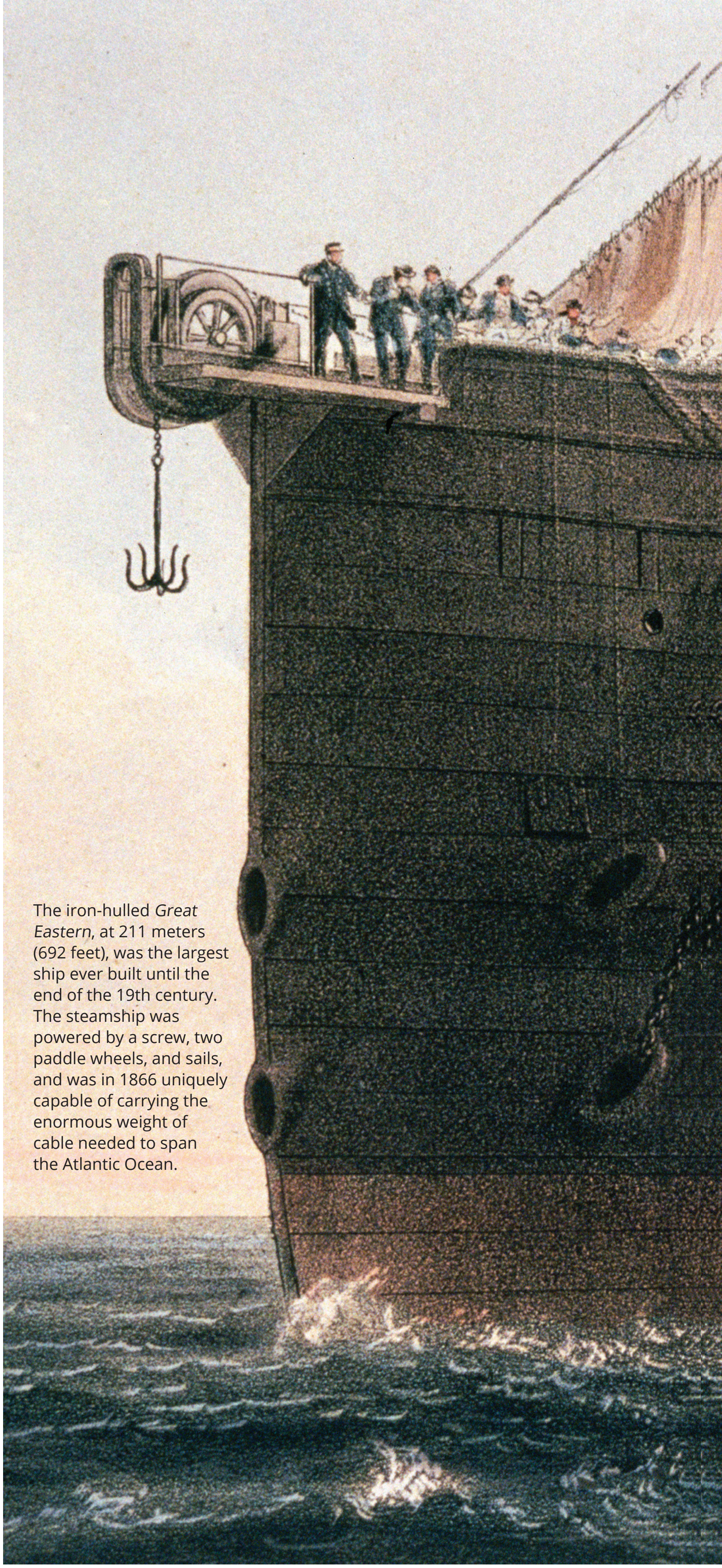
The snaps and kinks of stringing the first transatlantic cable.

It was 1853, and American industrialist Cyrus Field was feeling restless. Never mind that he had just returned from a four-month adventure across Ecuador, Colombia, and Panama, bringing home parrots, a jaguar, and the 14-year-old son of one of his guides. Ennui had set in.

Field had amassed a fortune from making paper, and at age 34 was already considered the 33rd richest man in New York. He had a Gramercy Park mansion, in which could be found his wife, a butler, his first five children, the guide's son, and his newly acquired souvenirs. He had lost interest in the paper business, and he was ready for a new adventure.

Then his brother introduced him to engineer Frederick Gisborne, who was part of a venture to connect Newfoundland with the North American mainland by laying a cable across the Cabot Strait to Nova Scotia. The idea of connecting Newfoundland, the easternmost point of North America, to the rest of the continent was intriguing because it would reduce the distance a transatlantic ship would have to physically carry a message from Europe before handing it off to a telegraph office, in Newfoundland, that could transmit it almost instantaneously the rest of the way to its recipient.

Field considered the idea, and then he had another. Why stop at Newfoundland? It oc-



The iron-hulled *Great Eastern*, at 211 meters (692 feet), was the largest ship ever built until the end of the 19th century. The steamship was powered by a screw, two paddle wheels, and sails, and was in 1866 uniquely capable of carrying the enormous weight of cable needed to span the Atlantic Ocean.

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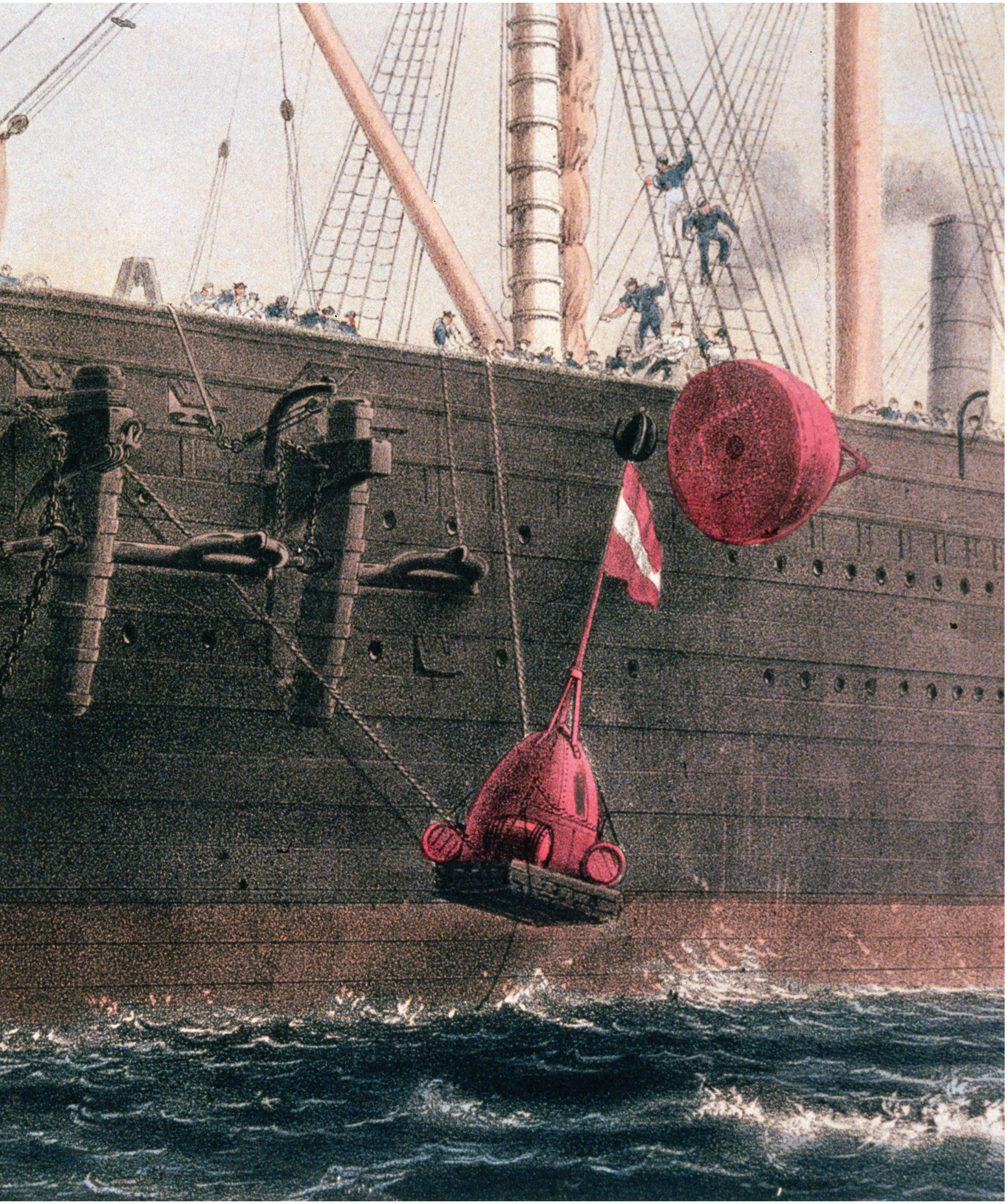
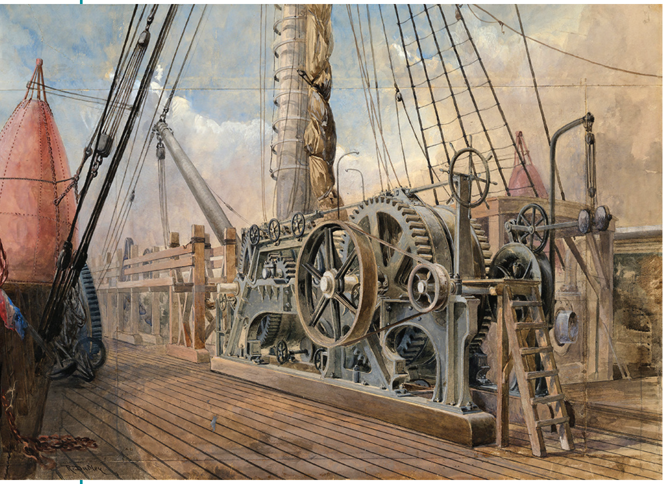




On the deck of the massive *Great Eastern*, complicated machinery designed by Henry Clifford paid out the rope as it jerked taut, as it went over the stern of the ship. Businessman and financier Cyrus Field [right] was photographed in 1863.

LEFT: HERITAGE IMAGES/GETTY IMAGES; RIGHT: CHARLES DEFOREST FREDERICKS/ HULTON ARCHIVE/ GETTY IMAGES

curred to him that a submarine cable crossing the Atlantic might do more than shorten the two-week lag between continents—it would eliminate it entirely.

NOT QUITE SMOOTH SAILING

Field knew nothing about either oceanography or telegraphy. But he knew how to talk and, especially, whom to talk to. The next step was to gather funds, which Field accomplished with aplomb, in part by enlisting his rich neighbors. They included Peter Cooper, the industrialist and inventor who had made a fortune in locomotives, iron structural beams, and gelatin desserts, among other things. Field and his investors founded the New York, Newfoundland, and London Telegraph Company. "God knows none of us were aware of what we had undertaken," Field wrote years later.

Trouble dogged them from the beginning. Their first effort was to sink a line under the Cabot Strait, which separates Newfoundland from Cape Breton Island. They hired a steamer, the *James Adger*, to tow the *Sarah L. Bryant,* the vessel that would pay out the cable, but the foray was beset by bad weather and bad luck.

A subsequent attempt—no towing this time—worked, but at this point the venture had run out of funds. That was no issue for the sweet-talking Field, and he soon had new backers from both sides of the Atlantic Ocean. He partnered with British electrical engineer Charles Tilston Bright and John Watkins Brett, who had put a cable under the English Channel just five years earlier. Together they formed the Atlantic Telegraph Company.

JUST TWO WORDS: GUTTA-PERCHA

Telegraph cable, until that time, had been thin and poorly insulated and not fit for carrying signals across 2,000 miles at the bottom of the sea. Thankfully, there was a new material on the scene, gutta-percha, a polymer made from the sap of a Malaysian tree. Without it, the project would undoubtedly have failed.

The science of transmitting signals, particularly underwater, was not well understood, and there was still profound disagreement about the best construction for cabling. The ATC decided to use seven strands of copper wire twisted into a diameter of 0.083 of an inch. Surrounding this core were three layers of gutta-percha wrapped in tarred hemp, which was, in turn, embraced with iron wire. The result was a cable that weighed one short ton per mile.

Unfortunately, the weight was too much for even the largest ship in the world, the USS *Niagara*. So the partners enlisted two ships, the *Niagara* and HMS *Agamemnon*. With the cable split between two vessels, they had to decide between two methods of getting it across the Atlantic.

Electrical experimenter Edward Orange Wildman Whitehouse wanted to set out from Ireland with one ship spooling out half the cable and then splicing the second length mid-sea before continuing across the ocean. That way, Whitehouse reasoned, electrical communication could be maintained with the shore, enabling continual testing of the signal. Bright was more concerned with accomplishing the mechanical splice in the stormy mid-Atlantic, so he favored having the two ships embark from either shore and then rendezvous mid-sea where they would splice the cable at a time when the sea there was placid, and then sink it while going in opposite directions. Whitehouse's proposal won out.

After loading the cable—which took three weeks—they set out from Ireland's Valentia Bay on August 5, 1857. Five miles later, the cable snapped. They retrieved it, respliced it, and set out again. Whitehouse stayed ashore, while Field communicated with him using the freshly laid cable. But, as *Niagara* came up out of one particularly large wave, the cable popped again.

This time the loose end was too deep, and the adventure was put on hold for a year. The machines for letting out the line were redesigned with better brakes. William Thomson (not yet Lord Kelvin) refined his mirrored galvanometer, which could detect the faint signals emerging from a length of the submarine cable. And this time they would employ Bright's start-in-the-middle scheme.

QUEEN VICTORIA TO PRESIDENT BUCHANAN: CONGRATULATIONS

On June 25, 1858, *Agamemnon* and *Niagara* met in the middle of the ocean, their cables were spliced, and they sailed to opposite shores, communicating via the cable.

Two days later, they lost contact. They returned to the mid-ocean starting point, sacrificed the cable they'd just put down, respliced, and tried again. After another two days of seafaring, the cable snapped yet again.

Finally, in July they completed the crossing without incident. *Niagara* landed on August 4 in Bay Bulls Arm (now known as Sunnyside), Newfoundland, *Agamemnon* a day later in Valentia Island, Ireland. By the 10th, test messages were flying, and on August 16, Queen Victoria sent the first official message to President James Buchanan of the United States.

The communication was not instantaneous. That first official message, which consisted of little more than formal greetings, took about 16 hours to make the journey; transmission of each character took slightly over two minutes. Still, it beat, by nine days, the transit time of a message carried by a packet steamship.

News of the messages set off huge celebrations in the U.S. and England, including spontaneous parades and a fireworks show in New York City that was so spectacular that it set fire to the dome of city hall. ATC shares doubled, Bright was knighted, and Field would have been, said the queen, had he been a subject.

But right from the start the signal began getting weaker. Whitehouse, who had divined that higher voltage was necessary to increase the rate at which characters could be transmitted, ramped up the voltage from 600 volts to about 2,000, over Thomson's objections. After 23 days, and 732 messages, the cable stopped working entirely.

YOU'RE GOING TO NEED A BIGGER BOAT

Whitehouse was blamed, conspiracy theories sprang up, and the British and American governments formed a Board of Enquiry to figure out what happened. They determined that the cable was poorly designed, that it should have been tested, and that high voltage had likely degraded the gutta-percha.

Field, never undone by failure, started scraping together money to have another go, but the American Civil War put any further attempts on hold.

In 1866 things would be easier. For one thing, there was a bigger boat. Eight years earlier, the renowned engineer Isambard Kingdom Brunel had launched his *Great Eastern,* a ship so large that it could go from England to Australia and back without having to reload coal for the return trip.

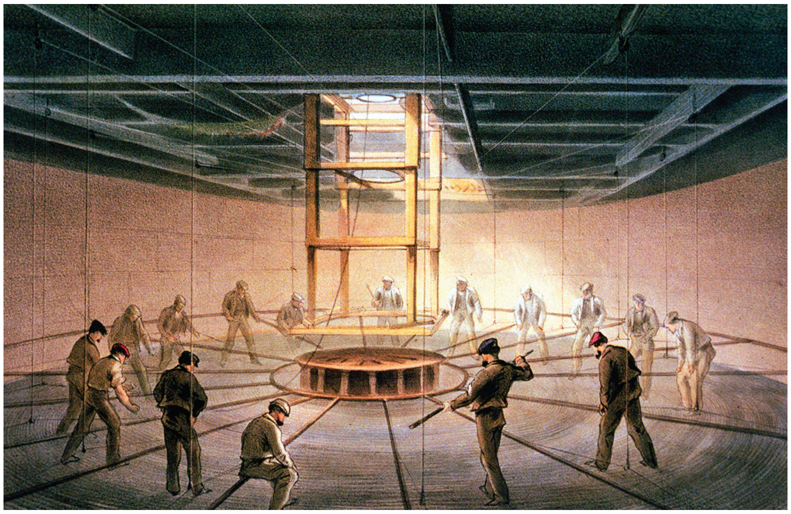
It was a noteworthy achievement, but it wasn't a superior solution to any known problem at the time. Except, possibly, one. Field, who had kept secret his ambition to use the vessel for his next attempt to lay a transatlantic cable, bought the 700-foot-long ship at auction for 2.5 percent of its building cost.

This time there would be no splicing, no fraught meetups in the middle of the sea. This time the cable had been hydraulically tested and was proven to work. This cable had four layers of gutta-percha instead of three; the core was wrapped in pitch-soaked hemp; and a new kind of steel—charcoal iron—acted as armor. Instead of 2,000 pounds per mile, this cable weighed 3,575.

On July 27, 1866, after an uneventful two weeks at sea—and in contact with Ireland all the while—Field arrived in Newfoundland with a transatlantic cable spooling out behind him.

The contact thereby established between the two continents would never again be broken. ■

Inside the *Great Eastern*, three tanks, like the one shown here, held the 2,400 nautical miles of cable.



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COMMUNICATIONS | 1876

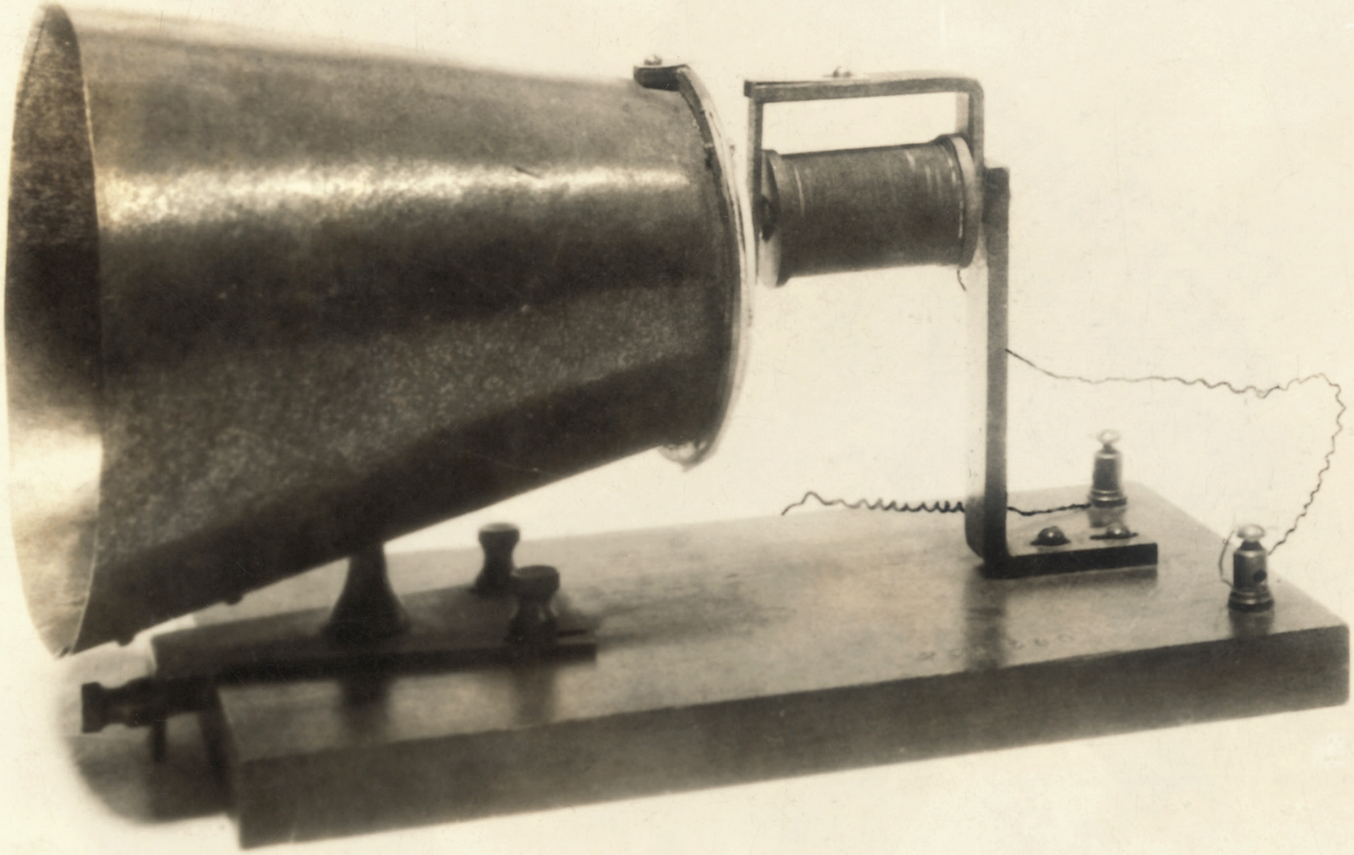
The Dawn of the Comm

Alexander Graham Bell's famous plaintive cry to his assistant Thomas Watson was the culmination of years of research that started with an interest in the mechanics of speech.

On March 10, 1876, Alexander Graham Bell was working on a new transmitting device when he spilled acid on his pants, prompting him to utter a phrase that would reverberate through history: "Mr. Watson, come here! I want to see you!" Thomas Watson, his assistant, was standing near a connected device in a nearby room and heard the phrase clearly—marking the world's first intelligible voice transmission over electric wires. The moment was the culmination of a long and complicated effort—aided by a few serendipitous mistakes.

Bell was born in Scotland in 1847 and later emigrated with his family to the U.S. Because of their father, Bell and his brother became interested in the mechanics off speech and attempted to create a mechanical version of the vocal organs, including larynx, vocal cords, tongue, and movable lips. They managed to make the machine say "mama" convincingly enough to make a neighbor think a baby was in distress.

Later, Bell also taught his Skye terrier to growl continuously. Bell would then manipulate the dog's mouth with his hands to make it say, "How are you, grandmama?" He



unications Revolution

later wrote, "people came from far and near to witness the performance." This was in the days before TV, of course.

Bell pursued a teaching career that included positions at several schools for the deaf in Boston. In the early 1860s, he found a book on the mechanics of vowel sounds, written in German. Bell knew little German and mistakenly concluded that the author had found a way to transmit vowel sounds electronically, piquing an interest in developing a similar but more capable device. It was, he is said to have explained, "a very valuable blunder. It gave me confidence. If I had been able to read German, I might never have commenced my experiments!"

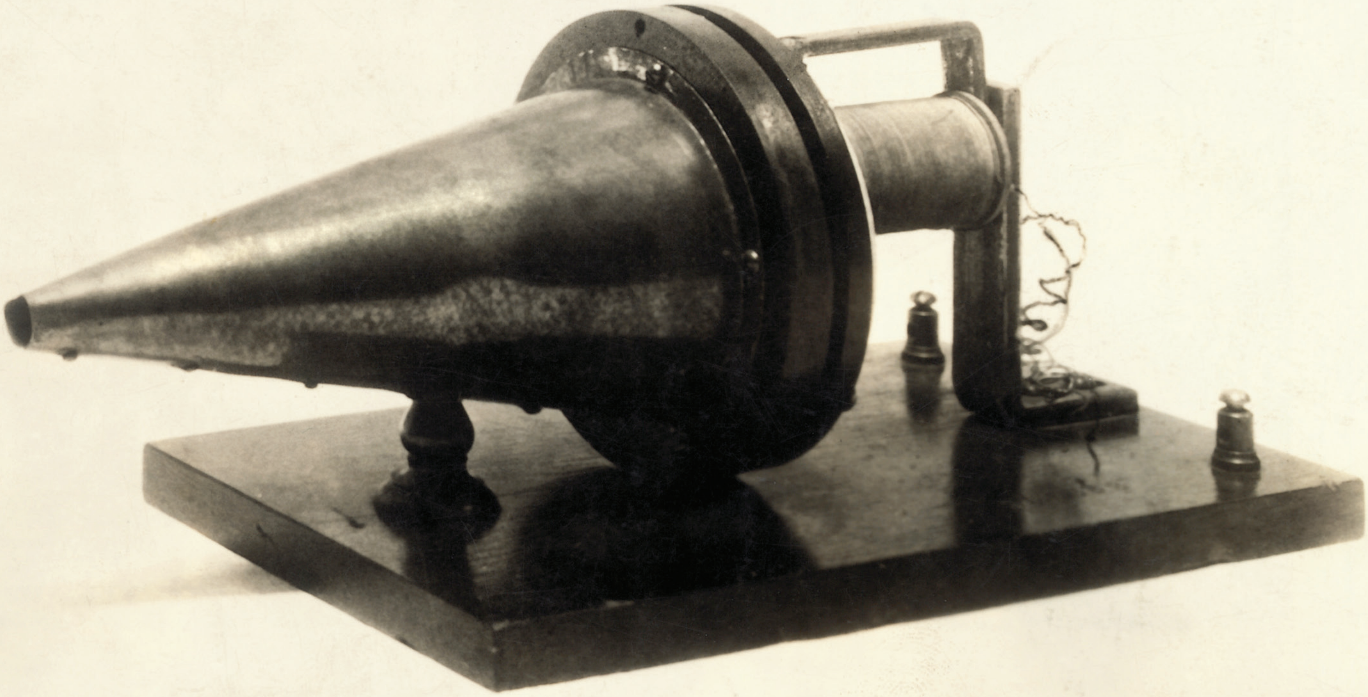
Around 1871, Bell became interested in creating a "harmonic telegraph" that could carry multiple signals across a single telegraph line. He was backed in this efforts by the parents of two of his deaf students—one of whom, Mabel Hubbard, he later married.

From his work with speech, Bell had a fundamental understanding of sound waves, and because he understood the structure of human ears, he had a concept of how sound might be reproduced. In Watson's remembrance, Bell described "an elongated electromagnet with a multiplicity of steel reeds tuned to many pitches and arranged to vibrate in proximity to its poles, as if the magnets of a hundred of these receivers were fused together side by side. These reeds might be considered as analogous to the rods in the harp of Corti in the human ear."

"It was Bell's first conception of a speaking telephone," Watson said in a speech delivered many years later, in 1915.

Alexander Graham Bell [above], in a photo from 1876, the year when he was 29 and exclaimed "Mr. Watson, come here! I want to see you." The instrument that conveyed the message included a transmitter [opposite] and receiver [below].

INSET: UNIVERSAL IMAGES GROUP/GETTY IMAGES;
BOTTOM: GEORGE RINHART/CORBIS/GETTY IMAGES



The first version of Bell's harmonic telegraph, in 1872, used pairs of tuning forks vibrating between the poles of an electromagnet. A fork on the transmitting end would vibrate at a certain pitch. That pitch would be converted into an on-off electrical signal and sent down a wire to a receiving fork, which would be stimulated by the signal to resonate at that same pitch. Bell's idea was that several of these pairs, tuned to different frequencies, could be used to simultaneously transmit signals over a single telegraph line.

This apparatus did not produce the desired results, but it convinced Bell he was on the right path with his research.

HARD WORK AND SERENDIPITY

Bell eventually replaced the harmonic telegraph's tuning forks with metal reeds, which needed to be adjusted from time to time. On June 2, 1875, Bell and Watson were adjusting reeds in separate rooms. Watson began plucking on a reed on his transmitter, and suddenly Bell rushed into the room and asked what Watson had done. Bell's receiver had emitted a tone, and yet the battery that drove the devices had not been disconnected.

It turned out that the plucked steel reed happened to have been magnetized and was generating a small amount of electricity, enough to send a signal that behaved exactly like a sound wave, causing the corresponding reed on Bell's receiver to move in concert, recreating the sound of the plucked reed. Bell "instantly recognized the transcendent importance of that faint sound thus electrically transmitted," Watson later wrote. "The speaking telephone was born at that moment."

"I have accidentally made a discovery of the greatest importance," Bell wrote that day. "I have succeeded today in transmitting signals without any battery whatever!"

Before they went home that night, according to Watson, Bell had sketched a model of what would later become known as a telephone, based on their discoveries that day. In July, they were using a receiver based on a stretched membrane of processed cattle intestine. Centered in this diaphragm was an armature of magnetized iron; as signals came down the line, an electromagnet connected to the line vibrated this armature and diaphragm, and produced sound. A transmitter on the other end produced signals in a similar manner, but in reverse.

On March 7, 1876, Bell received a patent for his method of "transmitting vocal or other sounds telegraphically, by causing electrical undulations, similar in form to the vibrations of air accompanying the said vocal or other sound."

With this design, Bell modulated the current of electricity with a "liquid transmitter" that used variable resistance to increase and decrease the current. A wire was attached to a diaphragm, which when struck by sound waves moved the wire up and down in a conducting liquid. This varied the resistance in the circuit and ultimately the amount of current being transmitted. Thus, the current moving through the wire would vary as the

Ahead of His Time?

Alexander Graham Bell is known for inventing the telephone, but there are other contenders for that title—including Johann Philipp Reis.

Reis was a self-taught scientist who developed a type of telephone in 1860. With this device, sounds vibrated a parchment membrane that drove two pieces of platinum in loose contact to create an undulating current. On the receiving end, the modulated current drove a homemade solenoid that vibrated against a wooden sounding box. After some initial attention, however, there was not much interest in Reis's invention and he did little to pursue his idea. In addition, Reis's description of how the device worked was inaccurate, and in a demonstration connected to a U.S. patent lawsuit against Bell, it failed to work.

However, in 1946 Britain's Standard Telephones and Cables company ran tests on a Reis device borrowed from London's Science Museum.

The company reported back to the museum that the transmitter and receiver could deliver

UNIVERSAL IMAGES GROUP/GETTY IMAGES (2)

sound waves varied, to be turned back into sound when it reached the receiver.

With that patented device, a listener could hear a person's voice, but not clearly enough to tell what they were saying. Finally, on March 10, as Bell was preparing to test a new version of the liquid transmitter, this one using dilute sulfuric acid as a conductor, he spilled some of the acid and uttered his famous call to Watson—and much to his surprise, Watson heard him clearly. The reflexive exclamation became the first intelligible voice transmission with a telephone.

ONGOING INNOVATION

Bell struggled to improve his technology, and investors encouraged him to focus on the more lucrative telegraph anyway. He did little direct work on the telephone after 1877, leaving further improvements to others.

But he clearly saw the tremendous potential of the device. He formed the Bell Telephone Company in 1877 and co-founded the original AT&T in 1885, launching an industry that changed the daily lives of people around the world.

Bell continued to pursue innovation in a wide variety of fields. He proposed a "vacuum jacket" to help people breathe—something like the later iron lung. He created a metal detector that was used, unsuccessfully, to search for the assassin's bullet that caused the death of President James Garfield. And he developed the "photophone," a wireless phone that transmitted sound via beams of light, which was tested successfully in 1881 across a 700-foot span.

> The first version of Bell's harmonic telegraph used pairs of tuning forks vibrating between the poles of an electromagnet—a transmitting fork that would vibrate at a certain pitch and a receiving fork that would resonate at that pitch.

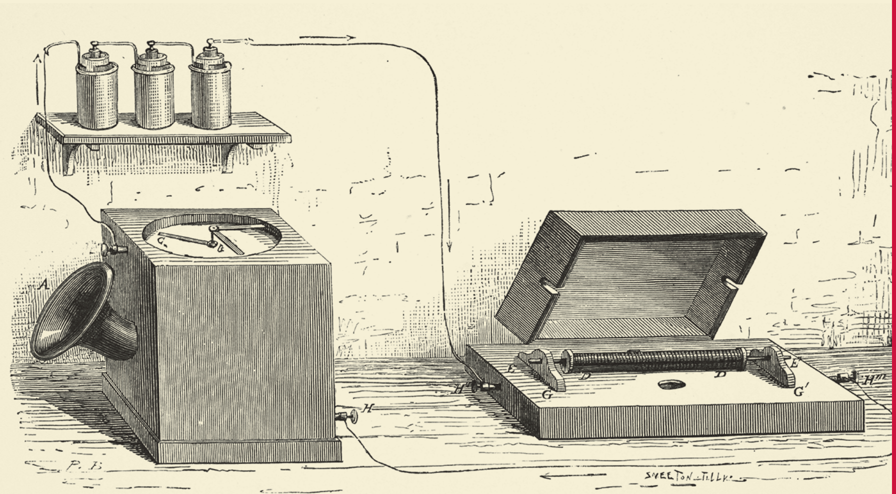
Bell served as president of the AIEE in 1891-1892 and was later awarded the Institute's Edison Medal—becoming the first person to be recognized for contributions to electrical communication, rather than electric power, a sign of the expanding world of electrical engineering. In 1976, the IEEE created the Alexander Graham Bell Medal, awarded for contributions in communications and networking.

Although his innovations were wide-ranging, it was Bell's invention of the phone that earned him a prominent place in history—although not always as he might have wanted. In 1890, Mark Twain, who viewed the phone as an intrusion on his privacy, declared that "It is my heart-warm and world-embracing Christmas hope and aspiration that all of us…may eventually be gathered together in a heaven of everlasting rest and peace and bliss, except the inventor of the telephone." ■

intelligible speech, "but the two together are not capable of operating as a telephone without substantial amplification."

STC declined to make these results public, and the tests did not come to light until papers about it were discovered at the museum in 2003. The upshot is that while it was not practical in the 19th century, the device was based on sound principles.

So to speak.



Johann Philipp Reis [far left], a teacher and self-taught inventor in Germany, built a working telephone in 1860 [right], but could not find support for it in Germany.

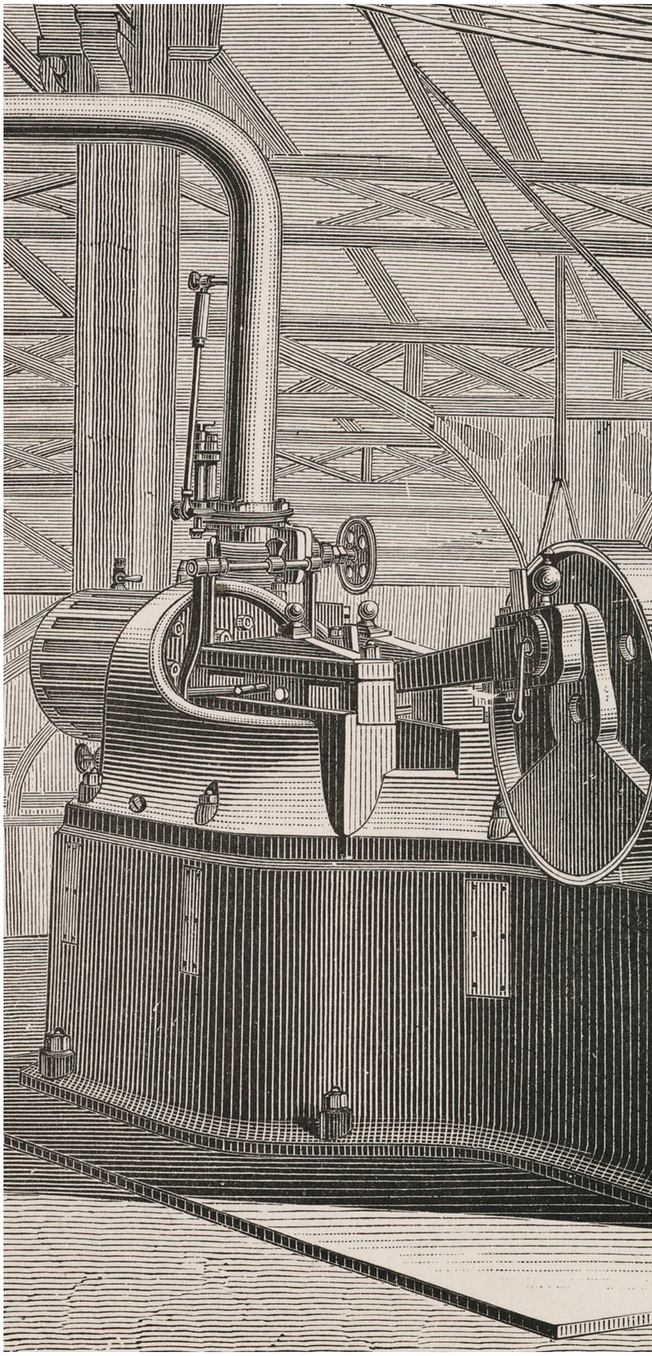
POWER | 1884

The Pearl Street Prototype

Edison's first large-scale generating plant set the standard for countless future plants—even though it was on the losing side of the AC/DC battle.

Thomas Edison was one of the most prolific inventors of all time, but he was also a shrewd one. So when he developed a practical incandescent light bulb in 1879, he was already thinking of the next steps in the project. To make the light bulb a viable mass-market product, he would need to provide a complete, end-to-end infrastructure for generating electricity and distributing it to homes and offices. The heart of that infrastructure, it turned out, would be the first large, successful commercial central generating plant in the United States: Pearl Street Station in Lower Manhattan. The station began serving customers in 1882 and in doing so, provided a prototype for the countless electric power companies that would come after it.

By the time Edison started building Pearl Street, there was enormous interest in the incandescent light bulb. The gas lighting typically used in cities often flickered and was dangerous, dirty, and hot. Electric lighting was already in limited use in dozens of cities around the world, with some grand homes having their own generators. Financier J.P. Morgan, one of Edison's investors and his first residential customer, had Edison install a system at his Fifth Avenue mansion. But those isolated plants were not scalable. As a result, Edison built several experimental centralized lighting systems, including one at the Paris Expo and another in London, in 1881.



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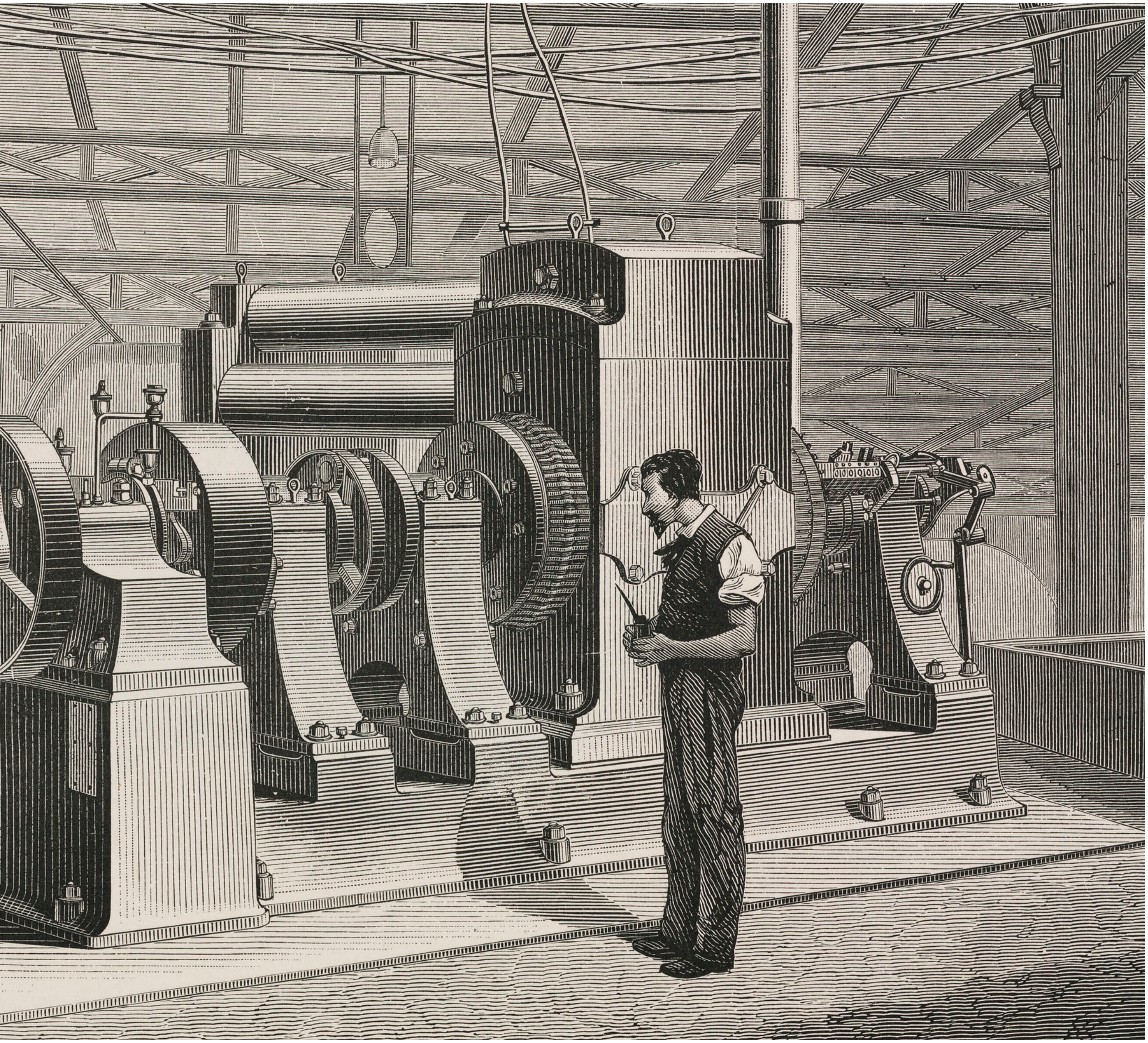
For his New York City project, Edison's ambition was to build an entirely new system that would generate electricity at a central location, distribute it to customers efficiently, and ultimately, do so at a scale that would make electric power widely affordable. "We will make electric light so cheap that only the rich will be able to burn candles," he supposedly declared.

For the generating plant, he selected two buildings on adjoining lots. One build-



ing—257 Pearl Street—housed the electrical and mechanical equipment. The other, 255 Pearl Street, was used for offices, storage, and sleeping quarters for the workers.

The location in Manhattan was no accident: Edison wanted to maximize the impact that the generating station would have on public awareness. The square mile of New York that the station would serve included the stock exchange, banks, brokerages, business offices, and newspaper publishers—the investors, opinion makers, and other "influencers" of the day.

ELEPHANTINE DYNAMOS

In 1880, to build his new system, Edison formed the Edison Electric Illuminating Company of New York, a predecessor of today's Consolidated Edison. He himself took on the role of chief engineer for the entire project. To create the full electrical grid that he envisioned, he and his engineers would have to deploy hundreds of components—most of them invented or built by him and his engineers. They would need large-scale items such as dynamos and countless smaller

In 1882, the year when his Pearl Street generating station began operation, Thomas Edison exhibited one of his steam-driven dynamos at the Crystal Palace Exhibition in London.

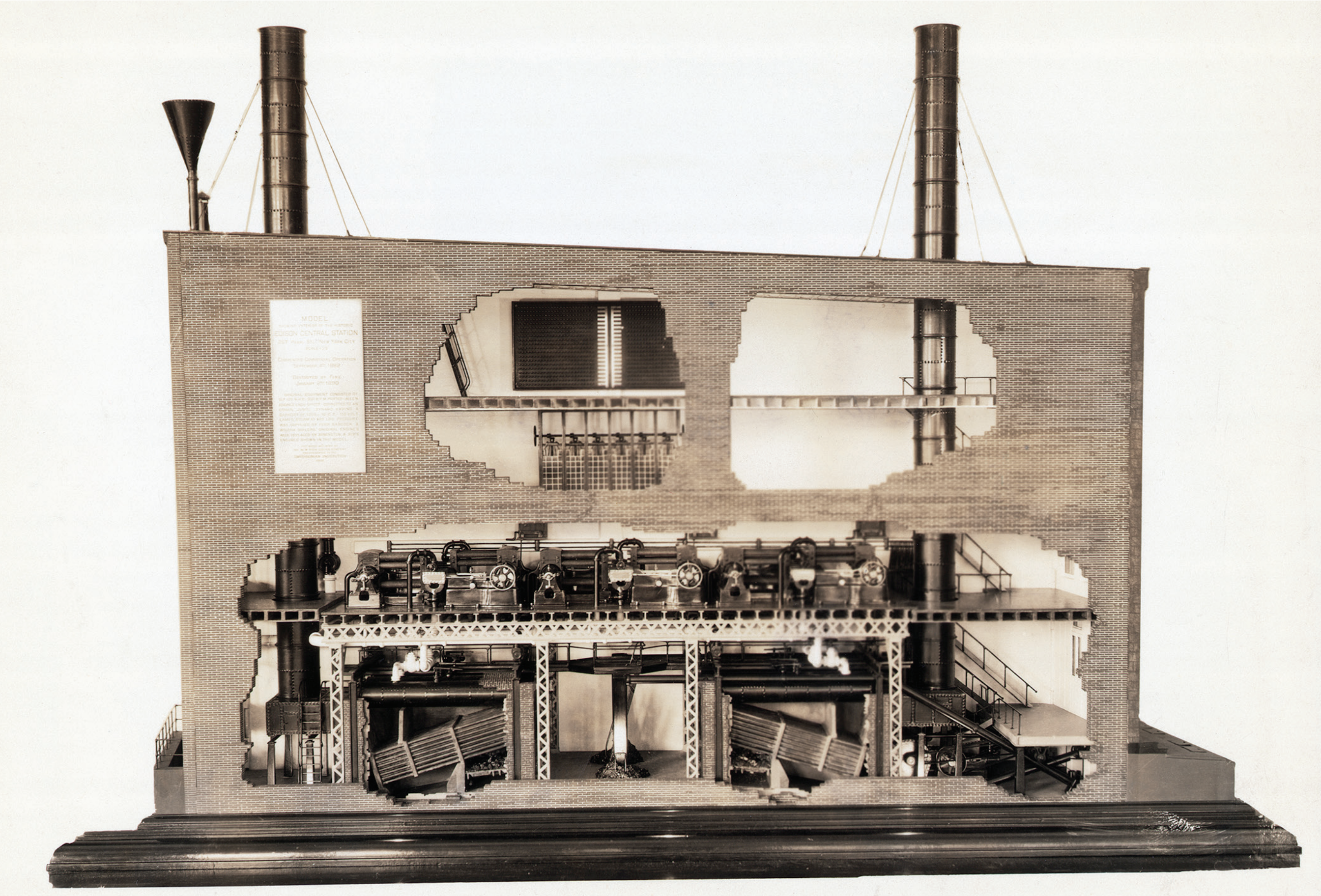
ones such as fuses, switches, distribution lines, junction boxes, light fixtures, and sockets. And meters. To measure how much electricity customers used, Edison developed a device that used the flow of electricity to plate zinc onto a carefully weighed electrode. Meter readers would later weigh the electrodes to determine how much energy had been used.

The dynamos were a particular challenge. There were none large enough to meet Edison's needs, so his team developed "Jumbo," a 27-ton machine that produced a grand total of 100 kilowatts, enough to power about 1,200 light bulbs. It was four times larger than the dynamos that had previously been available. Named after a famous circus elephant, six Jumbos were built and installed at Pearl Street.

These were direct-current generators. Generators produce electricity by exposing a coil of wire to a magnetic field that is moving with respect to the coil. The coils are typically mounted in a rotating armature that spins in a magnetic field, producing alternating current (AC). To produce direct current (DC), as Edison's dynamos did, requires a commutator, which reverses the contacts to the generating coils every half turn (every 180 degrees). By having multiple coils, and therefore multiple poles, it's possible to get a DC voltage with a reasonably small ripple. The peaks in the ripple correspond to points in the rotation where the voltage induced in a coil is at a peak.

Initially, these dynamos were driven by low-speed, coal-fired steam engines connected via a system of belts. These worked well for running factory machinery, but Edison found that their operation fluctuated too much for the generation of electricity. Instead, a new type of high-speed steam engine with heavier fly wheels was developed, and six of these were coupled directly to the dynamos.

The two Pearl Street lots were narrow—about 50 feet wide in total—so the station had to make use of its vertical space. The first floor held boilers that powered the steam engines, while the six engine-and-dynamo



A scale model of Edison's Pearl Street generating station shows the boilers on the ground floor and the dynamos on the floor above.

BETTMANN/GETTY IMAGES

assemblies were on the floor above. This configuration required significant modifications to the facility. The building "was originally erected for commercial purposes, and as it was incapable of sustaining the weight of the engines and dynamos planned to be installed on the second floor, the old flooring was torn out, and a floor of heavy girders supported by stiff columns was substituted," wrote John Lieb, the station's chief engineer, and later, president of AIEE in 1904-1905.

The floor above the dynamos housed six copper wire resistance coils, one for each dynamo. As the electrical load on the system increased, for example in the early evening as people turned on lights, the current flow in a circuit increased and the voltage would decrease. To keep the voltage stable, it was necessary to increase the strength of the magnetic field in the dynamos. That's what the resistance coils were for—workers used them to manually vary the current flowing through the dynamo's field magnets. A pair of signal lights—one red and one blue—notified them when the voltage ran too high or too low.

Edison famously championed DC over AC, and it eventually created practical problems for him. For one, the voltage in a DC circuit cannot be changed easily or with high efficiency. Edison settled on a voltage of 110 volts dc, and that relatively low voltage severely limited the distance over which he could supply power—it was the main reason why he had to limit the service area for the station to about a square mile.

Edison's original distribution system was two wires—what we would now call a "load," at 110 V DC and a "neutral," at zero volts. He later upgraded this to a three-wire system, which had been pioneered in the UK. With two generators connected in series, and a neutral wire connected to the high-voltage terminal of one generator and the low-voltage of the other, he could provide either 110 or 220 volts. With this system, less current flowed in each of the circuit's two "legs" for any given load, and therefore much less copper conductor was required.

For distribution, the Pearl Street plant initially used underground conduits, rather than the tangle of wires used for telegraph and arc-lighting systems. These were pipes carrying, at first, two conducting wires, separated by rope and insulated with beeswax, linseed oil, and asphaltum. About 15 miles was initially laid under New York City's streets.

SUCCESS—AND OBSOLESCENCE

Pearl Street Station was put into commercial operation at 3:00 on the afternoon of September 4, 1882, when Edison flipped a switch in the office of J.P. Morgan, one of the investors in the Pearl Street enterprise. On that first day, Edison had fewer than 90 customers—but by the end of the year, that figure had grown to 513. "I have accomplished all I promised," he told a reporter. Customers continued to sign up, and Edison set up similar DC stations in the city and licensed many others around the world.

From a technical standpoint, Pearl Street was a clear success. The station operated from its launch in 1882 until January 1890, when it was partially destroyed by fire. Working around the clock, Edison and his team restored service in 11 days, and that station continued to run until 1894.

But financial success took a while. The costs of building an entirely new demonstration plant were high, of course, as were the operating expenses. Edison didn't charge customers until the plant was proven to be reliable, with the first bill going out in January 1883. Nevertheless, the plant became profitable within a couple of years, in 1884.

Edison once told a reporter that it would take an earthquake to stop Pearl Street's operations—but in the end, they were simply eclipsed, doomed by a combination of technological advancement and Edison's reluctance to embrace alternating current. With the increased use of electricity, power had to be transmitted over greater distances, and industrial users needed electricity at higher voltages—factors that made DC power less desirable. As a result, more and more AC systems were coming online and the use of DC power declined. Pearl Street Station was retired and dismantled in 1895.

In just a dozen years, Pearl Street Station established the commercial viability of electric lighting and showed how electricity could be delivered efficiently on a large scale. And as the first residential, commercial, and centralized electric utility system, it provided a basic formula, parts of which are still used to deliver electricity to homes and businesses all over the world. ■

POWER | 1884

Growing Up

The formation of the American Institute of Electrical Engineers was a pivotal moment in the transformation of electrical engineering into a profession.

In the late 19th century, the world began to glimpse the immense power of electrical technology. Telegraph wires began crisscrossing landscapes, forming continental webs that allowed instant communication among distantly spaced cities and towns. Even the mighty Atlantic Ocean was bridged, when underwater cables connected Europe and North America. And in New York City, in 1882, incandescent lights gave interior spaces an ethereal glow when Thomas Edison's Pearl Street Station began supplying power to a quarter-square-mile area.

The Franklin Institute, in Philadelphia, saw an opportunity. The organization, founded in 1824 as a hub for promoting science and technology, had been hosting lectures and exhibitions to describe and support the emerging electrotechnologies. And now, to celebrate the era of wonders that was so obviously dawning, it resolved to sponsor an International Electrical Exhibition, in 1884.

The event aimed to attract electrical experts, engineers, and manufacturers from all over the world and promised to reveal a dazzling future powered by ingenuity, imagination, and innovation. The electric-power trade journal *Electrical World* gushed that "the forthcoming exhibition will be the grandest of [its] kind the world ever saw."

The exhibition was a significant milestone in the history of electrical engineering because it marked a transition into a more mature phase of development. Such a gathering demanded the presence of an American national society of electrical engineers, a group that would welcome the distinguished guests as well as honor their contributions to the burgeoning field.

There was just one problem. No such society yet existed in America.

NATHANIEL KEITH: FOUNDER OF THE AIEE

So it fell to a 45-year-old chemist, mining engineer, and magazine editor named Nathaniel Shepard Keith to take the initiative and organize a national society of electrical engineers. In the spring of 1884, just months before the exhibition was to take place, he reached out to such luminaries as entrepreneurs Thomas Edison, Elihu Thomson, Edward Weston, and Edwin J. Houston, asking them to help him shape the future of this nascent society.

In all, Keith enlisted 25 prominent figures to receive the "foreign electrical savants, engineers, and manufacturers" who would attend the exhibition, according to the April 15, 1885, issue of *The Operator*, the major U.S. electrical journal at the time. As Keith noted in the "call" that went out as an invitation to participate in the event, "It would be a lasting disgrace to American electricians if no American electrical national society was in existence to receive them with the honors due them from their collaborators in the United States."

Thomas Edison, a founding vice president of the American Institute of Electrical Engineers visited Charles P. Steinmetz, AIEE president in 1901–1902, at General Electric's Schenectady, New York, laboratory in 1922. The two examined porcelain and wood demolished by Steinmetz's million-volt lightning generator.

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Key figures in the establishment of the American Institute of Electrical Engineers included [opposite page, clockwise from left:]: Elihu Thomson, seen here demonstrating arc welding in 1897; Nikola Tesla; Edward Weston; Nathaniel Shepard Keith; and Norvin Green.

The formation of the American Institute of Electrical Engineers, the AIEE, was a pivotal moment in the transformation of electrical engineering into a profession. Electrical technologies had become the foundation of a thriving industry, fueled by fundamental breakthroughs in electric power and lighting. Electrical engineering was poised to create a new era of progress, driven by the collaborative efforts of some of the most brilliant minds of that time.

THE FIRST EE TECHNICAL CONFERENCE

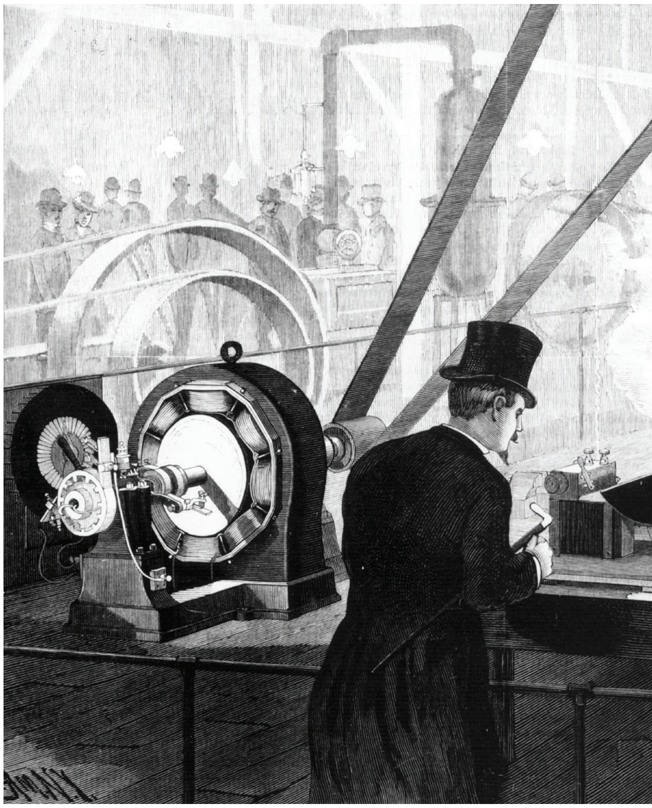
The AIEE—a predecessor of today's IEEE—hosted its inaugural technical meeting on October 7 and 8, 1884, during the Electrical Exhibition. Not only was this the first formal technical conference on electrical engineering held in the United States, it also came at a time when the industry was shifting from a dependence on individual inventors to an orientation based more on professional engineers working within companies.

Researchers presented papers, which were collected into a journal, *Transactions of the AIEE*, published after the event. The papers are an eclectic and intriguing bunch. Among the most notable is one by Houston, chief electrician of the exhibition, titled "Notes on Phenomena in Incandescent Lamps." Houston describes a phenomenon that was then becoming known as the Edison effect. Referring to "the peculiar high vacuum phenomenon observed by Mr. Edison in some of his incandescent lamps," Houston wrote, "I wish to bring it before the Society for the purpose of having you puzzle over it." (More on the Edison effect later).

Beyond the AIEE technical meeting, the Electrical Exhibition played a transformative role. Displays of state-of-the-art electrical technologies anticipated a day when electric light and power would be integral aspects of daily life. The exhibition featured historical exhibits, a collection of publications on electricity and magnetism, and cutting-edge demonstrations, including competitive testing of incandescent lamps and dynamos.

EDISON STEALS THE SHOW

Of all of the presenters, Edison and his six companies stole the show. Edison's exhibit was the largest, most spectacular, and most diverse, encompassing practically every invention he had ever made. Outside the exhibit hall, a brilliant star made of Edison's incandescent lamps adorned the southeast tower. Inside, Edison presented a complete central generating station system and an isolated lighting plant, both fully functional. The inventor himself was on hand for the lighting of a magnificent pyramid of lights consisting of 1,200 lamps, creating a stunning spectacle. *Electrical World* exclaimed that "the flood of light [was] almost blinding and far exceed[ed] anything as yet witnessed at the show."

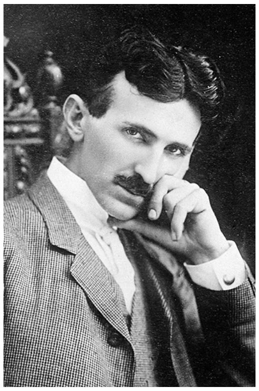


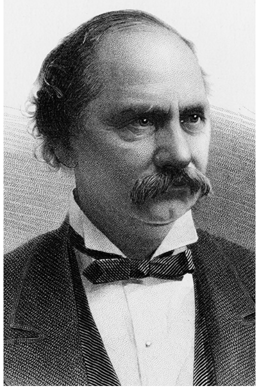
Amid Edison's sprawling collection of exhibits was an "apparatus showing conductivity of continuous currents through high vacuo," which became known as the "Tri-Polar Incandescent Lamp." It showcased the Edison effect, which referred to the flow of electrons, stimulated by heat, between electrodes in a vacuum. We now call it thermionic emission. It was the underlying principle of the vacuum tubes that would dominate electronics until the 1950s.

THE PROFESSIONALIZATION OF ELECTRICAL ENGINEERING

With 282,779 paid attendees, the 10-day

CLOCKWISE FROM LEFT: HULTON ARCHIVE/GETTY IMAGES; ROGER VIOLLET/GETTY IMAGES; SSPL/GETTY IMAGES; HISTORY COLORADO; KEAN COLLECTION/GETTY IMAGES





Electrical Exhibition was declared a success, showcasing American electrical expertise and bringing together inventors and other practitioners who traded notes, inspired each other, and began building a global community. The newly formed AIEE was able to gain a strong and secure foothold in the emerging field by enlisting some of its most distinguished practitioners and making a splash with timely and intriguing technical sessions.

Dugald Jackson was just an undergraduate at Pennsylvania State College (now University) when he attended the exhibition. He was among nine future presidents of the AIEE in attendance.

Writing in the *Transactions of the AIEE* in 1934, Jackson, who had assumed the AIEE presidency in 1910, reflected on the importance of the event. "The year 1884 was significant and auspicious for the American International Electrical Exhibition," he said. "In that year, the Institute was founded. Also, in that year it demonstrated the cooperative spirit possessed in the field of electrical engineering, a spirit which the Institute has maintained untarnished." ■

Founding Electrical Fathers

The Institute of Electrical and Electronics Engineers traces its history to the founding of the American Institute of Electrical Engineers in the spring of 1884. Notable early members of the AIEE included:

Alexander Graham Bell, an inventor of the telephone, and president of the AIEE in 1891-1892.

Thomas Edison, inventor of the phonograph, practical incandescent lamp, generating station, and many other devices.

Norvin Green, president of the Western Union Telegraph Company and a financier instrumental in obtaining funding for the expansion of the company. Green served as the first president of the AIEE, in 1884-1886.

Edwin J. Houston, Elihu Thomson's collaborator on the arc-light system, and president of the AIEE in 1893-1895.

Charles Proteus Steinmetz, developed vital theories in magnetism and AC circuits, was later chief consulting engineer of General Electric and president of the AIEE in 1901-1902.

Nikola Tesla, made advances in arc lighting, alternating-current induction motors, and AC distribution systems.

Elihu Thomson, a developer of arc lights, who also described the principles of resistance welding and was president of the AIEE in 1889-1890.

Edward Weston, inventor of a direct-current generator and carbon arc lamp, and president of the AIEE in 1888-1889.

POWER AND TRANSPORTATION | 1885

Inspired by the Light

Galileo Ferraris built an AC induction motor two years before Nikola Tesla, but is largely forgotten today.

Deep in the Piedmont region of Italy, near France, the old city of Turin sits on the Po River. Since Roman times, Turin has been a hub of culture, arts, and sciences in Northern Italy. And it was also the birthplace, in 1847, of Galileo Ferraris, an often-forgotten pioneer in the establishment of electrical engineering.

Born to a pharmacist and his wife, Ferraris grew up with an interest in science and energized by the culture of Turin. After earning degrees in civil engineering at the University of Turin, Ferraris stayed to teach physics and engineering at the school and to conduct research in mechanics, optics, and thermodynamics. Fascinated by the emerging technology of electricity, Ferraris was sent to Paris in 1881 as an Italian representative to the International Electrical Exhibition at the Palais de l'Industrie, along the Champs-Élysées.

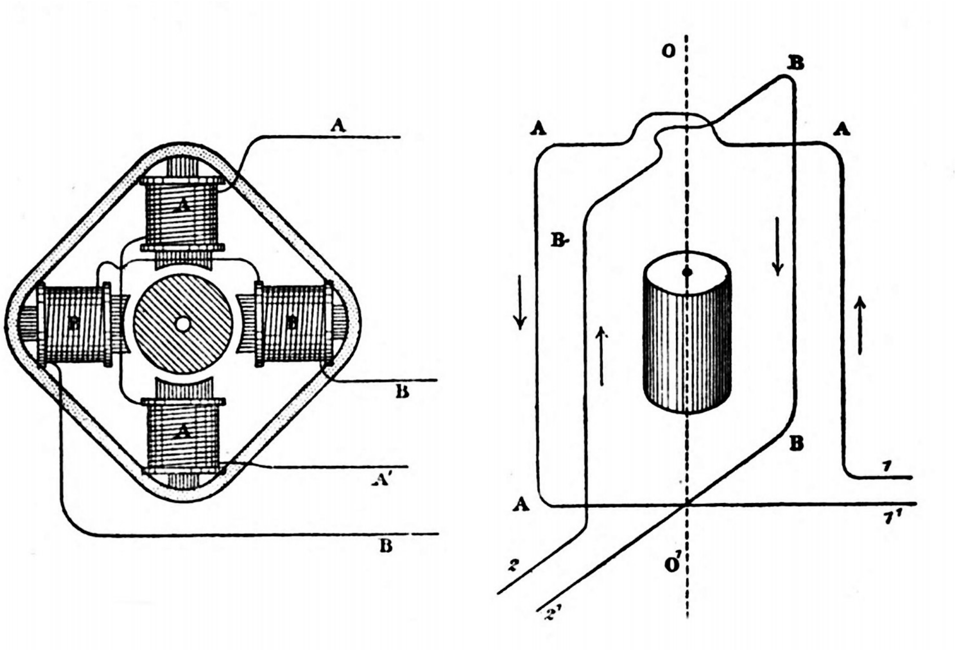
It was a huge and seminal event, with more than 1,700 exhibitors from 15 countries. Among the wonders on display: Alexander Graham Bell's telephone and Gustave Trouvé's electric car. Suspended from the ceiling of the vast exhibition hall, courtesy of the brothers Albert and Gaston Tissandier, was the world's first electrically powered flying vehicle—a dirigible outfitted with an electric motor made by Siemens. When the sun went down, a thousand of Edison's incandescent lights lit up the hallways at the exhibition. Held at a time when electricity was becoming less of a hobby for eccentrics and more like an emerging industry, the exhibition was also notable for setting standards for the volt, ampere, and ohm.

After the exhibition, Ferraris became one of the leading electrical researchers in Italy. The

Galileo Ferraris around 1890, at approximately 43 years of age.

DE AGOSTINI / ICAS94/GETTY IMAGES

Ferraris's alternating-current induction motor [near right] used two pairs of electromagnets, one pair perpendicular to the other. They created rotating magnetic fields that caused a copper tube in the center to rotate. Nikola Tesla is thought to have been unaware of Ferraris's work, although his induction motor [far right] looks a lot like Ferraris's.



WIKIPEDIA

following year, he established the School of Electrotechnology with Laboratory at Turin's Museo Industriale. At the time he was especially interested in electrical measurements, and in one of his earliest papers on electricity he studied the minimum currents needed to obtain audible signals over a telephone circuit.

SEEING THE LIGHT

A couple of years later he was appointed to organize the electricity section at the Italian General Exhibition in Turin, held in 1884. It was in connection with this event that Ferraris began his most important body of work, on alternating-current systems and machines. In one of his early AC projects, he took the "secondary generators" (otherwise known as transformers) invented by Lucient Gaulard and John Dixon Gibbs in 1882 and showed how they could be used to ramp voltage up to 20 kV and transmit 2 kW of power from Turin to the town of Lanzo, a distance of 40 km. This AC system had a frequency of 133 Hz.

He studied the open iron cores of transformers to better understand their functionality and also developed methodologies for performing calculations for alternating current. Ferraris measured eddy and hysteresis currents in the iron cores, with an eye toward boosting transformer efficiency. He also studied improvements that had been made by engineers including the Hungarians Károly Zipernowsky, Miksa Déri and Ottó Bláthy, who had introduced the closed iron-core transformer.

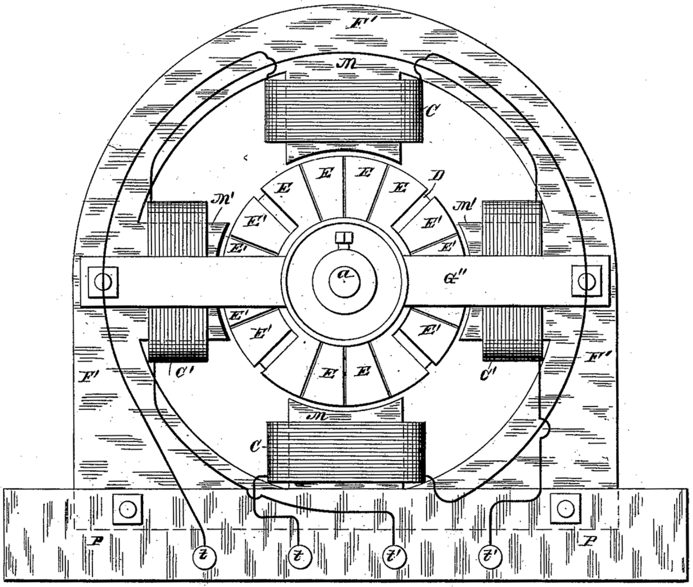
Another of Ferraris's achievements around this time was using Maxwell's theory of electromagnetism to describe how a transformer operated. He said he had been inspired by his work experimenting with phase differences in light waves; later, in 1885, the idea of exploiting a revolving magnetic field to produce rotational torque came to Ferraris after studying the polarization of light waves. From this insight he was able to use alternating currents to achieve mechanical rotation without commutation, which had never been done before. It was the foundation of a whole class of electric motors, called induction motors, that is ubiquitous today.

The culmination of his work was a prototype of a two-phase induction motor, first demonstrated in 1885. The motor had two pairs of stationary coils. The coils of each pair were oriented in the same direction but perpendicular to the other pair. AC current of the same frequency circulated through the coils, but the current in one pair was displaced with respect to the other pair by a phase angle of 90 degrees. This configuration set up a rotating magnetic field, as Ferraris understood it would. He found that a copper or iron tube inserted into that revolving field would spin.

What was happening was that the rotating field surrounding the copper tube induced eddy currents in the tube. Those currents resulted in a magnetic field that interacted with the rotating field produced by the coils, which made the tube rotate. In so doing, the machine converted electricity into electromagnetic forces, and then into mechanical work.

Ferraris also showed that the rotational direction of the tube could be reversed simply by swapping the electrical contacts on one of the coil pairs.

A couple of years later, around 1887, Nikola Tesla also invented an induction motor [left], working in a lab at 89 Liberty Street in New York City. Tesla, it is thought, was unaware of Ferraris's work. Today, induction motors are used in air conditioners, refrigerators, electric vehicles, and countless other systems. The global market for these motors was worth nearly $20 billion in 2022, according to one estimate.



U.S. PATENT AND TRADEMARK OFFICE

THE TRUE INVENTOR OF THE INDUCTION MOTOR

Ferraris's induction motor and use of transformers were forerunners of the alternating-current revolution that would sweep the United States and other countries starting in the late 1890s, thanks largely to the efforts of Tesla and his business partner, George Westinghouse. But even in 1890, visionaries were starting to see a future where electrical power was generated in one location and transmitted via cables to villages and cities tens or even hundreds of kilometers away.

At the 1891 International Electrotechnical Exhibition in Frankfurt, Ferraris was heralded as "the father of the three-phase system"—and as the inventor of the induction motor. Two years later, he demonstrated his machine, which today would be called an asynchronous polyphase induction motor, at the Chicago World's Fair.

Ferraris died at age 50, in 1897. He had developed pneumonia but nevertheless continued teaching until, days before his death, he stopped a lecture midstream and told his students, "Gentlemen, my machine has stopped working."

A monument to Ferraris in bronze shows him holding his two-phase motor is in a courtyard at the Turin Polytechnic Institute. Nearby is Ferraris Avenue, which many tourists probably think is named for the car. But for anyone who bothers to look, the real story is encapsulated on an IEEE plaque at the Polytechnic Institute which honored Ferraris with an official Milestone in 2021. ■

Electrons and Altruism

Galileo Ferraris was what we'd call a workaholic. Deeply devoted to the study and teaching of the principles of electricity, he never married or had children. He did, however, see that his work could have a bigger benefit for his community.

Ferraris refused to file for patents on his inventions. He believed his work belonged to everyone, and for the greater good, and he would freely demonstrate his machines to all who came to his lab. This refusal to legally document his breakthroughs also led to his name being omitted from some accounts of the history of electrical engineering.

Nikola Tesla filed a patent for a polyphase electric motor in May 1888, three years after Ferraris demonstrated such a motor, and eight months after Ferraris presented his theory for the invention. In the Westinghouse lawsuits at the turn of the century over the technology, Tesla was able to convince judges that he had come up with the concept in 1887.

When he wasn't teaching, Ferraris became a city councilor in Turin and used his post to promote the benefits of electrification. He led the effort to install electric street lighting in the city and showed how extending lighting to the suburbs would benefit the economy, allowing stores to stay open after dark.

Horse-drawn streetcars provided Turin's public transportation, and when some suggested an electric streetcar system powered by accumulators, or rechargeable batteries, Ferraris sketched out a different idea: cars using electrical distribution through overhead or underground conductors, which became the dominant technology.

Ferraris also saw electricity as a true public utility rather than a private service that could only be afforded by the wealthy. His main argument was that in poor families, children were often left unsupervised during the day because mothers had to go to factories to work. With cheap power, a mother could have an electric loom in her home, which would let her work while keeping an eye on her children. So add another to the list of Ferraris's inventions: the hybrid work model.

COMMUNICATIONS | 1895

The Great Integrator

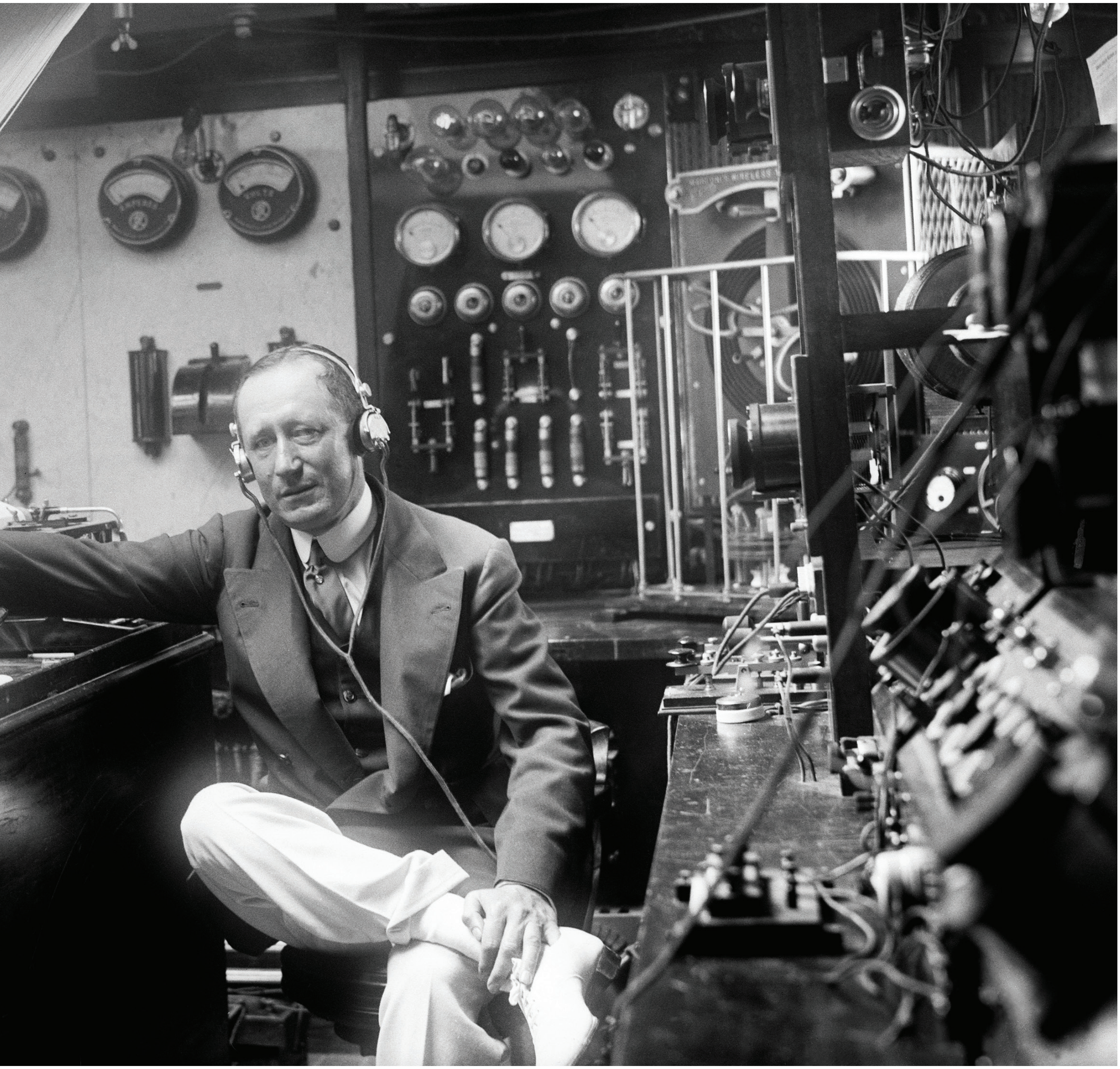
Guglielmo Marconi took a systematic approach to transform radio into a global industry.


BETTMANN/GETTY IMAGES

Other than brilliance, wealth and connections are the two most important assets for an inventor. Guglielmo Marconi had plenty of all three. Born in 1874 in Bologna, Italy, Marconi was the son of a wealthy Italian aristocrat, while his mother was part of the Jameson Irish whiskey dynasty. Young Guglielmo attended private schools in England and Italy and had his own tutors. He soon showed a clear affinity for science. In 1894, at the age of 20, Marconi was engrossed by the phenomenon of electromagnetic waves, which had been predicted by the Scottish physicist James Clerk Maxwell in the 1860s and verified only a few years earlier, in 1888, by the German physicist Heinrich Hertz.

Marconi left a clear record of his intentions in notebooks he kept from the ages of 17 to 19. From the start, he was focused on the practical implications—and the commercial potential—of wireless communication. In particular, he set out to determine whether electromagnetic waves could be used to communicate wirelessly, over great distances, following the earth's curvature. There wasn't a consensus then that it was possible. At the time, the quickest way to send messages was by telegraph wire, using Morse code.

Marconi's early work basically integrated the previous ideas, discoveries and achievements of half a dozen experimenters including Augusto Righi (one of Marconi's teachers),



In the early 1920s, Guglielmo Marconi, then in his late 40s, used to set off occasional commotions in the press by suggesting that he had received signals from Mars. He is shown here in the radio room on board his yacht *Elettra* in 1922.

Nikola Tesla, and especially, Hertz.

In a series of experiments between 1886 and 1888, Hertz had produced electromagnetic waves by connecting a battery across an induction coil and a "spark gap." An interrupter chopped up the battery's direct current and produced something like alternating current across the coil, which increased the voltage to a high enough level (usually thousands of volts) to ionize the air in the tiny gap between the electrodes, producing a spark. (In later work, after Hertz, a telegraph key in series with the battery let an operator tap out signals in Morse code.)

When a spark formed in the gap, it opened the way for current to flow. That current fluctuated rapidly and erratically, acting as a sort of oscillator. That meant accelerating charges, which, according to Maxwell's equations, radiate electromagnetic waves. Hertz's rig fed these waves to a dipole antenna to facilitate their radiation into space.

Improved versions of the spark-gap transmitter included a capacitor, then usually a Leyden jar, which eventually allowed the operator to adjust the frequencies and tune the transmitter.

In 1891 Tesla improved Hertz's apparatus by using an AC generator and by replacing the induction coil with a transformer carefully wound with coils that could handle high-frequency currents. He also added an induction coil and found that by adjusting both the capacitor and the induction coil he could generate much higher frequencies than was possible with Hertz's apparatus. Tesla described his circuit, which became known as a Tesla coil, in a famous lecture at a meeting of the American Institute of Electrical Engineers, one of the IEEE's forerunners, at Columbia University on May 20, 1891.

Marconi began his experiments in 1895 on the estate of Villa Griffone, the main residence of the Marconi family, in the hills southwest of Bologna. (The villa is now the site of the Marconi Museum.) Like Hertz, Marconi designed a transmitter using an induction coil and a spark-gap oscillator to feed radiofrequency power to an antenna. He set up a receiver on the other side of a natural obstacle, Celestini Hill, visible from his second-floor laboratory in the villa's "Silkworm Room."

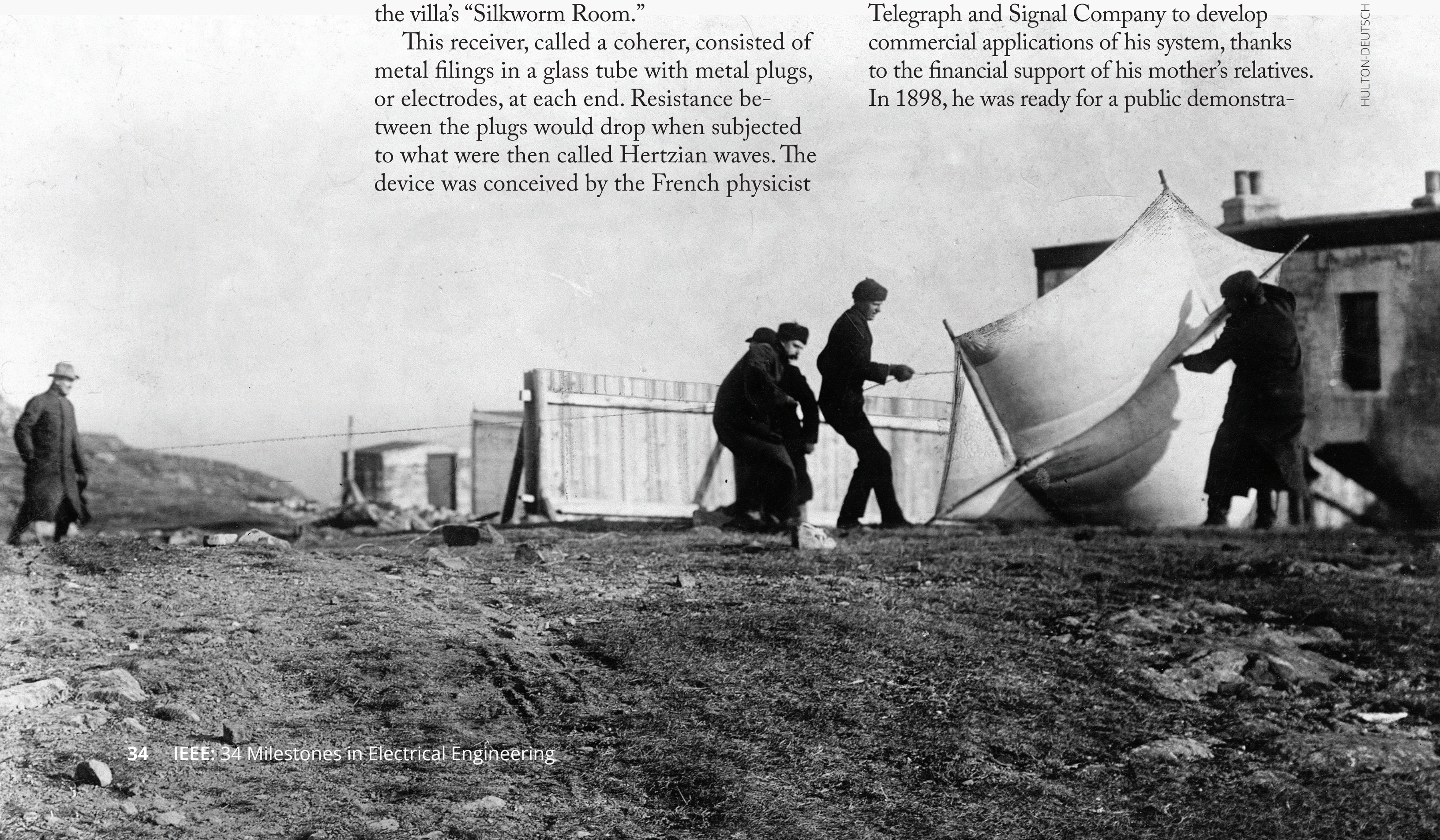
This receiver, called a coherer, consisted of metal filings in a glass tube with metal plugs, or electrodes, at each end. Resistance between the plugs would drop when subjected to what were then called Hertzian waves. The device was conceived by the French physicist Édouard Branly around 1890 and was improved by physicists Oliver Lodge, Alexander Popov, and Jagadish Chandra Bose, working separately. In fact, in his 1895 experiment at Villa Griffone, Marconi used a coherer similar to those built by Lodge.

During the experiment, a transmission of a signal was received on the other side of the hill, at a distance of about 2 km (just over a mile). This reception confirmed that electromagnetic waves could be transmitted and received when there was no line of sight between the transmitter and receiver. His brother fired a gunshot to let Marconi know that the signal had been received.

OFF TO ENGLAND

In early 1896, Marconi headed to England, along with his mother, Annie, to seek investors for his research and customers for his technology. Within months, and thanks to his mother's connections, a cousin, Henry Jameson Davis, helped the 22-year-old Marconi prepare a British patent application and arranged for him to demonstrate his wireless apparatus to officials of the British Post Office, which oversaw wire telegraphy in England.

In 1897, only two years after his first experiments, Marconi organized the Wireless Telegraph and Signal Company to develop commercial applications of his system, thanks to the financial support of his mother's relatives. In 1898, he was ready for a public demonstra-



In 1901, Marconi watched workers using a kite to hoist an antenna during a test at his receiving station at Signal Hill in Newfoundland. He claimed to have received a signal transmitted from Poldhu, Cornwall, England.

HULTON-DEUTSCH COLLECTION/CORBIS/GETTY IMAGES tion. His system was used for the press to cover a yacht race off the English coast, and for the first paid “Marconigrams,” by Lord Kelvin. Soon he received another British patent for improvements to reduce interference and noise.

Meanwhile, he was improving the technical capabilities of his radios enormously. In 1899 the fledgling company set up a wireless station in South Foreland, England, and another one 50 km away in Wimereux, France, to send messages across the English Channel.

Tesla had continued to improve his wireless system, particularly by conducting experiments in Colorado Springs from May 1899 to January 1900. Upon returning to New York from Colorado, Tesla announced that he planned shortly to transmit a message across the Atlantic. Determined to beat Tesla, Marconi worked with John Ambrose Fleming to build a powerful transmitter in Cornwall in southwest England. In December 1901, Marconi rushed to Newfoundland in Canada to set up a receiving station where he received the first transatlantic signal, transmitted from Cornwall. This feat, accomplished when Marconi was 27, made him internationally famous.

In 1907, the Marconi International Marine Communication Company established a commercial transatlantic wireless telegraph service between Clifden, Ireland, and Glace Bay, Nova Scotia, Canada. Both of the stations were equipped with a new kind of transmitter based on a rapidly rotating disc that produced sparks synchronized with an alternator. The transmitters at the stations were rated at 300 kilowatts.

SAVED AT SEA

Marconi was awarded the Nobel Prize in Physics in 1909, the same year that 1,500 passengers and crew on board the ocean liner *Republic* were saved by wireless telegraphy after a shipwreck off the Massachusetts coast.

In his Nobel lecture, Marconi concluded, “Whatever may be its present shortcomings and defects, there can be no doubt that wireless telegraphy—even over great distances—has come to stay, and will not only stay, but continue to advance. If it should become possible to transmit waves right round the world, it may be found that the electrical energy traveling round all parts of the globe may be made to concentrate at the antipodes of the sending station. In this way it may someday be possible for messages to be sent to such distant lands by means of a very small amount of electrical energy, and therefore at a correspondingly small expense.”

In 1920, an opera performance from a Marconi station in England became the first live radio broadcast to reach multiple continents, leading Marconi and colleagues to found the British Broadcasting Company in 1922. In 1920, the Institute of Radio Engineers, a precursor of IEEE, selected Marconi as the third recipient of its Medal of Honor for “his pioneer work in radio telegraphy.

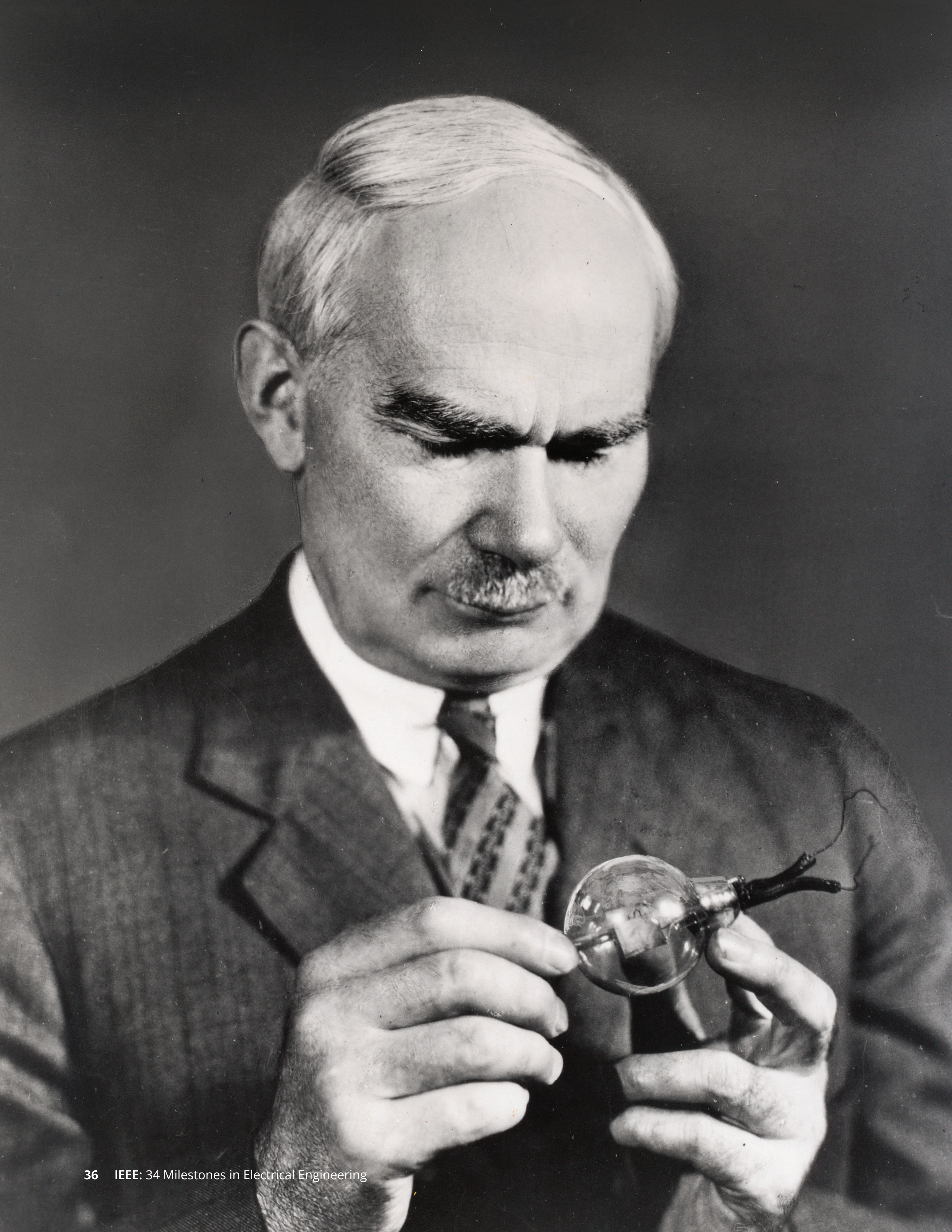
Surprisingly, though, as broadcast radio was taking off in the 1920s, Marconi focused much of his attention on shortwave communication for government and corporate uses. He also envisioned the use of shortwaves in what would come to be known as radar, in a talk in 1922 to a joint meeting of the IRE and the American Institute of Electrical Engineers (the IEEE’s other predecessor).

Today, thousands of visitors each year visit Villa Griffone to remember Marconi’s 1895 experiments and to imagine what it was like for a young man to hear a gunshot signaling that he had verified a scientific theory and set a path toward a new level of worldwide communications. ■

Out of the Shadows

A year after Marconi’s death in 1937, Enrico Fermi, the Italian-American physicist who worked on the Manhattan Project, wrote an article about Marconi’s work, crediting him for pressing on in the face of skepticism in the scientific community. Many believed, Fermi wrote, that the transmission of radio waves between stations was not possible if one station was located beyond the horizon of the other. The thinking was that radio waves emitted by one station “would leave shadowed” all stations below the horizon of the transmitting station. “It was lucky for humankind that these arguments, which might seem *a priori* reasonable and well founded, did not prevent Marconi from experimenting with long-distance transmissions,” Fermi wrote in 1938, the year he himself was awarded the Nobel Prize in Physics.

That radio waves travel beyond the horizon, Fermi explained, was due to “… the influence that the higher layers of the atmosphere, thanks to their ionization, exert on the propagation of electromagnetic waves.” Radio waves bounce off the ionosphere to get around the Earth’s curvature. Marconi had benefited from a phenomenon that neither he nor any of his contemporaries had even guessed—and that nobody would have discovered if someone hadn’t just tried. “Rarely can experience, not driven by a theoretical concept, achieve far-reaching results,” he concluded.



Triodes and Tribulations

The enormous radio industry was made possible by the triode, which itself was made possible by genius—and a lot of litigation.

If some inventions are delivered on the shoulders of giants, others come to fruition when giants try to shoulder each other out of the way. The birth of the triode made possible the amplification of electronic signals and thereby enabled the fledgling field of electronics to flourish, eventually, into a multibillion-dollar business. Its invention is attributed to Lee de Forest. But in creating the tube—and making it useful—de Forest had to borrow from, battle, and even be bettered by others of similar stature.

Thomas Edison, is, arguably, the first giant to whom de Forest is indebted. In the early 1890s, he was toying with a light bulb and noticed that particles from the carbon filament were winding up on the glass. He stuck a metal plate inside to stop the accretion. An underling hooked up that plate to the positive end of a battery and noticed that the current flowed from filament, through empty space, to the plate. The phenomenon came to be called the Edison effect (it is now known as thermionic emission). The cause was unknown, its usefulness a matter of conjecture—J.J. Thomson had yet to discover the electron. But Edison patented it (No. 307,031, awarded in 1884), and then he and the underling put the modified bulb aside.

Two decades later, John Ambrose Fleming, a physicist who had worked for the Edison Electric Light Company in London and later for Guglielmo Marconi, recalled the Edison effect when trying to find a way to measure alternating current. His basic idea was to convert it to direct current, which was then easier to measure. He wrapped a metal plate around a filament, forming a cylinder around it, and applied an alternating current between the cylinder and the filament. He found that what he called a current of "negative electricity" would flow from the filament to the cylinder (or plate) but not in the opposite direction.

What was happening was that the filament, which was heated, was ejecting electrons. Recall that the current applied to the tube was alternating. So when the voltage on the cylindrical plate was positive with respect to the filament, the plate attracted those electrons and current flowed through the tube. When the plate was negative with respect to the filament, the electrons were repelled and no current could flow across the gap. Fleming had created what we now call a diode, a device needed to convert alternating current to direct current. His device is generally regarded as the first vacuum tube.

Fleming, who won the IRE Medal of Honor in 1933, patented his "oscillation valve," gave the rights to Marconi, and moved on. Marconi, though, saw its potential as a detector of radio waves, which could be heard through headphones. It worked, in fact, but not well enough to pursue further.

GETTING HIS HANDS DIRTY

While Fleming was tinkering in England, Lee de Forest was getting into all kinds of inventions and more than a little trouble in the U.S. De Forest was the son of a preacher, Henry de Forest, but against Henry's wishes, Lee abandoned the cloth. He did go to Yale, like his father. But instead of studying the

Lee de Forest holds an Audion [facing page], the first triode vacuum tube. In 1904, a couple of years before he invented the Audion, de Forest's company erected a tower at the St. Louis World's Fair [above].

LEFT: IEEE HISTORY CENTER; RIGHT: ALAMY

From an experimental radio station he ran in New York City, de Forest made the first radio broadcast of presidential election results in 1916, when Woodrow Wilson was reelected.

EVERETT COLLECTION/ALAMY

classics, he attended Yale's Sheffield Scientific School, where he started dreaming up inventions right off the bat. There was an ear cleaner, a pants presser, a chainless bicycle with hydraulic gears, a pipe filter, and an underground trolley system, among many others.

After earning a Bachelor of Science degree in 1896, he started studying electrical theory with the legendary physicist Josiah Willard Gibbs (another Yale man, who had earned the first American doctorate in engineering in 1863). De Forest earned his own doctorate by conceiving a system to improve the transmission of electromagnetic waves. Subsequently, he wrote to Tesla and Marconi, seeking employment. They never wrote back.

So he took a job in Western Electric's dynamo department, while simultaneously trying to develop a better wireless receiver. He soon partnered with a somewhat shady speculator named Abraham White, who was eager to have a business to hype. De Forest was happy to be hyped, and together they formed the de Forest Wireless Telegraph Company. In hopes of raking in cash, the pair set up a glass-enclosed laboratory where potential investors could see de Forest at work sending and receiving wireless messages from Manhattan all the way to… Staten Island. They designated a car "Wireless Auto No. 1," parked it in the financial district, and sent stock quotations, wirelessly, to a broker nearby. In 1904, at the World's Fair in St. Louis, they built a 300-foot tower with "de Forest" spelled out in bright lights. The publicity worked, spurring White to advertise the company's capabilities somewhat prematurely.

To receive radio signals, their wireless system depended on a "spade detector," as de Forest called it, that he had developed in 1903. "Developed" may not be quite the right word. "Copied" might be more accurate. It turned out that de Forest's device was remarkably similar to the electrolytic detector made by Canadian inventor Reginald Fessenden earlier that year.

At least that's what the courts thought—Fessenden won his patent case in 1906, which led to the end of the de Forest Wireless Telegraph Company and to White running off with all its assets and rights. (Fessenden earned an IRE Medal of Honor, in 1921. He tried to return it when he discovered it was not solid gold, like Marconi's, but plated.)

The collapse of de Forest's business did not end his drive to invent.

AND GRID MAKES THREE

Before Fleming moved on from his oscillation valve, he had given a report to the Royal Society in 1905 about the device. De Forest read it and soon started trying to come up with his own version. Some of his early efforts were puzzling. For example, the earliest devices were not vacuum tubes—he was sure that ionized gases were essential to current flow. In fact, this mistaken belief led to the device's name. His assistant, C. D. Babcock, squished together "audio" and "ionized" to create *Audion.* In 1906, de Forest presented this Audion to an October meeting of the American Institute of Electrical Engineers in New York City.

The fanfare was limited. Though improved, it didn't do much that the Fleming tube didn't already do. And the Fleming tube had yet to find a real purpose. But a month later de Forest added one little element—and the result was one of the most important breakthroughs in the history of electronics. Between the filament and the plate, he added a zigzag of wire, which he called the grid. A relatively feeble, small-voltage signal applied to the grid had a great effect on the flow of current between the other two electrodes, the cathode (filament) and the anode (plate). Now the electrons flowing between anode and cathode could be controlled. This improved tube, which de Forest called a grid Audion, had the potential not just to detect radio signals, but to amplify them.

De Forest received patent No. 879,532 for this three-electrode tube, or triode, in 1908. With it, he was able to broadcast musical events, including Caruso singing at the Metropolitan Opera on January 12, 1910. But radio as we know it didn't spring into being with the advent of the Audion. The broadcasts worked, but they were faint and plagued by interference and hissing. And there was too much variation in the triodes themselves. "What appears to be a fixed law for one bulb may not hold for another," admitted de Forest.

Those problems persisted, and radio languished, until a 20-year-old Columbia undergraduate, Edwin Howard Armstrong, became obsessed with improving the triode. He studied it exhaustively, and in 1912 he conceived the regenerative circuit. In essence, the circuit diverted a tiny bit of the current arriving at the tube's plate (or anode) and fed it back into the grid, thereby boosting the input signal to the grid. The technique improved—by a factor of several thousand—the tube's amplifying capabilities, permitting not only vastly more robust output from a radio receiver but also the ability to pull in much weaker signals.

According to Armstrong's sister, his stunning invention sent the college junior dancing around the house hollering "I've done it! I've done it!" That dance signaled the true beginning of radio, the start of its breathtakingly rapid progression from a cottage industry, a pastime mainly for hobbyists, to a vast and thriving global industry.

It turned out that the regenerative circuit had another astounding capability. Increase the feedback sufficiently, and the circuit would oscillate at frequencies high enough to generate radio waves. This made it much easier and simpler to transmit voices and music, as opposed to the dots and dashes of Morse code.

THE WINNER?

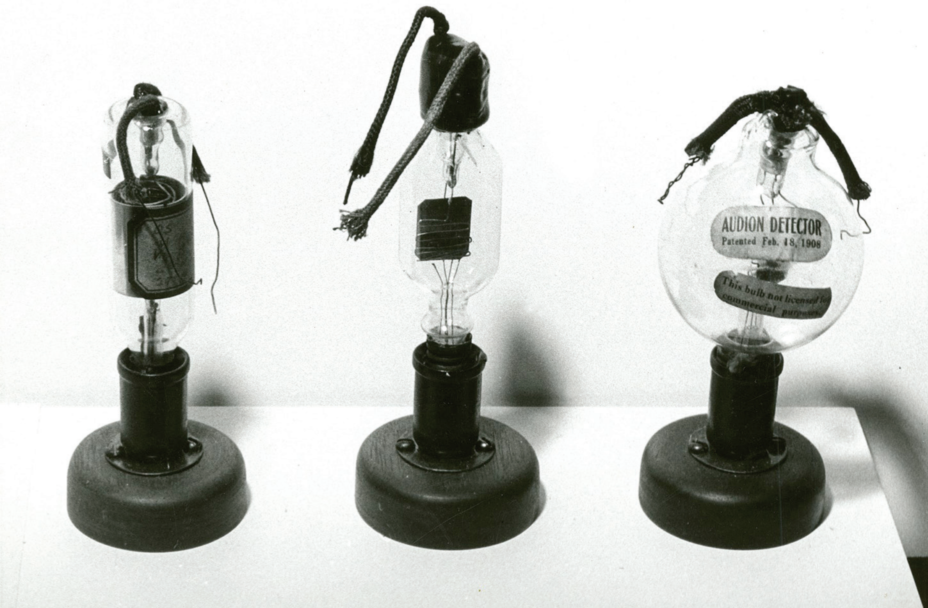
Predictably, de Forest did not react to Armstrong's breakthroughs with much grace. Armstrong wanted to file for a patent almost immediately after making his discovery, but as a college student, he didn't have the money. His father refused to give him the $150 he needed, telling him he would have to wait until he graduated. He sold his motorcycle but still came up short. He finally managed to scrape up enough funds in January 1913 and was issued a patent in 1914. But in 1915 de Forest began filing competing patent claims, insisting that he had invented regeneration, based on a notebook entry made in the summer of 1912. There was no indication that de Forest at that time understood the feedback mechanism or its value. Nevertheless, the resulting patent war would go on for two decades.

In 1922 a Federal Circuit Court of Appeals made a seemingly final judgment in favor of Armstrong. The jubilant inventor flew a flag bearing nothing more than the number 1,113,149—his 1914 patent number—in view of de Forest's home. But de Forest had by then sold his competing patents to AT&T, which, like de Forest, had no intention of giving up the fight. There were more legal decisions and appeals, and ultimately, in 1934, the U.S. Supreme Court ruled in de Forest's favor.

A few weeks after the Supreme Court's decision Armstrong, who in 1917 had won the first Medal of Honor bestowed by the Institute of Radio Engineers, tried to return the medal during an IRE convention. The IRE's board refused to take it back, and 1,000 IRE members gave Armstrong a thundering standing ovation. Tearing up with emotion, Armstrong said, "This is the highest honor a radio engineer can hold. I give you my heartfelt thanks, and I assure you they come from the bottom of my heart."

Armstrong also won the AIEE Edison Medal in 1942, along with a lifetime membership. De Forest would get one in '46.

With his 1934 victory, de Forest took to calling himself "Father of Radio"—in fact, that's what he titled his autobiography. The courts might have agreed. His peers thought otherwise. ■



An assortment of early vacuum tubes includes an Audion [at right].

IEEE HISTORY CENTER

COMMUNICATIONS | 1933

The Serpent in the Garden of Eden

Edwin Howard Armstrong, FM, and the hazards of genius.

No single person did more for radio broadcasting than Edwin Howard Armstrong. And, arguably, no single inventor ever suffered more legal and emotional trauma.

For nearly two decades, Armstrong fought a legal battle to gain recognition and compensation for one of the greatest breakthroughs in the early history of radio: the regenerative circuit. He filed a patent application in 1913 for the innovation, which vastly improved the ability of a triode vacuum tube to amplify and receive incoming radio signals, boost the audio output from radio receivers, and, when used as an oscillator, transmit voice signals. But the lengthy, high-stakes legal drama it brought was exhausting and painful. As Armstrong later wrote, “Seldom can an inventor look philosophically upon the bane of his existence, patent litigation, and find much good therein. He might as well be expected to become philosophical about the serpent in the Garden of Eden.”

Armstrong’s remarkable career and life would be characterized by those two aspects: breathtakingly brilliant innovation in radio technology, and ensuing patent litigation, typically against large, rich, and powerful corporations. His follow-up to the regenerative circuit was the superheterodyne, a circuit that enabled a radio receiver to lock on to a signal and efficiently filter out interference. After filing for a U.S. patent in 1918, he and French engineer Lucien Lévy battled it out for several years, until the courts essentially sided with Lévy, who was awarded an American patent in 1929.

Seemingly interminable legal challenges weren’t enough to dissuade Armstrong from continuing to experiment with wireless technology, however. In the 1920s he began working on what would become the achievement for which he is most commonly remembered: frequency modulation. At a time when voices and music were impressed on to a radio carrier wave by modulating the carrier wave’s amplitude, Armstrong was one of many engineers who perceived the significant potential advantages of modulating the wave’s frequency instead. Within five years he devised one of the first workable approaches to high-fidelity frequency modulation (FM) radio. But his claims would lead to another monumental battle, in and out of the courts, that would delay the large-scale rollout of FM radio for decades and take a crushing toll on Armstrong himself.

HIGHER FIDELITY

Armstrong was already well known for his work on the regenerative circuit, done while he was a student at Columbia University, where

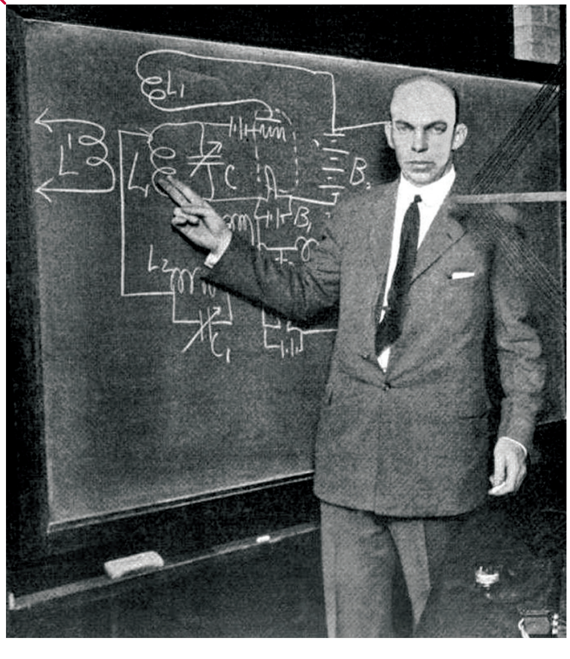
In 1923, Edwin Armstrong built the world’s first portable radio as a gift to his new wife, Esther Marion McInnes.

BETTMANN/GETTY IMAGES

he earned a bachelor's degree in electrical engineering in 1913 (see "Triodes and Tribulations, p. 36). When the U.S. entered World War I four years later, he joined the Army Signal Corps and invented a method for detecting enemy communications, and he installed a radio system for the French based on the technique he'd devised.

The superheterodyne was next. After creating his initial design, he and his assistant worked with engineers from General Electric Company to simplify the circuit. The new version was used in a home radio set, the Radiola, that was a huge commercial success for RCA in the 1920s. Around this time, Armstrong apparently became friendly with David Sarnoff, whom he had known for years. Armstrong also married Sarnoff's secretary, Esther Marion McInnis (who went by her middle name). As a wedding gift, in 1923, Armstrong gave his new wife the world's first portable radio. That same year, Armstrong became a millionaire (which was a big deal then) by licensing his super-regeneration patents to RCA and becoming the company's largest shareholder.

In the 1920s, there was a lot of interest in improving the quality of radio broadcasts. These amplitude-modulated (AM) broadcasts were plagued by static and other forms of interference. Quite a few radio engineers thought switching to FM might lead to audible improvement.



On June 28, 1922, at Columbia University, Armstrong demonstrated his superregenerative receiver circuit to members of the Radio Club of America. Visible to the right, near Armstrong's shoulder, is the loop antenna for the receiver.

But there was also a fair amount of skepticism about FM as well. In 1928, a prominent mathematician at AT&T, John Renshaw Carson, published an article in the July issue of the *Proceedings of the Institute of Radio Engineers* (one of the IEEE's predecessors) that demonstrated mathematically that FM would not enhance quality. In his IRE article, Carson concluded that "static, like the poor, will always be with us."

When Carson's article came out, Armstrong was a professor at Columbia, working on the FM challenge in a basement laboratory at the university. Already wealthy, he declined to accept a salary from Columbia so that he could focus on his research, rather than teaching.

The FM systems that many scientists were exploring at the time were based on narrow-band FM—as were Carson's calculations that had "shown" FM to be ineffective. In fact, radio research in general was largely focused on putting more information into narrower frequency bands. But Armstrong took a different route, and over the course of thousands of experiments turned his attention to wide-band FM.

This work resulted in "the discovery of a new principle in noise reduction, the application of which furnishes an interesting conflict with the principle that had been the guide to the art for years," Armstrong later wrote. In essence, he found that the use of frequency bands that were much wider than the audio bandwidth did indeed have a significant effect on quality. He wrote that "the power gain of the signal-to-noise ratio increases as the square of the frequency bandwidth used, and gains of a thousandfold or more can be realized in practice."

SUCCESS—AND REJECTION

Armstrong patented his approach to FM in 1933 and demonstrated it to Sarnoff later that year. He spent most of 1934 learning that his system had many more capabilities than he had patented. Much of this testing occurred in RCA's leased space on the 85th floor of the Empire State Building, with an antenna mounted on the building's spire.

On November 6, 1935, he presented a

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paper on FM at a meeting of IRE. One of the landmark publications in electrical engineering, the paper was published the next year in the *Proceedings of the IRE* under the title "A Method of Reducing Disturbances in Radio Signaling by a System of Frequency Modulation." It laid out the technical case for FM as a "very greatly superior" technology in comparison with AM. The paper describes the specific characteristics of an FM system that were necessary for it to exceed the performance of an AM system, while acknowledging its greater complexity. After presenting his findings at the IRE meeting, Armstrong rolled out a prototype FM receiver and demonstrated its ability to eliminate static.

At RCA, Sarnoff, who was now running the company, was less enthusiastic. Sarnoff had created RCA's broadcast network of AM radio stations, and he reportedly said later that he was expecting an invention that would simply eliminate static from AM transmission, not "start a revolution" that would require new equipment. In addition, RCA was intent on developing its television and home facsimile systems into businesses and so had little interest in their AM stations investing large amounts in another radio format. So Sarnoff rejected the new radio technology, and RCA ended Armstrong's Empire State Building experiments in 1935.

Armstrong decided to continue on his own. Cashing in some of his RCA stock—he was, after all, the company's largest shareholder—he established the first wide-band FM radio station, W2XMN, in Alpine, New Jersey, in 1939. Other broadcasters formed the Yankee Network of FM stations in New England, with Armstrong's assistance.

RCA eventually saw the value of FM and in 1940 offered Armstrong $1 million for the non-exclusive use of his patents. But Armstrong insisted on receiving the same licensing fees that he charged other companies. RCA began to work on its own FM patents, which it claimed did not infringe on Armstrong's. Other companies, licensing from RCA, stopped paying licensing fees to Armstrong. Then the FCC adopted a controversial plan—backed by RCA—to change the FM radio band from 42–50 MHz to 88–108 MHz. The plan went into full effect in 1949, making existing FM transmitting equipment and some 400,000 receivers that had been sold to date all obsolete. The decision essentially reset the FM broadcasting market back to zero.

He found that the use of frequency bands that were much larger than the audio bandwidth did have a significant effect on quality.

POSTHUMOUS TRIUMPH

In 1948, Armstrong sued RCA for patent infringement. RCA's lawyers managed to delay the trial for five years with pretrial motions and numerous depositions. In the early 1950s, Armstrong himself reportedly predicted that "they will stall this along until I am dead or broke." He was right.

With the lawsuits and ignored patents eating away at his wealth and his state of mind, Armstrong lashed out at his wife, Marion, in November 1953. She promptly left him. Armstrong, overcome with grief, put on his hat, scarf, and coat and jumped from the window of his 13th-floor Manhattan apartment. He was found on the morning of February 1, 1954. Hearing of the death, Sarnoff reportedly told a friend, "I did not kill Armstrong," and he wept openly at the inventor's funeral. At the time of Armstrong's death, he had 21 patent lawsuits related to FM before various courts.

In the 1930s, Armstrong had thought that wideband FM radio, with its superiority over AM, would rapidly become dominant. But even then, he said, the one thing that could slow it down was "those intangible forces so frequently set in motion by men, and the origin of which lies in vested interests, habits, customs, and legislation."

Those forces did slow FM down, but they didn't stop it. Armstrong's widow, Marion, continued to pursue patent litigation against various companies, and she won or successfully settled all 21 pending suits, amassing some $10 million—including a $1 million settlement with RCA. In doing so, she vindicated Armstrong's long legal struggles and affirmed his role as the inventor of wideband FM. And by the early 1970s, FM radio itself was reaching more and more listeners, and was well on its way to dominating the radio bands. ■

COMPUTING | 1939-1945

Bombes Away

Bletchley Park's cryptologists created the tools and procedures to turn Axis messages into a torrent of actionable intelligence.

"We shall fight to the end thinking of you and confident as a rock in the victory of Germany," wrote Admiral Günther Lütjens to his führer on May 26, 1941. The next morning two British battleships sent his boat, the *Bismarck*, the largest and most powerful battleship ever built by Germany, to the bottom of the sea, 800 miles off the coast of Brest. Lütjens and most of his crew of more than 2,000 perished.

The location of the ship was known to the British military thanks to perhaps the best cryptography operation ever assembled up to that point, with hundreds of mathematicians, cryptologists, engineers, technicians, and clerks decoding German messages at Bletchley Park, a rambling old mansion 46 miles northwest of London. In 1945 that staffing level would peak at around 12,000.

Tommy Flowers [below] led the design and construction of the Colossus machines.

BREAKING THE ENIGMA

The messages that gave away the *Bismarck*'s position—like the great majority of encrypted messages sent by German forces throughout the war—were encrypted with a kind of rotor enciphering machine called Enigma. These devices looked like typewriters but with wheels, or rotors, where the carriage would normally go, and circular windows for each letter instead of typebars. Press a letter on the keyboard and one or more of the wheels would turn and light up one of the letter windows. Most Enigmas had three rotors and for one of those machines, every time an operator struck a key, the possible combinations that could come into play that resulted in that letter being enciphered into another letter numbered about 15.8 quintillion (158 followed by 17 zeroes). It took two people to operate the machine. One would type the message while the other wrote down the encrypted output, after which it was sent off, typically as Morse code.

Bletchley had been set up by Admiral Sir Hugh Sinclair, head of the Secret Intelligence Service, who wanted a base for the Government Code and Cipher School to work with the SIS. Aware of the threat of electromechanical encryption, he bought Bletchley himself when the government wouldn't cough up the funds. In September 1938, a staff of 150, calling themselves "Captain Ridley's Shooting Party," moved in.

The GC&CS brought in Alan Turing, a British mathematician and logician who had recently built an electromechanical binary

LEFT: THE HISTORY COLLECTION/ ALAMY; TOP: EVENING STANDARD/HULTON ARCHIVE/ GETTY IMAGES

multiplier for his Ph.D. project. Another early recruit was mathematician Gordon Welchman.

They started off with a gift from Poland, a machine they called the bombe that was used to decrypt Enigma messages. With Turing, Welchman, and other "professor types" on hand, the Bletchley group soon had their own bombes. They broke the German army Enigma in January 1940 ("The Green," they called it), and soon after, the one used by the Luftwaffe's liaison officers ("The Red").

Their success was so great that it created some unforeseen problems. For one thing, acting on the deluge of pristine intelligence might tip the Germans to the fact that their codes had been broken. Another problem was that they had not yet worked out how best to deliver so much good material in a timely way.

IMPRESSING CHURCHILL

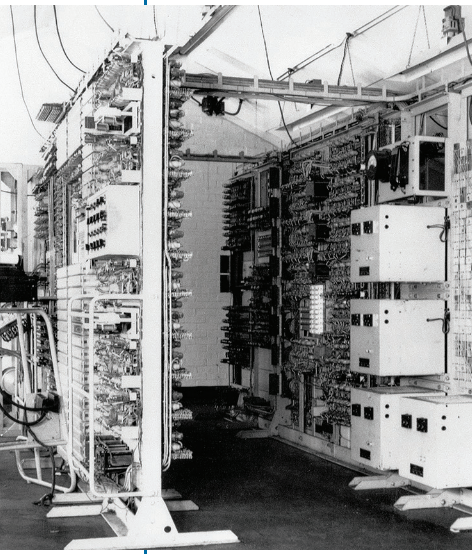
Eventually, special liaison units were created to bring the priceless information to commanders in the field. After the sinking of the *Bismarck*, Churchill stopped by Bletchley, met Turing, and was duly impressed. Turing seized the opportunity to ask for more money, and the request was granted. By 1944 the expanding team at Bletchley had 70 bombes and was decoding roughly 84,000 Enigma messages each month. Five reports an hour, 24 hours a day, were assembled from this mammoth mass of raw intelligence by specialized agents and sent out to those who needed it.

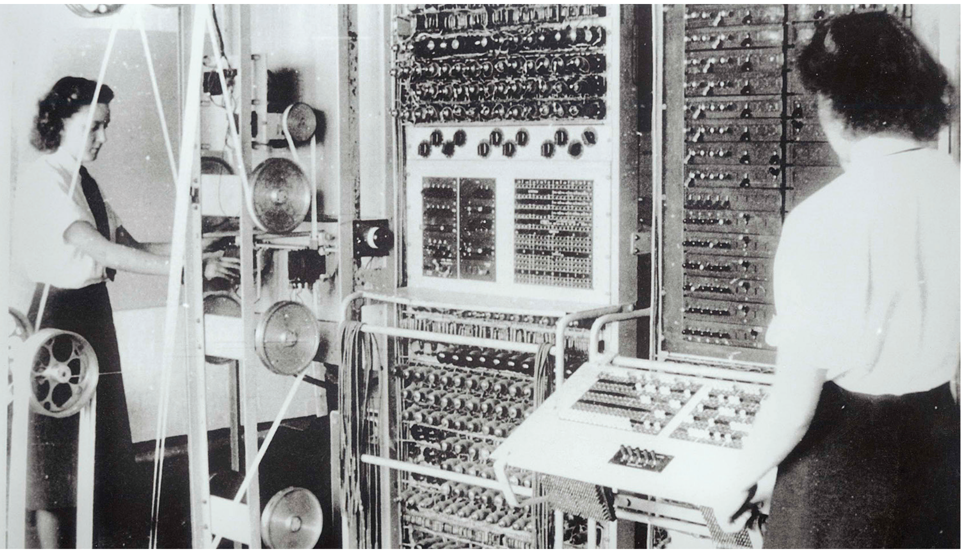
The intercepted Enigma messages, though, were typically of a tactical nature. For the highest level of communications, to and from Hitler and his commanders, the Germans had other machines. The Lorenz Schlüsselzusätze 40, or SZ 40, (and later SZ 42) used an encryption system originally developed by the American engineer Gilbert Vernam during World War I. It converted text into a stream of seemingly random binary five-bit numbers, each number representing a letter. The numbers were then transmitted by teletype.

Engineer Tommy Flowers, then working on telephone switching systems for the Post Office Research Station at Dollis Hill, pro-

Built in the 1880s, Bletchley Park [above, left] was originally the home of Sir Herbert Samuel Leon, a financier and Liberal Party Member of Parliament. The three-rotor Enigma machine [above] was the main encryption system used by the German armed forces. Of the approximately 37,000 Enigma machines built during or before World War II, 318 are known to have survived, and are mostly in private and museum collections.

SSPL/GETTY IMAGES





The Colossus machine [above] was designed to break teletype messages encrypted with cipher machines known as Schlüsselzusätze. They were operated by members of the Women's Royal Naval Service.

BLETCHLEY PARK TRUST/SSPL/GETTY IMAGES (2)

posed creation of a new machine to drastically speed up the solution of the Lorenz messages. He was rebuffed by the Bletchley bosses—largely because of Welchman, who particularly disdained Flowers's confidence in tubes. But Flowers went ahead anyway, leading a team at Dollis Hill and committing his own personal funds to the project. The machine that resulted, called Colossus, is considered by some to be the world's first electronic digital computer. (It was a special-purpose machine, however, unlike later systems, which could be programmed for different tasks.)

To build Colossus, Flowers, the son of a bricklayer, proposed to use 1,600 tubes for the first machine, the Mark I. This idea was met with skepticism and was largely why Welchman managed to turn other Bletchley administrators against the plan. Tubes, as any radio listener of the day knew, died all the time. But Flowers knew from his experience with telephone switching systems that tubes wore out from being turned on and off. If the machine was just left on, there wouldn't be a problem. He was right, and eventually each of the Mark II Colossus machines would use 2,400 tubes without a hitch, both types of machines staying on for most of the rest of the war.

FLOWERS: VINDICATED BUT SNUBBED

The Colossus machines (eventually 10 of them were delivered to Bletchley) simulated the rotors of an SZ 40 using a kind of bit-stream generator based on rings of thyratrons, which were a neon gas tube that could store one bit of data. These thyratron rings, or "ring counters," were of different scales, representing the 12 different rotors of an SZ 40. The message to be decrypted was read into a Colossus on paper tape, with the data encoded as punched holes and spaces and read optically with a photoelectric cell. The first machines could read 2,000 characters a second, as long as the tape didn't break (which it often did). Still, such data input was a monumental achievement—far beyond anything achieved up to that point.

"The initial function of Colossus was to help determine the starting point of the wheels," wrote historian Allison Marsh in a 2019 article published in *IEEE Spectrum*. "Colossus read the cipher's stream of characters and counted the frequency of each character. Cryptographers then compared the results to the frequency of letter distribution in the German language and to a sample chi-wheel combination," she explained. The chi-wheels were a group of rotors in the SZ 40 machines that moved in unison to encrypt letters. By "continually refining the chi-wheel settings until they found the optimal one," Marsh noted, the British cryptographers could solve a message, typically in about four days.

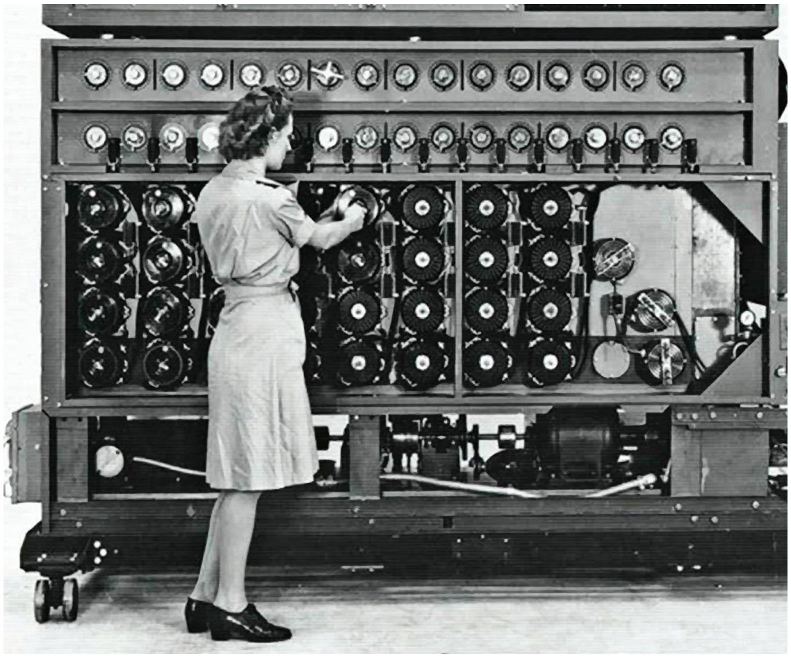
To implement that basic algorithm the Colossus machines used a decision tree, but it could only go so far. When it got bogged down, a human, typically a member of the Women's Royal Naval Service (they were called "wrens"), would jump in to assist with the decision-making. In a sense, the machines were forerunners of interactive computing.

The wrens who operated the Colossus machines were treated to quite a spectacle in those days when a radio was about the only electronic system most people ever encountered. As one wren, Eleanor Ireland, put it: "All these huge clicking valves pulsating; the whole thing was pulsating. They generated a great deal of noise, of course, as one valve after another pulsed in, and then the whirring of the tapes. It was quite noisy."

Messages decrypted with Colossus provided intelligence of enormous strategic value, including reams of data used to plan the D-Day invasions in June 1945. And yet after the war, the British government offered Flowers a measly £1,000, which covered only a small fraction of what he had personally spent on Colossus.

Most of the technical details of Bletchley's achievements were kept secret for decades—bombes and Colossus machines and even their plans were destroyed. But today, with a working reconstruction of a Colossus begun in the 1990s, Bletchley is now a historic site. There's also a plaque, recognizing the IEEE Milestone awarded in 2003 to the approximately 3,000 men and nearly 9,000 women who worked at Bletchley, helping to make the fog of war more transparent. ■

To break Enigma-encrypted messages, British and later American codebreakers used a series of machines called bombes. Pictured here is an American bombe.



NATIONAL CRYPTOLOGIC MUSEUM

The American Bombe

One of the most successful fruits of the Bletchley bombes was the tracking and destruction of U-boats in the Atlantic. But in February of 1942, the German navy added a fourth rotor to their Enigmas.

Without the ability to read enemy messages, losses in the Atlantic skyrocketed, from some 400,000 tons per month to 700,000. As many of those losses were from American ships bringing supplies to England, the U.S. decided it needed to get in on the decryption game.

In July 1942, British codebreakers handed over full blueprints and wiring diagrams to two U.S. Navy lieutenants. So the U.S. Navy began building its own bombe, with its cryptanalysis unit, the OP-20-G.

To lead the effort, the Navy recruited Joseph Desch, the director of research at the National Cash Register Company's Electrical Research Laboratory. Desch had already proved his mettle by making high-speed electronic counters for the war effort.

By mid-1943, Desch felt ready to show off his first two bombe models, Adam and Eve. But after working for just a few hours the rotor contacts burned away and oil spurted everywhere. Meanwhile, Bletchley had finally produced a four-rotor bombe of its own.

To avoid being reduced to being just a manufacturer of the new British bombe, Desch quickly fixed the rotor contact problem and a few other issues, producing two new models, Cain and Abel. Not only did they work, they were 25 to 30 percent faster than the British ones.

The Americans soon had 120 bombes, twice as many as the British, and each weighing 2.5 tons. But like those at Bletchley Park, the bombes of OP-20-G were broken down and destroyed after the war to keep their inner workings secret. Only one of them still exists, in non-working order, at the U.S. National Cryptologic Museum in Maryland.

Desch, a humble man, received a Medal of Merit from President Truman in 1947, though he was forbidden from saying why. In 2001, the IEEE designated as a Milestone the United States Naval Computing Machine Laboratory, in Dayton, Ohio, where the bombes were built.

COMMUNICATIONS & COMPUTING | 1939-1967

The Usefulness of 'Totally Useless Things'

Claude Shannon's ideas redefined information, setting the world on a path that would lead to the digital revolution.

By the 1940s, there were many ways to send information electronically—telephone, telegraph, radio, television. And everybody knew what information was. It was a message from home, popular and classical music over the air, a call from the hospital, data in an experiment measuring annual crop yields. Basically, information was content.

That began to change in 1948, when Claude Shannon, an engineer and mathematician at Bell Telephone Laboratories, published a key paper that redefined information, and even made it possible to measure it. His ideas crystalized a profound shift in understanding that formalized the new discipline of information theory, transformed communications engineering from an art to a science, and set the world on a path that would lead to the digital revolution.

ENTERING THE WORLD OF INFORMATION

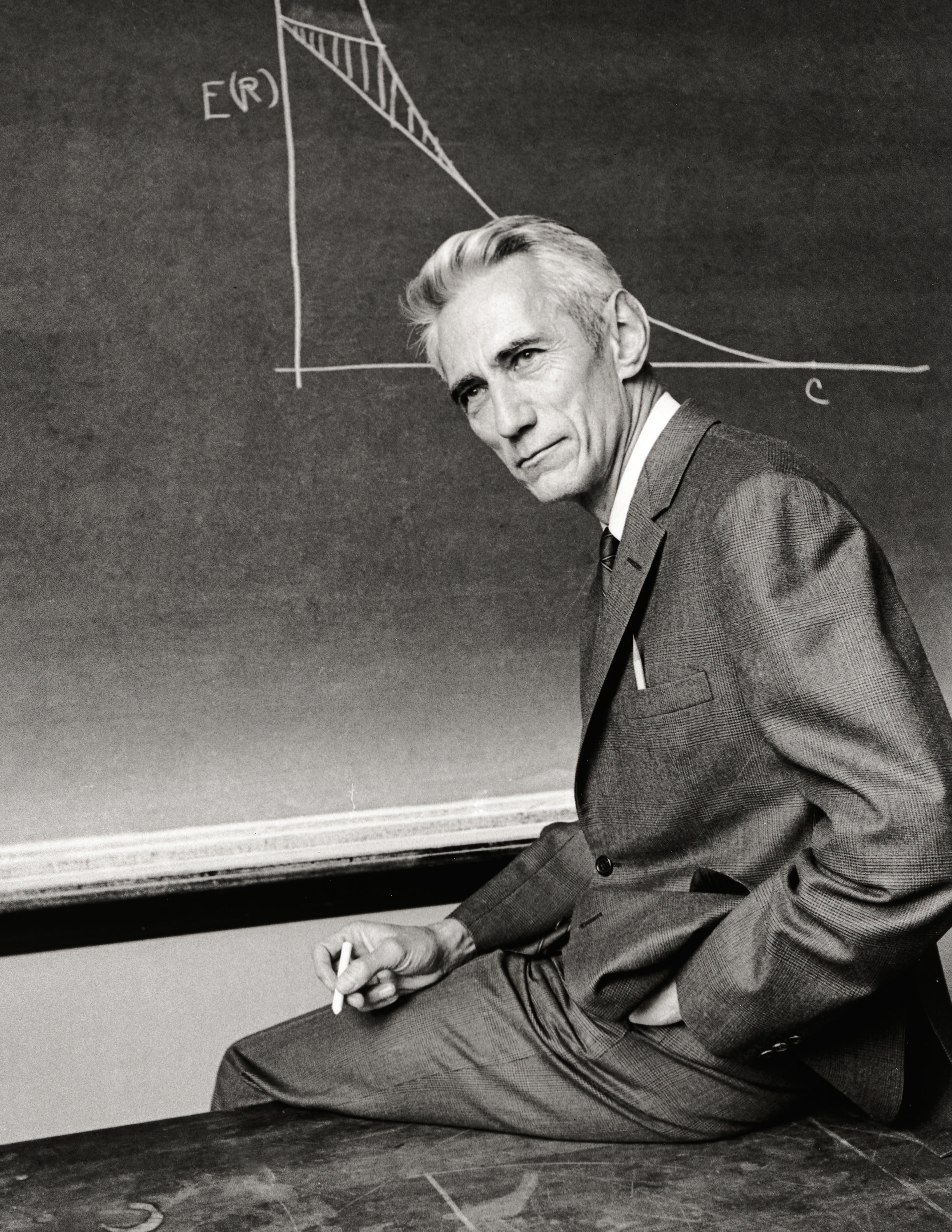
Shannon was born in Northern Michigan on April 30, 1916, and as a boy liked to do mathematical puzzles, play with radio kits and Erector sets, and build model airplanes. In 1936, he graduated from the University of Michigan with two degrees, one in electrical engineering and one in mathematics. He went on to M.I.T., where he earned a master's degree in engineering and a Ph.D. in mathematics in 1940.

At M.I.T., Shannon was exposed to information processing early on when he was put to work maintaining Vannevar Bush's "differential analyzer." This was a room-size analog computer that used wheel-and-disc mechanisms to solve differential equations by integration. He also completed a master's thesis, "A Symbolic Analysis of Relay and Switching Circuits," a version of which was published in 1938 in the *Transactions of the American Institute of Electrical Engineers* (AIEE, one of the IEEE's predecessor societies). Howard Gardner later called it "possibly the most important, and also the most famous, master's thesis of the century." It won an award from the AIEE in 1940; in later life, Shannon said this was his favorite honor out of the dozens he had won in his lifetime.

Shannon's thesis showed that a system of mathematical logic invented in the 1840s called Boolean algebra could be used to improve the way that relays in telephone routing switches were arranged. Shannon demonstrated that circuits used to control a complex

Mathematician, electrical engineer, computer scientist, cryptographer, juggler and prankster: Claude Elwood Shannon, seen here in 1968 at age 52, was one of the 20th century's greatest minds.

MIT MUSEUM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system, such as a telephone switching network, could be represented by Boolean algebra. Once you did so, you could analyze and solve problems in designing these circuits using standard techniques associated with this logical system. Circuits could now be designed and then evaluated with formal mathematical principles, before they were built. Boolean algebra was the binary underpinning of what became, years later, the dominant logic of digital computers.

After M.I.T., Shannon joined Bell Labs in New Jersey in 1941. There he worked on war-related projects, such as control systems for directing anti-aircraft fire and secure communications systems, including one used by Churchill and Roosevelt in their transatlantic conferences. During this period, he wrote a "A Mathematical Theory of Cryptography," which was not published until 1949 for security reasons—and became a linchpin in modern cryptography.

FORMULATING A NEW THEORY

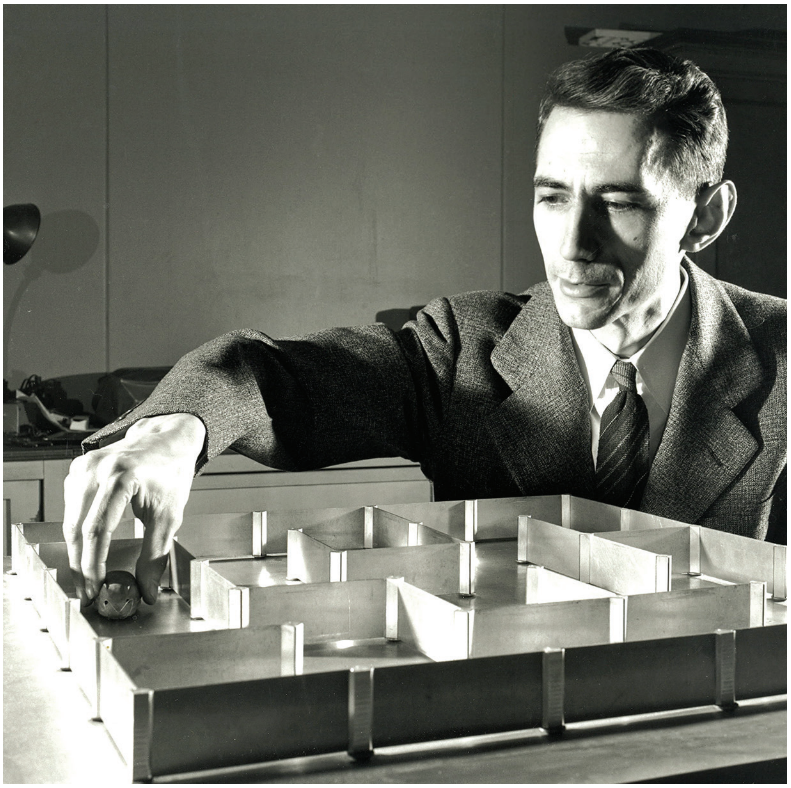
Even as he remained busy with war-related work, Shannon was thinking about information theory. This activity finally led to his landmark paper, "A Mathematical Theory of Communication," published in 1948 in the *Bell System Technical Journal*.

In the paper, Shannon offered a simple statement: "The fundamental problem of communication is that of reproducing at one point, either exactly or approximately, a message selected at another point." He went on to explore mathematically, and at a fundamental level, how that could be done efficiently in the presence of noise in a communications channel connecting those two points.

With his theory, Shannon introduced a number of new, and often counterintuitive, ideas. One of these was the definition of information as something separate from the traditional idea of content. "Frequently the messages have meaning.... These semantic aspects of communication are irrelevant to the engineering problem," he wrote. Instead, he thought of the information sent in a transmission in terms of probability. If a message was a paragraph that was identical to what the receiver was expecting, it contained no information in Shannon's reckoning. On the other hand, if a message was a string of completely random characters, each of which having the exact same probability of occurring in the string, the message had maximal information (but zero content). Interestingly, by this measure, a message in a language conveys *less* information than that random string, because the letters that make up a word, and the words in a sentence, follow known and distinct probabilities.

Shannon's further insight was the concept of information entropy, which measures the amount of information conveyed by a message. It does this by measuring the randomness of individual characters. For example, the entropy of any single character in a random string of characters is higher than, say, the entropy of the letter "e" in the word "pear" in a message in English text. By defining the information content of a message and establishing a way to measure its entropy, Shannon could determine how much information, at minimum, would be necessary to transmit the message.

Shannon's paper was also the first to introduce the word "bit" (from "binary digit") in print, although he later said a colleague at Bell Labs, John Tukey, had previously used the term in a memo. With the simple probabilities involved in the choice of 0 or 1, the bit represented a basic unit of uncertainty—a tiny piece of information. This later led to an



While at AT&T Bell Laboratories in 1950, Shannon built a reconfigurable maze with logic hidden beneath it. The logic was capable of solving the maze by moving around a carved wooden mouse, called Theseus, by means of magnets and motors. When Theseus hit a dead end, the logic recorded the misstep and avoided it on the next attempt. Constructed years before integrated circuits, Shannon's circuitry was based on 110 electromechanical relays, divided among logic and memory functions.

AT&T ARCHIVES AND HISTORY CENTER

By defining the information content of a message and establishing a way to measure its entropy, Shannon could determine how much information, at minimum, would be necessary to transmit the message.

understanding that encoding information—words, music, etc.—into bits leads to the most efficient means of transmitting information. In the analog world of the mid-20th century that concept stunned engineers and scientists and forced them to think in a new way about communications and information.

Shannon demonstrated mathematically that a communications channel could be described using two factors—bandwidth and noise. Bandwidth is the range of electromagnetic frequencies that make up the channel and are therefore available to carry information. Noise is related to the probability that a symbol will be changed to another as it travels through the channel. He provided a way to calculate the theoretical maximum rate, called the Shannon Limit, at which data can be sent error-free over a channel, given a specific channel bandwidth. And he showed that error-free communications were possible if additional bits were added to the encoding scheme to detect errors. The overall transmission rate, including error detection, could not exceed the channel's maximum capacity, of course.

Shannon's paper provided a rigorous mathematical understanding of the transmission of information, and its limits, regardless of the type of communications system involved. Engineers have been applying and building on its concepts right up to the present day, devising error-correction and encoding schemes that get closer and closer to the Shannon Limit. It also led to methods for acquiring, compressing, storing, and encrypting data.

That one paper would have been enough to guarantee Shannon a place in the pantheon of great thinkers of the 21st century. But Shannon published another paper a few months later, "Communication in the Presence of Noise," in the *Proceedings of the Institute of Radio Engineers* (one of the IEEE's predecessor societies). This paper elaborated on many of the concepts of the first paper, and introduced some dazzling new ideas. One of these was the quantization of analog signals by sampling them and then converting the samples to binary values, the foundation of what is known today as pulse code modulation. Shannon, along with future IEEE president Bernard Oliver, was granted a patent on the technique in 1956.

RESIDENT GENIUS AT ENTROPY HOUSE

Shannon left Bell Labs and started teaching at M.I.T. in 1958, living near Boston with his wife, Betty, in a home he called "Entropy House," where visitors could view his numerous awards. These included the IEEE Medal of Honor (1966), the National Medal of Science (1966), the Harvey Prize (1972), and the Kyoto Prize (1985). In 1972, the IEEE Information Theory Society began bestowing a Shannon Award, named in his honor.

Throughout his career and into retirement, Shannon maintained an intense and wide-ranging curiosity, exploring areas such as artificial intelligence, cryptography, and the use of probability theory to guide stock investments. At Bell Labs, he rode through halls on a unicycle while juggling, and later wrote a mathematical theory of juggling. He built a computer based on Roman numerals, an automatic Rubik's Cube solver, and a machine that analyzed a person's coin flips to predict whether they will call heads or tails—among many other gadgets.

"I've always pursued my interests without much regard for financial value or value to the world," he cheerfully told journalist John Horgan in 1992. "I've spent lots of time on totally useless things."

Shannon's insights launched a revolution in communications and computer science that is still ongoing. He lived to see much of that impact, before passing away on February 4, 2001. But there was much more to come. And there still is.■

COMPUTING | 1946

Faster Than a Speeding Artillery Round

Conceived to calculate weapons firing tables, ENIAC today is celebrated as the first digital computer.

On Friday, February 15, 1946, 100 distinguished U.S. scientists, military and government officials, and academics gathered at the University of Pennsylvania's Moore School of Electrical Engineering in Philadelphia for the public dedication of something none of them had ever seen before: a large-scale, high-speed electronic digital computer.

This machine, the Electronic Numerical Integrator and Computer (ENIAC), was secretly built at the Moore School by 200 workers over a two-year period and funded by the U.S. Army. The 30-ton computer filled a 1,500-square-foot room, dwarfing the people standing next to it.

It relied on 17,486 vacuum tubes (five times more than any previous device), 70,000 resistors, 10,000 capacitors, 1,500 relays, and 6,000 manual switches, and it consumed 174,000 watts of power. Holding it all together were some 5 million hand-soldered joints. Altogether, the project cost nearly $500,000—almost $8 million in 2023 dollars.

Compared to devices that preceded it, ENIAC operated at what was considered unfathomable speed: roughly 60 times as fast as a typical electrically driven analog computer of the time, called an analog differential analyzer.

The day before the official dedication ceremony, the computer was demonstrated for the press. Reporters watched as ENIAC computed the trajectory of an artillery shell that took 30 seconds to go from the gun to its target. A human could compute such a trajectory in three days, and a differential analyzer could do it in perhaps 30 minutes, but ENIAC calculated the 30-second trajectory in just 20 seconds, faster than the shell itself could fly.

The members of the press were stunned, according to C. Dianne Martin, writing in the December 1995 issue of *IEEE Technology and Society Magazine*. The reporters produced a slew of breathless stories, many of them attributing humanlike thought capabilities to the machine. ENIAC was described variously as a "wonder brain," "magic brain," and "man-made robot brain."

Engineers and officials associated with the development of ENIAC included J. Presper Eckert Jr. [far left], John Brainerd [second from left], Lt. Herman H. Goldstine [fourth from left], and John Mauchly [fifth from left].

UNIVERSITY ARCHIVES AND RECORDS CENTER/UNIVERSITY OF PENNSYLVANIA

A photograph taken on the occasion of the original press conference announcing ENIAC, in February 1946, was published in countless periodicals. Depicted, from left: Pfc. Homer Spence [background, far left], J. Presper Eckert Jr., John Mauchly, Jean Jennings (Bartik), Lt. Herman H. Goldstine, and Ruth Lichterman (Teitelbaum).

BETTMANN/GETTY IMAGES

"ENIAC was referred to as a child, a mathematical Frankenstein, a mechanical Einstein, a whiz kid, a predictor and a controller of weather, and a wizard," Martin wrote. "Even headlines characterizing ENIAC as a calculator or computer used metaphorical language that raised public expectation and even fear of the new machines."

WARTIME NEED FOR COMPUTING SPEED

Such flights of fancy were in stark contrast to the machine's prosaic origin. In 1939, with World War II on the horizon, U.S. Army leaders assessed the military's preparedness after two decades of peacetime and found it lacking. The Ordnance Department's Ballistic Research Laboratory at the Aberdeen Proving Ground in Maryland, responsible for weapons research and development, soon identified a pressing problem: the need to calculate firing tables required for new weapons coming into service.

At that time, human computers relied on firing tables to perform complex math equations to predict the path of artillery shells based on factors such as temperature, wind, and air density. Differential analyzers had been used since the 1920s to compute such tables, but these wheel-and-disc devices were difficult to work with, requiring the precise alignment of gears to program them accurately. The most advanced of these by far was the Rockefeller Differential Analyzer Number 2, built by Vannevar Bush in 1942, based on a more primitive machine he'd built in 1931.

As World War II began, the calculations required to prepare such firing tables for different types of artillery, antiaircraft guns, and bombsights overwhelmed the Ballistic Research Laboratory's computation facilities.

So the Army began searching for ways to accelerate its computations and expand its computational capabilities.

AN INTEREST IN METEOROLOGY

The Army's eventual solution came from an unexpected source. In the 1930s, John W. Mauchly, a physics professor at Ursinus College in suburban Philadelphia, began researching the sun's effects on weather. The calculations he had to perform combined information about weather with data about sunspot activity and other data obtained from the Weather Bureau in Washington, D.C.

Mauchly paid students 50 cents an hour to be his computers, but they could not keep up with the volume of data. Mauchly soon realized he needed machine calculation. He had built an analog computer to perform harmonic analysis associated with research on barometric pressure waves, and he was also trying to build a digital computer that would help with the statistical analysis. But neither effort was reaping the results he needed.

So in the summer of 1941, Mauchly signed up for a course at the University of Pennsylvania in the emerging field of electronics. The class, part of a new program designed to educate students in defense technology, was taught by J. Presper Eckert. Eckert was an engineer who had only just graduated from the university's Moore School, which was then starting to undertake work for the U.S. Army.

INNOVATIVE ENGINEERING TEAM

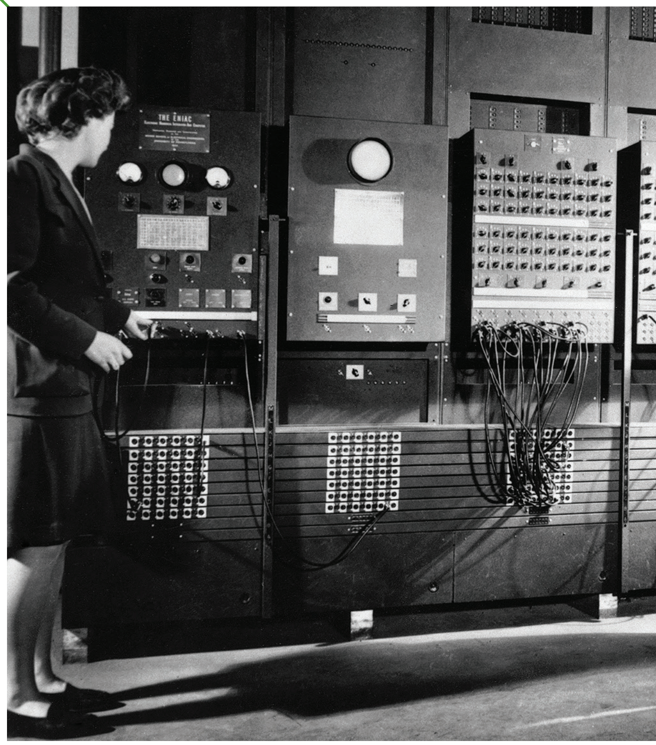
Mauchly and Eckert formed a friendship and partnership that was successful in part because of their different personalities: Mauchly was gregarious and laid-back, and Eckert, somewhat high strung. They embarked on the research project that became known as ENIAC. Mauchly, after joining the Moore School faculty himself, in 1942, wrote a memo outlining his concept for a vacuum tube-based computer, what would be the first large-scale programmable digital electronic computer. The Army quickly recognized that such a machine could confer an extraordinary military advantage in World War II if it could calculate range tables for Allied artillery battalions at the kind of speeds Mauchly believed it could.

Pioneering Women: 'The ENIAC 6'

During World War II and in the years immediately following, most "human computers" at Penn's Moore School and elsewhere were women, as were their direct supervisors. Many of them had experience on production lines in the emerging vacuum tube-based electronics industry of World War II.

Though seldom involved in hardware design, women assisted in ENIAC's creation, and even made it work when the men who designed it were unable to do so. "It was hard because the program was complex, memory was very limited, and the direct programming interface that connected the programmers to the ENIAC was hard to use," said author, lawyer, and documentarian Kathy Kleiman, in a 2002 interview with IEEE journalist Joanna Goodrich. Kleiman helped produce a 2014 documentary about the ENIAC programmers, and wrote *Proving Ground: The Untold Story of the Six Women Who Programmed the World's First Modern Computer.*

The six were chosen from among the Moore School's women computers and became ENIAC's first programmers: Kathleen ("Kay")

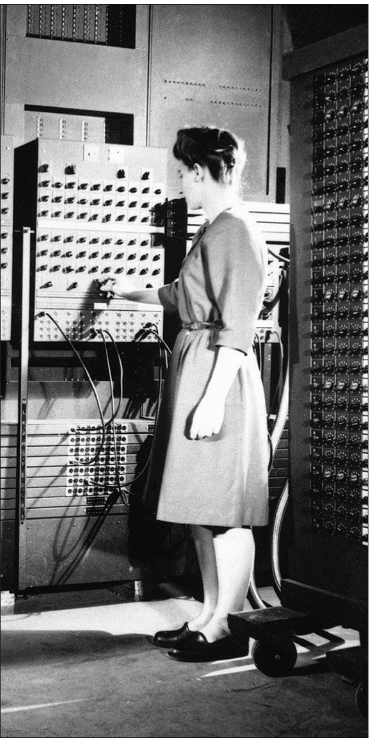


UNIVERSITY ARCHIVES AND RECORDS CENTER/UNIVERSITY OF PENNSYLVANIA

Almost all of ENIAC's operators were women, as was typical in the early days of computing. Shown here are Frances Bilas [left] and Jean Jennings.

McNulty Mauchly Antonelli, Jean Jennings Bartik, Betty Snyder Holberton, Marlyn Wescoff Meltzer, Frances Bilas Spence, and Ruth Lichterman Teitelbaum.

Because the original ENIAC had no internal storage, it had to be programmed manually (though it evolved to become the first operating stored-program computer). It was these first six computers—the "ENIAC 6"—who designed algorithms and physically programmed the machine. That they could reconfigure the machine in whatever manner was necessary to complete a task suggests they knew as much—possibly more—about the functioning of the machine as the men who designed it.



Herman H. Goldstine, Army mathematician and liaison officer, asked Mauchly and Eckert to prepare a formal proposal for the Army, which they delivered a year later. Goldstine and John G. Brainerd, director of wartime research at the Moore School, secured funding for the proposal from the Ballistic Research Laboratory. (Goldstine and Brainerd were later the recipients of the 1980 IEEE Computer Society Pioneer Award and the 1975 IEEE Founders Medal, respectively.)

Work on the ENIAC project officially began in May 1943, with Eckert in the role of chief engineer and Mauchly as principal consultant. The men were assisted in development by a team of design engineers that included Arthur Burks, Jeffrey Chuan Chu, Jack Davis, Harry Huskey, Frank Mural, Thomas K. Sharpless, and Robert F. Shaw.

There were plenty of skeptics, including Vannevar Bush and George Stibitz, who had designed massive relay-based computers for Bell Labs. Stibitz predicted that the ENIAC team would never finish the machine before the war ended, and he was right. ENIAC did not become operational until November 1945. Its first job, in December of 1945, was a complex calculation for researchers at Los Alamos of the feasibility of the proposed design for the hydrogen bomb. When the program was run, it revealed several flaws in the design, flaws that the Army later determined almost certainly would not have been found otherwise.

A LASTING LEGACY

ENIAC's designers quickly grasped that it would have limitations. First and foremost, it should have been able to store programs, which it couldn't. Also, Mauchly and Eckert designed it with counter circuits to perform addition; they realized that combinatorial logic circuits would have been a better choice. Even before the war ended and ENIAC became operational, Mauchly, Eckert, and Army leaders were already planning for ENIAC's successor.

Following ENIAC's formal introduction to the public in February 1946, the scientific community was not uniformly in favor of pursuing the technology. Some wanted tax dollars to go toward improving relay calculators and differential analyzers. But all the breathless media coverage of ENIAC created a public impression of computers as indispensable and infallible tools that would help forge an exciting, if somewhat startling, future. Mauchly and Eckert's work inspired an enormous rush of computer development starting in the late 1940s that eventually spread all over the world.

ENIAC served as the leading computational device for the United States' most pressing scientific problems until at least 1952. Housed in a specially designed building at Aberdeen Proving Ground, it was used for both military and nonmilitary applications—including weather forecasting, wind tunnel design, and cosmic ray study—as well as other feats. In 1949, a team lead by George Reitwiesner used ENIAC to compute the decimal expansion of π to 2,035 places, more than doubling the previous record.

Mauchly and Eckert themselves had recognized other scientific, business, and commercial applications for ENIAC. In 1946, they left the university and together founded the world's first computer company, the Eckert-Mauchly Computer Corporation. They built ENIAC's successor, the Electronic Discrete Variable Automatic Computer (EDVAC), which they delivered to the Army in 1949 while simultaneously designing one of the first commercial computers in the U.S., the UNIVAC.

In 1950, their company was sold to Remington Rand, which later merged with Sperry Corporation to become Sperry Rand, which itself eventually merged with Burroughs Corporation to form Unisys.

In addition to their pioneering contributions to computing through their work on ENIAC, during their careers, Mauchly and Eckert invented or contributed to fundamental computer techniques, including the stored program, subroutines, and programming languages.

For their many achievements, IEEE honored both Mauchly and Eckert with the Harry H. Goode Memorial Award in 1966 and the Emanuel R. Piore Award in 1978. Both were also named charter recipients of the IEEE Computer Society Pioneer Award in 1980. Today, the IEEE Computer Society continues to honor their legacy by presenting the Eckert-Mauchly Award in recognition of outstanding contributions to computer and digital systems architecture. ■

SEMICONDUCTORS | 1947

How the Transistor Amplified Change

Though decades of research hadn't produced a working transistor, postwar developments and the ingenuity of two Bell Labs physicists made the dream a reality.

As the end of 1947 approached, physicists John Bardeen and Walter Brattain, working out of a nondescript laboratory building in Murray Hill, New Jersey, were testing what would become the world's first transistor, arguably the greatest invention of the 20th century. The project had been germinating at Murray Hill's Bell Labs for years. And a great deal was riding on it.

A reliable transistor would allow for the replacement of the power-hungry and fragile triode vacuum tubes that were then used to amplify an electric current. A solid-state device would make electronic systems drastically smaller and more rugged. The impact—in radios and beyond—would be huge.

But decades of research and development had failed to produce a working transistor. Some 20 years earlier, Austrian physicist Julius Edgar Lilienfeld had patented a design for a germanium transistor, but had been unable to get it to work consistently. Part of the problem was the difficulty involved in purifying germanium crystals, which were derived from zinc ore. Advances after World War II enabled the production of much purer germanium crystals, however, and that made all the difference.

BIRTH OF THE TRANSISTOR

Bardeen and Brattain, under the supervision of physicist William Shockley, were working on a three-terminal device that would take a low-power signal into an input terminal and then control a larger current flowing between two other terminals, thereby amplifying the original signal.

But as late as early as December 1947, all their attempts had been unsuccessful. Some of their experimental devices would work momentarily and then fail. The problem, they believed, was that a surface layer of electrons was blocking an applied electric field and preventing it from penetrating the semiconductor and modulating the flow of current.

After repeated false starts, Brattain had an idea. He glued a small strip of gold foil around the edges of a triangle-shaped wedge made of plastic. He then sliced the foil at a vertex of the triangle with a razor, creating two very narrowly spaced gold contacts. These two contacts became two of the three terminals of the transistor. These were known as the emitter and the collector.

To operate it, they took the triangle and used a spring to gently push the vertex—the one with the barely separated gold contacts—into a slab of germanium. This germanium slab served as the transistor's third terminal, called the base. With the base grounded, a small positive voltage on the emitter, and a much larger negative voltage on the collector, the transistor began functioning as they hoped it would.

Charge carriers, consisting of both elec-

Beautiful and ungainly, the first transistor consisted of a triangle of plastic belted by two strips of gold foil. At the lower point of the triangle there was a hair-thin slit in the foil, which was pressed (by the squiggly spring) into a slab of germanium. One side of the slit was the transistor's emitter and the other was the collector. The grounded bottom of that germanium slab served as the transistor's base.

AT&T ARCHIVES AND HISTORY CENTER

trons and positively charged "holes," began migrating between the electrodes and through the germanium. The small positive voltage at the emitter resulted in a trickle of current between the emitter and the base. That current, in turn, created much larger changes in a current flowing between the grounded base and the collector, with its stronger negative voltage. It was a bit rickety, but it was reliable, and it made the decades-old dream of a reliable solid-state amplifying device a reality. Because it depended on that triangle point being in contact with the slab of germanium, it was called the point-contact transistor.

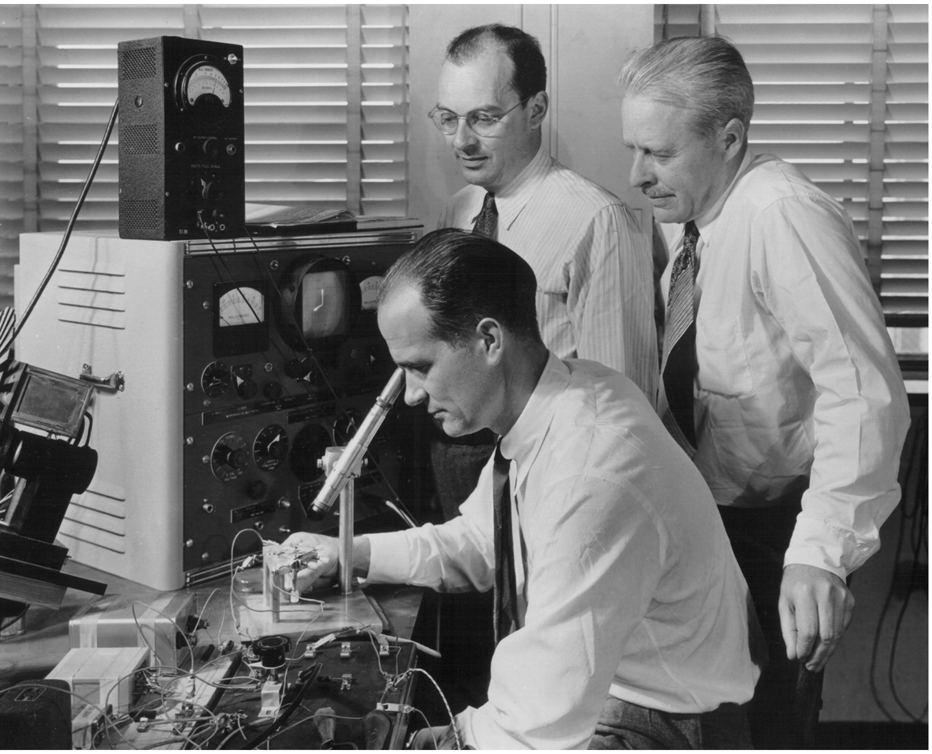
Two days before Christmas in 1947 Brattain and a colleague demonstrated the new invention for half a dozen engineers and executives at Bell Labs. They put it in a simple circuit connected to a microphone and a loudspeaker and used it to amplify speech, demonstrating a power gain of 18 or more.

Interestingly, the details of how the new device actually worked were initially somewhat sketchy and remained so for years. This pioneering device did not depend on the field effect, confounding the belief of essentially all the physicists trying to build a transistor in those days. In 1957, 10 years after the device was demonstrated, Caltech professor R.D. Middlebrook, who would go on to do pioneering work in power electronics, wrote that "because of the three-dimensional nature of the device, theoretical analysis is difficult and the internal operation is, in fact, not yet completely understood."

It wasn't obvious, even to experts, that the transistor was going to revolutionize electronics. In 1953, electrical engineer Donald G. Fink told *Time* magazine, "Is it a pimpled adolescent, now awkward, but promising future vigor? Or has it arrived at maturity, full of languor, surrounded by disappointments?" Fink, a past president of the Institute of Radio Engineers, one of the IEEE's predecessors, would go on to oversee the establishment of the modern IEEE and serve as its first general manager, in 1963.

In 1971, the IEEE awarded Bardeen its highest recognition, the Medal of Honor. The institute cited him for "his profound contributions to the understanding of the conductivity of solids, to the invention of the transistor, and to the microscopic theory of superconductivity." Bardeen also won a Nobel Prize for Physics in 1956, sharing it with Brattain and Shockley, for the invention of the transistor. (Shockley was honored not for the pioneering point-contact transistor but for a different, later design, called the bipolar junction transistor.) In 1972, Bardeen shared a second Nobel Prize in physics, for a theory of superconductivity.

The classic Bell Labs publicity photograph of the inventors of the transistor suggests a harmony and spirit of cooperation among the three that was entirely fictitious. In the photo, John Bardeen and Walter Brattain are standing and William Shockley is seated.



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ALL HAIL THE... IOTATRON?

Before Bell Labs introduced the device that would come to be known as the transistor, in June 1948, the company had to figure out what to call it. They considered "Semiconductor Triode," "Surface States Triode," "Crystal Triode," and "Iotatron," all of which lacked a certain zing. Legendary engineer John R. Pierce, who had supervised the trio of inventors, Bardeen, Brattain, and Shockley, coined the term "transistor." This was a combination of the word "transconductance," which is a property of vacuum tubes, and "istor," a suffix that had been used to name such electronic devices as the resistor, varistor, and thermistor.

As soon as the first transistor was created, work began on improvements. Germanium was an excellent conductor, but it was tricky to purify, and the devices could only operate within a relatively limited temperature range. There were theories that silicon would be a better replacement.

Scientists at Bell Labs and at Texas Instruments each developed transistors fabricated with silicon crystals, and at Bell Labs, in 1954, physical chemists Morris Tanenbaum and Calvin S. Fuller developed a process in which high-performing, layered semiconductor devices could be fabricated by diffusing chemical elements into pure silicon crystals.

Despite these advances, germanium transistors outsold silicon ones well into the late 1950s. This was because high carrier mobility allowed germanium to perform better. The early silicon transistors were hampered by unstable surface states, in which electrons are trapped at the surface of the crystal and prevent other charges from reliably penetrating the surface to reach the silicon layer.

Work continued on silicon. In 1957, at Bell Labs, researcher Mohamed Atalla introduced a new method of semiconductor device fabrication: a silicon wafer coated with an insulating layer of silicon oxide that would allow charges to penetrate the conducting silicon below the surface. Called surface passivation, this method proved critical to the ability to fabricate multiple transistors on a single piece of silicon and connect them into an electronic circuit—known as an integrated circuit, or chip.

THE START OF EVERYTHING

With the invention of the integrated circuit, it became possible to make circuits much smaller and much more rugged than ever before. Moore's Law, which was first described in 1965, pointed out that the number of transistors that could be placed on a microchip was, at that time, doubling about every two years. This growth in transistor density has led to chips with 20 billion transistors; the Apple M2 microprocessor is an example.

The transistor was the realization of a long-held dream of efficiently controlling the flow of electrical current and amplifying signals in a small package. Transistors have spurred innovation in countless sectors of modern society. Starting with hearing aids and radios, they moved on to televisions, computers, medical devices, vehicles, spacecraft, smartphones, and countless other products. ■

A Toxic Work Environment?

Though Bell Labs felt it had created an effective team by assigning Shockley, Bardeen, and Brattain to the transistor project, that didn't guarantee that the three men would work well together. Shockley was put in charge of the project, with Brattain running the experiments and Bardeen interpreting the results. This division of labor seemed to make sense and played to each man's strengths. Shockley saw his role as a manager providing direction while giving space to the others to work on their own.

The problem arose when it came to claiming credit

A 1999 PBS program about the invention of the transistor showed that, in Shockley's mind, he had been responsible for managing the project. He told Bell Labs that meant the transistor should be patented under his name.Bardeen and Brattain, on the other hand, believed it had been a joint effort—and they made their displeasure with Shockley's stance known.

Bardeen characterized the working environment as "intolerable." There's a famous photo of the three scientists (see page 58), released at the announcement of the invention, in which Bardeen and Brattain are watching as Shockley looks through a microscope. The photo irritated Brattain, who felt it made Shockley look more "hands on" than he really was. Soon Brattain asked for a transfer to a different lab and Bardeen took another job, at the University of Illinois. Shockley, however, continued working at Murray Hill, where, in 1948, he conceived and developed the junction transistor, for which he received sole credit.

At the 1956 Nobel Prize ceremony where all three were credited with the transistor's invention, there was little interaction between them. However, after the ceremony, the three ran into each other and spent the evening talking about their days together, the hatchet seemingly buried.

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Richard W. Hamming paused in a computer room in 1980. At the time he was working at the Naval Postgraduate School in Monterey, California, where he was on the faculty from 1976 to 1997.

COMMUNICATIONS | 1947

First-Class Troublemaker

A snafu with a 10-ton computer set Richard Hamming on the path to error-correcting codes.

Just before quitting time on a Friday afternoon in 1947, Richard Hamming started running some calculations on what was, at the time, the world's most powerful relay computer. The calculations would take time, he knew, so he left the machine running unattended at Bell Telephone Labs' New York City facility to do its work over the weekend. When he returned on Monday morning, however, he was crestfallen to see that there were no results. Early in the calculating process, the computer had detected an error that lay somewhere in the vast amount of code. The machine detected something was wrong, but not what, causing it to stop completely.

The computer Hamming was using, a Bell Labs Model V relay computer, weighed 10 tons and had 9,000 relays. Programs and data were entered into the machine on punched paper tape; the results of a program were read out by means of the same medium. A complex program required rather a lot of paper tape. A single typographical error—which might translate into a single incorrect bit—would force a computer to stop. But that wouldn't happen until the computer had to execute the line of code that included the error. And there was no telling where that might be.

Hamming later recalled thinking, "If a machine can find out that there is an error, why can't it locate where it is and change the setting of the relay from one to zero or zero to one?" That question stayed on Hamming's mind, and he eventually developed a coding scheme that automatically corrected just such an error. This solution—called the Hamming Code—helped keep Bell Labs' computers and the Bell System's telephone switching equipment up and running.

Such error-correcting codes also represented a significant step forward for the information age, establishing a concept that has since been used in everything from compact discs to satellite communications, opening the door to a new technical discipline focusing on coding theory.

A KEY CAREER CHANGE

Growing up, Hamming planned to be an engineer, based on the realization during his freshman year of high school that he was better at math than his teacher. He applied for college scholarships but got only one—from the University of Chicago, which did not have an engineering school. He decided to take the scholarship and major in mathematics. After earning a Ph.D. in the subject at the University of Illinois in 1942, he joined the faculty at the University of Louisville in Kentucky.

In 1945, Hamming was contacted by a friend with a mysterious job tip. The work would be interesting and would be part of the U.S. World War II effort, and not many more details would be forthcoming. Hamming nevertheless accepted, and he found himself in Los Alamos, New Mexico, working on the Manhattan Project. His wife, Wanda, soon joined him to run a desk calculator. (She would later work for Hans Bethe and Edward Teller.)

Hamming's job was to maintain the IBM computers at Los Alamos, of which there were five. They were based on electromechanical relays and counters and were used to perform some of the most difficult calculations required to design the first atomic bombs, such as those related to the hydrodynamics of the implosion that would initiate the atomic chain reaction. The physicists would set up the equations and start the process, and Hamming would then keep watch on the machines, freeing the physicists to focus on creating the bomb. The computers were housed in a large room, reminiscent of a "mad scientist laboratory," Hamming recalled. He described his role as being a "computer janitor."

Computers were new to Hamming, but he quickly saw their enormous potential. "I realized that it meant that science was going to be changed," he told journalist Tekla S. Perry in 1993 during an interview for *IEEE Spectrum*. He understood that by handling more and more complex calculations, the machines would enable researchers to explore a wider range of problems with greater speed.

A DEEPER DIVE INTO COMPUTING

After the war, Hamming was hired by Bell Labs' math department in Murray Hill, New Jersey. There, he found himself working with a small group of young colleagues who had been involved in research during the war and were interested in exploring new ideas.

The youngsters included Claude Shannon and John Tukey. Shannon would earn a place among history's greatest information theorists. Tukey devised a fast Fourier transform (FFT) algorithm for translating signals to and from the frequency domain; it is one of the most widely used algorithms ever, with uncountable applications in engineering, science, mathematics, and music.

"During the war, we all had to learn things we didn't want to learn to get the war won, so we were all cross-fertilized," Hamming told Perry. "We were impatient with conventions." They were, he added, "first-class troublemakers" who "did unconventional things in unconventional ways and still got valuable results. Thus, management [at Bell Labs] had to tolerate us and let us alone a lot of the time."

Hamming had been hired by Bell Labs in 1946 to work on elasticity theory, but he spent much of his time working with and thinking about computers. Other researchers at the lab would go to him when they were unable to solve problems with the hand-cranked desk calculators that were common at the time, and Hamming would show them how the labs' electronic computers could help. This work ultimately led him to that frustrating weekend in 1947 when a single unknown error shut the computer down.

Hamming thought about the error problem for a while and eventually came up with a solution. To detect errors, computers at the time added an extra parity bit to a sequence of code. This reflected whether the ones and zeros should add up to an odd or even number, making it possible to check whether something had gone wrong in that sequence, but not where in the sequence the problem was. Hamming added more bits to those sequences, making it possible to automatically identify precisely which bit was erroneous and—crucially—to then repair it by flipping it, taking advantage of the relatively straightforward "either-or" choice of binary code. He also developed a method for arranging those additional bits efficiently. These techniques—which became known as the Hamming Code—could find and correct a single error in a sequence of data or find two errors

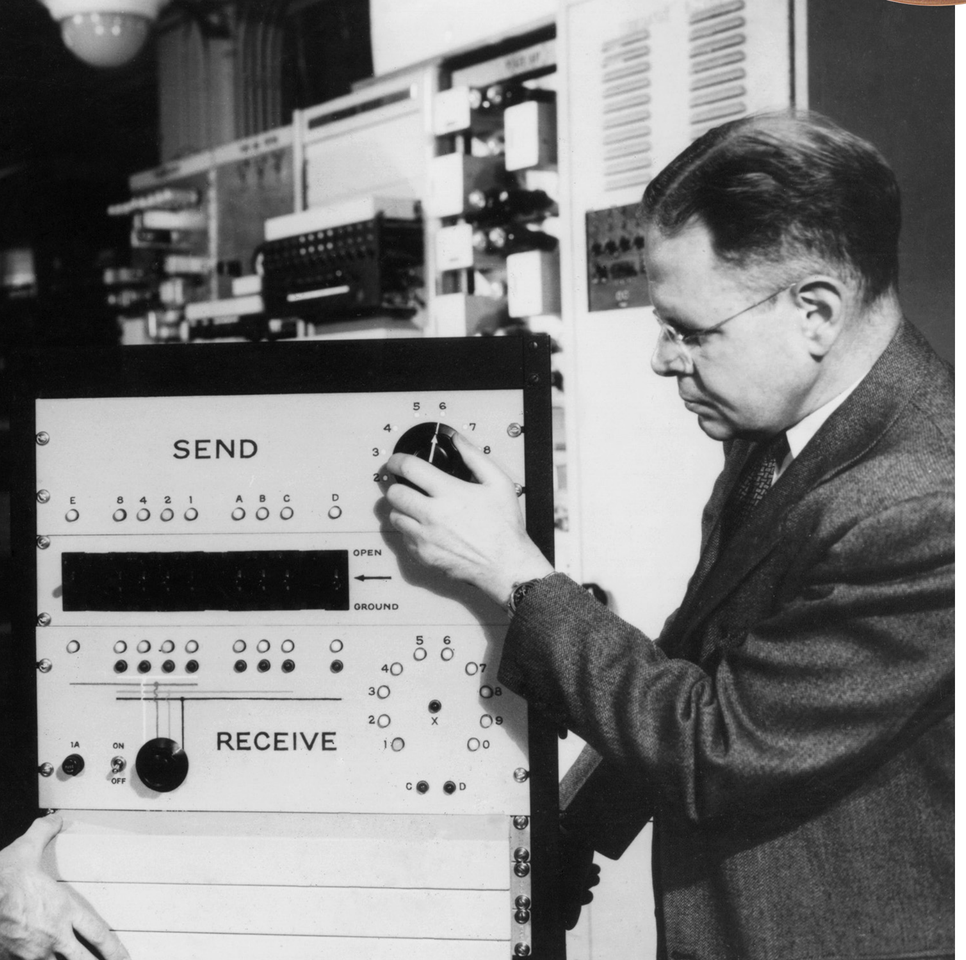
A Bell Labs publicity photo from 1950 shows Hamming [at left in the photo] and engineer B. D. Holbrook flanking a system built by Holbrook to demonstrate Hamming's error-correcting code. In 1988, the IEEE created the Richard W. Hamming Medal [far right].

and correct one of them. Hamming presented the concept and the mathematical formulas involved in a landmark article, "Error-Detecting and Error-Correcting Codes," published in 1950 in the *Bell System Technical Journal*.

Hamming codes are insufficient for long messages that may contain more than two errors. The value of error correction was incontrovertible, however. Hamming codes inspired the development of a wide variety of sophisticated error-correcting codes that are now commonly used in both computing and mathematics.

Incidentally, Hamming codes can also be used for data compression, the process of deliberately removing bits from code with the intention of restoring them later. the codes treat the bits that are missing as if they were errors, and "correct" them, not by switching them from one value to the other—0 to 1 or vice versa—but by determining what they should be and reinserting them. A notable modern application is reducing the size of music and video files, making them easier to store, transmit, and stream.

RIGHT: IEEE; BELOW: AT&T ARCHIVES AND HISTORY CENTER



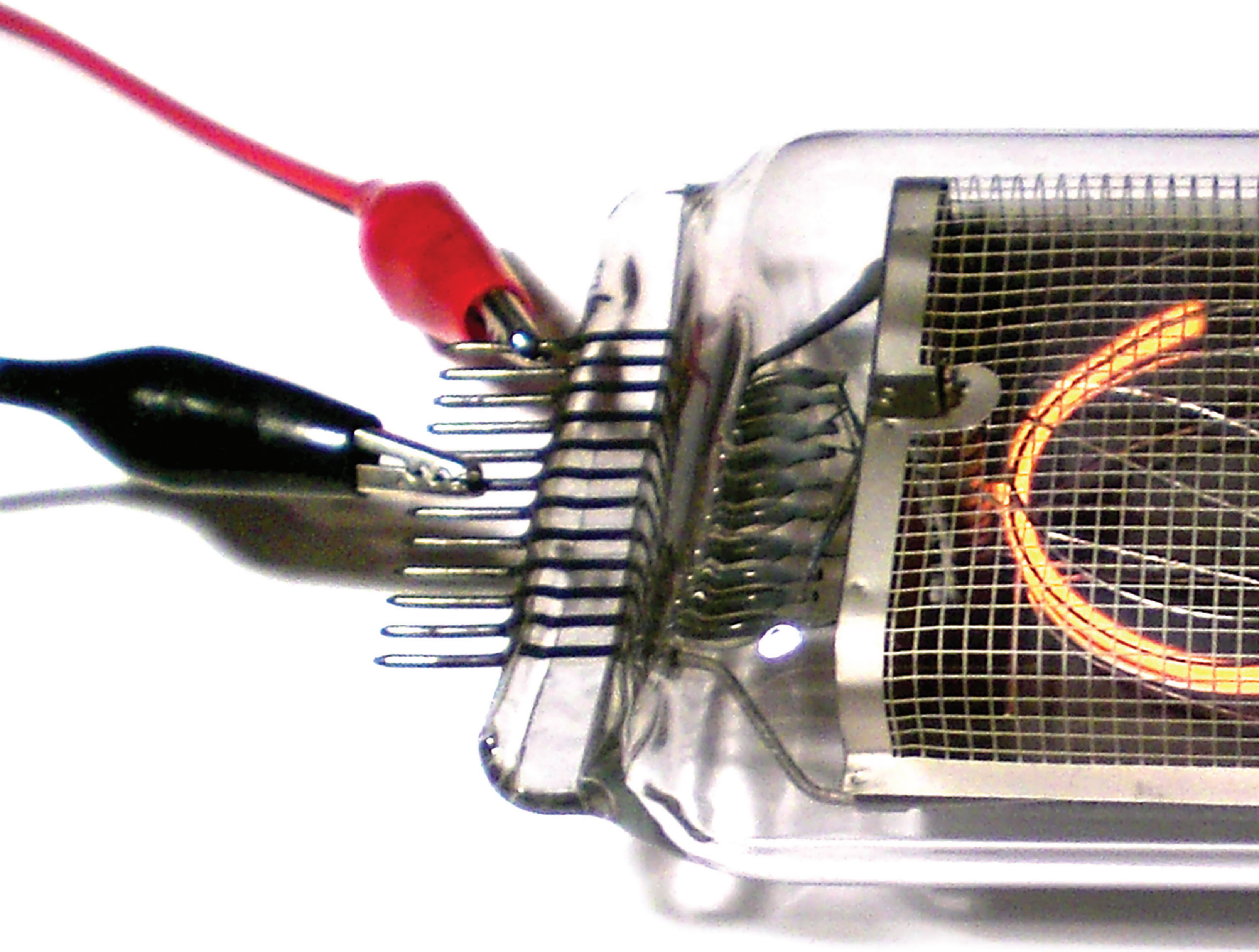
BEYOND THE CODE

Hamming is best known for inventing error-correcting codes, but during his time at Bell Labs he worked on remarkably varied and important projects and problems, including traveling wave tubes, the equalization of television transmission lines, an early programming language, and the stability of complex communication systems. He also developed the Hamming Window—essentially, a statistical tool that enables users to accurately reconstruct a signal, using the FFT of the signal, and based on a sample that isn't an integer number of periods of the signal.

In 1976, at age 61, Hamming left Bell Labs and ended his research career, largely because he believed that older scientists should not stay on the job too long, but rather make room for younger researchers and new ideas. After leaving Bell, he took a full-time position at the Naval Postgraduate School in Monterey, California. He had already published books on computer science, and he continued to write. He also taught at Stanford University, City College of New York, University of California at Irvine, and Princeton University.

Hamming was made an IEEE Fellow in 1968, for "contributions to numerical analysis, information coding, and improved operation of computing centers." The same year, he won the prestigious A.M. Turing Award from the Association for Computing Machinery. Many other honors followed, including the IEEE's Emanuel R. Piore Award in 1979 for his work in error-correcting codes, operating systems, programming languages, and numerical computation. In 1988, the IEEE created the Richard W. Hamming Medal, which honors contributions to information sciences, systems, and technology.

Hamming was also known for his sharp wit. "Once," he is reported to have said, "when Sir Isaac Newton was asked how he made all of his discoveries, he replied, 'If I have seen further than others, it is by standing on the shoulders of giants.' Today, in the programming field, we mostly stand on each other's feet." ■



JENS BOOS

VACUUM ELECTRONICS | 1955

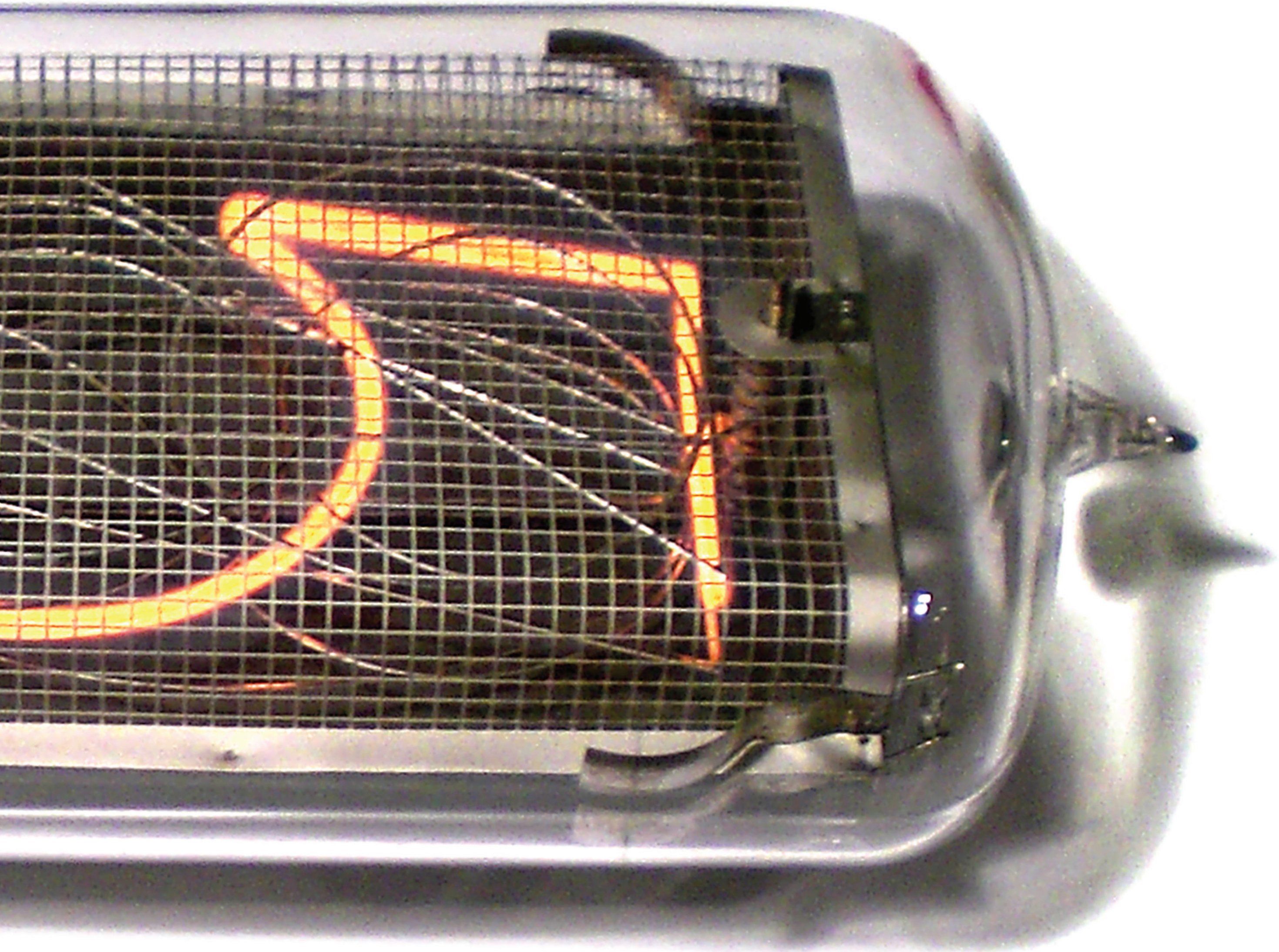
A Sprinkling of Nixie Dust

By the 1930s, neon had conquered urban signage. Times Square and Piccadilly Circus were awash with the stuff. In the United States alone in 1940, some 2,000 neon signmakers were feeding the country's glowing demands.

As it would turn out, glowing neon would transcend signage and play a surprising, pivotal role as electronics took off and became a major industry in the 1950s. Early in that decade, counters, calculators, clocks, and meters had mechanical, and often imprecise, displays.

Then, in the mid-1950s, came a brilliant innovation: neon-filled glass tubes that could display digits and other characters, providing an instantaneous display. They dominated the numbers racket worldwide until seven-segment LED displays came along about 20 years later.

But the Nixie tube, as the device was called, arrived in fits and starts. Sputtering into existence, if you will.



The culturally tumultuous 1960s were an era of mop tops, miniskirts, and Nixie tubes. Only the tubes have survived.

MAKING THE GAS GLOW

The story starts in 1857, when physicist Heinrich Geissler showed that applying a few thousand volts to electric terminals at the ends of an elongated tube filled with certain kinds of gas would cause the gas in the tube to glow brightly. Neon signs were a straightforward application of Geissler's discovery. However, because the gas inside the tubes lit up from one end to the other, the only way to spell something out was to shape the glass tubes into characters, which put a limit on how small you could make those characters. Worse, the fixed nature of such a display ruled out reconfiguring characters instantly, for example in response to electronic signals.

But what if, instead of being affixed to the end to receive a current, the cathode—bent however you wished—was inside the tube? Then you'd be free to shape the wire, rather than the glass. Hermann Pressler and Hans Richter patented just such a device in 1938. Illustrations in that patent show one tube spelling Radio and another spelling Tuba.

The F9020AA Nixie tube was manufactured by CSF (now Thomson-CSF) in France starting in 1962. It was used in some high-end clocks.

And there's also a single tube that has two separate electrodes, each shaped into a distinct word—on and off—in the same tube. With a switch, voltage could be shifted from one electrode to the other, changing which word was lit up.

Four years earlier, the chief engineer at Lorain County Radio Corporation, in Ohio, Hans P. Boswau, had patented a design for a similar tube. According to the definitive article on the history of Nixies, written by physicist Jens Boos and published in 2018 in *IEEE Spectrum*, Boswau's patents "contain the first complete descriptions of what later came to be called the Nixie tube." Crucially, instead of stacked words, Boswau had stacked digits. But Boswau's tube was never manufactured. It's unclear if he even made one.

BETTER CALL SAUL

Then, in 1954, the vacuum tube producer National Union came out with the Inditron, also a stack of digits in a tube of neon. But in its design each hand-shaped number served as either a cathode, when selected to light up, or an anode, when not selected, making for some overly complicated control circuitry.

Burroughs, an adding machine company, saw an opportunity. However, lacking in-house expertise in gas-discharge physics, they roped in Saul Kuchinsky, who'd engineered the Inditron at National Union.

If one name attaches itself to the Nixie tube in the annals of history, it ought to be his. Burroughs also bought the company Haydu Brothers, of Plainfield, New Jersey, expert makers of vacuum tubes. "Those two moves gave Burroughs everything it needed to develop a numeric indicator tube," Boos wrote in his *IEEE Spectrum* article.

A Gap in the Glow: What Creates the Dark Space?

Like a neon sign, a Nixie tube is filled with neon and argon—the mixture allows the voltage to be lower. But in the Nixie, the ionized gas in the tube is not lit homogenously. In fact, the glow seems to be around, but not on the number. This happens because, when high voltage splits the atoms of the gas into positively charged ions and negatively charged electrons, the electrons fly to the mesh anode while the ions race to the negatively charged cathode, which is in the shape of a numeral. The voltage-driven flow of charges sets up a plasma, a kind of soup of ions and electrons that can carry an electrical current. Collisions among the particles in this plasma release photons of light, causing an orange glow. Much of the action is near the cathode.

When the positive ions hit that cathode, they pop metal atoms off of it, a phenomenon called sputtering. These sputtered atoms head out into the plasma. Energized and excited by collisions there, they become unstable and emit additional photons. Very close to the cathode, the electrons are traveling relatively slowly and there are far more of them than ions or atoms. The chance of an electron smacking into an ion or atom and producing photons is low. Slightly farther away, the light-producing collisions are much more likely to occur. So there is a thin, unlit area around the seemingly glowing digit. This space even has a name: it's called the Aston dark space, named after chemist, physicist, and Nobel Prize winner, Francis William Aston.

JENS BOOS

Led by Kuchinsky, the new team got to work improving the Inditron. For one thing, the numbers would no longer act as anodes when off. Instead, a mesh anode would be wrapped around all of the digits. And there would be no more hand bending of wires—for mass manufacture of the tubes, the digit-shaped cathodes would be stamped out of sheet metal. As the digits were stacked on top of each other, they were arranged in a way that would minimize the amount of light blocked by the numeral-cathodes in front. A common configuration was, front to back, 6 7 5 8 4 3 9 2 0 1. The cathodes were separated by tiny ceramic spacers.

In some early prototypes, neon ions hitting the cathode would erode it and cloud the tube before 24 hours had passed. So Kuchinsky and the Haydu team added mercury to the mixture of neon and argon to absorb some of the ions and lower their energy, which protected the cathodes. This and other measures extended the life of the tubes, first to 5,000 hours and later to 200,000 (though the mercury also made the tubes hazardous if they were broken).

X MARKS THE SPOT

Supposedly, Kuchinsky's first sketch of the tubes had the words "Numerical Indicator Experiment No. 1," which would become NIX1, and eventually Nixie. According to Burroughs engineer Roger Wolfe, Kuchinsky thought that words with a k or x made for good marketing.

Whatever the etymology, Burroughs introduced the Nixie tube at the 1955 Western Electronic Show and Convention, a huge annual meeting co-organized by the Institute of Radio Engineers, one of the IEEE's predecessors. The following year, Kuchinsky and two colleagues from Burroughs presented a paper on Nixies at another IRE conference, the International Electron Devices meeting, in Washington, D.C. By then, Nixies were all the rage. More than two dozen companies worldwide were making them in many sizes. (Soviet makers never paid a licensing fee, of course, and they further economized by using upside down 2s for 5s.) Nixie tubes could soon be seen in counters, calculators, multimeters, and all kinds of industrial and scientific equipment, in laboratories, at NASA's mission control, in nuclear power plants, on Wall Street, and anywhere else where a numerical readout was needed.

HAYDU BROTHERS/JENS BOOS

Then, in the 1970s, the Nixie-killer arrived. LEDs were cheaper and easier to use, if less elegant; you can't have a graceful typeface when the digits are made with the same seven segments.

But it was never completely lights-out for the Nixie. Retro-minded engineers and hobbyists started collecting them and, with the explosion of the internet, they saw a full-on revival in the 2000s. So many Nixie tubes had been produced in their heyday that there were still plenty to be had for enthusiasts. The Nixie clock, never a much of a thing in the 1960s, became a steampunk essential. You can still buy a Nixie chessboard and a Nixie watch (famously worn by Steve Wozniak).

- Electrical uniformity
- One simple plug-in tube
- Uses standard socket
- Bright numbers for highest visibility
- Low power required
- Operates directly off Beam Switching Tubes or any voltage source
- Radical simplification of circuitry
- Long Life
- Rugged construction
- High quality
- Low cost

HB 106

DIRECT NUMERICAL READING
10 POSITIONS — 0 TO 9
HIGHEST ACCURACY OF READINGS

"NIXIE"

in-line numerical indicator

An early ad from Burroughs Corp. shows an HB 106 Nixie tube, one of the first commercially produced Nixies.

In the 21st century, Nixies became a pop-culture touchstone in a way matched by few other devices. In a climactic scene in the 2023 blockbuster thriller *Oppenheimer*, the countdown to the Trinity atomic bomb test is shown occurring on Nixie tubes—even though they wouldn't be invented for another 10 years. There are smartphone apps with Nixie-look numerals, and also modern alternatives to Nixies, called "Lixies" and "Plexitubes," typically used in clocks. And perhaps the greatest testament of all, at least one Nixie fan has turned his enthusiasm into a successful manufacturing business. In 2023, a man named Dalibor Farný in the Czech Republic celebrated his first decade of producing and selling new Nixie tubes.

The Nixie dust hasn't settled yet.■

SEMICONDUCTORS | 1958

The 'Flying Wire' Touches Ground

With his co-workers out on vacation, Jack Kilby used the time alone to get a new assignment—and create the invention that would win him a Nobel Prize.

One of the most momentous inventions of the 20th century, the semiconductor integrated circuit, was discovered when the inventor found himself with two free weeks to think outside the box. Or, to be more precise, outside the module.

In 1958, Jack Kilby, a young electrical engineer from Kansas, took a job at Texas Instruments. Kilby had just left Centralab, which was among the first companies to have tried to commercialize new transistor technology. Kilby had led the small Centralab team working with transistors, and TI hired him based on his experience. TI planned to set Kilby to work on electronics miniaturization in general, but had not yet assigned him to any specific projects.

TI had a defense contract to miniaturize computer module technology. Kilby expected TI would assign him to the project, called the Micro-Module program, and he did not want the assignment. TI had also just begun getting involved in transistors, and Kilby wanted to continue working with the technology.

He was just settling in at TI and becoming acquainted with his colleagues when he found himself almost alone in the company's Dallas lab with little to do, as nearly everyone else at TI left for a two-week summer vacation.

Normally bustling offices and workshops were quiet, giving Kilby a chance to experiment with making a monolithic circuit—in which the multiple transistors and other devices making up the circuit were fabricated together on the same slab of semiconductor. If he could demonstrate progress, he felt, he would be able to make a case for getting the assignment he preferred.

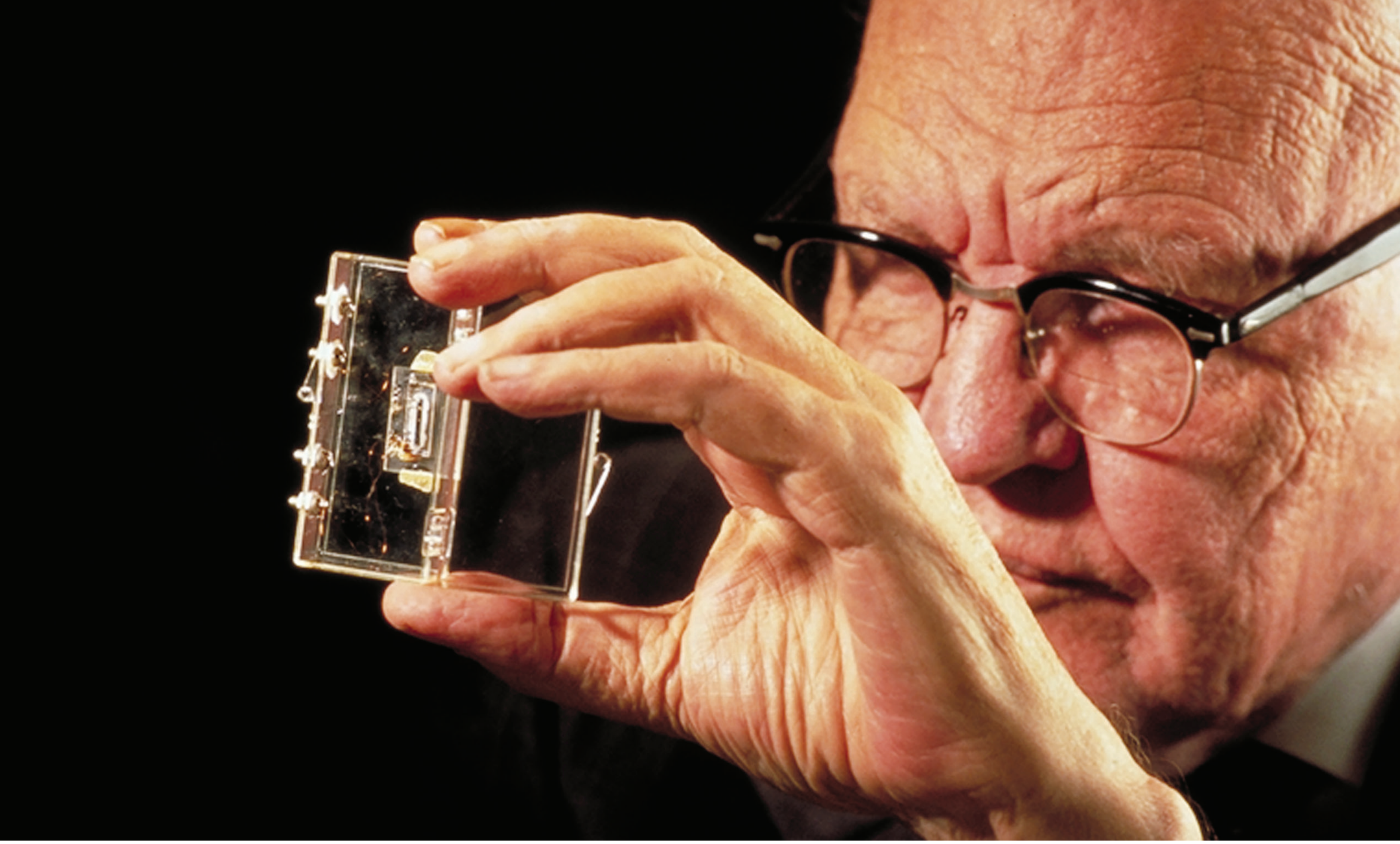
FIGURING OUT THE IMPOSSIBLE

Computers of the 1950s were assembled from electronic modules that each performed a discrete function. Modules were assembled on printed circuit boards that had a power connection on one end and wiring that connected them to other modules. In order to make a complex circuit like an adder, multiple modules had to be wired together in the proper sequence.

This meant hours of wiring and hand soldering, creating a bewildering tangle of wiring. Furthermore, one broken wire or poorly soldered joint too often resulted in the failure of the entire system.

Then, as now, there was perpetual demand

TEXAS INSTRUMENTS ARCHIVES/DEGOLYER LIBRARY/SMU



Jack Kilby holds one of the prototypes of his original, 1958, integrated circuit, mounted on glass.

for faster, more powerful computers. Improving performance or adding functionality required adding a massive number of interconnected modules. The more complex the computer became, the more wire and modules were needed. At a certain point, the accumulation of modules would result in a barely manageable tangle of many wires and would make computers too big, too heavy, and too expensive to be practical. Engineers called this problem the "tyranny of numbers."

The defense contract that TI had was from the U.S. Army Signal Corps, which wanted to address this problem with standard-sized modules, or "Micro-Modules," which ideally would fit together with minimal custom wiring.

TIME TO THINK

Kilby felt that even if the Micro-Module program minimized the rat's nests of wiring in computers, it failed to adequately address the issues of size, weight, and cost. Kilby expected that if he could build an entire circuit on a semiconductor substrate it might replace the Micro-Module concept, and whether it did or not, such an accomplishment might still get him assigned to TI's transistor operation instead.

He tried building a phase-shift oscillator, which was commonly used to demonstrate linear circuits, from a germanium wafer. As he wrote in *IEEE Transactions on Electron Devices* in July 1976, "I obtained several wafers, diffused and with contacts in place. By choosing the circuit, I was able to lay out two structures that would use the existing contacts on the wafers." These wafers were the semiconductor foundation of the circuit he was building.

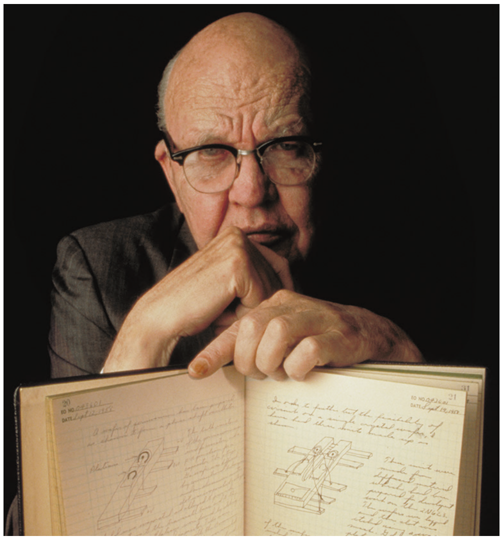
"Technicians Pat Harbrecht and Tom Yeargan cut the wafers into bars about 1/16-inches wide and 0.4-inches long. Metal tabs were alloyed to the back of the bar to provide contacts to the bulk resistors," Kilby continued. "Black wax was applied by hand to mask the

Even though the Kilby device was filed first with the patent office, Noyce's application was granted a patent first because Kilby's integrated circuit took longer to analyze.

mesas, one for the transistor and a larger one for a diffused region forming a distributed RC [resistor-capacitor] network."

On September 12, 1958, Kilby demonstrated three phase-shift oscillators that he had constructed using integrated circuitry for a group of TI engineers, who were duly impressed. The company deliberately let its Micro-Module contract lapse in favor of pursuing Kilby's "solid circuit."

The patent for the new solid circuit was filed in February 1959, and the invention was introduced at a press conference at the Institute of Radio Engineers convention in New York the following month. (The IRE merged into the IEEE in 1963.) In retrospect, Kilby's invention incorporated all the key concepts that would define what would later be called "integrated circuits."



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CALIFORNIA DREAMIN'

Around this time Robert Noyce, the research and development director at Fairchild Electronics, a small company located in an area that later would become known as Silicon Valley, had been trying to invent a way to combine transistors in a manner that was easily reproducible.

Fairchild wanted to attract defense contractors looking for ways to miniaturize electronics, similar to the business TI was doing with the Signal Corps on the Micro-Module project. But where Kilby had to justify the use of transistor technology as a replacement for modules, Fairchild's technological starting point was transistors.

Still, like Kilby, Noyce understood that an entire circuit constructed out of a semiconductor would be a stunning breakthrough.

In an IEEE oral history recorded in 1977, interviewer Michael Wolff mentioned to Noyce that Noyce's colleague at Fairchild, Gordon Moore, said that the Fairchild researchers were galvanized by a "rumor" that Texas Instruments was going to announce, at that March 1959 IRE convention in New York, that it had built and tested an integrated circuit. Paraphras-

No Salute from the Armed Forces

Although the U.S. and other armed forces would eventually become one of the earliest and largest customers for semiconductor electronics, their initial response could be nicely summarized by a single Yiddish word: *meh*.

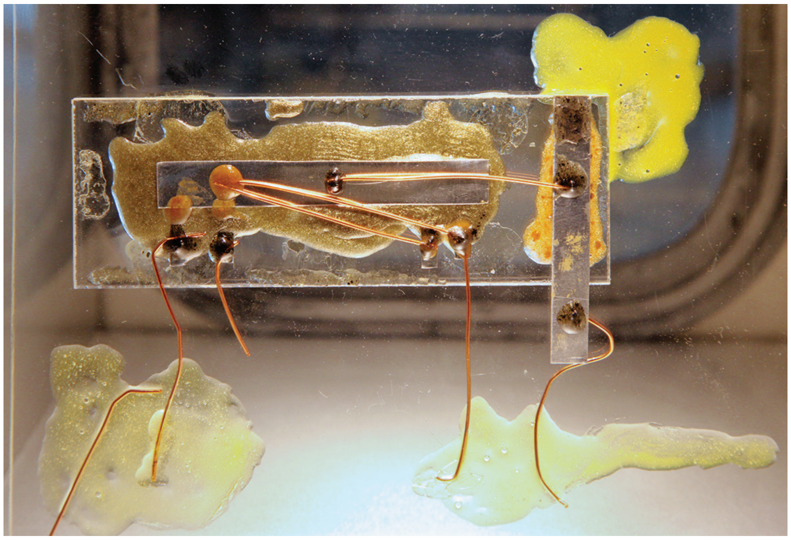
As Kilby wrote: "The Navy had little interest, and no programs were established. The Signal Corps expressed some interest and began to define a contract which would show that the technique would be fully compatible with the Micro-Module. Unfortunately, the demonstration they had chosen required silicon p-n-p transistors. These proved quite difficult to fabricate, and by the time the techniques were mastered, the Micro-Module program was in serious trouble.

"The 'solid circuit' concept caused a major debate within the Air Force," Kilby added. "A substantial budget had been established for work in molecular electronics. If the solid circuit was indeed a molecular electronics concept, support was assured.

But most of the strong molecular electronics supporters felt that the TI approach did not qualify. It was a circuit, and they were not going to have circuits anymore. Worst of all, it even had resistors, and resistors wasted power."

The invention that changed the world may have been bypassed completely by the U.S. Armed Forces, except it was noticed by a small group of Air Force officials at the Wright Air Development Center at Wright-Patterson Air Force Base.

They saw the integrated circuit as, in Kilby's words, "an orderly transition to the new era, and that by providing a systematic design approach it eliminated the need to invent the thousands of new devices that would be required for future equipment."



Jack Kilby [opposite] holds open his lab notebook to show the page in which he drew a diagram of his pioneering integrated circuit. A replica of the first integrated circuit [above, left] as displayed in the Heinz Nixdorf MuseumsForum in Paderborn, Germany. Robert Noyce [above], at Fairchild, came up with a different approach to an integrated circuit around the same time as Kilby.

LEFT: FLORIAN SCHÄFFER/WIKIPEDIA; RIGHT: TED STRESHINSKY/GETTY IMAGES

ing Moore, Wolff said, "that news spurred a meeting [at Fairchild] that was held to discuss, 'What are we going to do about this?'"

Not long after, Noyce disclosed in the interview, he conceptualized an entire integrated circuit in one extraordinary day. "I just went in and probably had a discussion with Gordon Moore or Vic Grinich or somebody like that initially. I said something like, 'Hey, here's a way to do the whole job of making some logic circuits instead of making individual transistors.' There wasn't any need for describing what the utility of the thing would be around that shop. That was well known. It was a question of coming up with a compatible set of schemes to come up with the structures that would work electrically. Then we proceeded to try to realize the structures and file patent applications on it."

Noyce's concept drew on work he had been doing on what he called "unitary circuits." Like Kilby's solid circuit, Noyce's unitary circuit would encompass all the key elements of an integrated circuit. There were key differences in the construction, however. One of the major differences was in the connections. Kilby's architecture included a loop of gold wire to connect circuit elements. TI described this as the "flying wire."

Noyce proposed a device that interconnected the diodes, transistors, resistors, and capacitors into the silicon chip using aluminum metal lines applied to the top of the chip's oxide coating. This scheme, called metallization, would prove to be easier to implement and more reliable. Noyce and Fairchild wanted to patent this improved integrated circuit and wrote an application that not only detailed the invention, but also pointed out the differences from Kilby's patent.

Fairchild also wanted to make sure that TI did not end up with a significant lead in the market. The company hastened to create a product it could demonstrate as quickly as possible. It built a flip-flop that it demonstrated at a trade show in August 1959. The first commercial product from TI based on Kilby's solid-circuit technology was a flip-flop introduced in 1960.

Even though the Kilby device was filed first with the patent office, Noyce's application was granted a patent first because Kilby's integrated circuit took longer to analyze. TI and Fairchild battled each other in court over which took precedence. The dispute was finally settled in 1966, when TI and Fairchild agreed to recognize each other's patents and cross-license others.

Today, both Noyce and Kilby are credited with inventing the integrated circuit. Kilby was awarded the 2000 Nobel Prize in Physics "for his part in the invention of the integrated circuit" (Nobel Prizes are not granted posthumously and Noyce died in 1990). Kilby acknowledged Noyce's contributions several times in his speech accepting the award. Among Noyce's many awards was the IEEE's Medal of Honor, the Institute's highest recognition, in 1978.

To this day, September 12 is recognized in Dallas as "Jack Kilby Day." ■

PHOTONICS | 1960

A Winding Path to the Straight Beam

With a limited number of applications for masers, the search was on for a way to increase their frequency, bandwidth, and data-carrying capacity.

The story that leads to bouncing beams of light off the moon, communicating with probes in outer space, chatting over fiber optics, vision-correction eye surgery, fast high-definition printing, CD players, holograms, precision targeting, scanning prices at the supermarket, and the world's best cat toy, starts with putting a toddler in a fridge.

It was 1930, and Theodore Maiman was just three and a half years old when he told his mother that the light in the family's refrigerator stayed on when its door was closed. She said it didn't. He insisted it did. She cleared out some space in the appliance, put the boy inside, and closed the door. He was right—the light stayed on. His mother had it fixed.

It was Ted Maiman's first experiment with light, but not his last. Thirty years later, one of his subsequent experiments produced the world's first laser.

Before skipping that far ahead, though, it is instructive to skip backward a bit. Someone had to come up with the fundamental concept for the laser, and that someone was Albert Einstein.

In 1916, Einstein published two papers about the quantum nature of light. In one, he theorized that if a photon were to collide with an atom, under certain circumstances it would cause the atom to emit another photon. That photon, in turn, would stimulate the emission of a photon from another atom, and so on, in a cascade. Furthermore, all of these photons would be in phase with each other, and traveling in the same direction—in other words, coherent. He called the phenomenon the stimulated emission of radiation.

Thirty-seven years would go by before a fruitful experiment was conducted using stimulated emission of radiation. In 1953, Columbia University's Charles Townes, with his student James Gordon and postdoc Herbert Zeiger, sent a stream of excited ammonia molecules through an electrostatic focuser. This device winnowed less excited molecules from the stream and let the more energized molecules into a resonant microwave cavity.

In the cavity, the energized molecules emitted microwave-frequency photons that triggered the release of other photons from other molecules, the supply of which was being continuously replenished by the incoming stream. The result was a coherent beam of microwave radiation.

Townes and his students decided over lunch to name what they had just accomplished microwave amplification by stimulated emission of radiation (MASER). Townes would even-

Theodore "Ted" Maiman posed with one of his experimental laser assemblies, including a coiled xenon flashtube, in 1960.

HRL LABORATORIES

Maiman's original laser was based on a ruby crystal within a coiled xenon flashtube.

HRL LABORATORIES

tually share a Nobel Prize for the maser with Aleksandr Prokhorov and Nicolay Basof, who had done something similar in Russia.

However, there were a limited number of applications for masers. At the time, microwave frequencies were considered too long to carry bits at a rate sufficient to justify using bulky and expensive microwave equipment for communication. The higher the frequency, the greater the potential bandwidth. If the output could be shifted into, say, visible light, the frequency would go from about 24 GHz to at least 450 THz, with a concomitant increase in data-carrying capacity.

DEAD ENDS

Five years after his maser breakthrough, Townes co-authored a paper explaining how one might go about making such a thing—a variation of a maser that operated in the visible spectrum. "Infrared and Optical Masers," written with his brother-in-law, Bell Labs physicist Arthur Schawlow, described how an optical cavity with mirrors at either end might be able to do with photons in the visible spectrum what he had done with his resonant-cavity maser in the microwave realm.

The paper ignited blazes of research around the world. At Westinghouse, Irwin Wieder and his team tried energizing a ruby using a tungsten lamp. It was too weak. IBM researchers thought light entering a square-sided crystal at 45 degrees would bounce around without the need for a mirror. They used a polished, calcium fluoride crystal doped with uranium, but they just couldn't get adequate amplification. At Bell Labs, Ali Javan, a former student of Townes's, tried a mixture of helium and neon in a long tube. But he, too, failed.

Gordon Gould, an earlier graduate student in physics at Columbia, had once discussed with Townes making a type of maser using visible light. Gould had in fact beaten Townes to print with a paper proposing such a thing—indeed, he was the first to actually use the acronym LASER. Now at a private research company, TRG, Gould felt the idea was his and he was eager to be the first to create an actual working device. But the project was funded by the U.S. Department of Defense, which deemed it classified, and, thanks to Gould's dabbles with Communism 10 years earlier, he was not allowed to work on it.

Townes had a go at it himself, but he chose to use potassium gas, which proved too corrosive, eating up the seals on his tubes and blackening the glass.

RUBY, MY DEAR

At last we get to Maiman. It's 1959, and he now has an M.S. in electrical engineering and a Ph.D. in physics from Stanford—and a job at Hughes Aircraft Company. He'd led an effort to redesign the maser there, reducing what had once been a massive 2.5-ton apparatus to 4 pounds. Hughes gave him $50,000 to tackle the laser after the Townes paper came out.

To reach the finish line first, Maiman knew he had to keep things simple. That meant not turning to gas as the lasing medium, which he knew would require endless fussing. He also wanted to avoid using cryogenics, a dependency that had complicated the maser and kept it from being a practical device.

Maiman had used a ruby in his maser manipulations. And, for a laser, he felt, a synthetic pink ruby would suit his needs. But then Westinghouse's Wieder (whom Maiman had mentored at Stanford) published a paper that showed that the ruby's fluorescent quantum

A Beam from China

The surge of research activity triggered by Townes's and Schawlow's paper of 1958 reached even China. And the timing was fortuitous: 1958 was the year Mao put his Great Leap Forward into action, in an effort to catch up with the technological developments of the West. Thanks to this coincidence, researchers at the Changchun Institute of Optics, Fine Mechanics, and Physics switched on their own laser just a year after Maiman turned on his.

They were later, and theirs was a more arduous path. For one thing, at that time there were no off-the-shelf flashbulbs manufactured (or imported) in China. So Wang Zhijiang, who directed the laser project, made his own. He also knew that the light from any part of the tube that extended past the gem was wasted. "The spiral xenon lamp used widely abroad is really a half-cooked product," he declared, so he made his straight. But it needed helium and that too was neither manufactured nor imported.

They sent someone traveling around the country looking for a source. After six months he found several canisters that had been sitting in a light bulb factory for more than 10 years. The ruby they got hold of was riddled with impurities and optical defects. They had to mold the gem into an odd shape to compensate.

Wang also designed a spherical imaging lighting device that was more efficient than the elliptical diffuse illumination of Maiman's laser. Wang was sick at home when the laser finally fired up and proved itself. But it was a great leap forward—straight forward.

efficiency—the percentage of photons that would end up used in the beam—was a mere 1 percent.

That would make it an impossible medium for a laser. Maiman considered alternatives, but none were satisfactory. He had used rubies and he still suspected they might be able to work in an optical maser. He decided to go back and confirm Wieder's evaluation of ruby's quantum efficiency. He took his own measurements and calculated that the number was closer to 70 percent than to 1 percent.

With renewed confidence in the pink rock, he coated the ends of a cylinder in layers of silver. With a millimeter-sized hole in the center of one of the silver caps, the light could escape in a beam—if his idea worked.

He needed a light source powerful enough to excite a sufficient quantity of the chromium atoms in the ruby crystal into becoming the sought-after laser beam.

SURROUNDED BY DOUBTERS

Maiman needed a light source powerful enough to excite a sufficient quantity of the chromium atoms in the ruby crystal into becoming the sought-after laser beam. Blasted by the light source, electrons in the chromium atoms would jump energy levels, emitting photons when they returned to lower levels. Thus would begin the avalanche: the emitted photons would beget more photons, and because the ends of the tube were silvered, these photons would sweep back and forth in the tube, multiplying with each pass.

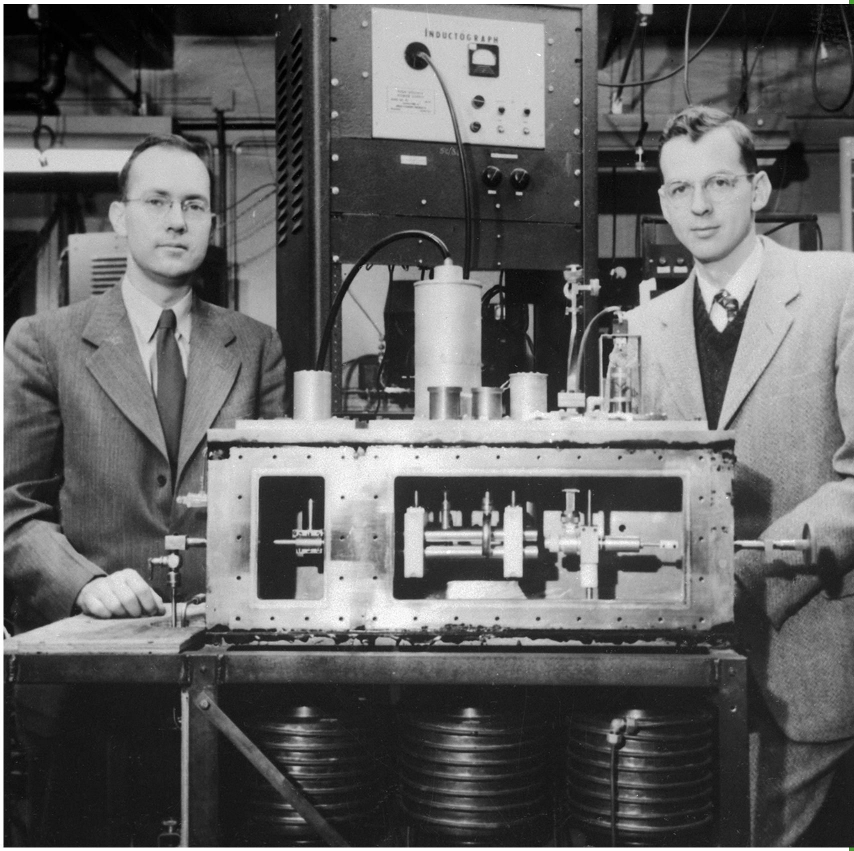
To kick things off he figured he needed a specific kind of light. “The number that I calculated to have enough brightness capable of driving a ruby into laser action was close to 5,000 Kelvin,” Maiman wrote in his memoir. “That is a temperature similar to the surface of the sun!” Then he remembered having read about strobe lights that reached brightness temperatures of more than 8,000 Kelvin.

Soon he was scouring photography catalogs looking for the perfect flash. General Electric's FT-506 Xenon flashtube seemed to fit the bill. It was bright enough, and the shape of the tube was a spiral that just happened to fit right over the ruby cylinder.

Maiman proceeded with his experiment, but with waning confidence. In April of that same year, Albert Clogston, a research physicist and head of the Bell Labs department that was trying to make its own laser, visited Hughes and declared that any attempt using ruby was not workable. “You will be wasting time, effort, and money in a futile project if you continue,” he insisted. Meanwhile, a friend of Maiman's, optical physicist Peter Franken, was preparing to teach a course at the University of Michigan and had titled one of his planned lectures, “Why a laser is not feasible.”

Nevertheless, on May 15, 1960, Maiman flipped the switch on his flashbulb-powered ruby laser. He started with 500 volts—and his Memoscope registered something. Then he started inching up the voltage. “When we got past 950 volts on the power supply, everything changed! The output trace started to shoot up in peak intensity, and the initial decay time rapidly decreased,” he wrote in his memoir. “Voilà. This was it! The laser was born!” ■

Charles Townes [left] and James Gordon flank the first maser, which they built at Columbia University.



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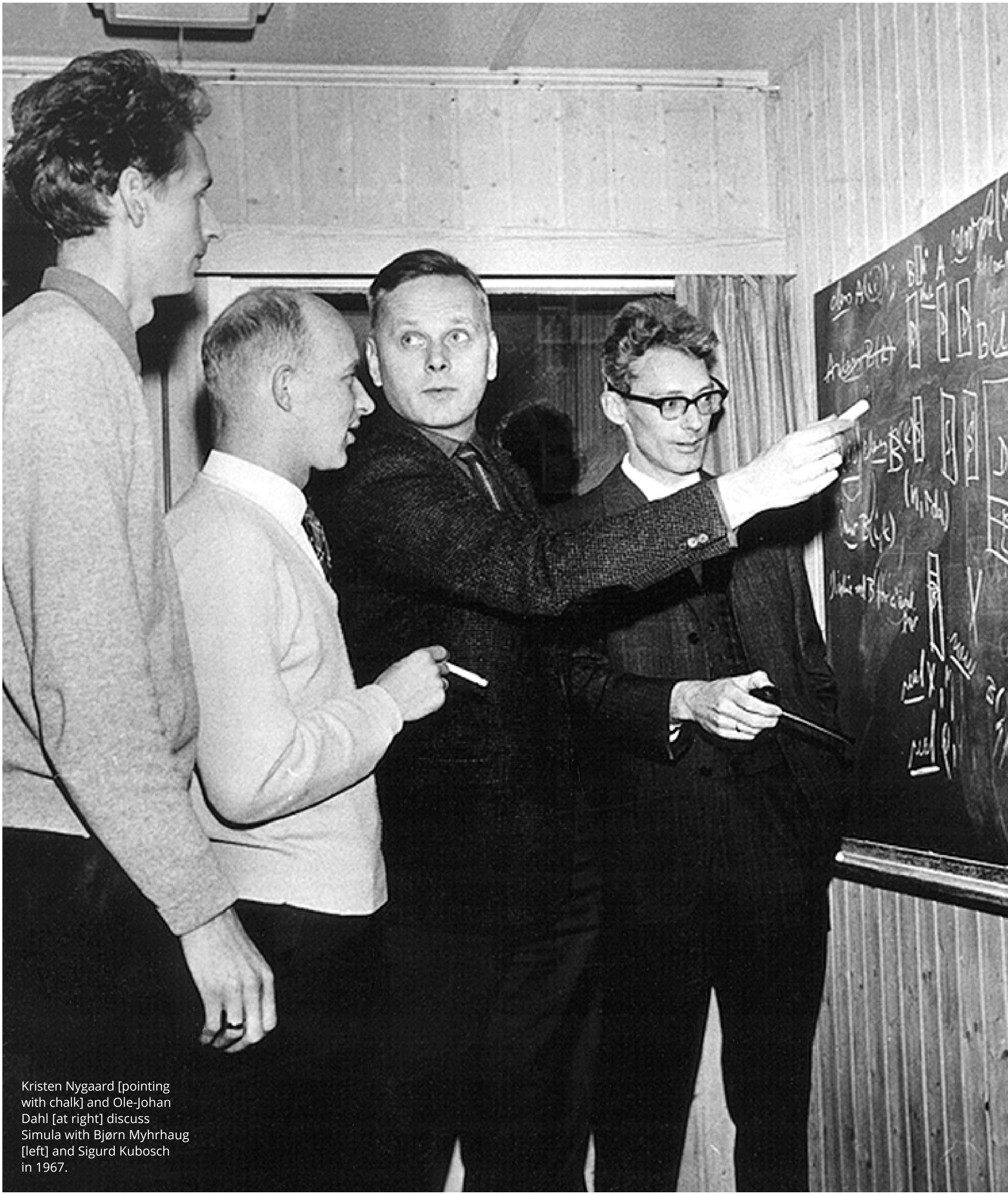


Kristen Nygaard [pointing with chalk] and Ole-Johan Dahl [at right] discuss Simula with Bjørn Myhrhaug [left] and Sigurd Kubosch in 1967.

UNIVERSITY OF OSLO

SOFTWARE | 1961-1967

How to Make Scrambled Eggs

Take three eggs out of the carton, crack them, scramble them, and throw them on the griddle. Describing this process precisely is not unlike Nygaard and Dahl's approach to simulation language.

Java, Python, C++, SQL—what do they have in common? They share a core programming paradigm that's the basis for many modern computer languages: object-oriented programming.

This shared characteristic is thanks to the revolutionary work in the 1960s of two Norwegians, Kristen Nygaard and Ole-Johan Dahl. It earned them the IEEE John von Neumann Medal in 2002 "for the introduction of the concepts underlying object-oriented programming through the design and implementation of SIMULA 67."

The two met in the 1950s while working for the Norwegian Defense Research Establishment, the research and development arm for the country's armed forces. Both moved on to the Norwegian Computing Center in Oslo in 1961, where they took on the challenge of creating a language that would enhance the increasingly sophisticated computers then being built. Nygaard had long been interested in ways to conceptualize complex, real-world systems. In his early experiments, he had problems trying to describe the heterogeneity of a system and its operation.

Nygaard was a gifted mathematician, who, after being drafted into military service in 1948, was assigned to the NDRE to calculate the diameter of the uranium rods needed for the construction of Norway's first nuclear reactor. For this task, the NDRE began using Monte Carlo simulations—but with all of the calculations done by hand. It was monotonous, painstaking work. Nygaard reportedly told a colleague years later that he hoped his work was correct since he didn't want to be responsible for Europe's first nuclear accident.

"In that [simulation] model, the physical paths and histories of a large number of neutrons were generated and a statistical analysis of their properties was used to estimate the proper choice of rod diameter," he wrote in 1986.

TRANSFERRING MILITARY LESSONS TO THE CIVILIAN WORLD

Nygaard's grueling hand-calculation experience at the NDRE turned out to be excellent preparation for his next gig, at the NCC. His first assignment there was to develop a language that could be used to create computer simulation programs. At the NCC, he quickly realized that many of the civilian projects there had the same type of methodological challenges he had seen while working with the military at the NDRE.

He understood that what was needed to create simulation programs, first and foremost, was a language that made it easy to describe complex systems. Recognizing that computer-aided simulation could be an enormous discipline within the then-burgeoning field of computer science, Nygaard focused on formalizing for systems description in a way that would streamline the processing of standard concepts in simulation.

Excited about this new project, he wrote what became a well-known letter about his progress to French operational research specialist Charles Salzmann in January 1962. “The status of the Simulation Language (Monte Carlo Compiler) is that I have rather clear ideas on how to describe queueing systems, and have developed concepts which I feel allow a reasonably easy description of large classes of situations,” Nygaard wrote. “I believe that these results have some interest even isolated from the compiler, since the presently used ways of describing such systems are not very satisfactory.… The work on the compiler could not start before the language was fairly well developed, but this stage seems now to have been reached. The expert programmer who is interested in this part of the job will meet me tomorrow. He has been rather optimistic during our previous meetings.”

The “expert programmer” joining him the next day was Dahl, the son of a sailor and a schoolteacher who grew up in a small town on the Norwegian coast. As a child, Dahl showed promise as a math prodigy. His family moved to Sweden during the Nazi occupation of Norway, and Dahl, then 13, missed the eighth grade. It didn’t matter. “The Professor,” as the child was called, was able to pass the high school entrance exam and then assisted his math teacher in explaining concepts to his fellow students.

Dahl had worked on an early model of the Ferranti Mercury computer, a British machine powered by more than 2,000 vacuum tubes and 2,000 germanium diodes, at the NDRE. He had created a unique language for it that led to his master’s thesis at the University of Oslo, “Multiple Index Countings on the Ferranti Mercury Computer.”

Hello, World!

Nobody uses SIMULA to write programs any more. But a SIMULA program will have familiar elements to any programmer proficient in object-oriented languages. Consider a SIMULA program to output the message “Hello World!” kindly posted by the University of Michigan for a computer course some years ago.

```
Begin
  while 1=1 do begin
      outtext (“Hello World!);
      outimage;
   end;
End;
```

For comparison, here’s how you’d do it in C++:

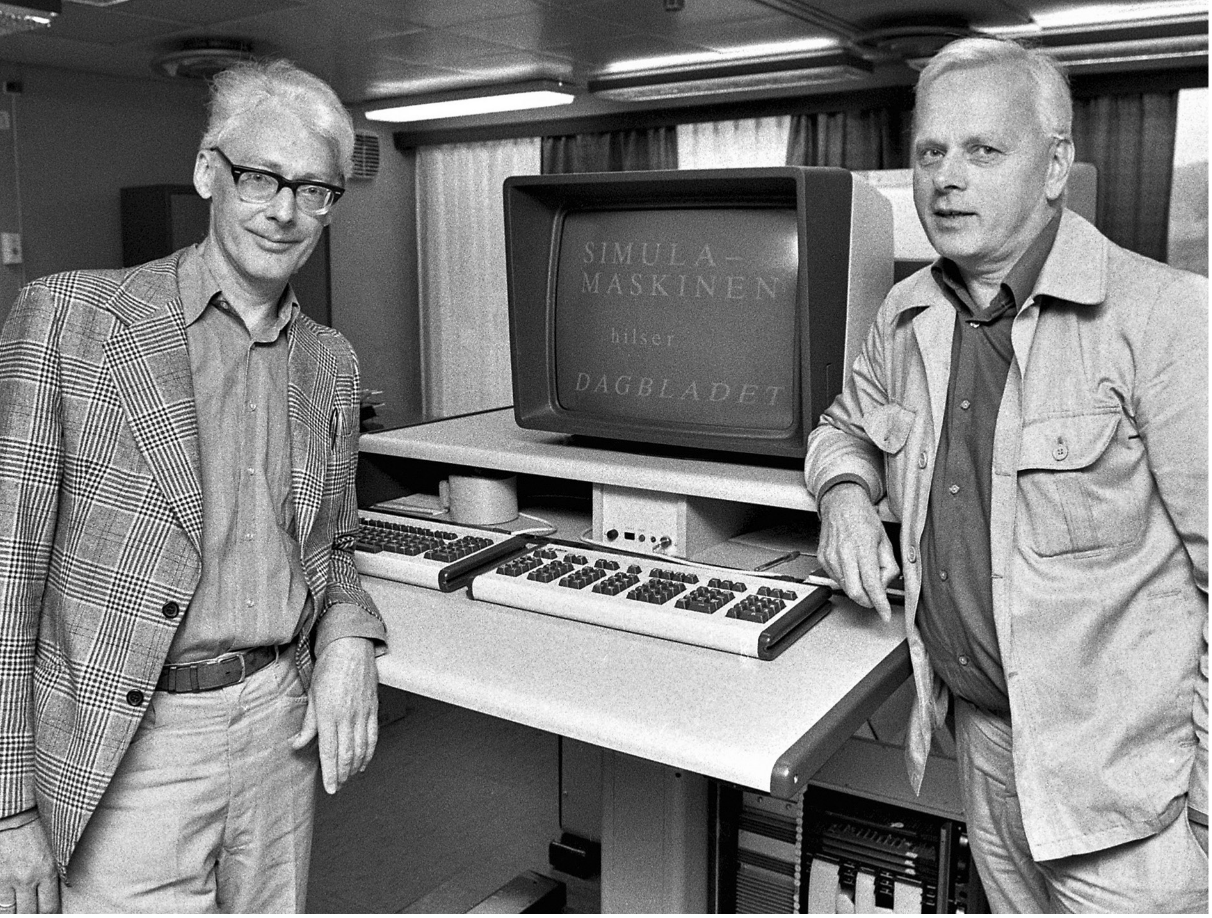
```
  import std;
     int main()
     {
std::println(“Hello, World!”);
      }
```

Nygaard and Dahl knew each other well by the time they were both with the NCC, and not unlike other genius pairings, they didn’t always get along. Supposedly, a new employee at the NCC once called the switchboard operator to tell her about two men fighting in front of a blackboard in a corridor. The operator is said to have replied, “Relax, it’s only Dahl and Nygaard discussing SIMULA.”

FINDING THEIR GROOVE

Such passion fueled their crowning achievement, the creation of the SIMULA language in 1962. It was the world’s first programming language used for simulating systems, or processes, that can be described as a series of discrete events, each occurring at a specific time. For example, the process of making scrambled eggs might be described as withdrawing three eggs from a carton, cracking them into a bowl, scrambling them, pouring them onto a hot griddle, and so on.

As Nygaard wrote of the development: “SIMULA should give its users a set of concepts in terms of which they could comprehend the system considered and a language for precise and complete description of its properties. It should thus be a tool both for the person writing the description and for



Ole-Johan Dahl [left] and Kristen Nygaard in the 1970s.

RUNE MYHRE

people with whom he wanted to communicate about the system.

"At the same time this system description should, with the necessary input/output and data analysis information added, be compilable into a computer simulation program, providing quantitative information about the system's behavior."

While it was created as a simulation language, Nygaard and Dahl saw that it could also be used for general-purpose programming. SIMULA showed how programs could be organized as a system of interacting, executing components that would enable it to work in many other applications having nothing to do with simulation.

Seeing SIMULA's potential, the men took what they learned from creating SIMULA and refined it to come up with SIMULA 67, a new general-purpose language that was released in 1967. SIMULA 67 used class prefixing as a mechanism to allow the simulation-specific features of SIMULA I to be used in this new, general-purpose language. It was here that Nygaard and Dahl came up with the four major characteristics that remain hallmarks of language development:

- Objects, which are made up of interacting components and contain all of the important data
- Methods, which are functions that define the behaviors of an object
- Inheritance, which allows code to be reused in different ways
- Modules, or self-contained units of code, which can be used in different parts of an application.

This style of organizing the code and data of a program is the heart of object-oriented programming. Basically, objects are operated on by coded procedures known as "methods."

The advantage of OOP is that it creates an intuitive way of modeling real-world problems. Objects can correspond to physical things, such as a person, described by a name, address, and telephone number. Or they can be systems, such as a small computer program, or an old-school telephone switching network. OOP's popularity grew and became the basis of legendary, revolutionary languages like C++ and Java. Object-oriented programming is the trunk of the tree that makes up most of the large software systems we use today.

Besides the IEEE von Neumann Medal, the pair received the ACM Turing Award in 2001. In addition, the Association Internationale pour les Technologies Objets annually awards two prizes named in honor of Dahl and Nygaard. The two men died within six weeks of each other during the summer of 2002. ■

CONSUMER ELECTRONICS | 1962-1967

The Great Race for Time

Watchmakers on three continents wrestled with fitting a massive quartz timer into a relatively tiny wristwatch—at an affordable price. The winner was the consumer.

The impulse to measure diurnal time goes back millennia, with the earliest known sundials (which can be accurate to within a minute) erected about 3,500 years ago. Since then, progress in timekeeping has involved making timepieces smaller and more portable, each time at the expense of accuracy that has always been regained after subsequent improvements.

The advent of the mechanical clock in the 14th century was a watershed moment, revolutionizing scientific observation, aiding the development of other machines, and changing our perception of time. The mechanical wristwatch, with intricate works driven by unwinding springs, became common in the mid-1800s. As convenient as they were, though, these watches were imprecise and needed to be wound by hand. With inevitable refinements, including the adoption of electronics and especially of quartz timing, wristwatches became extraordinarily accurate. In fact, for a brief moment, a quartz electronic wristwatch was among the most precise timepieces ever created.

In the early 20th century, the development of quartz oscillators established a new avenue to more precise timekeeping. The first quartz clock was built by Canadian-born engineer Warren Marrison and Joseph W. Horton at Bell Labs in 1927. Quartz clocks were large devices, but they provided timing so precise that they became the new standard. In 1941, the National Bureau of Standards (the precursor to the National Institute of Standards & Technology, or NIST) began broadcasting a continuous timing signal based on a quartz clock.

THE RACE IS ON

All along, wristwatches had remained entirely mechanical, but in the late 1950s, American watch companies began to experiment with electrical components and eventually electronics in wristwatches

In 1957, the Hamilton Watch Company introduced the Hamilton Electric Watch, a jazzy, wedge-shaped, battery-powered watch using a balance wheel. Though it failed commercially, the Hamilton Electric inspired rival Bulova to adopt an innovation that would in turn set off a worldwide race to develop a quartz watch.

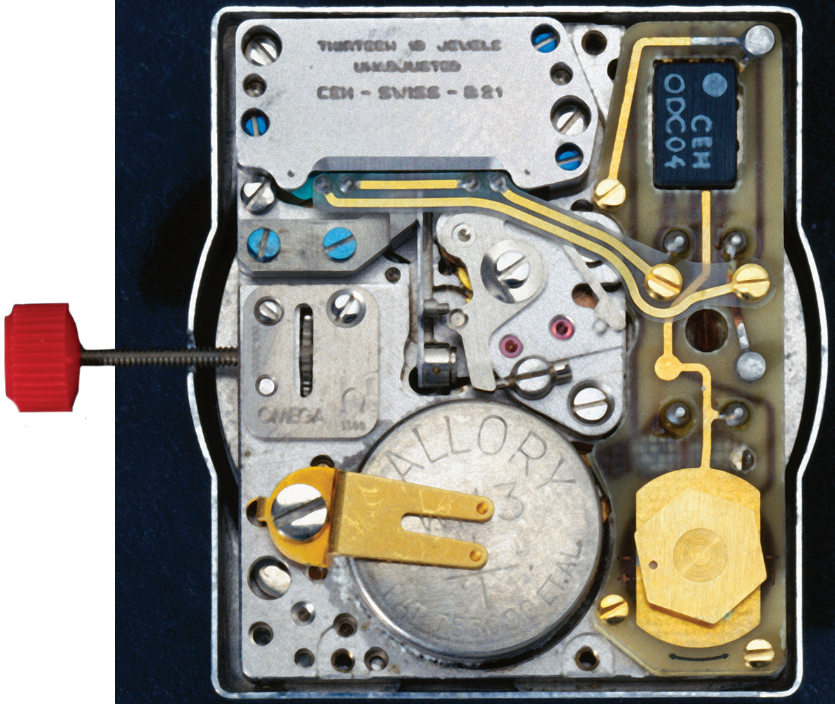
Bulova's watch was called the Accutron and it was introduced just in time for the Christmas holiday in 1960. Designed by Swiss electrical engineer Max Hetzel, the Accutron replaced the traditional balance wheel with a metal tuning fork. Hetzel's expectation was that the vibration of the tuning fork would be roughly analogous to the oscillation of a crystal, which proved correct. Hetzel's innovation resulted in the most accurate wristwatch of its time; accurate to 2 seconds a day. It was an immediate sensation.

The first quartz wristwatch, the CEH 1020, was one of a group of five prototypes identified as Beta 1. They were built in 1967 at the Centre Electronique Horloger in Neuchâtel, Switzerland.

CEH/CSEM NEUCHÂTEL/ARMIN H. FREI HERITAGE ESTATE

An Atomic Blast

Just how accurate was the Beta 21? Even more than the most accurate clock created at that point. In 1968, Max Forrer, then director of the CEH, noticed a 3-second difference between his new Beta 21 quartz wristwatch and a cesium atomic clock—a standard then considered the most accurate type of clock ever developed—in the lobby of Hewlett Packard in California. Forrer was convinced that the lobby clock, despite its reliance on cesium, must be incorrect. An investigation confirmed he was right; the lobby clock was indeed off by about 2 seconds. News quickly spread among the HP engineers that their atomic-controlled clock had been bested by a mere wristwatch. Quartz had made the big time. Cesium clocks were subsequently refined until achieving an accuracy within 0.02 nanoseconds a day. They remained the standard technology for timekeeping until recently being eclipsed by optical-lattice clocks, which lose 1 second every 13.8 million years. It's going to be a long time before you can get one of those on your wrist, however.



The Beta 21 quartz movement made its debut in wristwatches from 20 different Swiss manufacturers on April 10, 1970—four months after Seiko's Astron 35SQ.

SSPL/GETTY IMAGES

The Accutron's popularity—as well as Bulova's refusal to license Hetzel's patents—pushed development teams in Japan, Switzerland, and the United States to experiment with alternative approaches, looking to take advantage of what was clearly a huge untapped market for more accurate wristwatches.

SWITZERLAND TAKES THE LEAD

In 1962, 20 Swiss watch companies formed the Centre Electronique Horloger in Neuchâtel to develop a quartz wristwatch. Until this point, the world-dominant Swiss watchmaking industry had been focused on mechanical watches, but was now nervously eyeing the emerging electric watch technologies that could clearly upend the industry. Swiss watchmakers hoped that the formation of CEH would help them devise an even more precise wristwatch that would help them ward off rivals like Bulova that were innovating with electric and electronic watches.

Everybody knew that quartz clocks were the answer. The question was, could CEH fit a quartz timer in a wristwatch? In 1967, a prototype was created. Dubbed the CEH 1020, it was the world's first quartz wristwatch. However, it was not as power-efficient as the designers had hoped, so a second CEH team stepped in with an alternate design—the Beta 2—that could run for a year on a single battery. Both were submitted for testing at that year's International Chronometric Competition at the Neuchâtel Observatory.

The Beta 2 prototype shattered existing records and set new standards for accuracy, and with its long battery life, it was the clear winner to be pushed toward commercial viability under the name Beta 21 (known as "two-one").

BUT JAPAN GETS TO MARKET FIRST

At the same time, Japanese watchmakers were also experimenting with quartz timepieces.

In 1958 Japan's Suwa Seikosha (now known as Seiko Epson) created a large quartz clock for use by broadcasters. In 1960 the company began preparing a new version of a quartz clock for the 1964 Tokyo Olympics, for which the company was the official timer. In 1962 came Seiko's first tabletop quartz clock, followed two years later by the Olympic Crystal Chronometer.

By this time, everyone in the watch market was aware of what CEH was doing. Seiko intended to compete, but even though it had experience with quartz clocks, it had the same challenge its Swiss counterparts had: figuring out how to shrink a tabletop timer. A quartz wristwatch would need to be 1/300,000th the size of the broadcast clock Seiko had created.

By 1966, the company had created a quartz pocket watch prototype, and, a year later, a wristwatch version—following very closely the developments of their Swiss rivals at CEH. Seiko, like CEH, had prototypes, but everyone still had to figure out how to mass produce quartz wristwatches, and it did not look like it would be easy. Seiko set itself a goal of figuring out how to manufacture them and get them to market before the end of the decade.

The race was getting heated.

THE PRICE ISN'T RIGHT!

Seiko hit that deadline and became first to market when it released the Seiko Astron SQ, the world's first commercially available quartz watch, on Christmas Day 1969. It offered accuracy that varied by just ±0.2 seconds per day and ±5 seconds per month, compared to several seconds a day for the highest-precision mechanical watches available at the time, including Bulova's.

Unfortunately, at 450,000 yen (about $1,250 at the time, or $9,000 today), the watch cost nearly as much as a basic used car. Few of the timepieces were ever sold.

Nevertheless, with the release of the Astron 35SQ—and the models that followed—Seiko launched a revolution in the popularity of quartz wristwatches. The miniaturized, low-power-consumption, shock-resistant tuning-fork quartz oscillator, the 1-second ticking motion of the second hand to save power, and the open-type stepping motor enabling a compact coil, stator, and rotor arrangement became standard features in Seiko's watches—as well as in watches made by the company's competitors.

The first commercial quartz wristwatch to feature CEH's Beta 21 movement was the Omega Electroquartz, announced in late 1969 but not commercially available until 1970, just ahead of models from other Swiss brands such as Rolex, Patek Philippe, IWC, Piaget, Longines, and Rado. These early quartz watches often had futuristic designs that emphasized the technological advancements they represented.

The United States Shifts Gears

As Japan and Switzerland competed neck-and-neck to develop a commercial quartz watch, in the U.S., the Hamilton Watch Company tried to keep pace. The company had already been working on a battery-powered electromechanical watch and, like its competitors, started developing a quartz watch in 1967. However, it shifted gears and created the world's first electronic watch with a digital display, the Pulsar, which debuted in 1972. It had red LED numerals that allowed users to view the time by simply touching a button on the watch's side. It was revealed memorably to the world in 1973, on the wrist of Roger Moore, playing James Bond in the 1973 motion picture *Live and Let Die.*

SSPL/GETTY IMAGES

Digital wristwatches became more practical with the advent of the LCD (liquid crystal display), which opened new avenues for consumer goods. (For more on LCDs, see page 96).

The success—and relative affordability—of the Beta 21 prototype paved the way for the immense popularity of quartz wristwatches. With their light weight, relative simplicity, and maintenance-free reliability, quartz watches quickly became one of the most successful commercial electronic products of all time, with hundreds of millions manufactured.

The result of all this innovation—and the international competition it fostered—is that today, even the most affordable wristwatches offer exceptional precision. The electronics revolution has continued to advance, allowing watches to incorporate an increasing number of functions within a compact design.

RECOGNITION AND CONTINUOUS ADVANCEMENT

In 2002, the IEEE presented CEH with a Milestone Award in Electrical Engineering and Computing for its pioneering work on the quartz electronic wristwatch. That same year, the IEEE also presented Seiko with the Corporate Innovation Recognition Award, following that up with a Milestone Award two years later. The Astron 35SQ is permanently displayed at the Smithsonian Institution, and in 2014 was acknowledged as a Mechanical Engineering Heritage in Japan. ■

PHOTONICS | 1962

Seeing Red

Nick Holonyak Jr. understood that his red emitter was just the start. Soon, there would be other colors and eventually, a white light based on light-emitting diodes—what he called the "ultimate lamp."

Like many inventions, the light-emitting diode was created accidentally by an inventor searching for something else.

In 1962, at General Electric, Nick Holonyak Jr. was trying to produce a visible-light semiconductor laser. At the time, most of his competition was trying to make lasers out of commercially available semiconductor materials such as gallium arsenide or gallium phosphide. But Holonyak was interested in creating a novel crystalline material by combining them both, even though the conventional wisdom at the time held that such an alloy would not produce any crystals that could generate light.

The crystal that Holonyak was trying to produce was gallium arsenide phosphide. The typical method in those days was to heat a gallium arsenide crystal in a gas of phosphorous. But it was very time consuming, so Holonyak was pursuing a different approach, heating gallium arsenide and gallium phosphide together with a metal halide in a closed container called an ampoule.

"People told me that had I been a chemist instead of an electrical engineer, I would have known that growing a crystal this way was impossible," Holonyak said in an interview with *IEEE Spectrum* in May 2003. "No one in their right mind would have tried it." But the traditional method "would have taken billions of years to work," he joked. "You had to move the atoms and reassemble them in some chemical way."

Holonyak was working with gallium arsenide phosphide because it had an advantage, called higher bandgap, in comparison with gallium arsenide or gallium phosphide. The bandgap of a crystal refers to the amount of energy it takes to promote an electron from the crystal's valence band, in which the electron is bound to an atomic nucleus, to the conduction band, where electrons are free to move around the lattice and conduct electricity. The higher the bandgap, the greater

In 2004, Nick Holonyak Jr., who had created the first visible-light LEDs while working at General Electric in 1962, held a stoplight assembly outfitted with red LEDs.

RALF-FINN HESTOFT/CORBIS/GETTY IMAGES

Lighting the Way to Nobel Prizes

The invention of the LED resonated globally, transforming the market for numerical indicators more or less immediately and eventually revolutionizing the multibillion-dollar market for lighting of all kinds. It also paved the way for two Nobel Prizes in Physics—neither of which went to Nick Holonyak.

In 2000, two of Holonyak's former collaborators, Herbert Kroemer and Zhores I. Alferov, won for discovering semiconductor and low-energy laser technology, now used for cellphones, fiber optics, CD players, and barcode readers. Fourteen years later, three other researchers won for their breakthroughs that led to a high-brightness blue light-emitting diode, which was necessary to produce white-light LEDs. The three were Shuji Nakamura of the University of California, Santa Barbara and Hiroshi Amano and Isamu Akasaki, both of Nagoya University in Japan.

Neither the semiconductor lasers nor the blue LEDs would have been possible without Holonyak's earlier pioneering innovations. Russell D. Dupuis, director of the Center for Compound Semiconductors at the Georgia Institute of Technology, told the *New York Times* for its September 2022 obituary of Holonyak that in both cases, "the fundamental material contributions were made by Holonyak."

the amount of energy that is released when electrons combine in the crystal with electron deficiencies called holes. Those combinations release photons of light, and higher energy translates into higher-frequency photons. In the case of Holonyak's work, that meant the emission of red rather than infrared light.

In mid-September 1962, Robert Hall, one of Holonyak's colleagues and competitors at GE, demonstrated an infrared laser diode. Not even a month later, on October 9, Holonyak startled his colleagues by demonstrating a red glow from a tiny crystal—the first visible-light laser diode.

Fifty years later, Holonyak spoke of the competition with his GE colleagues that led to that stunning day. In an interview with *GE Lighting* in September 2012, he described his combative attitude: "If they can make a laser, I can make a better laser than any of them because I've made this alloy that is in the red—visible. I'm going to be able to see what's going on. And they're stuck in the infrared."

Holonyak understood that his red emitter was just a start. Soon, there would be other colors and eventually, a white light based on light-emitting diodes (LEDs). Such a light would, in theory, be many times more efficient than the incandescent bulbs that then dominated lighting. They're the "ultimate lamp," he said, because "the current itself is the light."

"A LIFE BEYOND WHAT WE'RE SEEING"

In an article in the February 1963 *Reader's Digest* titled "Light of Hope—or Terror," Holonyak predicted that LEDs and laser-based lights would someday replace incandescent bulbs, which hadn't changed much since Thomas Edison's day. "We believe there is a strong possibility of developing the laser as a practical light source," he said. "Much more experimental work must be done, and it might be 10 years or more before such a lamp could be ready for wide use."

GE immediately put the LEDs and lasers on the market—but at a price few could then afford. For the lasers, the initial price was $3,200 (about $31,000 today), soon reduced to $1,600, according to an article in the February 2003 newsletter of the IEEE Laser and Electro-Optics Society. The first commercially available LEDs were a relative bargain at $260 each (around $2,500 today). Nowadays, LEDs run a few pennies a piece.

And today they're in our flat-screen TVs, laptops, traffic and brake lights, railroad crossing signals, streetlights and floodlights, ceiling fixtures and counter lights, elevator buttons, and countless other places. They're *literally* everywhere. They have prevented the emission of billions of tons of greenhouse gases because LED lights use about one-fifth of the power of a comparable incandescent bulb, and they last about 10 to 20 times as long. LEDs are also somewhat more efficient than fluorescent lamps and a lot less harmful to the environment, because, unlike fluorescents, LEDs do not contain mercury.

Holonyak's prediction of 10 years of development before LEDs could start replacing incandescent and fluorescent lamps turned out to be rather optimistic; it actually took closer to 40 years. But now, the U.S. Department of Energy estimates that by the end of this decade, more than 80 percent of all lighting purchases will be LED. The global market for LEDs will exceed $109 billion by 2025, according to market consultancy Grand View Research. As Holonyak told the University of Illinois in 2002, "Edison's name is famous, but we made his light obsolete."

In the GE interview, Holonyak remembered feeling that he was onto something big when his first successful laser diode, which he called "the magic one," lit up for the first time.

"I know that I'm just at the front end," he said, "but I know the result is so powerful…there's no ambiguity about the fact that this has got a life way beyond what we're seeing."

WORLDWIDE RECOGNITION— AND THE HIGHEST FROM IEEE

In 1963, after finishing his research at General Electric's Advanced Semiconductor Laboratory, Holonyak returned to his alma mater, the University of Illinois Urbana-Champaign, as an endowed professor of electrical and computer engineering and physics. He died in Urbana in September 2022 at the age of 93.

Over his lifetime, Holonyak was awarded 41 patents and upwards of a dozen prestigious awards. These included, in 2003, the IEEE's Medal of Honor, the institute's highest award, for "a career of pioneering contributions to semiconductors, including the growth of semiconductor alloys and heterojunctions, and to visible light-emitting diodes and injection lasers." This wasn't his first high honor from IEEE—in 1989, the Institute presented him with an Edison Medal commemorating "an outstanding career in the field of electrical engineering with contributions to major advances in the field of semiconductor materials and devices." Holonyak is one of only 13 people in the long history of the organization who have won both the Medal of Honor and the Edison Medal.

And in 2022 the IEEE established a major new award in his honor. The IEEE Nick Holonyak Jr. Medal for Semiconductor Optoelectronic Technologies recognizes an individual or small team that has made outstanding contributions to semiconductor optoelectronic devices and systems. The first award will be presented in 2024 at the annual IEEE Vision, Innovation, and Challenges Summit and Honors Ceremony. ■

After Holonyak died in 2022, Milton Feng, one of his first students, led a remembrance in which Holonyak's coworkers, students, and fellow researchers held aloft a red LED heart.

THE UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

SOFTWARE | 1964

You Say 'LOGON,' and I Say 'Hello'

By making computing more accessible—and fun—BASIC laid a cornerstone for personal computing, shifting the balance of control from system owners to end users—whether visionaries or just regular folks.

BASIC was not the first programming language, nor the most versatile, let alone the most powerful. It was, however, the first that was easy to learn and easy to use. By turning one of the biggest entry barriers to computer programming into a mere speed bump, BASIC was instrumental in popularizing computing, contributing to the mass market adoption of computers (desktops in particular), and encouraging significantly wider participation in the endeavor. BASIC created an avenue to innovation—a path taken by Steve Wozniak, Steve Jobs, Bill Gates, and Paul Allen, to name a famous few among many.

Most programming languages look like gibberish to the uninitiated, characterized by nonsense syllables, seemingly random alphanumeric symbols, and punctuation marks assigned inscrutable new meanings. At the beginning of the modern computing era, few would even attempt to parse early languages such as Fortran and LISP.

DARTMOUTH ROOTS

In the late 1950s and early 1960s universities with more august engineering programs were exploiting government contracts to install some of the most powerful computers then available, machines built by early computing giants such as IBM. In 1963, Dartmouth secured a more modest machine, a small mainframe manufactured by General Electric—a GE 225.

It was plenty big enough for Dartmouth professor John G. Kemeny (who had worked on the Manhattan Project at Los Alamos) and mathematics professor Thomas E. Kurtz, who had already decided how to put it to best use. The two wanted to make computing widely available, and freely accessible, to all students.

"Our vision was that every student on campus should have access to a computer, and any faculty member should be able to use a computer in the classroom, whenever appropriate," Kemeny said in a 1991 interview with EDUCOM, a higher-education consortium that promotes computing. "It was as simple as that."

If beginners were ever going to be able to use computers almost immediately to solve problems, there were two major impediments to overcome. One was the recondite nature of programming languages, which inevitably led to a long learning curve. The other was that the computers of the day could handle just one program at a time. Anyone wishing to use a computer was likely to find themselves waiting in line for hours, days, or even weeks to take their turn.

The two Dartmouth professors worked on both problems in parallel and solved them nearly simultaneously.

Kemeny and Kurtz had both been involved in prior attempts to construct more simple programming languages. They had collaborated on one in 1956 (which had not been adopted), and in 1962, for example, Kemeny had worked with a student on another, which they

The first computer time-sharing system was installed at Dartmouth College in May 1964.

RAUNER SPECIAL COLLECTIONS LIBRARY/DARTMOUTH COLLEGE

Dartmouth professor (and future president) John Kemeny led a class in the BASIC programming language [top]. Kemeny's partner in the creation of BASIC was Thomas Kurtz [above].

puckishly called the Dartmouth Oversimplified Programming Experiment (DOPE).

Dartmouth's acquisition of a mainframe the following year presented the opportunity to achieve their goal of democratizing computing. They redoubled efforts on the language they would eventually call Beginner's All-purpose Symbolic Instruction Code. BASIC had an easy-to-learn syntax using 14 common English words as simple commands. With a limited but flexible set of commands all rooted in English, almost anyone could quickly grasp how to write lines of code and craft a computer program.

"[Kemeny and I] wanted the syntax of the language to consist of common words, and to have those words have a more-or-less obvious meaning," Kurtz said in an interview with *Time* magazine in 2014. "It is a slight stretch, but isn't it simpler to use HELLO and GOODBYE in place of LOGON and LOGOFF?"

Kemeny and Kurtz also strived to develop a system that would enable a computer to handle more than one program at a time. This concept, of sharing any single computer's resources, had been a topic of discussion among researchers for years.

The two created a system that made it possible for a computer to accept multiple programs and, instead of running them in sequence, apportion its time among them. They called their approach the Dartmouth Time Sharing System.

BASIC was introduced on the Dartmouth campus, and the first time a BASIC program successfully ran was in the basement of College Hall at 4 a.m. on May 1, 1964. DTTS was implemented at the same time.

GOODBYE, PUNCHED CARDS

The DTSS operating system for which BASIC had been developed also revolutionized computer access by allowing anyone to type their program into any teletype terminal at any time. Wait times to enter a program dropped to mere seconds. A program that might be expected to take a week to execute would still take about a week, but the computer would be able to pause from time to time to complete other, less complex programs.

The combination of BASIC, time-sharing systems like DTSS, and remote terminals also marked the beginning of the end for punched cards, until then the primary method of data entry. BASIC's success at Dartmouth was almost immediate. By 1967, 80 percent of those who were freshmen in 1964—the year BASIC came out—had learned how to write and debug programs.

BASIC's success beyond Dartmouth was also rapid. Using telephone wires and relying on DTSS, Dartmouth allowed high schools in the region, as well as Harvard and Princeton, to use its computer. GE commercialized both DTTS and BASIC, but access to BASIC was free. Many other companies, including Digital Equipment Corp. and Hewlett Packard, created their own versions of the language.

By making computing more accessible, BASIC laid a cornerstone for personal computing, and opened a path for future tech giants to start their journey into the digital world.

STEPPING STONES TO MICROSOFT: BASIC AND THE ALTAIR 8800

The first commercially successful microcomputer was the Altair 8800, produced as a DIY kit in 1975 by MITS. Based in Albuquerque, New Mexico, the electronics company had started out a few years earlier making parts for model rockets and electronic calculators.

After the Altair 8800 was featured on the January 1975 cover of *Popular Electronics*, the hobbyist computer started flying off the shelves—at the price of $397, about $2,270 today. Many thousands were sold—a surprise to MITS, which had anticipated selling a few hundred at most.

RAUNER SPECIAL COLLECTIONS LIBRARY/DARTMOUTH COLLEGE (2)

One of those hobbyists was Harvard dropout Bill Gates, who had been programming in BASIC since high school. With his high school friend Paul Allen, then a programmer at Honeywell, he began creating a version of BASIC for the Altair, called Altair BASIC; it would become Microsoft's first-ever software product.

BASIC also played a crucial role in making computers fun. Apple cofounder Steve Wozniak created Integer BASIC for the Apple I and Apple II computers in 1976, which quickly led to games like the Atari's Breakout that same year. Demonstrating Breakout was the "most satisfying day of my life," he said in a 1984 *BYTE* magazine interview. "I knew that being able to program [arcade games] in BASIC was going to change the world." The Commodore 64, one of the most successful home computers of the 1980s, came with a built-in BASIC interpreter.

Microsoft created its drag-and-drop interface with Visual BASIC in 1991, which also ultimately led to Windows 3.0, and then Microsoft Office, possibly the most successful software package of all time.

JUST THE BASICS

BASIC brought about a monumental improvement in the accessibility of computer power, shifting the balance of control from system owners to end users—whether visionaries like Bill Gates and Steve Jobs or just regular folks like the 92 percent of Americans who now use a computer.

Kemeny and Kurtz made the programming syntax so easy even a child could learn it. In fact, Ben Shneiderman, a computer science professor (and IEEE Fellow) wrote a children's book on BASIC in 1984 called *Let's Learn BASIC*, inspired by his 8-year-old daughter.

Even while president of Dartmouth, from 1970 to 1981, Kemeny remained a champion of BASIC, as did Kurtz. In the 1980s, Kurtz served on the committee that developed ANSI standards for BASIC. In 1985, the two introduced True BASIC, an updated version of the language, and started a company to market it. The IEEE honored both men with the IEEE Computer Pioneer Award, Kemeny in 1985 and Kurtz in 1991. ■

COBOL: The Language That Will Not Die

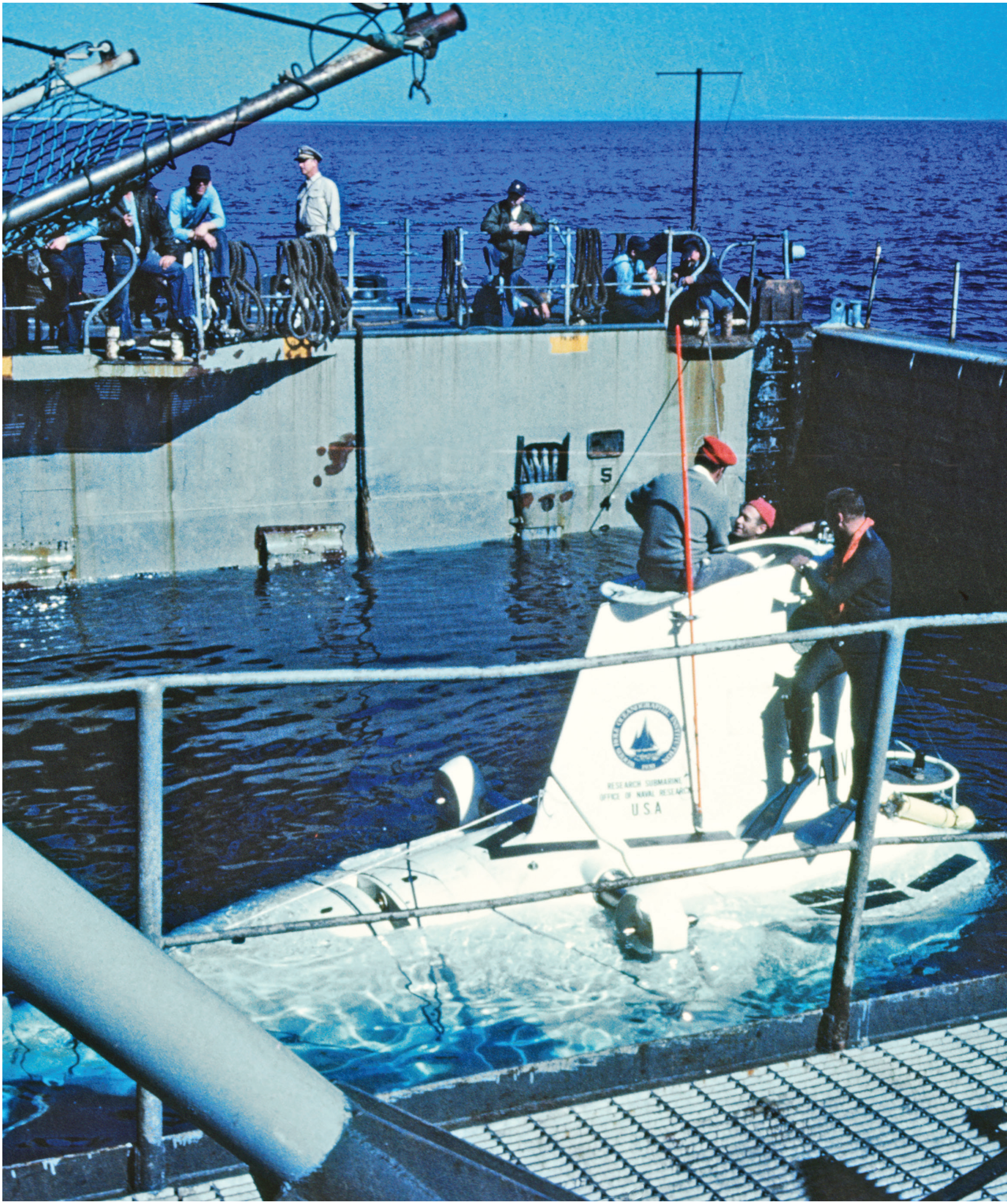
Common Business Oriented Language, or COBOL, is one of the oldest programming languages still in use today. Developed in 1959 for the U.S. Department of Defense, it was based partly on the programming language FLOW-MATIC, which had been designed by computer programming pioneer Grace Hopper. It is still, 64 years after its debut, the basis for an astonishing fraction of today's legacy mainframe and enterprise-level financial and administrative systems.

For decades COBOL was the programming language everyone loved to hate. Academics and industry insiders have been predicting its demise almost since it first came on the scene, warning programmers that focusing solely on this language would be career suicide.

During the height of the COVID-19 pandemic, when the number of people applying for unemployment insurance surged, COBOL-built systems crashed in multiple states, compelling state agencies to put out pleas for programmers to help. The development made news internationally, given that COBOL is decades old and considered clunky, and that many companies had moved away from it.

And yet COBOL not only survives, but thrives.

The language has endured because it is still well suited for processing large amounts of data, which is why it has been the language of choice for banks, insurance companies, airlines, federal and state agencies, traffic systems, pension funds, and payroll systems. Financial institutions that were still using COBOL had managed to successfully develop mobile services. Though recent developments in artificial intelligence could cause fundamental shifts in the popularity of programming languages, it's likely that those industries will continue to need programmers who can work on these legacy systems. In fact, after the pandemic, there was an uptick in interest from programmers who were banking on the fact that COBOL would not be going away anytime soon.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RESEARCH SUBMARINE
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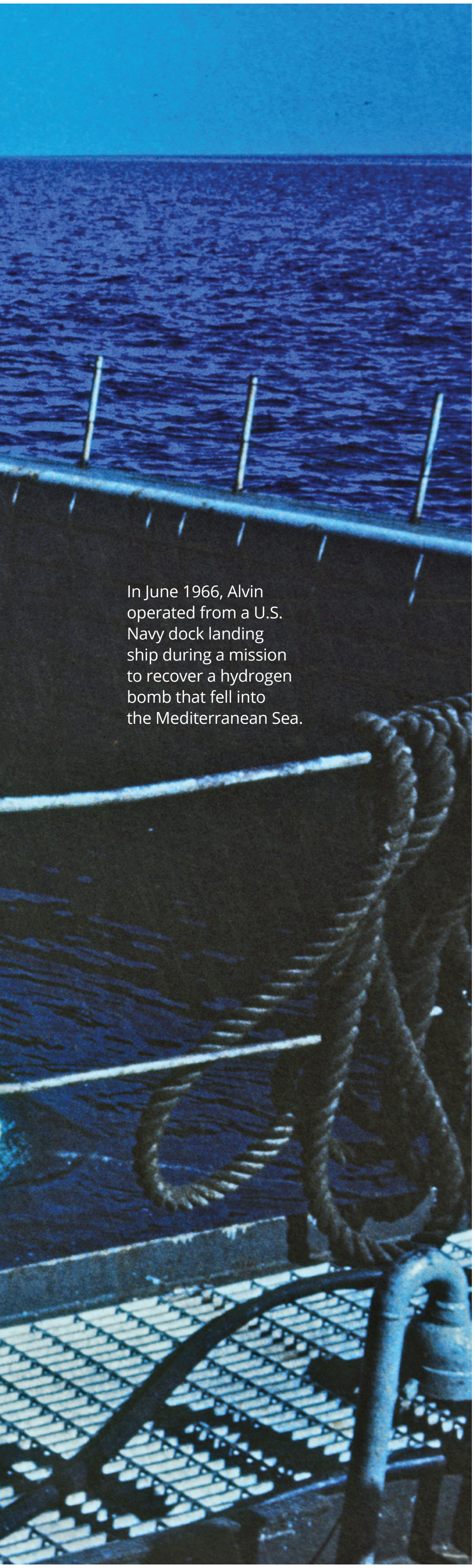


In June 1966, Alvin operated from a U.S. Navy dock landing ship during a mission to recover a hydrogen bomb that fell into the Mediterranean Sea.

WOODS HOLE OCEANOGRAPHIC INSTITUTION

OCEANIC ENGINEERING | 1965-1984

Voyage to the Bottom of the Sea

Alvin, the world's first maneuverable submersible, is still plumbing the secrets of the oceans.

In 1956 the ocean floor was like another planet: mysterious, unexplored, and inaccessible. That the best way to investigate it was probably to send a few uncrewed probes was the opinion of many of the 103 scientists who had convened in Washington, D.C., in February of that year to come up with ideas and strategies about how to start plumbing the deeps.

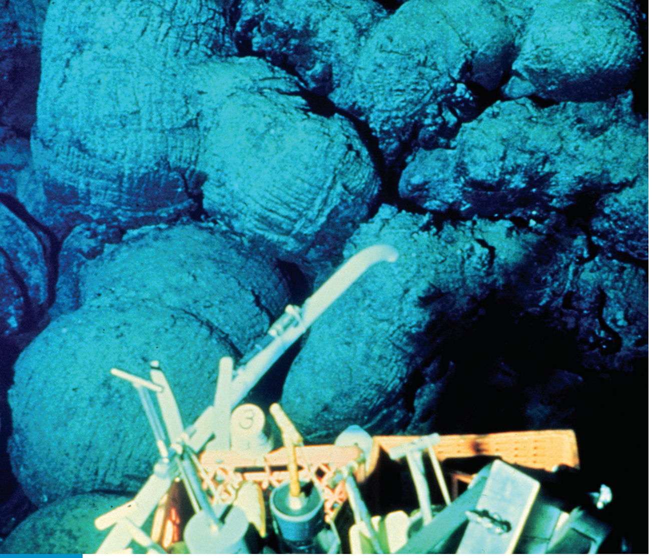
One researcher wasn't buying it. Allyn Vine, a geophysicist at the Woods Hole Oceanographic Institution (WHOI), argued that it was essential that humans, not just machines, visit the sea bottom.

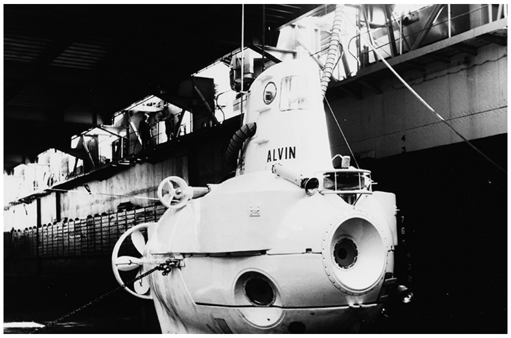
Vine wasn't the only one championing human presence in the sea. At that symposium in Washington, Bob Dietz from the U.S. Office of Naval Research and the Swiss oceanographer and engineer Jacques Piccard gave a talk about Trieste, a crewed bathyscaphe operated by the French Navy that had dived nearly two miles beneath the surface of the Mediterranean. Vine's enthusiasm, combined with the Trieste presentations, swayed some of the attendants and eventually led to several projects to build subs for science.

Soon after the meeting, members of the Office of Naval Research, with Vine in tow, traveled to Italy to check out the Trieste. Rather than take notes and reverse engineer it, the U.S. Navy decided to just buy it outright, for $250,000.

SMALLER IS BETTER

But the bathyscaphe was a massive affair, weighing 50 tons when empty and 150 when loaded with the gasoline and iron pellets used as ballast. It had a two-person spherical steel cabin, a sphere being the shape most inherently resistant to external pressure. It was affixed beneath an enormous





Roving along the rift they found a strange land of hydrothermal vents and, astoundingly, life that thrived on it—in water so deep that light never reached it.

hull, or "float," that held both breathing gas and ballast. That size and heft meant Trieste was too unwieldy for the kind of agile maneuvering the explorers had in mind. It was even too heavy to be loaded on a transport boat—it had to be towed wherever it was going.

So in 1962 WHOI solicited bids for a smaller, maneuverable submersible. Harold 'Bud' Froehlich, an engineer at General Mills (yes, the breakfast-cereal people), submitted the winning design. Froehlich had worked on a mechanical arm for Trieste.

The vehicle that was built by the General Mills team, for $472,517, weighed just 15 tons and was 7 meters long, compared to Trieste's 18 meters. Like the Trieste it had a roughly 2-meter-diameter steel crew sphere that was suspended below a hull containing ballast, life support, and a battery-powered propulsion system. The systems, tanks, and instruments in the hull were exposed to the extreme pressures at depth. The three-person crew sphere was outfitted with a single plexiglass window. What enabled the vehicle to be so much lighter than the Trieste was the extensive use of strong but lightweight syntactic foam, which gave it buoyancy. Pieces of Allyn Vine's first and last names were combined for the vehicle's moniker: Alvin.

RECOVERING A LOOSE NUKE

The vehicle made its first descents—tethered and in shallow water—on June 5, 1964. In 1965 it earned its navy certification by diving, unconnected by any kind of line to land or ship, to 1,800 meters (6,000 feet) off the Bahamas. Then, in 1966, Alvin was given a chance to show its worth for the U.S. Navy, which had funded its construction.

In January of that year, a B-52 bomber collided in midair with the stratotanker that was supposed to refuel it over Spain. The tanker exploded and the bomber came apart, dropping the four hydrogen bombs it had been carrying. Three were recovered on land in Palomares. The other landed in the Mediterranean and sank to the bottom. Alvin was called in, combed the sea floor, and, after two months, found the bomb. But as an attempt was made to attach lift lines to the bomb, it slipped away into greater depths. Alvin found it again two weeks later, and it was finally safely hauled out of the water.

A year later a swordfish attacked Alvin and managed to lodge itself in Alvin's skin. The submersible returned to the surface, and the fish was cooked for dinner.

At the end of 1968, about to be dropped into the ocean for its 307th dive, the cable holding Alvin snapped, and the submersible fell into the sea south of Nantucket. As the sub began to fill with water, the crew and a passenger escaped out the open hatch with only bruises, but the sub then sank 1,500 meters to the ocean floor. Ten months later, Alvin was salvaged, relatively unscathed.

LEFT AND RIGHT: WOODS HOLE OCEANOGRAPHIC INSTITUTION; MIDDLE: NATIONAL ARCHIVES

Alvin sampled volcanic rock at a seafloor vent in 1977 [far left]. The submersible was secured to the well deck of a U.S. Navy ship during the Palomares mission [middle left]. Alvin was commissioned at Woods Hole, Massachusetts, on June 5, 1964 [near left].

DISCOVERING ALIEN LIFE—ON EARTH

Alvin's more routine trips were filling in some of the bigger holes in our understanding of the deep sea. For example, in the early 1970s, it was a major contributor to the French-American Mid-Ocean Undersea Study (FAMOUS), which explored the Atlantic Mid-Ocean Ridge and observed the sea floor spreading there, helping to confirm the still-fresh theory of plate tectonics.

In 1973 Alvin's steel crew sphere was swapped for one of titanium, extending its depth rating from 2,000 meters to 3,650. Now Alvin could explore the Galapagos Rift, leading to one of the great discoveries of the 20th century.

"We had discovered something new upon Earth," was how Robert Ballard, the famed oceanographer, put it. Roving along the rift they found a strange land of hydrothermal vents, and, astoundingly, life that thrived on it—in water so deep that light never reached it. Giant clams and meters-long tubeworms were filled with microorganisms that were metabolizing the hydrogen sulfide found there. In other words, these were lifeforms dependent not on photosynthesis—like all other life known to humankind—but rather on chemosynthesis.

A similar expedition to the East Pacific Rise revealed strange chimney-like formations and "black smokers" vomiting thick dark plumes, and more life nearby. In one case, a smoker drew Alvin toward it, melted its plastic probe, and marred the vessel's skin.

FINDING THE *TITANIC*

Thrilling though it was to discover alien life in the black depths, the journey that brought Alvin worldwide fame was its visit to the *Titanic*, 600 km off the coast of Newfoundland, in 1986. The expedition was the first time Alvin would deploy the remotely operated Jason Jr., a small robotic camera vehicle that slid into the wreck where the larger vessel couldn't go. The video that Alvin and Jason Jr. recorded provided the world with the first glimpses of the ship since it went down in 1912.

After its multiple overhauls, there's not one piece of Alvin that is the same as it was in 1966. There's more titanium, four thrusters where there used to be one, and the sphere has been enlarged to fit five people instead of just three. It's been upgraded with new robotics, high-resolution cameras, an acoustic navigation system, and new syntactic foam. It now weighs more than 20 metric tons.

Since 1965, it's made more than 5,000 dives, taking more than 15,000 people below the surface. In 2023, Alvin's unblemished, 58-year safety record was hailed after the loss of the OceanGate Titan, a submersible that imploded, killing five explorers, during a descent to the *Titanic* wreck site in June of that year.

Ocean engineers quoted in the press after the disaster pointed out the crucial differences between Titan and Alvin. Where Alvin always used a spherical crew compartment, Titan went with a cylinder. Where Alvin used steel and later titanium, Titan used carbon fiber. Most critical, where Alvin was fully pressure tested and certified before it took any people into the deeps, Titan's backer placed his faith in an unproven system of real-time strain-gauge monitoring.

In July 2022, Alvin made its deepest dive ever, to 6,453 meters, in the Puerto Rico Trench. That same year, IEEE honored WHOI by making the submersible an official IEEE Milestone. Subsequently, the submersible was busy exploring microbial biofilms and larva at the East Pacific Rise, off the coast of Costa Rica. As of 2023, Alvin, after at least seven major upgrades and refits, is in a very small group of IEEE Milestones that are still very much on the job. ■

CONSUMER ELECTRONICS | 1968

The Carrot Juice Revolution

The long and twisting road to the large-screen TV started with a botanist's surprising discovery almost a century before the journey began.

Today's electronics industry offers flat-panel displays that are variations of multiple technologies, each with different strengths and weaknesses. Liquid crystal displays became the most dominant of them all thanks to a singular combination of qualities.

LCDs consume little power; small ones can easily run on watch batteries. LCDs also integrate well with semiconductor electronics, for several reasons including the low power requirements. LCDs can be manufactured less expensively compared to most alternatives, though the process of increasing their size from panes the size of watch faces to laptop monitors and much larger television screens was fitful.

It was a long and twisting road, and it started with pioneering work done by Richard Williams and George H. Heilmeier at RCA's laboratories in the 1960s. But the discovery of liquid crystals themselves can be traced back to a bunch of carrots in the 1880s.

One day in 1888, Austrian botanist Friedrich Richard Kornelius Reinitzer extracted from some carrots an ester of cholesterol and benzoic acid called cholesteryl benzoate. Like a good botanist, he then examined the solution under a microscope.

What he saw was astounding—and confusing. The substance seemed to have properties of both a solid and a liquid. Reinitzer showed his findings to colleagues at the Vienna Chemical Society before collaborating with the German physicist Otto Lehmann, who later called the substance *Flüssige Kristalle* (liquid crystals).

Finding practical applications for liquid crystals was difficult, however. The Marconi company used liquid crystals to create an electrically switched light valve in the 1930s, but the phenomenon remained a scientific curiosity.

BETTER LASER MODULATION? NOPE

It took another 30 years to discover that liquid crystals might be a big business. Working out of RCA's David Sarnoff Research Center, research chemist Richard Williams discovered he could use electronics to get a liquid crystal to modulate light passing through it. This caught the attention of Heilmeier, a fellow RCA researcher who had previously worked on molecular crystals and theorized that Williams's research could lead him to a better way to modulate lasers.

Heilmeier quickly figured out that the technology could be far more valuable in another application entirely—TVs. As he told *IEEE Spectrum* after he won the 1997 IEEE Medal of Honor, "I started my work on liquid crystals [not] because I was interested in publishing lots of papers on their fundamental properties. I knew exactly why I was interested in liquid crystals: Flat-panel display technology was a major priority at RCA Laboratories in the 1960s, given the company's position in color television."

RCA researcher George Heilmeier demonstrated an early RCA liquid-crystal display around 1964.

HAGLEY MUSEUM AND LIBRARY


RCA

RCA's Big Loss

In 1968, RCA was one of the world's most formidable tech companies. It had pioneered electronic color TV in the early 1950s and the first weather satellite in 1960. It would soon send high-resolution cameras to the moon. And it seemed to be on the edge of an even bigger development with flat-screen LCD TVs.

However, funding issues tied to research and company politics began to simmer in the late 1960s. RCA began licensing its color cathode-ray tubes to other companies and would often include licenses on other inventions, including the LCD.

It soon became apparent that many of these companies planned to use the LCD in products that could be quickly and profitably manufactured, while RCA toiled away on an LCD TV.

But in 1976, less than a decade after the LCD's unveiling, RCA sold off its liquid crystal operation. What began as an American innovation would mature under the auspices of firms in Europe and Asia.

RCA's last big hurrah—or last gasp—was its CED Videodisc system in 1981, which gave viewers their first opportunity to have video libraries of TV shows and movies—and which was soon killed by home videotape machines.

GE, which ironically had been one of the firms that started RCA as a wireless communications company in 1919, purchased it in 1986. GE then sold off its assets until the only thing left was the iconic RCA brand name, which has been sold and resold since. As of 2023, the owner was VOXX International, a maker of automotive and consumer electronics products.

George Heilmeier [pictured, right] and technician Louis Zanoni exhibited RCA's LCD prototypes at trade shows in the 1960s.

HAGLEY MUSEUM AND LIBRARY

Heilmeier focused his attention on nematic liquid crystals, whose molecules were all roughly aligned in the same direction. He suspected that if he could precisely apply powerful voltages to such crystals, he could cause their molecules to reorient themselves in relation to the resulting electric field. This effect might in turn be used to change the absorption spectrum of a dissolved dye. As an *IEEE Spectrum* profile of Heilmeier noted in 1994, "he tried dissolving organic dye molecules into nematic liquid crystals and then applying an external electric field to control molecular alignment of both the dye and the solvent."

He did manage to get the crystals to switch dramatically between red and colorless, but he gave up on that material when further experimentation led to the discovery that applying higher voltages to a different type of liquid crystal induced turbulence that could reflect light. This phenomenon, which Heilmeier referred to as "dynamic scattering," could be controlled with careful application of current.

IT COULD HAVE BEEN MAGIC

Heilmeier rigged up a demonstration for RCA management, who were greeted with an electrical wire connected to two pieces of glass. When a switch was flipped on, a previously clear liquid crystal sample turned bright white. It might as well have been magic.

Heilmeier's prototype was an important breakthrough in moving toward a world of liquid crystal display screens. The most obvious problem with it—the need to apply heat to create the effect— was soon solved by Heilmeier's team thanks to a synthesized crystal known as anisylidene p-aminophenyl acetate (APAPA). By modifying APAPA's structure and combining several of the resulting compounds they were able to create a mixture that exhibited the nematic behavior necessary for an LCD display to work at room temperature, which would be necessary if LCDs were ever going to become commercially viable.

A big advantage of Heilmeier's LCD was its low power consumption—it could run at levels compatible with existing integrated circuits. A numeric display required only 10 to 15 volts to operate; for comparison, a popular display in those days, Nixie tubes, required voltages at least 10 times higher. (See "A Sprinkling of Nixie Dust," on page 64.)

A previously clear liquid crystal sample turned bright white. It might as well have been magic

GETTING THE "BIG PICTURE"

In the 1960s RCA was one of the largest consumer electronics brands in the world, with businesses and intellectual property in radio, records, phonographs, and television. The company's leadership saw the great promise of liquid crystal displays in electronics and home entertainment.

So in 1968 the company organized a major media event in New York City to trumpet its new invention. RCA officials showed how the LCD worked and talked up potential uses, including ones in electronic clocks, aircraft instruments, and picture displays.

After technical presentations and the unveiling of prototype LCD displays, James Hillier, then vice president of RCA Laboratories, took the podium, according to *The TVs of Tomorrow*, a book about RCA's LCD program by Benjamin Gross. Hillier managed to hint at future, portable televisions while getting in a jab at long-suffering fans of the New York Mets. "You could take such a set to the beach and, in between bikini watching, see the Mets on TV figure out a new way to lose a ball game," he declared.

Ultimately, the LCD became a great success story – but not for RCA (see sidebar, p. 98). Not long after RCA announced the breakthrough, RCA managers gave the project to the company's semiconductor division, where the technology met with skepticism about its merits. As a practical matter, researchers would need many more years to refine liquid crystal and related technologies to give the display the kind of reliability demanded by the consumer market. Furthermore, manufacturing LCD screens larger than just a few square centimeters proved unexpectedly difficult.

Eventually, RCA management also soured on LCDs, which no longer seemed like a profitable investment. Instead, the company chose to prioritize its computer business, in a disastrous attempt to compete with IBM.

RCA kept its LCD program going until 1976, but long before that, they ruled out building an LCD TV. Disappointed, Heilmeier left the company in 1970.

Others jumped on the technology, however. Companies such as Sharp, Seiko, and Casio incorporated LCDs in products that needed only small screens that could be manufactured with consistent quality. This made the late 1970s the era of pocket calculators, digital watches, and countless other products incorporating small LCD screens—all without the RCA brand. LCDs would subsequently be incorporated in clock radios, compact disc players, camcorders, microwave ovens, and even a few small TVs.

In 1982 Seiko Epson released the Epson TV watch, a 1.2-inch LCD television worn on the wrist, which portended the future in screen technology. Six years later, Sharp unveiled a 14-inch, 92,000-pixel full-color LCD television that finally fulfilled Heilmeier's dream.

Neither of these televisions used the dynamic scattering technology developed at RCA. Instead, they featured a new "twisted nematic" LCD, developed in the early 1970s at the Swiss firm Hoffmann La Roche. Each element of this display consisted of a pair of glass plates containing a liquid crystal helix capable of changing the orientation of polarized light. This setup was placed between a pair of crossed polarizers. Light passing through one polarizer would rotate along the helix and pass through the polarizer on the other side. An applied voltage, however, would disrupt the helix and prevent any light transmission. By creating an array of these tiny liquid crystal shutters and selectively allowing light to pass through a series of red, green, and blue filters, it was possible to create the full gamut of visible colors.

This was the technology that came to dominate the TV market, starting around 2006. But that domination was not absolute. The first organic light-emitting diode TV was introduced in 2007, and OLED TVs have been gaining market share ever since. The flat panel TV market now consists almost entirely of LCDs and OLEDs. And of course, smaller LCDs continue to be built into thousands of products.

In 1976 Heilmeier received the IEEE David Sarnoff Award, and was awarded the IEEE Medal of Honor in 1997, both for his pioneering work on LCDs. RCA's work on LCDs was declared an IEEE Milestone in 2006. ■

UCLA SAMUELI SCHOOL OF ENGINEERING

COMMUNICATIONS | 1969

Spinning the Web

Jolted into action by the launch of Sputnik, the U.S. agency ARPA set the stage for the worldwide internet revolution.

The first moonwalk. Woodstock. ARPAnet. The year 1969 was a transformative year.

Born out of the Cold War imperative to win the space race, ARPAnet was the first public packet-switching network, allowing multiple users in remote locations access to varied applications on different computer platforms.

On October 29, 1969, the first ARPAnet message was sent from UCLA to the Stanford Research Institute and contained only the letters "lo"—the full text was supposed to read "login," but the system crashed before the final three letters were transmitted. From that "lo," we behold the internet revolution.

UCLA's Boelter Hall housed one of the four original ARPAnet nodes in 1969.

SPACE RACE LEADS TO ARPA—AND ARPANET

The launch of Sputnik 1 in 1957 shocked the United States, igniting fears that the country was losing the Cold War technology race. A year later, President Dwight D. Eisenhower created the Advanced Research Projects Agency to bring top engineers together to conceive and develop new military technologies, including large-scale computer networks.

In 1966, a computer scientist at ARPA, Bob Taylor, proposed that ARPAnet, then under development, become a way for computers in remote locations to share resources. It would take two more years for four remote computers—at the University of California campuses at Santa Barbara and Los Angeles, the Stanford Research Institute, and the University of Utah—to be able to exchange data.

It was an attempt, on October 29, 1969, to send a message from the computer of UCLA professor and IEEE member Leonard Kleinrock to a computer at SRI that caused the crash that reduced "login" to "lo." The second attempt succeeded. "Login" appeared, more messages were sent, and ARPAnet was born.

By 1973, 30 academic, military, and research institutions scattered across the continental U.S., Hawaii, Norway, and the United Kingdom had joined ARPAnet.

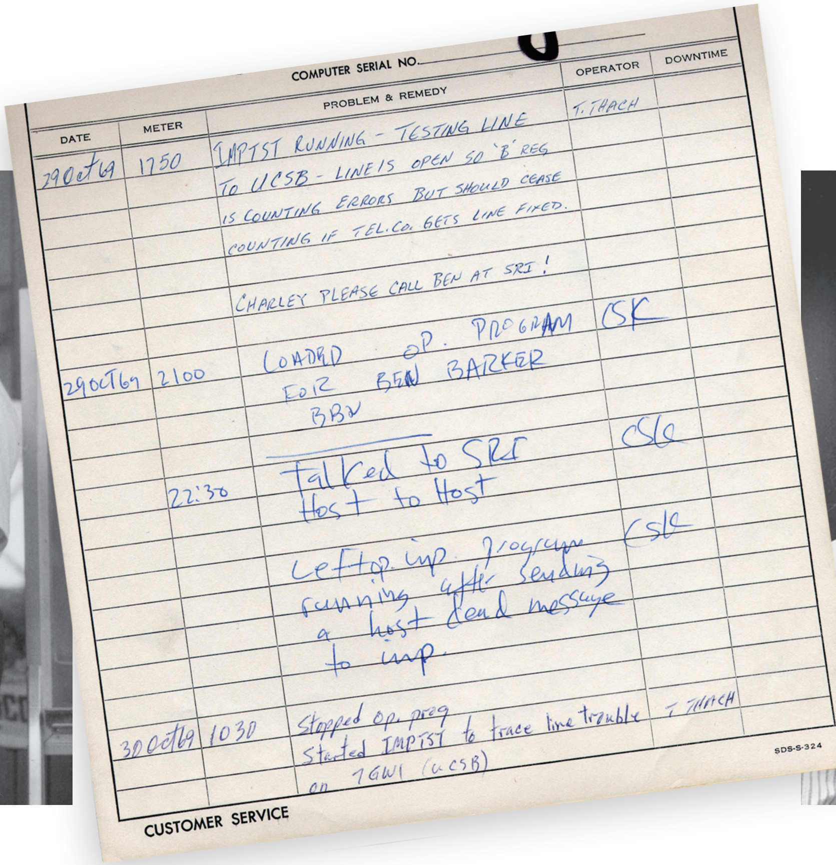
PACKET SWITCHING MAKES THE DIFFERENCE

Computer networks had existed before, of course, such as the Semi-Automatic Ground Environment, dating from the late 1950s. But networks like SAGE, which was the technical infrastructure of the North American Aerospace Defense Command, were designed to link machines of a similar type. ARPAnet, on the other hand, was intended to allow machines of any type to communicate. At the time, researchers who needed to access different kinds of computers needed multiple terminals, one for each type of computer they needed to access.

A separate but fateful decision was to use packet switching for network communications. To that point, circuit switching prevailed. In circuit switching, network equipment sets up a dedicated path back and forth—a physical circuit—for the duration of each call. Data is transmitted in a continuous stream.

With packet switching, data streams consist of discrete packets of a predefined number of bits. Each packet contains the destination address, so the network knows where to send it. This convention makes it possible to send any two packets on entirely different routes, traveling through different computers on the network, on their separate ways to their common destination. It also requires every computer in the chain to examine every packet received, keep those packets that are addressed to it, and forward those addressed to other computers.

The problem was, organizations connected to ARPAnet were reluctant to waste precious computing time on such menial housekeeping tasks. The solution was to attach a smaller

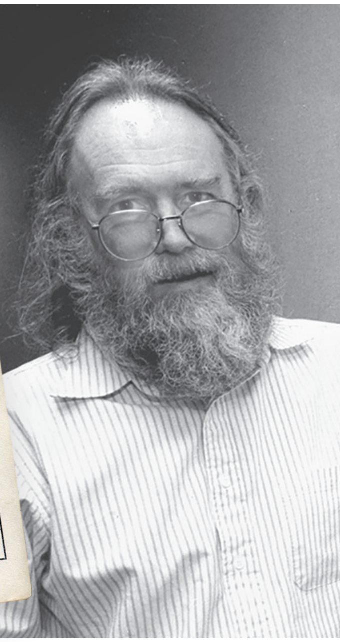


COMPUTER SERIAL NO.

DATE	METER	PROBLEM & REMEDY	OPERATOR	DOWNTIME
29Oct69	1750	IMPTST RUNNING – TESTING LINE TO UCSB – LINE IS OPEN SO 'B' REG IS COUNTING ERRORS BUT SHOULD CEASE COUNTING IF TEL.CO. GETS LINE FIXED.	T. THACH	
		CHARLEY PLEASE CALL BEN AT SRI !		
29OCT69	2100	LOADED OP. PROGRAM FOR BEN BARKER BBN	CSK	
	22:30	Talked to SRI Host to Host	CSK	
		Left op. imp. program running after sending a host dead message to imp.	CSK	
30Oct69	1030	Stopped op. prog Started IMPTST to trace line trouble on 7GW1 (UCSB)	T. THACH	

SDS-S-324

CUSTOMER SERVICE



The first ARPAnet message was sent from the computer of UCLA professor Leonard Kleinrock [above]. A note written by Charles Kline [above, middle] notes that the message went through, "host to host." Jon Postel [above, right] helped create the Domain Name System in 1985.

computer to every computer on the network to handle the traffic. These smaller computers were originally called interface message processors. Years later that function would be handled by dedicated systems called switchers and routers.

There are several advantages to packet switching, but one of the most important is that packet switching is more reliable. With circuit switching, if any network node fails for any reason, the circuit is broken, and the communication ends. If a node fails in a packet-switching network, IMPs can send packets on any other available route. Other advantages include flexibility and speed—if there is heavy traffic in one part of the network, packets can be routed around it via other nodes to avoid the congestion. Packet switching was invented, separately, in the early 1960s by IEEE member Paul Baran in the U.S. and Donald Davies in the U.K. Baran's article proposing packet switching, "On Distributed Communications Networks," was published in the March 1964 issue of *IEEE Transactions on Communications Systems.*

THE INTERNET TAKES OFF

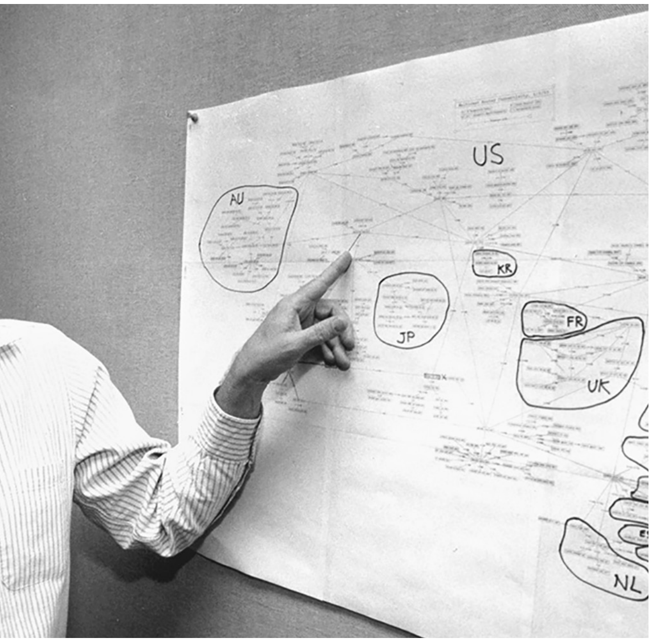
BBN won the contract to build ARPAnet. The company devised one of the first standard interfaces that would allow different computers to communicate with each other, a simple serial interface in which data was streamed one bit at a time. Commercial versions would follow.

In the early 1970s, more and more networks began to join ARPAnet, sharing information among themselves at 56,000 bits per second, then considered blazingly fast. Such a speed required a common set of rules for handling data between the many interconnected networks.

In 1974, two computer scientists at UCLA, IEEE member Robert E. Kahn and Vinton Cerf, proposed a new data-handling method in an article for *IEEE Transactions on Communications*. In the article, titled "A Protocol for Packet Network Intercommunication," they called their new scheme transmission control protocol. TCP essentially describes how two nodes in a network connect and terminate their connection. It also handles details of each transmission, reassembling received packets in proper order, for example, and asking for retransmission of missing packets. To that end, TCP segments data streams and packages each segment with a header, additional data that includes formatted information about the order of segments in the stream, and more.

Kahn and Cerf also developed the Internet Protocol, which specified how these data seg-

FROM LEFT: UCLA SAMUELI SCHOOL OF ENGINEERING (2); IRENE FERTIK/USC NEWS SERVICE



ments would be forwarded along the correct network links. When combined with TCP, an IP address enables internet traffic to find its destination to any internet-connected device in the world.

TCP/IP was completed in the late 1970s, and in 1983 Version 2 of the ARPAnet went online.

Throughout the 1980s, more affordable technology and a proliferation of desktop computers accelerated the growth of local area networks. These were groups of connected computers in a relatively small area that traditionally had a common internet connection. The upshot was that the increasing number of computers on the ARPAnet started making it difficult to keep track of so many different IP addresses.

To address this issue, the Domain Name System was created in 1985 by IEEE member Paul Mockapetris and Jon Postel at the University of Southern California. The DNS "phone book" converted IP addresses, which are numerical, into user-friendly names, for example ones ending in ieee.org, thereby laying the groundwork for the World Wide Web. For this achievement, Mockapetris and Postel won the IEEE Internet Award in 2003.

In 1990, with the internet expanding, the private sector getting involved, and commercialization just around the corner, ARPAnet was officially decommissioned.

A WEB WITHIN A WEB

The emergence of DNS, the widespread adoption of TCP/IP, and the increasing popularity of email ushered in an era of astounding growth and activity on the internet. In just one year between 1986 and 1987, the network expanded from 2,000 to 30,000 hosts. However, the system was still clunky: Users still needed to have fairly advanced technical skills, and no one could agree on the best way to format documents.

In 1989, British computer scientist Tim Berners-Lee, working at CERN in Geneva, Switzerland, presented a proposal. He envisioned a novel way of organizing and linking the vast amount of information available on CERN's computer network—a "web of information"—enabling quick and seamless access.

The key to Berners-Lee's vision lay in the use of "hyperlinks" to connect documents. His Hypertext Markup Language (HTML) included a set of tags that could be used to format text. One set of tags surrounding a string of text would instruct a computer to render that string in bold type; another set of tags would instruct the computer to create a hyperlink.

In 1990, Berners-Lee not only developed Hypertext Transfer Protocol (HTTP), the language employed by computers to communicate HTML documents over the internet, but also designed the Universal Resource Identifier (URI) system. The URI, one type of which is the URL (universal resource locator), offered a unique address that facilitated easy retrieval of web pages. For example, a user could click on a string of text, or hyperlink, and would see a web page specified in the link more or less immediately. (It was the implementation of a vision first conjured up by Vannevar Bush in 1939.)

In 1991, the code for creating web pages and the accompanying browsing software were made freely available on the internet to anyone who wanted to create their own website. At that point, there was one website—CERN's. By 1992, there were 10. By 1995, 23,000. By 2000, 17 million. September 2023? Nearly 2 billion. ■

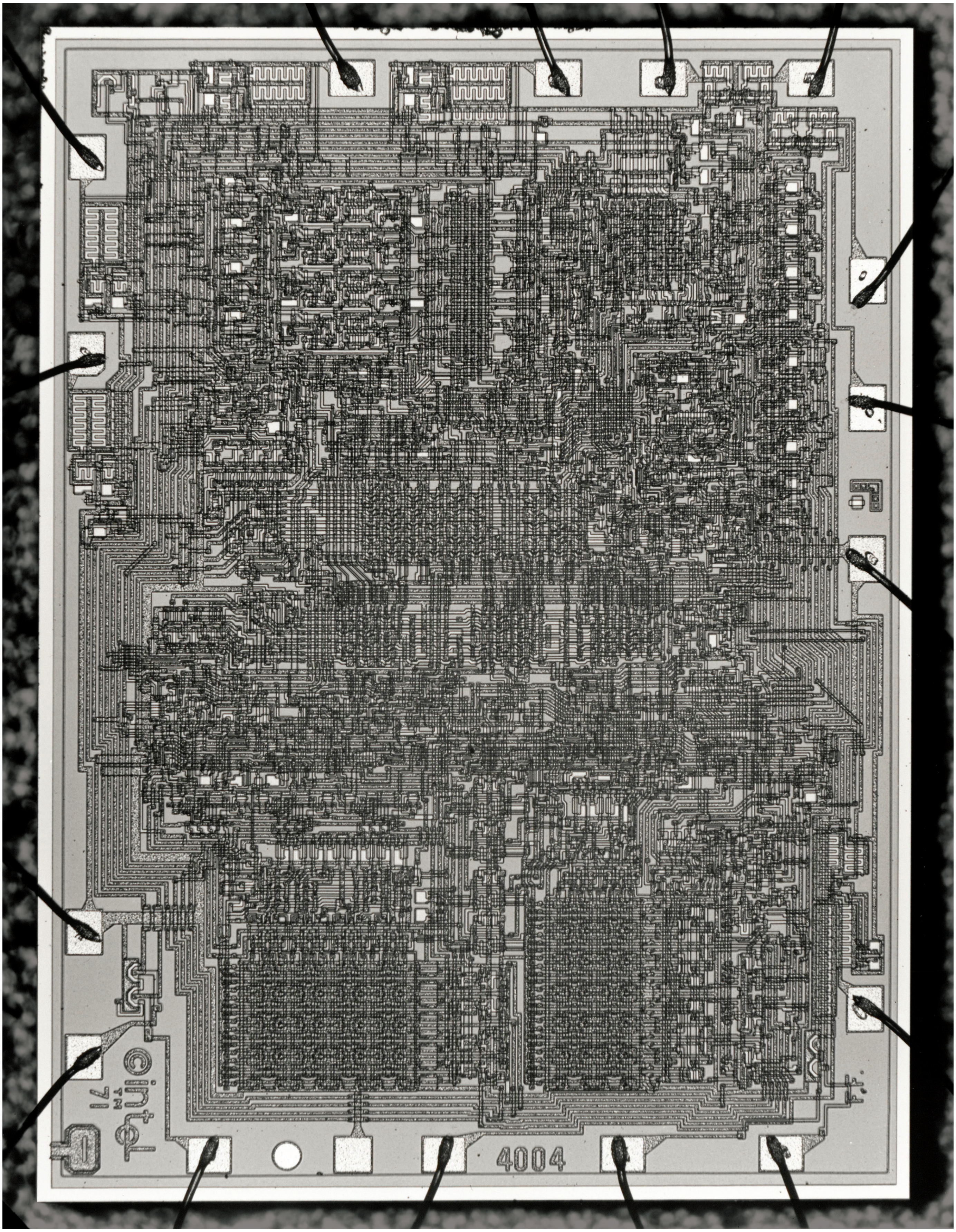
More to Be Done

A great many people played instrumental roles in creating the internet. Vinton Gray Cerf stands out among them not only for contributing a fundamental technology with TCP/IP, but for helping to shepherd internet innovation ever since. His contributions in "co-creating the internet architecture and providing sustained leadership in its phenomenal growth in becoming society's critical infrastructure" resulted in his receiving the 2023 IEEE Medal of Honor.

Even after 50 years, Cerf told *IEEE Spectrum* in an April 2023 interview, the internet still needs work. "I got involved in this and haven't stopped because there's always more to be done. It doesn't get boring, ever."

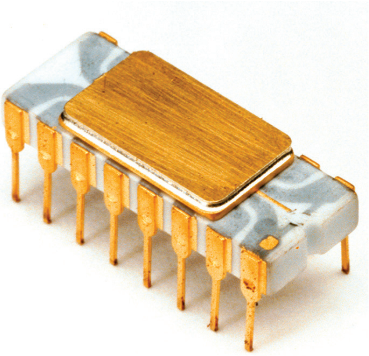
"Patience and persistence," Cerf added. "I'm not going to see the end of this. I feel like I'm in chapter two of what will be a much longer story about the history of interplanetary networking."

PETER ADAMS/IEEE SPECTRUM



INTEL (4)

Chipping Away at Complexity



The search for a better, faster calculator changed one company's business—and the world.

Intel was founded in 1968 with a plan to design an inexpensive semiconductor memory that could replace core memory and that could be churned out in the millions. In 1969, Intel was still working on designing semiconductor memories, and to keep revenue coming in while that business got on its feet, it was taking on custom projects involving other kinds of products. One of those side jobs was the development of new processor chips for a company that made desktop calculators—an effort that took Intel outside of its core business. At least until the late 1970s, at which point it became Intel's core business.

The project was rushed and understaffed and drew primarily on four key engineers—one brand new at Intel and another who didn't even work there. What they came up with, in January 1971, was the Intel 4004, the world's first microprocessor—a complete, general-purpose central processing unit (CPU) on a single chip.

Masatoshi Shima, one of those four key engineers, was clear on the technical importance of this innovation. "I believe that the biggest invention with the microprocessor was the replacement of hardwired logic by software," he said in an oral history for the IEEE History Center recorded in 1994. "Nobody knew how to do it. After the 4004, it was easy."

The 4004 was followed by a relentless stream of successors that packed more and more computing power into smaller and smaller spaces—and brought fundamental change to society, industry, and the daily lives of billions of individuals.

FAGGIN GETS BUSY

In April 1969, Intel signed an agreement with Busicom, in Japan, to develop a custom set of chips for a new office calculator. Shima, then one of Busicom's engineers, visited Intel to share his employer's plans: the company was looking for a dozen new chip designs for its calculator, including chips for interfacing with specific peripherals and storing data and code and two custom-made, large-scale integrated circuits that would make up the CPU.

Intel assigned Marcian Edward "Ted" Hoff Jr., head of the company's applications department, to work with Busicom. Looking at the proposed solution, Hoff was worried that it was

Look closely at the lower right corner of the photomicrograph of the die for the Intel 4004 microprocessor [opposite page] and you'll see the initials of Federico Faggin [below, left]. The 4004 project was led by Marcian Edward "Ted" Hoff [below].

too complex and would require too many chips, and that Intel would have trouble delivering it.

Hoff proposed a different approach that called for using programmable processors rather than custom-designed circuitry. His design would use just four chips—one 256-byte program-memory chip (named the 4001), one 40-byte data-memory chip (4002), one peripheral-interface chip (4003), and one general-purpose logic chip as a full CPU (4004). This approach would mean reduced complexity and would entail the development of fewer chips. Hoff then worked with Stanley Mazor, an Intel engineer, to create specs for each chip and come up with a production schedule.

In October 1969 the two companies agreed to proceed with Hoff's approach. Busicom planned the rollout of its new calculator to fit with Intel's development schedule, and Shima planned to come back to Intel in April 1970 to see how the work was progressing.

But there was a problem. Intel was not at all ready to create the four new chips in the planned timeline. The company had limited staff to devote to the project. Hoff and Mazor were not chip designers, and the Intel employees who did have the necessary skills were busy working on memory chips. Moreover, the plan required the design of new, highly complex chips—processor chips, not memory chips—which meant they were outside Intel's core expertise. So the effort stalled.

Enter Federico Faggin, an engineer hired from Fairfield Semiconductor. On his first day at Intel, Faggin learned more about the Busicom project—and was stunned. "When I saw the project schedules that were promised to Busicom, my jaw dropped," he wrote in the Winter 2009 issue of *IEEE Solid State Circuits Magazine*. "I had less than six months to design four chips, one of which, the CPU, was at the boundary of what was possible; a chip of that complexity had never been done before. I had nobody working for me to share the workload; Intel had never done random-logic custom chips before, and, unlike other companies in that business, had no methodology and no design tools for speedy and error-free design."

Faggin also learned that Busicom's Shima would be returning for his follow-up visit in just a few days—and that Busicom had not been told about the delay. When Shima arrived and saw how things stood, he was not happy. "Shima was furious when he found out that no work had been done in the five months, and he became very angry at me," Faggin recalled. "Literally calling me names.… It took almost one week for Shima to calm down."

SHIMA PITCHES IN

Shima was furious, but he was also practical. He decided to pitch in and help Faggin, and a new, even more ambitious schedule was drawn up that called for finished chips by December 1970—about nine months away.

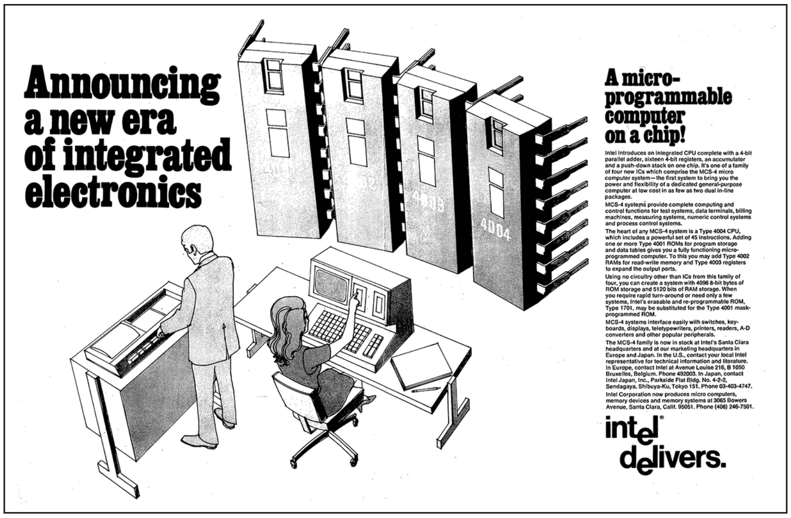
Faggin decided to work on all four chips at once, staggering them a bit so that work started on the least complex chip, and once that was underway, work started on the next most complex, and so on. "This made it possible to incrementally develop the methodology and the building blocks I needed to use for the most complex chip, the 4004," he wrote.

Hoff and Mazor had already developed the chips' architecture and basic specifications. Faggin and Shima worked on development, with Faggin focusing on the circuit design and layout while providing overall supervision of the project, and Shima doing detailed logic design and logic simulation.

At the time, most commercial ICs were bipolar ICs. Metal oxide semiconductor (MOS) ICs were slower and less reliable, but they were attracting interest because of a growing

The 4004 microprocessor was one of four chips Intel designed for the Busicom 141-PF printing calculator. The calculator was introduced in Japan in October 1971.

INTEL (4)



Announcing a new era of integrated electronics

A micro-programmable computer on a chip!

Intel introduces an integrated CPU complete with a 4-bit parallel adder, sixteen 4-bit registers, an accumulator and a push-down stack on one chip. It's one of a family of four new ICs which comprise the MCS-4 micro computer system—the first system to bring you the power and flexibility of a dedicated general-purpose computer at low cost in as few as two dual in-line packages.

MCS-4 systems provide complete computing and control functions for test systems, data terminals, billing machines, measuring systems, numeric control systems and process control systems.

The heart of any MCS-4 system is a Type 4004 CPU, which includes a powerful set of 45 instructions. Adding one or more Type 4001 ROMs for program storage and data tables gives you a fully functioning micro-programmed computer. To this you may add Type 4002 RAMs for read-write memory and Type 4003 registers to expand the output ports.

Using no circuitry other than ICs from this family of four, you can create a system with 4096 8-bit bytes of ROM storage and 5120 bits of RAM storage. When you require rapid turn-around or need only a few systems, Intel's erasable and re-programmable ROM, Type 1701, may be substituted for the Type 4001 mask-programmed ROM.

MCS-4 systems interface easily with switches, keyboards, displays, teletypewriters, printers, readers, A-D converters and other popular peripherals.

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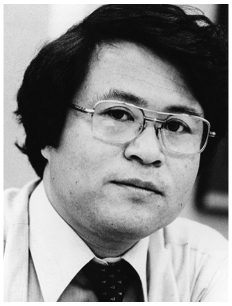


Intel heralded the introduction of the 4004 microprocessor with an advertisement in *Electronic News* magazine in November 1971 [top]. Masatoshi Shima was part of the team that designed the 4004 [above, middle], as was Stan Mazor [above].

expectation that MOS technology would allow engineers to build increasingly dense ICs at lower cost.

Faggin was versed in physics, and he and his colleagues at Fairchild Semiconductor had devised several innovations that made MOS more practical. One was to build transistors with silicon gates, rather than metal gates. This improved the reliability of MOS transistors considerably. Faggin also correctly intuited that to work properly, a silicon-gate transistor would have to have a buried contact, a technique he had invented at Fairchild that greatly increased the density of connections and devices possible on the chip. Finally, there was a commonly used technique in MOS circuit design called the bootstrap load—another of Faggin's innovations at Fairchild. Implementing it seemed to require adding a capacitor, but that necessitated another masking step during the MOS manufacturing process, and that was a very expensive proposition. One of Faggin's great breakthroughs was figuring out how to implement a bootstrap load without adding an extra masking step.

When he got to Intel, he explained all these innovations to Intel's manufacturing engineers, who devised an improved process for making silicon gate transistors with buried contacts and including bootstrap loads. This architecture and the associated manufacturing process contributed to the success of the 4004 but also started MOS IC technology on a rapid trajectory to becoming the most dominant IC type.

In December, Faggin received the first 4004 wafer from Intel's manufacturing operation. He started to test it, but nothing happened. He quickly discovered that one masking layer had accidently been left out during manufacturing. A month later, in January 1971, a new batch of wafers arrived. Faggin tested them alone in his lab—and they worked.

The 4004 packed 2,300 MOS transistors in a die that measured 0.12 inch by 0.16 inch. It incorporated a four-bit adder for doing addition, an accumulator for keeping track of partial sums, and 16 registers for temporary storage. It could execute about 60,000 instructions per second.

When testing the 4004 at Busicom for the first time, Shima was "fully aware that the outcome of the two-year project would be determined in that one moment. I pushed the reset button, but hesitated before releasing it," he wrote. He then typed in some numbers, which successfully printed out. "I felt my heart pounding and my entire body flash hot with excitement, while my head alone remained sober."

Intel had agreed to make the 4004 for Busicom exclusively. But the two companies soon struck a deal that allowed Intel to sell the 4004 for non-calculator applications in return for better pricing for Busicom. Intel released the processor commercially in November 1971 at a price of around $200.

The 4004 was the first complex random-l ogic circuit built using silicon gate MOS technology. Some argue that there were ICs built prior to the 4004 that could be called microprocessors, but there is no argument that the 4004 was the first successful microprocessor, and that it paved the way for subsequent microprocessors from Intel and other companies.

The four key engineers involved gained widespread recognition for their microprocessor-related efforts. Hoff received the IEEE Cledo Brunetti Award in 1980, and the IEEE/RSE Wolfson James Clerk Maxwell Award in 2011. Faggin received the IEEE W. Wallace McDowell Award in 1994. In 1997, all four were given the Kyoto award, with a citation that summed up the impact of their work: "Of all devices invented by humans, nothing has had greater impact in such a short period of time than the microprocessor. The progress of electronics we now enjoy was triggered by the development of the 4004; electronic technology would not have developed as it did, were it not for the achievements of the four engineers." ■

Nearly 40 years after he built the first digital camera, Steven Sasson posed with it for a picture (digital, of course).

CONSUMER ELECTRONICS | 1975

How a Brilliant Kludge Ended an Era

An electrical engineer at Kodak could see the future of photography—but his bosses couldn't.

Rolls of camera film were once as much a staple of leisure time as beach umbrellas and playing cards. For generations of families, dropping off a roll of film for development, picking up prints, and displaying the best ones in albums or frames punctuated the passage of time as much as holidays and anniversaries. So the introduction of handheld digital cameras in the mid-1990s represented not just a technological leap, but a profound cultural shift as well. A way of life ended, and a different one—similar in some ways, radically different in others—began.

Rochester, New York-based Kodak was the king of photographic film. The company had some 60,000 employees in the late 1970s, supervised and directed by handsomely compensated executives. None could possibly have suspected that the start of the company's decline could one day be traced to the 1973 hiring of an electrical engineer named Steven Sasson, fresh out of grad school. He was assigned a seemingly innocuous task, to find a possible use for a new charge-coupled device (CCD) that had just been introduced by Fairchild Semiconductor. What could he do with a light-sensitive integrated circuit that captured digital images by converting incoming photons to electrons?

Sasson set out to build an all-new, all-electric camera. He pieced it together like the experiment that it was. There was, to begin with, the Fairchild CCD, which was monochrome and 100 pixels by 100 pixels. He used a lens and an exposure control mechanism from a Kodak 8-mm movie camera, enclosed in a simple blue, rectangular box. He borrowed an analog-to-digital converter from a Motorola digital voltmeter. His goal was to capture and store an image on the camera so it could be played on another device. That meant he needed a storage medium, which turned out to be audiotape on a portable Memodyne data cassette recorder (he said later that cassette tapes were, at the time, the only permanent form of digital storage available). He also had to invent a device that converted information stored on the tape into digital images that could be shown on a TV screen.

Sasson's kludge looked like it was made in somebody's basement. It was as big as a car battery and ran on 16 AA batteries. Still, it was the first digital camera.

They were intrigued, but not that much. They figured that the development of digital cameras that could rival traditional ones was more than a decade away. And what would consumers do without prints?

GEORGE EASTMAN MUSEUM

WHY WAIT FOR FILM?

At age 24, Sasson took the world's first digital photo on December 12, 1975. (At the time, the disco hit "Fly, Robin, Fly" was the No. 1 song in the U.S.) His photo of a coworker, lab technician Joy Marshall, took 23 seconds to record onto the tape and the resulting image wasn't much to look at. Marshall's hair was rendered fairly well, but her face had very little detail, because the system struggled with tones that weren't either light or dark. "Needs work," was Marshall's verdict.

Sasson worked steadily, improving the system until he was ready to demonstrate it for Kodak executives. They were intrigued, but not that much. They figured that the development of digital cameras that could rival traditional ones was more than a decade away. And what would consumers do without prints?

Perhaps, too, they couldn't imagine a technology that could mean the death of film. So for years, Kodak kept its hand in digital photography, but without firm plans to introduce a commercial product.

Sasson was granted a U.S. patent for the camera, which belonged to Kodak, in 1978. He continued to work on digital photography, and in 1994—almost two decades after completing his first experimental model —he worked with colleagues to design the NC2000, a variation of the Kodak DCS 200 digital camera. Like other early digital Kodak cameras, it was based on a single-lens-reflex camera body from Nikon. The purchase price, when it was introduced, of $18,000 limited sales to news organizations.

Kodak did see a financial windfall because of its digital-technology patents, but would never fully embrace digital photography, even as competitors flooded the market and film was obviously starting to become obsolete.

Also in 1994, Apple produced a handheld, all-electronic consumer camera for under $1,000, the QuickTake 100. It only sold about 50,000 units, but Apple's initiative and laser-like focus on giving consumers what they wanted fostered awareness of digital photography and better products, mostly from other manufacturers. What Apple's marketers understood was that the key to marketing digital cameras was the instantaneous nature of digital photography—photos could be seen and shared instantly with friends and family.

A "PHOTOGRAPHIC SYSTEM"

In a 2000 paper presented at the IEEE International Symposium on Circuits and Systems, two Kodak employees, IEEE Fellow Majid Rabbani and senior member Ken Parulski, foresaw the pivotal role smartphones would play in making digital photography ubiquitous. "In the future, digital TV set-top boxes may provide an alternative to the PC as the center of digital photography," they wrote. "Or, as hand-held devices like cellphones and palm-size organizers increase in capability, they may provide mobile platforms for digital photography systems. By featuring wireless, high data rate Internet connectivity, these devices will allow users to send and receive digital pictures wherever they travel."

Sales of digital cameras peaked in 2012, the same year that the first cellphones with embedded cameras were introduced in the U.S. The images from these smartphones were far from ideal, and nowhere near as sharp as what film offered at the time, but smartphones made photography instant, easily storable, and shareable—and also disposable. Picture-taking

The Epson R-D1: the First Digital Rangefinder Camera

Since the first photographs were snapped in 1826 in France, photography has produced countless remarkable or oddball cameras. One of the most fascinating of these was the Epson R-D1, the first digital rangefinder camera, which was introduced in 2004.

Since the World War I era, rangefinders had been enabling photographers, including serious amateurs, to take photos discreetly and unobtrusively in crowded or fluid situations, such as on city streets. A rangefinder's focusing system worked by capturing two slightly different angles of a subject and then superimposing them. Seen through a viewfinder, the superimposed images lined up when the image was in focus on the film plane. To make the R-D1, Epson teamed up with camera maker Cosina Voigtländer to produce a digital rangefinder that had old-school manual controls.

The camera had a classic look and feel but included a 6.1-megapixel digital imager from Sony. It provided a cozy mix of the past and present, circa the early 2000s, at a retail price of about $3,000. The camera even included what looked to be a film-winding lever, even though the camera did not use film (the lever actually cocked a mechanical shutter). "This feature delighted more than a few enthusiasts already nostalgic for the fast-fading world of film cameras," *IEEE Spectrum* recalled in 2018.

Introduced in 2004, Seiko Epson's R-D1 was the world's first rangefinder digital camera.

YOSHIKAZU TSUNO/AFP/GETTY IMAGES

took on a different meaning than when consumers had prized every print, even those in which the subjects' eyes were disappointingly closed. And, equipped with stabilization technologies, highly sensitive image sensors, and artificial-intelligence-based image enhancement, the latest smartphones can take pictures far better than what could be done with the best film cameras on the market 20 years ago.

In 2010, *IEEE Spectrum* named digital photography one of top 11 technologies of the 2000s and hailed Sasson's contributions. "Being an electrical engineer, [Sasson] thought it would be cool to create a new, all-electronic camera, with no moving parts, rather than sticking the CCD into an existing mechanical body," wrote *IEEE Spectrum*. "He spent about a year on the effort, working on it in between other assignments, cobbling together the materials he needed from catalogs and used-parts bins."

Sasson's original digital camera is on display at the Smithsonian Institution's National Museum of American History, in Washington, D.C. "This was more than just a camera," Sasson, an IEEE member, told the *New York Times* in 2015. "It was a photographic system to demonstrate the idea of an all-electronic camera that didn't use film and didn't use paper, and no consumables at all in the capturing and display of still photographic images."

In 2008, in a ceremony at the White House, President Obama awarded Sasson the National Medal of Technology and Innovation.

In 2012, Kodak filed for bankruptcy. It sold off its patents and emerged from bankruptcy the following year, reimagining itself as a commercially focused digital imaging company. It still manufactures and markets photographic film, however, through a British-owned company called Kodak Alaris. ■


COMPUTER
TEXAS INSTRUMENTS
MYSTERY WORD
SECRET CODE
LETTER
SAY IT
SPELL
REPLAY
REPEAT
CLUE
OFF
GO
ON
MODULE SELECT
ERASE
ENTER
© TI 1978
Speak & Spell™

CONSUMER ELECTRONICS | 1978

What the 'Little Professor' Taught Texas Instruments

How an electronic toy helped children learn to spell—and set the stage for the introduction of Siri and Alexa.

Already renowned for inventing a method of fabricating integrated circuits, Texas Instruments solidified its position as an electronics industry pioneer in the 1970s by commercializing the first single-chip microcontroller, being among the first to introduce and sell handheld calculators and helping to create the market for microcomputers. Nobody expected that the next big thing out of Texas Instruments would be a toy for children.

And not even the designers of the Speak & Spell realized at first that they had done groundbreaking work for an entirely new semiconductor product that would propel TI to even greater success: the digital signal processor (DSP).

Early in the 1970s, engineers Paul Breedlove and Gene Frantz had worked together to help build TI's "Little Professor."

This was a kind of reverse calculator for children. At the time, calculators were viewed with suspicion by educators, who feared they would keep children from memorizing multiplication tables, and that students would become too dependent on the technology for test answers.

The Little Professor, however, avoided that problem. Instead of the child using the calculator to get the answer, the calculator asked the child what the answer was. When children turned on the Little Professor, they would see an incomplete equation on the display, "6 x 2 = —" for example. The child then had three chances to punch in the right answer before the device provided it and moved on to the next equation.

The Little Professor was not a great success. But at the time that Breedlove was developing the Little Professor, his young daughter was learning to spell. Breedlove noticed some similarities between teaching math and teaching spelling. Math involved showing the student an equation to solve. Spelling involved having a teacher enunciate a word so that a child could write out the letters corresponding to that word. Breedlove began to think about creating a Little Professor for spelling.

PUSHING THE LIMITS OF READ-ONLY MEMORY

The device would need technology to convert stored words into intelligible speech. Such technology existed in the early 1970s but it was very uncommon and extremely expensive—far more costly than would be practical

Introduced in 1978, Texas Instruments' Speak & Spell was not just a toy, it was the first product to use a speech-synthesizer chip and the first consumer product to execute digital signal-processing software.

SSPL/GETTY IMAGES

The original Speak & Spell team consisted of (from left) Gene Frantz, Richard Wiggins, Paul Breedlove, and Larry Brantingham. Inside the toy [far right] was a Texas Instruments microcontroller and, below that, one of the two read-only memory chips in the product.

TEXAS INSTRUMENTS ARCHIVES/DEGOLYER LIBRARY/SMU (2)

for a toy. Texas Instruments had been researching speech synthesis for a while, and Breedlove convinced management that the company should fund his idea for the spelling toy. In November 1976 a team that included Breedlove, Frantz, and fellow engineers Richard Wiggins and Larry Brantingham was given $25,000 ($130,000 in 2023 dollars) from the company's small budget for pie-in-the-sky ideas. Due to an organizational slip-up, the four also had the freedom to work for a period of time with little oversight from management.

They knew the spelling device had to be solid state and rugged enough to withstand a child's handling. It also had to "voice" a word in the same way a teacher might quiz a student and allow the child to try to spell it on a keyboard.

Perhaps most important, the device needed to use inexpensive technology—which wasn't easy considering they were scoping out a product that would be revolutionary. And they knew that speech synthesis would require an amount of memory then considered enormous.

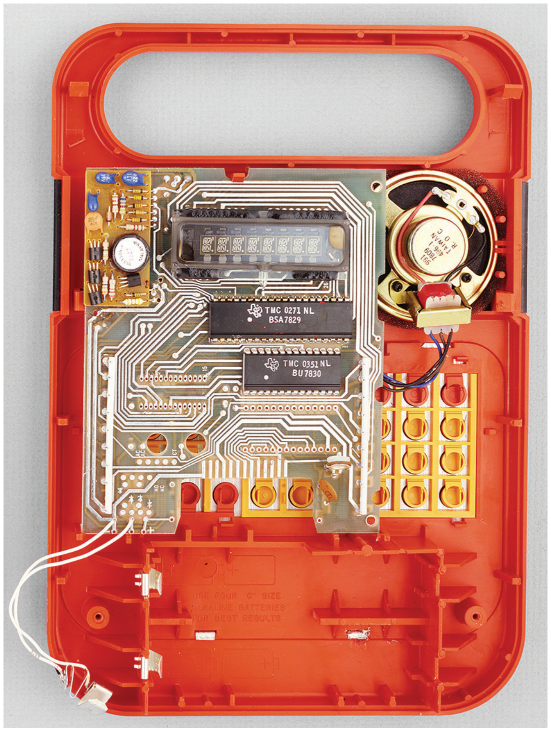
Knowing the proposed product would require some cutting-edge tech, the team realized it would have to economize everywhere it could in order to make the device affordable.

One of the cost-controlling measures involved process technology. They could go with complementary metal-oxide semiconductor technology (CMOS) or with older tech such as negative-channel or positive-channel metal-oxide semiconductor (NMOS and PMOS, respectively). The first two were better technological choices, but slower PMOS was the least expensive option. They designed in PMOS.

One key problem the team needed to solve was how to maximize the audio storage of hundreds of words. Wiggins, a Harvard-trained expert in voice-processing algorithms, came up with the idea to use linear predictive coding. This technique would allow the synthesizer chip to generate a speech signal for a whole word using a small amount of data. LPC was a means of minimizing the amount of dedicated memory required, because with LPC, a device doesn't have to store digitized recordings of entire words.

Even using LPC, however, the amount of memory required was enormous. The standard size for a ROM chip was 16 kilobits. The team designed a 128kb ROM; each Speak & Spell would have two. In addition to a controller, it included a single-chip speech synthesizer that they had to create themselves.

The fact that the four were able to work independently from TI management on the project helped them develop the innovative device.



Frantz pointed out in an October 2019 *IEEE Spectrum* article that freedom from oversight helped in the creation of the TMS5100 chip, which Wiggins and Brantingham designed. "They made the appropriate compromises to get that puppy to work," he said.

MARKETING JITTERS

The resulting product was a 10-by-7-inch orange handheld console containing several hundred words that children most commonly misspelled. Push a button and the machine would "say" a word. The user then tried to spell the word, typing on a tiny keyboard, the letters appearing on a vacuum-fluorescent display.

If the spelling was correct, the device congratulated the child. If it was incorrect, they were encouraged to try again. TI considered having Speak & Spell blow "raspberries" for a wrong answer, but they nixed that idea because they felt it would encourage children to type the wrong answer just to be rewarded with the noise.

There was some worry at TI about how a computer-like toy that talked to children would be received. Talking dolls and toys had been on the market before, but these were operated by pulling a string or a lever, and people knew the voice came from a tape or a tiny grooved disc. A voice from this small box might seem more sinister. As pointed out in a case history on the Speak & Spell in *IEEE Spectrum* in February 1982, "exposure to talking machines was limited to movies like *2001: A Space Odyssey*. In the movie, HAL, a sentient, talking machine, was cast as the bad guy. "Thus, TI learned, many consumers associated the characteristics of synthetic speech with a dull monotone."

Responding to marketing surveys, parents and teachers said they thought the Speak & Spell sounded cold and "computer like." And some felt their children would quickly grow bored with the device and move on to something else.

TI responded to the voice problem by selecting multiple phrases for the responses, some randomized and some sequential, resulting in a less monotonous, more human sound. To help keep the child's interest, engineers also developed some simple word games the device could play with the child to make sure the toy wouldn't be left languishing in a closet.

The original Speak & Spell made its debut at the 1978 Consumer Electronics Show and was a huge hit. Crowds marveled at the first educational toy that could generate speech rather than simply play it back from a tape or a record. Millions were sold, and TI introduced versions for other languages, as well as for other subjects with Speak & Math, Speak & Read, and Speak & Music.

The synthesizer chip the Speak & Spell designers created, the TMS5100 (also known as the TMC0281), was the world's first speech synthesizer IC. Though it ran digital signal processing software, it was not a DSP chip as we understand them today. But it is considered an important precursor. Texas Instruments would announce its first DSP, the TMS 32010, in 1982, and begin selling it a year later. TI was not the first company to commercialize a DSP (Bell Labs has that distinction), but it was among the first and most successful.

In 2009, the Speak & Spell was named a Milestone by the IEEE and a plaque for that honor was dedicated at Texas Instruments' North campus in Dallas. Today the toy is still available from BasicFun!, a marketing firm based in Orlando, Florida.

Today's Siri, Alexa, and the talking toaster oven are all the grandchildren of that original Speak & Spell. ■

Phoning Home

TI's Speak & Spell was so advanced, it could even enable interstellar communication.

Well, in the movies, anyway. In *E.T.*, the film about a friendly extraterrestrial who, desperate to reach his compatriots, hacked his way into young Gertie's Speak & Spell and used it along with a foil-wrapped umbrella, walkie-talkie, coffee can, and various other household items to "phone home."

Today, sophisticated electronics are so ubiquitous some of us don't even bother to marvel at the fact that we can ask a digital assistant to order us a sandwich, or demand that our car parallel park itself. *E.T.* captures a singular moment in our not-that-distant past when a toy had such wondrous capabilities it could be the epitome of high tech.

After the movie was released in June 1982 and immediately packed theaters, the TI marketing department quickly developed a version with E.T. pictured on the box and a new module featuring the creature's voice. They repackaged the popular TI-1030 pocket calculator in red plastic and included a small E.T. doll in the box.

CONSUMER ELECTRONICS | 1979

‘Everything Else is Gaslight’

Digitizing music—and putting it on a spinning disc—required innovation and genius on many fronts.

Once upon a time recorded music was analog. There was no streaming, no easy wireless transmission to another room in your house, and no pocketable music libraries. Just plastic media that typically ended up scratched, worn out, melted, or warped. And making a copy meant making a copy, and that, invariably, meant degradation in sound quality.

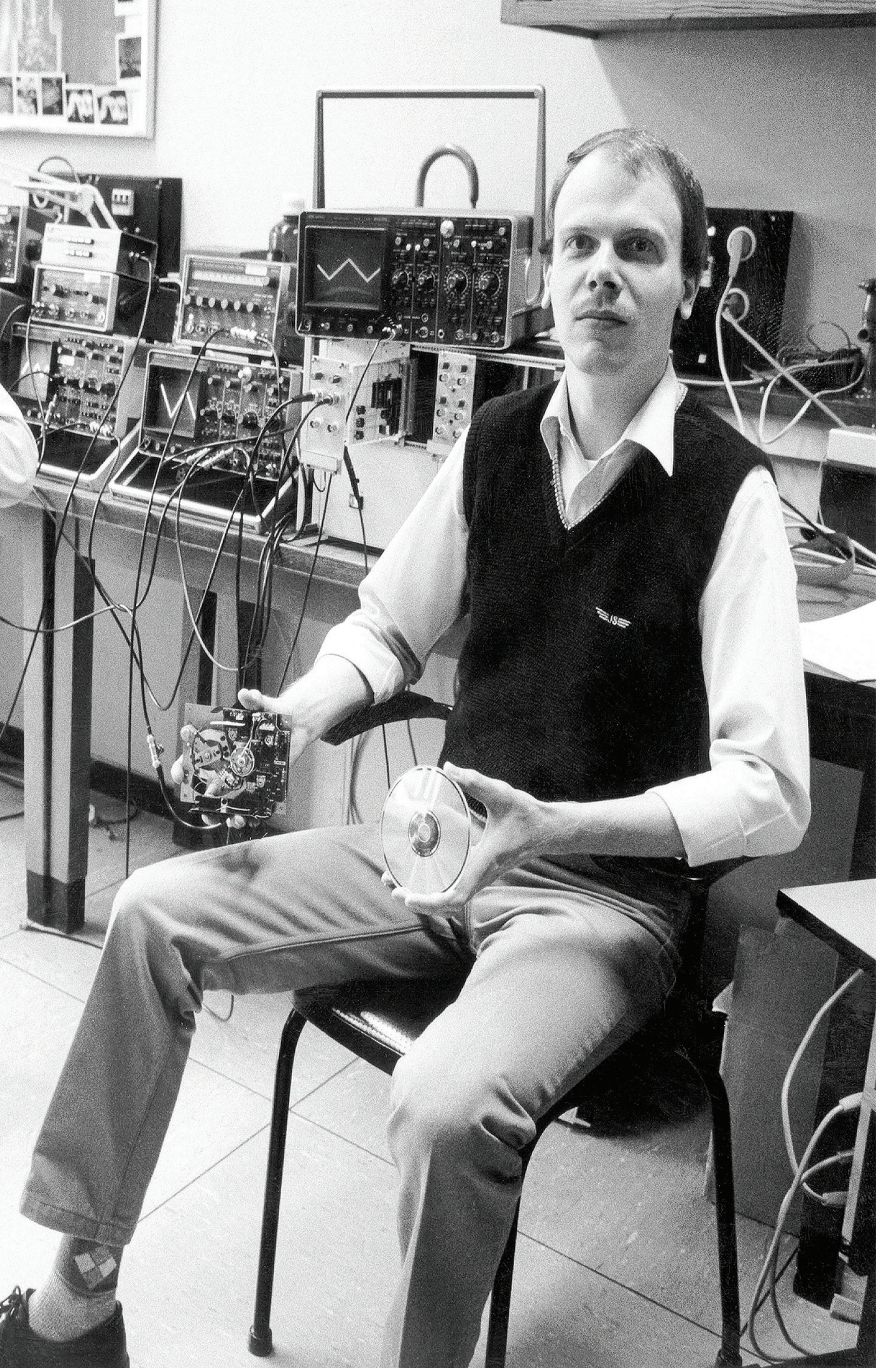
Nowadays, music is digital (notwithstanding a diehard minority of vinyl purists). There are no skips, pops, or crackles, and you can play your favorite tune a billion times and not wear it out. The CD was the first leap into this digital audio paradise, and to make it required a mountain of innovation in optics, lasers, materials, coding, sampling, servo systems, and error correction. And all of that advanced tech would need to be made available on the cheap. But the origin story of those shiny little discs of joy begins not with sounds, but with images.

HIGH-TECH FLIP-BOOK

In 1969, physicist Klaas Compaan came across a new method of creating holograms, invented at RCA, and he became enthralled with the idea of using the technology to store video. RCA had found a way to press holographic refraction patterns onto sheets of nickel, making a mold that could be copied inexpensively. Frames of any image, he realized, could be similarly stored, and projected from an LP-sized disc. He explained the idea to the head of optical research at Phillips, Piet Kramer, who instantly put him to work on the project.


ED VAN DER ELSKEN/ROYAL PHILIPS/PHILIPS COMPANY ARCHIVES

By 1970 the pair had created a glass disc with a photographic film that held images that were a mere millimeter square and could be projected on to a screen sequentially to produce a moving image. There were some problems, though. The images had to be developed on the discs, so there was no mold—and therefore no potential for inexpensive mass production. And, despite being the size of an LP, the disc could hold



In 1984, at Philips Research Labs, Kees Immink (left) held a videodisc and his colleague Joost Kahlman held a compact disc.

only a few minutes of film at most. Realizing they could store more on a disc by recording code representing the pictures rather than the pictures themselves, they turned the images into frequency-modulated signals.

Those signals were then turned into a stream of microscopic pits, or *kuilkjes* ("dimples" in Dutch), separated by smooth spaces, which would come to be called "lands." The procedure involved coating a glass disc with a thin layer of photoresist and shining a laser at it to create the pits, which were six microns wide.

To do that, and to read what they'd recorded, they used a laser. But incorporating one in a consumer product seemed somewhat absurd in the early 1970s. The unit that Kramer and Compaan borrowed for their experiments was four feet long and carried a price tag of $20,000.

With it, though, they created a tracking mechanism by splitting the beam into three parts. The center would read the pits while the movement of the side beams was monitored to keep the microscopically narrow line of pits and spaces centered. Before the end of 1971, they had a prototype for storing black-and-white video, and by the summer of 1972, they had one for color, which they showed off to Philips executives.

After this demo Philips decided to try storing music on the medium. While one group continued with what would become LaserVision, or LaserDisc, Lou Ottens, director of product development for audio, headed a separate initiative to make what would become the compact disc.

"Compact," Ottens knew, was key. Many of the researchers were enchanted with the idea of an LP-sized disc that could play 48 hours of uninterrupted music. But Ottens knew that such a product would never fly with the music industry, which understood that short and cheap sold best. The discs were to be the size of a beer coaster, he decided.

A TRUCE IN THE FORMAT WARS

By 1978, Philips had a working prototype digital audio disc player that showed clear potential for superiority over the LP, especially in terms of background noise and dynamic range. Sony, which had been working along the same lines, also had a prototype player, which it demonstrated for the press that September. With the aim of manufacturing a component-sized player for around $50, and hoping to avoid the format war then roiling the videocassette world (Betamax, anyone?), Philips made a remarkable decision: to join forces with other consumer electronics companies.

In October 1979 Philips and Sony formally agreed to work together on digital audio and to jointly establish a standard framework for disc-based digital audio, covering sampling rates, bit lengths, disc size, and so on.

By this time, the LaserDisc had failed to find much of an audience. That freed up a key

A brilliant coding scheme freed up space for as much as 30 percent more music.

engineer on the video project, Kees Schouhamer Immink, to move over to the CD project. Immink, a specialist in digital encoding, plunged right in. He thought that too much of the disc area was being wasted on storing information used keep the laser on track.

He developed a more efficient coding system, called Eight-to-Fourteen Modulation. EFM coding changed the way the optical head stayed on the trail of pits and spaces representing the data. First, it relied on more precise control of the head, and second, it established rules for the bits themselves, ensuring that the code would not generate too many consecutive pits or spaces, which could disrupt the tracking. By reducing the number of bits used to separate the eight-bit blocks of music data, it freed up space for as much as 30 percent more music.

Meanwhile, the company had begun a campaign to shrink all the electronics and make them affordable. It switched to gallium arsenide diode lasers (Sharp had just begun making laser diodes that were long-lasting enough for a CD player). They shrunk the objective lens, from four elements, which required expensive polishing and grinding, to a single lens that could do the same work and could be molded.

OUTSIDE IN—OR INSIDE OUT?

Still, there were some basic issues that had to be decided on by Sony and Philips. Would the spiral of data run from the outside in, like a record, or from the inside out? Inside to out was the decision. And the motor would change its speed as the laser tracked outward, that way the dimples in the center wouldn't have to be too bunched up. Sony wanted a higher sampling rate—they eventually settled on 44,100. Sony wanted a 16-bit digital-to-analog converter, instead of 14. When listening tests proved the superiority of 16-bit, Philips agreed.

The size of the disc, whether 115 or 120 mm, was hotly contested between the two companies. Philips's subsidiary Polygram had already set up a factory capable of turning out 115-mm discs. Sony wanted either 100 mm for a portable disc player or 120 mm; either would prevent the Europeans from gaining an early production advantage. As for playing time, Sony's president, Norio Ohga, who conducted and sang classical music, insisted that the compact disc store 75 minutes of music rather than Philips's proposed 60. This would enable most recordings of Beethoven's *Ninth Symphony*, as well as the first acts of many operas. One of the legendary recordings of the *Ninth*, conducted by Wilhelm Furtwängler in 1951, came in at 74 minutes. That suggested a disc diameter of 120 mm.

LEFT: BETTMANN/GETTY IMAGES; RIGHT: ROYAL PHILIPS/PHILIPS COMPANY ARCHIVES

Coding considerations also figured crucially here. Philips obviously backed Immink's EFM coding scheme; Sony wanted its own system. Eventually, Philips agreed to the 120-mm diameter, and Sony agreed to EFM. Ironically, EFM expanded audio capacity to 97 minutes, which could have made Beethoven's *Ninth* available even on Sony's 100-mm disc. Instead, the two corporations agreed to expand the production margins.

The only thing left to decide was the diameter of the hole in the center. Joop Sinjou, by then head of the Philips CD lab, slapped a Dutch 10-cent coin (a *dubbeltje*) on the table and said that would be the size. End of discussion.

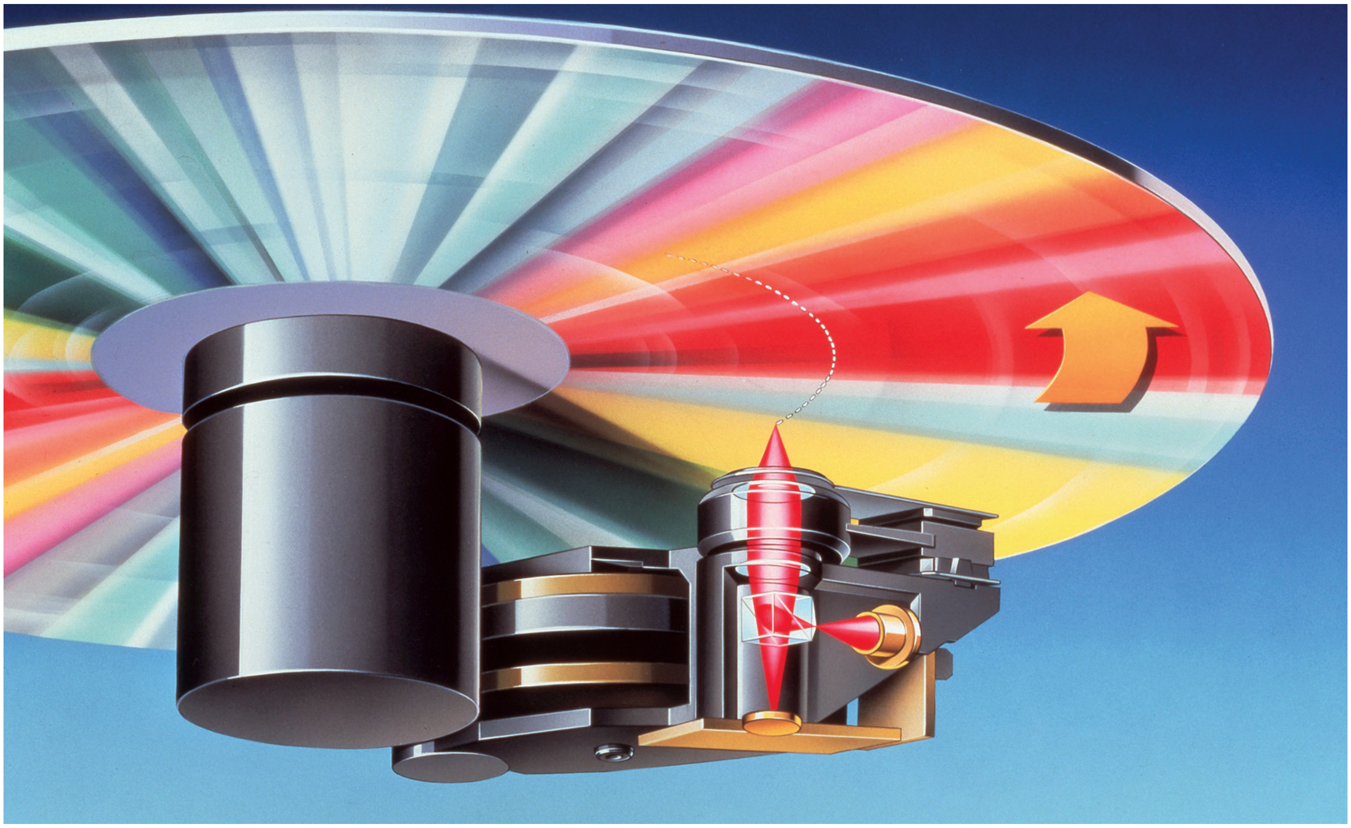
With standards agreed, it was time to make a product. From there Sony and Philips went their separate ways; Philips took 18 months to work out a design, tame their prototype of unruly wires and boards, and introduce their CD player to the world. It took Sony 12—Sony's CDP 101, launched in Japan on October 1, 1982, was the first player to reach a national market, six months before the two companies debuted their respective models worldwide.

The response was rapturous. Herbert von Karajan, perhaps the most popular conductor in the world at the time, famously endorsed the new medium by declaring: "Everything else is gaslight."

Despite the slowing demand, more than 110 million CDs were sold worldwide in 2022, well down from a peak of 2.5 billion in 2000. (That same year, 2022, the purist diehards bought so many records that vinyl outsold CDs in the United States, 41 million to 33 million.)

Nevertheless, the recorded-music business is overwhelmingly digital now, and there's no turning back. Philips's many breakthroughs and work in making music digital transformed the music industry and the way people listen to music. To recognize this achievement, the IEEE honored Philips with a Milestone Award in 2009. And Immink? The IEEE Fellow, active for many years in the IEEE Information Theory Society, has won several of the IEEE's most prestigious awards, including the IEEE Edison Medal in 1999 and the IEEE Medal of Honor in 2017. ■

At the Consumer Electronics Show in 1981, model Chris Payne demonstrated a prototype Sony compact disc player [above, far left]. A prototype Philips CD player, from 1979, was dubbed Pinkeltje ("littlefinger") [above, left]. A 1986 marketing sketch from Philips showed the laser mechanism [below].



ROYAL PHILIPS/PHILIPS COMPANY ARCHIVES

COMMUNICATIONS | 1979

An Unexpected Change of Direction

An exotic, superfast transistor paved the way for cellphones and helped make satellite communications commercially viable.

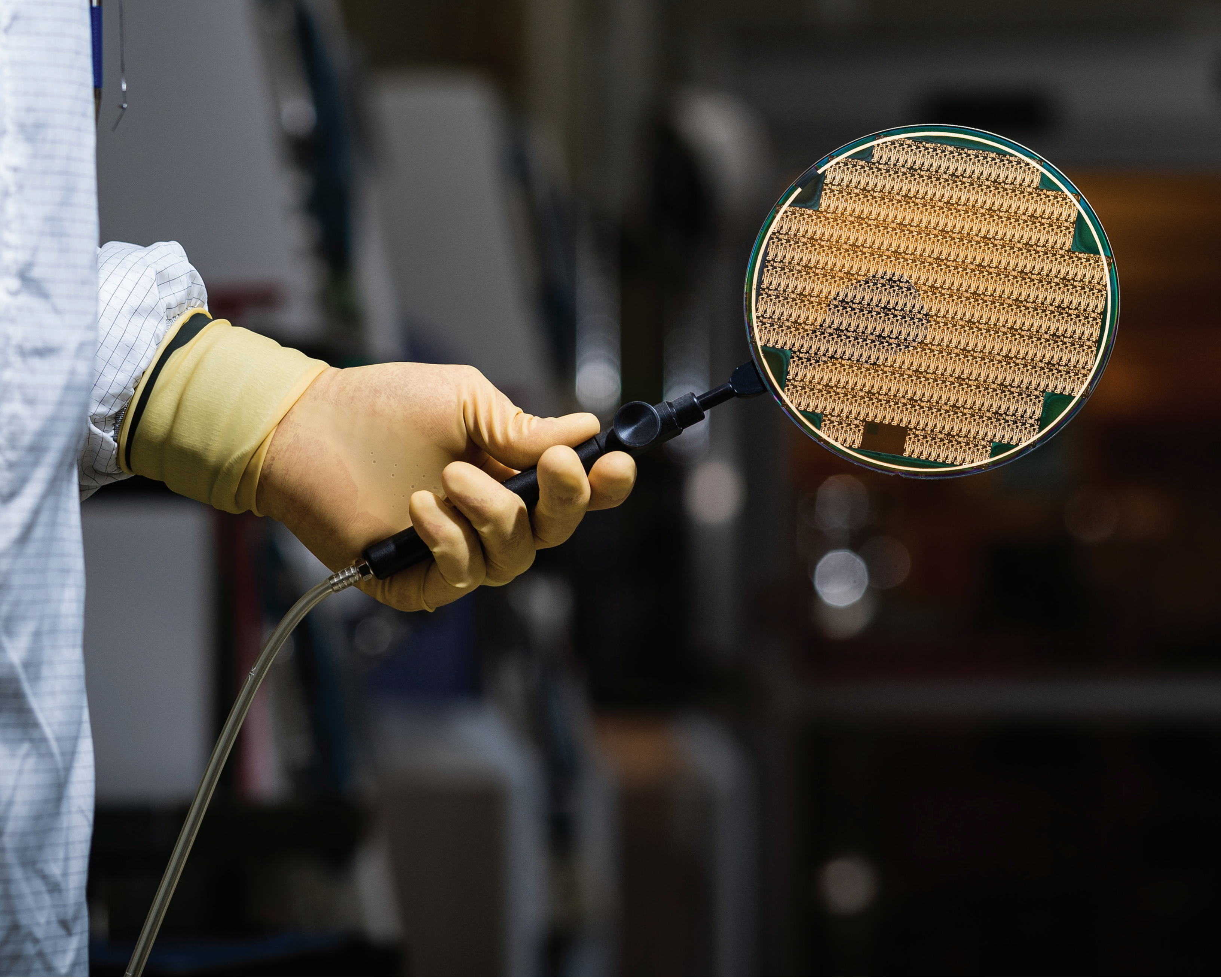
Takashi Mimura, who fabricated the first HEMTs in 1979 at Fujitsu.

Through the early 1960s, scientists working with semiconductors experimented with dozens of different materials: selenium, lead sulfide, copper sulfide, silicon carbide, and others. John Bardeen and Walter Brattain built the first transistor with germanium, and when Jack Kilby and Robert Noyce simultaneously invented the first integrated circuits in 1959, Kilby used germanium while Noyce used silicon.

At the time, silicon was difficult to work with, but it was also plentiful and cheap, and the young semiconductor industry quickly learned how to process it with relative ease. Silicon quickly emerged as the dominant semiconductor in electronics. Silicon is relatively slow, however, especially compared to gallium arsenide (GaAs), another material that semiconductor companies began to adopt in 1960s. GaAs transistors, for example, are significantly faster than silicon ones, enabling them to handle far greater frequencies and switching speeds. Every smartphone sold today has a GaAs amplifier, because this technology is the only inexpensive option for amplifying cellular microwave frequencies, above about 800 MHz and extending up into the tens of GHz.

But producing a reliable, cheap, and superfast GaAs transistor took a lot of work and a lot of time. The first breakthrough was a GaAs metal-semiconductor field effect transistor (MESFET), described by its inventor, Carver

LEFT: IEEE; RIGHT: BAE SYSTEMS



A wafer produced at a BAE Systems foundry in Nashua, New Hampshire [above] contained radio-frequency amplifiers based on high electron mobility transistors (HEMTs).

Mead of Caltech, in a letter to *Proceedings of the IEEE* in February 1966. By 1979, the GaAs MESFET had been refined many times, and physicist Takashi Mimura, who was working in a research group at Fujitsu in Japan on the devices, began to suspect that the GaAs MESFET was nearing the limit of how fast it could go.

Explaining this concern years later in the *Fujitsu Scientific & Technical Journal*, Mimura noted that "the GaAs MESFET is a high-speed device featuring extremely high-cost performance." He worried that all that was left for him to do was to squeeze incremental improvements out of the device. That wasn't a very happy prospect. "I was not interested in any follow-up research themes," he later wrote.

Earlier that year Mimura had read about a 1978 Bell Labs patent for a type of crystal structure called a doped heterojunction superlattice. Doping is the adding of impurities when a semiconductor is formed to alter its electrical properties. The Bell Labs patent described a way to accumulate electrons in a layer of GaAs sandwiched between layers of aluminum gallium arsenide (AlGaAs), both of them doped to have an excess of free-roaming electrons available for conducting current (n-type).

While he found the article interesting, the focus of the paper was the superlattices, which didn't have any direct relationship to GaAs MESFETS beyond including a GaAs layer. As Mimura put it in a paper of his own for the March 2002 issue of *IEEE Transactions on*

Microwave Theory and Techniques, "Although impressive, the technology was unfamiliar and did not jog me with any new ideas." The concept clearly stuck in his mind, however.

INSPIRATION STRIKES

The most common type of transistor in silicon integrated circuits had long been the metal-oxide-semiconductor field-effect transistors (MOSFET). Mimura resolved to build a GaAs MOSFET, but his initial results were not promising. He described one of them in a paper that he presented at the 37th Device Research Conference, sponsored by the IEEE Electron Device Society, in June 1979. Then he had a brainstorm.

"While [I was] talking with a conference attendee immediately after my presentation," Mimura noted in the 2002 IEEE paper, "I was suddenly seized by the will to look for ways to control electrons accumulated in the superlattice. Although I cannot exactly explain this unexpected change of direction, it probably came about because I had wanted to research more feasible subjects than GaAs MESFETs."

A three-layer superlattice, with the layers separated by two interfaces, or heterojunctions—a standard structure for transistors—might be unnecessary in this case. Two layers separated by a single heterojunction might work. "I came up with the idea of using a field effect to control electrons at the interface of a single heterojunction consisting of a pair of undoped GaAs and n-type AlGaAs; the field from a Schottky gate placed on the AlGaAs surface controls the electrons at the interface," Mimura wrote.

The result was a high-speed transistor that was far faster than a GaAs MESFET, and of course much, much faster than any silicon transistor. Although it had a novel structure, it was still a field-effect transistor, and so it is sometimes referred to as a heterojunction FET. But the name that caught on was High Electron Mobility Transistor, or HEMT. Fujitsu announced it in 1980.

HEMTS TAKE OFF

Despite the performance advantages of HEMTs, it took years to make them cost-

Flow Control

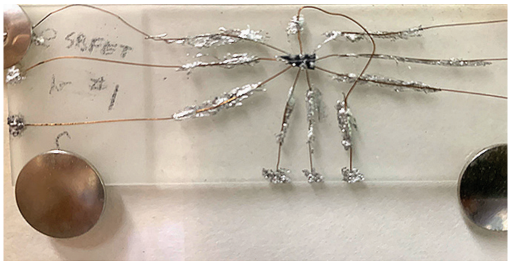
Over the Thanksgiving holiday in 1965, American engineer Carver Mead at Caltech built the first gallium arsenide metal semiconductor field-effect transistor (MESFET), based on a Schottky barrier gate. The gate is a potential-energy barrier that must be overcome before electrons can cross a metal–semiconductor junction. Mead's revolutionary transistor offered higher mobility of electrons, and also higher velocity of electrons, than silicon, making it ideal for high-frequency applications such as microwave communications and radio telescopes.

Mead came upon the idea while looking for a different way to control the flow of electrons in MESFETs. Until this point, impurities were added to increase the population of free electrons in the regions where current would flow, a technique known as doping. However, collisions with ionized impurities limited electron mobility. Mead's novel approach to use a Schottky barrier gate to control the flow of electrons instead of doping allowed for much higher electron mobility, which in turn led to much faster transistor operation.

His work on MESFETs became the basis for the later development of HEMTs, which are even faster and more efficient transistors. Mead tried to patent his device and to drum up commercial interest. Both efforts failed. The electronics industry, completely dominated by silicon, was not interested. A patent search for MESFETs returned prior art from 1925 and 1926 and another, later, patent from Bell Labs that, like the other two, was not functional.

Although Mead did not gain financially from his invention, it represents only a small part of his vast contributions to engineering and science, fields that he finds more similar than different.

"I've never made a distinction between science and engineering," he told the *IEEE Journal of Microwaves* in January 2021. "To me it was all figuring the thing out and being able to do things with it. And if you're doing what you think of as science, you have to figure the thing out and make the experiment work, which is all engineering work. And if you're doing what you call engineering, you have to figure out the fundamentals so you know what to build, and that's science. So to me they could never be pulled apart."



The first GaAs MESFET chip, as wired up on a microscope slide.

CALTECH

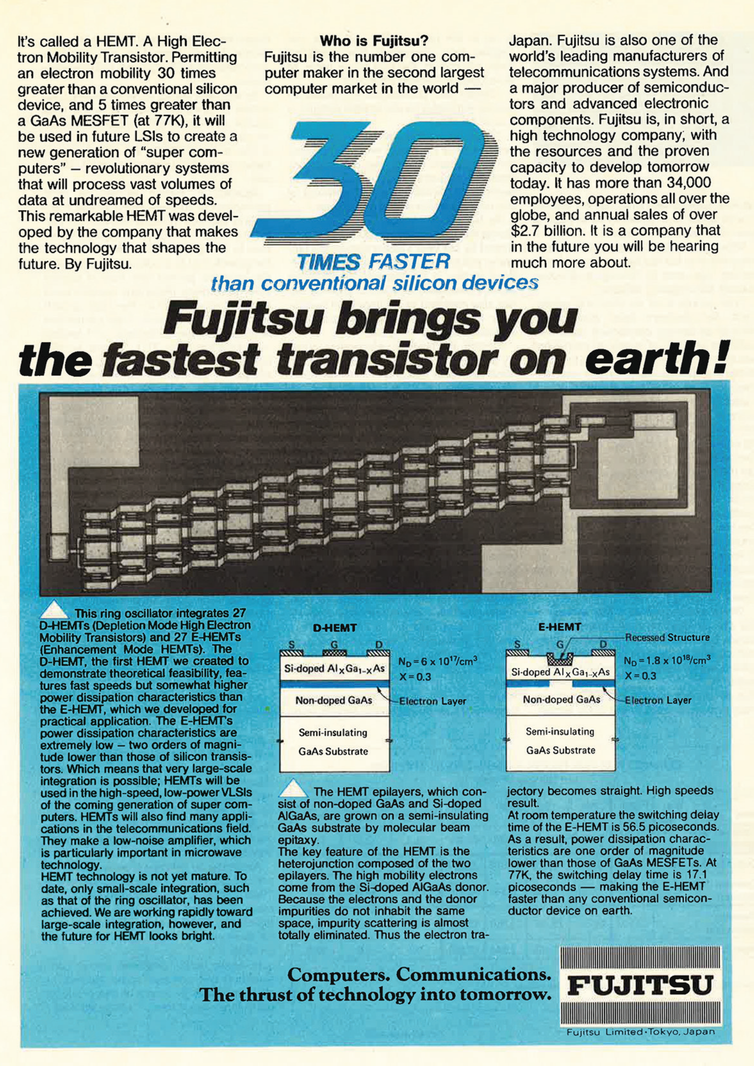
effective enough for high-volume applications. Making GaAs ICs has always been more expensive, and in 1980 the only way to produce HEMTs was by using molecular beam epitaxy, or MBE, an exceedingly slow process. Mimura was concerned that the low production rates and the high cost of producing the devices would relegate them to being a mere lab curiosity.

But in the early 1980s, HEMTs began to be adopted in space and military applications. At the IEEE International Solid-State Circuits Conference in 1983, a representative from the National Radio Astronomy Observatory, a U.S. research facility focused on studying space, watched a presentation by Mimura on a HEMT-based amplifier for use in satellite communications in the microwave band.

The representative was intrigued by the device's outstanding low-noise performance. Would HEMTs be good at amplifying very weak radio signals from space, he wondered. It turned out that they were. The first commercial use of a HEMT amplifier was just two years later, in 1985, at the Nobeyama Radio Observatory of the National Astronomical Observatory of Japan. The following year, radio astronomers at the observatory using HEMT amps made important discoveries about interstellar molecules in the Taurus Molecular Cloud, about 400 light years away. HEMTs were soon in great demand for radio telescopes around the world.

Next was satellite communications. In the late 1980s, cable TV and satellite TV were in an all-out battle for viewers, and both were eager to exploit technological advances to gain an edge. "The use of HEMTs began to take off in 1987 when they replaced conventional GaAs MESFETs as low-noise amplifiers in converters for satellite broadcast receivers," Mimura explained in the Fujitsu article. "The use of HEMTs enabled parabolic antennas to be downsized to less than half of the conventional ones and contributed to the explosive growth of satellite broadcasting in Japan, Europe, and elsewhere."

With further development and with economies of scale beginning to kick in, the cost of producing and using HEMTs began to drop. In 1988, driven by surging demand in the satellite TV industry, HEMT-based receivers reached 20 million units. The HEMT's ability to operate at frequencies above 10 GHz and with high gain and low noise made them indispensable in applications beyond satellite receivers, notably radar (including collision- avoidance systems for vehicles), instrumentation, and sensing. And with the rise of cellular telephony came the biggest application of all: in the amplifiers in the handsets.



It's called a HEMT. A High Electron Mobility Transistor. Permitting an electron mobility 30 times greater than a conventional silicon device, and 5 times greater than a GaAs MESFET (at 77K), it will be used in future LSIs to create a new generation of "super computers" – revolutionary systems that will process vast volumes of data at undreamed of speeds. This remarkable HEMT was developed by the company that makes the technology that shapes the future. By Fujitsu.

Who is Fujitsu?

Fujitsu is the number one computer maker in the second largest computer market in the world — Japan. Fujitsu is also one of the world's leading manufacturers of telecommunications systems. And a major producer of semiconductors and advanced electronic components. Fujitsu is, in short, a high technology company, with the resources and the proven capacity to develop tomorrow today. It has more than 34,000 employees, operations all over the globe, and annual sales of over $2.7 billion. It is a company that in the future you will be hearing much more about.

30

TIMES FASTER

than conventional silicon devices

Fujitsu brings you the fastest transistor on earth!

This ring oscillator integrates 27 D-HEMTs (Depletion Mode High Electron Mobility Transistors) and 27 E-HEMTs (Enhancement Mode HEMTs). The D-HEMT, the first HEMT we created to demonstrate theoretical feasibility, features fast speeds but somewhat higher power dissipation characteristics than the E-HEMT, which we developed for practical application. The E-HEMT's power dissipation characteristics are extremely low – two orders of magnitude lower than those of silicon transistors. Which means that very large-scale integration is possible; HEMTs will be used in the high-speed, low-power VLSIs of the coming generation of super computers. HEMTs will also find many applications in the telecommunications field. They make a low-noise amplifier, which is particularly important in microwave technology.

HEMT technology is not yet mature. To date, only small-scale integration, such as that of the ring oscillator, has been achieved. We are working rapidly toward large-scale integration, however, and the future for HEMT looks bright.

The HEMT epilayers, which consist of non-doped GaAs and Si-doped AlGaAs, are grown on a semi-insulating GaAs substrate by molecular beam epitaxy.

The key feature of the HEMT is the heterojunction composed of the two epilayers. The high mobility electrons come from the Si-doped AlGaAs donor. Because the electrons and the donor impurities do not inhabit the same space, impurity scattering is almost totally eliminated. Thus the electron trajectory becomes straight. High speeds result.

At room temperature the switching delay time of the E-HEMT is 56.5 picoseconds. As a result, power dissipation characteristics are one order of magnitude lower than those of GaAs MESFETs. At 77K, the switching delay time is 17.1 picoseconds — making the E-HEMT faster than any conventional semiconductor device on earth.

Computers. Communications.
The thrust of technology into tomorrow.

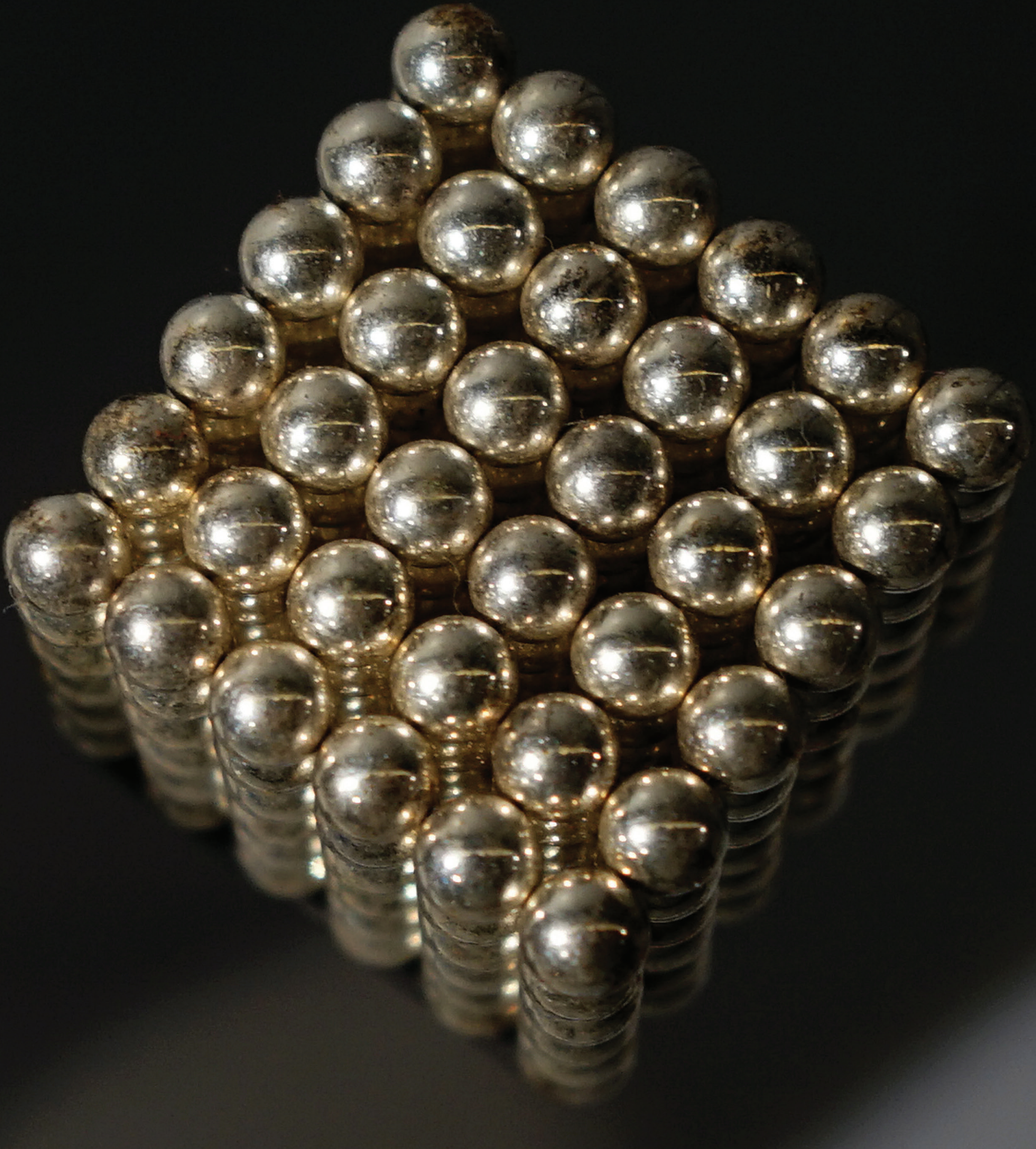
FUJITSU

Fujitsu Limited·Tokyo, Japan

A 1981 advertisement for Fujitsu's new gallium arsenide HEMT calls it "the fastest transistor on earth"—and it wasn't hyperbole.

FUJITSU

In 1990, Mimura and his Fujitsu colleague Satoshi Hiyamizu won the IEEE Morris N. Liebmann Memorial Award for their pioneering work on HEMTs. Mimura also received the Kyoto Prize in 2017, honoring those who have contributed significantly to the scientific, cultural, and spiritual betterment of mankind, in the advanced technology category. ■



MATERIALS/PHYSICS | 1983

Great Minds Thought Alike

In one stunning moment, two researchers realized they had independently invented the same new magnet—the Nd-Fe-B—which is now the world's dominant permanent magnet.

In the 1970s, samarium-cobalt magnets were the strongest and most durable permanent magnets on the market. But they were also very expensive, so countless researchers were searching for an alternative. Two of them eventually succeeded, creating the neodymium-iron-boron (Nd-Fe-B) permanent magnet, which was not only much less expensive, but also stronger.

However, this was anything but a collaborative effort. The two researchers—John Croat of General Motors and Masato Sagawa of Sumitomo—had never met before coming up with their discovery. They worked in secret at separate companies more than 6,000 miles apart, utterly unaware of each other's work.

That suddenly changed in 1983, when they separately presented their new discovery at the same conference in Pittsburgh. In a stunning moment, they suddenly realized—along with many of their colleagues—that they had independently invented the same magnet.

To say the new magnet would be a winner would be putting it mildly. Today, Nd-Fe-B magnets are by far the dominant permanent magnet, and they comprise a market worth between $15 billion and $20 billion a year. And that market is growing as the world turns increasingly to electric vehicles, wind-turbine generators, and electric aircraft such as drones and eVTOLs.

TWO CONVERGING PATHS

At the time, there were two problems with samarium-cobalt magnets: the samarium, and the cobalt. Samarium is one of the most uncommon rare earth elements. And in the 1970s, the price of cobalt surged because of war and instability in Zaire (now the Democratic Republic of the Congo), then the source of 60 percent of the global supply of cobalt. That development "basically stopped our research on samarium-cobalt magnets," Croat later told *IEEE Spectrum*. Like many other magnet researchers, he began exploring the use of other materials for permanent magnets.

Meanwhile, at Fujitsu Laboratories, Sagawa was looking for ways to increase the strength of samarium-cobalt magnets. But he, too, was thinking about alternatives. "I wondered why there is no iron compound [in the magnets]," he said in an interview with *Spectrum* in 2022. Iron was much cheaper and much more widely available than cobalt, he noted, "and iron has higher magnetic moment than cobalt. So, if I can produce rare earth iron magnets, I thought I would have higher magnetic strengths and much lower cost."

He did succeed in developing a higher-strength samarium-cobalt magnet, but he also continued to be interested in the idea of a rare earth iron magnet. However, Fujitsu forbade him from researching iron-based magnets. So he resigned and joined Sumitomo.

Croat and Sagawa came to similar conclusions about how to proceed. Beyond the choice of iron, one of the most abundant elements on earth, it also made sense to use one

The neodymium-iron-boron magnet is the most powerful permanent magnet in widespread production.

UNIVERSAL IMAGES GROUP/GETTY IMAGES

Do Permanent Magnets Have a Post-Rare Earth Future?

In March 2023, an executive at Tesla startled electric-motor specialists by insisting that Tesla's next drivetrain would be based on a permanent-magnet motor that would "not use any rare earth elements at all." Magnetics researchers quickly discounted the claim as nonsense, pointing out that there were no powerful permanent magnets available that did not use rare earth elements. Moreover, no synchronous traction motor had ever been built that was both powerful and efficient and that eschewed the use of rare earth permanent magnets.

Shortly after Tesla's bold claim, IEEE Fellow Jia Ping Liu, a professor at the University of Texas in Arlington, polled some of his colleagues at a magnetics conference, asking what they thought of the announcement. "Nobody fully understands this," Liu told *IEEE Spectrum*. A 2019 study by Roskill Information Services in London, found that more than 90 percent of the permanent magnets used in automotive traction motors were neodymium-iron-boron.

For years, researchers have been trying to create a powerful magnet not dependent on rare earth elements. Part of the interest is linked to the domination of rare earth element production by one country—China, which accounts for 85 percent of rare earth processing and 92 percent of rare earth magnet production, according to *Politico*.

But it has been a long, difficult, and, so far, fruitless quest. By 2023 many organizations, including companies such as Hitachi, DA Technology in South Korea, and the Spanish company IMA, had spent considerable sums in pursuit of a powerful, durable magnet that was rare earth free. In addition, the U.S. Department of Energy spent tens of millions of dollars on research and grants to developers of non-rare earth permanent magnets. And yet in 2023, the only powerful non-rare earth permanent magnet was an experimental iron-nitride compound being developed by Niron Magnetics in Minneapolis. In the summer of 2023, Niron was pledging to have the magnet on the market by the end of 2024.

One of the early and important uses of neodymium-iron-boron magnets was in hard-disk drives [above]. They were used in both the spindle motor that rotated the disk as well as in the motor that moved the actuator arm (the pointed component on top of the disk). John Croat [above right] and Masato Sagawa [far right] invented neodymium magnets simultaneously but independently.

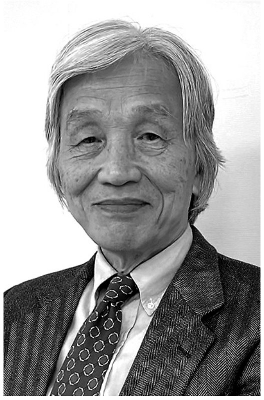
ISTOCK

of the other, common, light rare earths, four of which are relatively inexpensive. "Dr. Sagawa and I knew at the start that if we wanted to make an economically viable magnet… we had to make the permanent magnet from one of these four rare earths," he said. But work on samarium-cobalt magnets had shown that the new magnet would require a rare earth element with a specific kind of electron configuration in order to provide coercivity, which is the resistance to demagnetization. Only two of the candidates—neodymium and praseodymium—had the required electron configuration. As a result, he said, "both of us set out with the intention of making a rare earth iron permanent magnet from neodymium or praseodymium."

In the end, the more abundant neodymium won out in both of their efforts. And boron, they both found, added stability to the magnet and helped it remain magnetized at higher temperatures, an essential attribute for applications in electric motors or generators.

There was one important difference in the two projects' approaches, however. Croat used a bonding manufacturing technique that involved melt-spinning and pulverizing the Nd-Fe-B alloy, mixing it with a resin, and molding it into a magnet. Sagawa used a sintering technique, in which the alloy is

Boron, they both found, added stability to the magnet and helped it remain magnetized at higher temperatures, an essential attribute for applications in electric motors or generators.



LEFT: JOHN CROAT; RIGHT: MASATO SAGAWA

ground into a microscopic powder, aligned in a magnetic field, heated, and then pressed into the desired shape.

These different techniques resulted in different qualities in the two types of Nd-Fe-B magnets, which in turn made them suitable for different applications. The bonded magnets can be produced more inexpensively, and they can easily be made in flat rings or other shapes. In general, they are especially suitable for smaller motors, such as stepper motors, servo motors for robots, and spindle motors. Sintered magnets cost more to make, but they are stronger and structurally durable, and are used in larger motors, for example in electric vehicles, and in generators.

NEGOTIATING A COMMERCIAL PLAN

In November 1983, Croat and Sagawa presented their new magnets at the Metals and Magnetism Conference in Pittsburgh, where they both learned of each other's project. But the similarity of their inventions soon raised some practical considerations.

Both Sumitomo and General Motors filed patents for the Nd-Fe-B magnets, "within weeks of each other," Croat said. General Motors ended up with the patent in North America, and Sumitomo ended up with the patent for Japan and Europe. "This meant," Croat explained, "that neither company could market worldwide—and they had to market worldwide to be economically viable." The two companies negotiated a solution, and "ended up with an agreement where we cross-licensed each other, which allowed both companies to… manufacture and market the material worldwide," Croat recalled in his interview with *IEEE Spectrum*. Under the agreement, Croat explained, each company could only sell products based on its own manufacturing method—bonded magnets for GM, sintered magnets for Sumitomo.

Soon after they were introduced, Nd-Fe-B permanent magnets played a key role in the personal computing revolution of the 1980s. For example, "if the neodymium-boron [magnet] was not found, it would have been difficult to miniaturize the hard-disk drive," Sagawa explained. Previously, he said, "the hard-disk drive was very big," weighing more than 20 pounds.

In the much smaller hard drives made possible by the Nd-Fe-B magnets, the sintered version of the magnet was used in in the actuator motor and the bonded version was used in the spindle motor to rotate the hard disk. "This was a very important invention for the start of our IT society," he noted. Nd-Fe-B magnets now account for about 60 percent of the permanent-magnet market, by value.

Today, they are helping to usher in another societal revolution—the energy transition that is expected to shift the world away from fossil fuels. In particular, the magnets are key to wind-turbine generators and electric-vehicle motors, and demand for them is expected to grow rapidly in the next decade. In 2022, Croat and Sagawa received the IEEE Medal for Environmental and Safety Technologies for their work—
a recognition of the next chapter in the Nd-Fe-B story, and of the ongoing impact of their discovery. ■

PHOTONICS | 1993

A Highly Imperfect Crystal

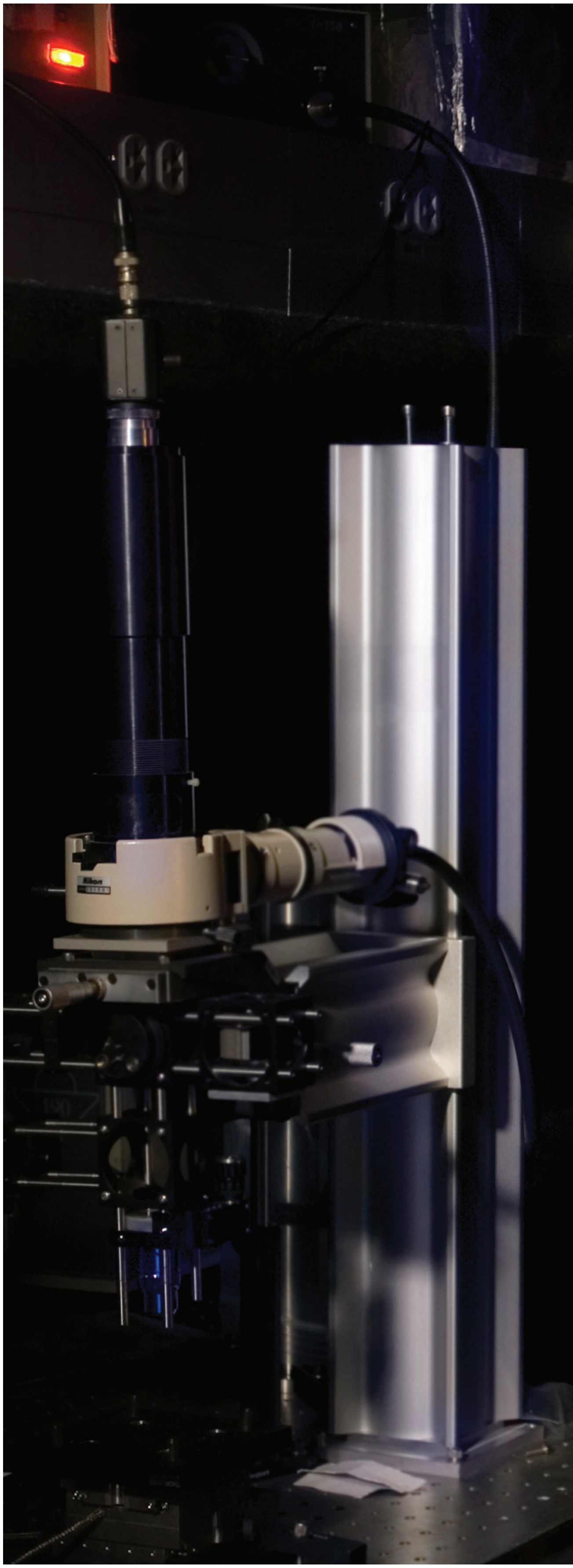
By the 1970s, researchers understood that gallium nitride's wide bandgap allowed it to emit photons in the green, blue, and purple regions of the visual spectrum. Such an optoelectronic property would become the basis of multibillion-dollar industries in lighting and lasers.

One day in 1874, a self-taught chemist from southwestern France was experimenting with an early spectroscope when he came across something new.

Paul-Émile Lecoq de Boisbaudran extracted several milligrams of an odd metal from a sample of sphalerite, a sulfide mineral, that had been dug up in the Pyrenees mountain range. Intrigued, he isolated 75 grams of this substance from four tons of crude zinc ore and saw two new wavelengths in his spectroscope, measuring 4,170 and 4,031 angstroms. While purifying it, he noted that the metal had a melting point of just 30 degrees C. It melted in his hand like a chocolate bar.

Boisbaudran named the new element gallium, from the Latin word Gallia for France. It remained little more than a curious square in the periodic table until scientists began experimenting in the 20th century with how electricity interacted with various crystals.

Then the weird metal would shine. By the 1960s, researchers understood that a gallium compound, gallium nitride, was one of a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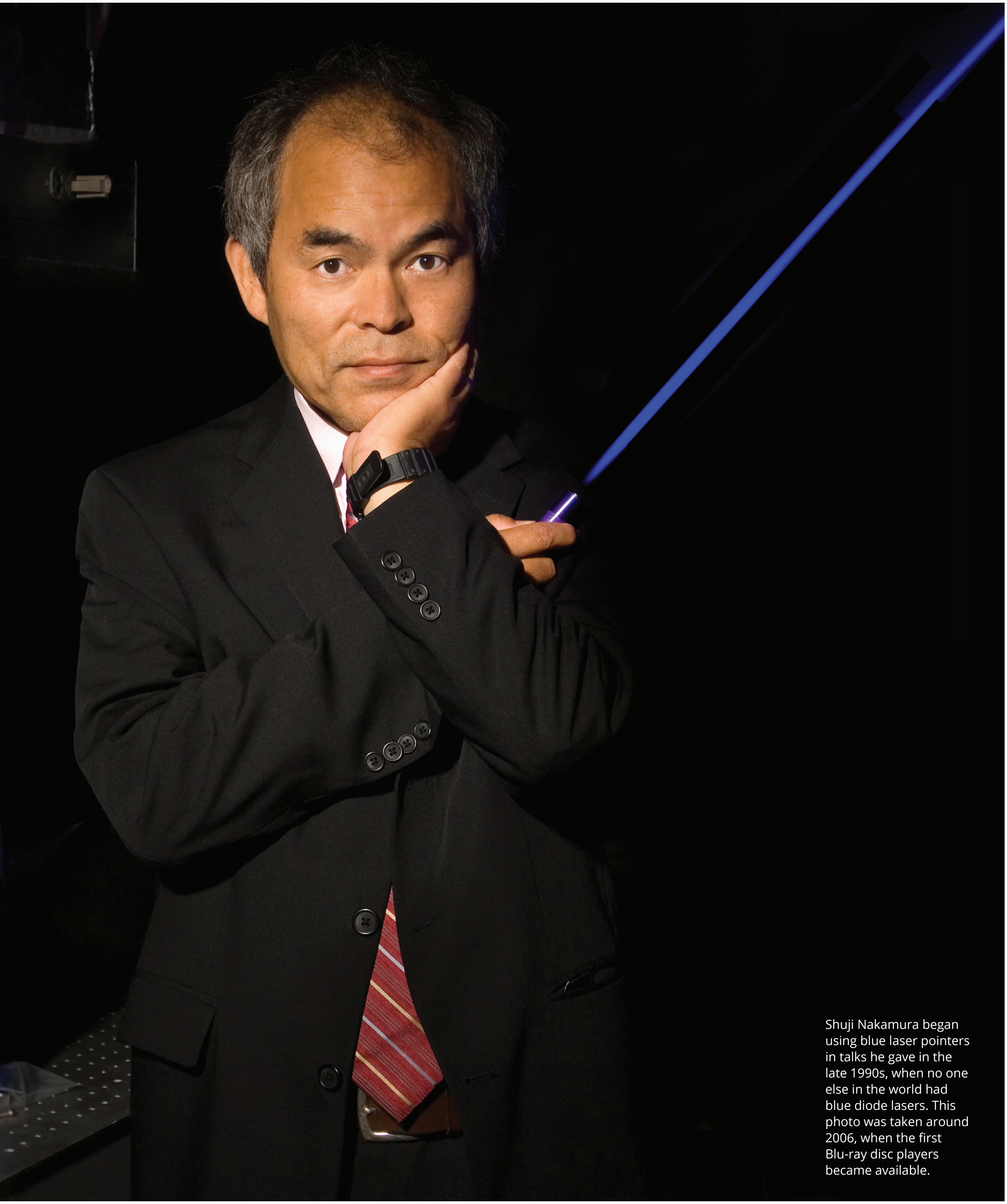
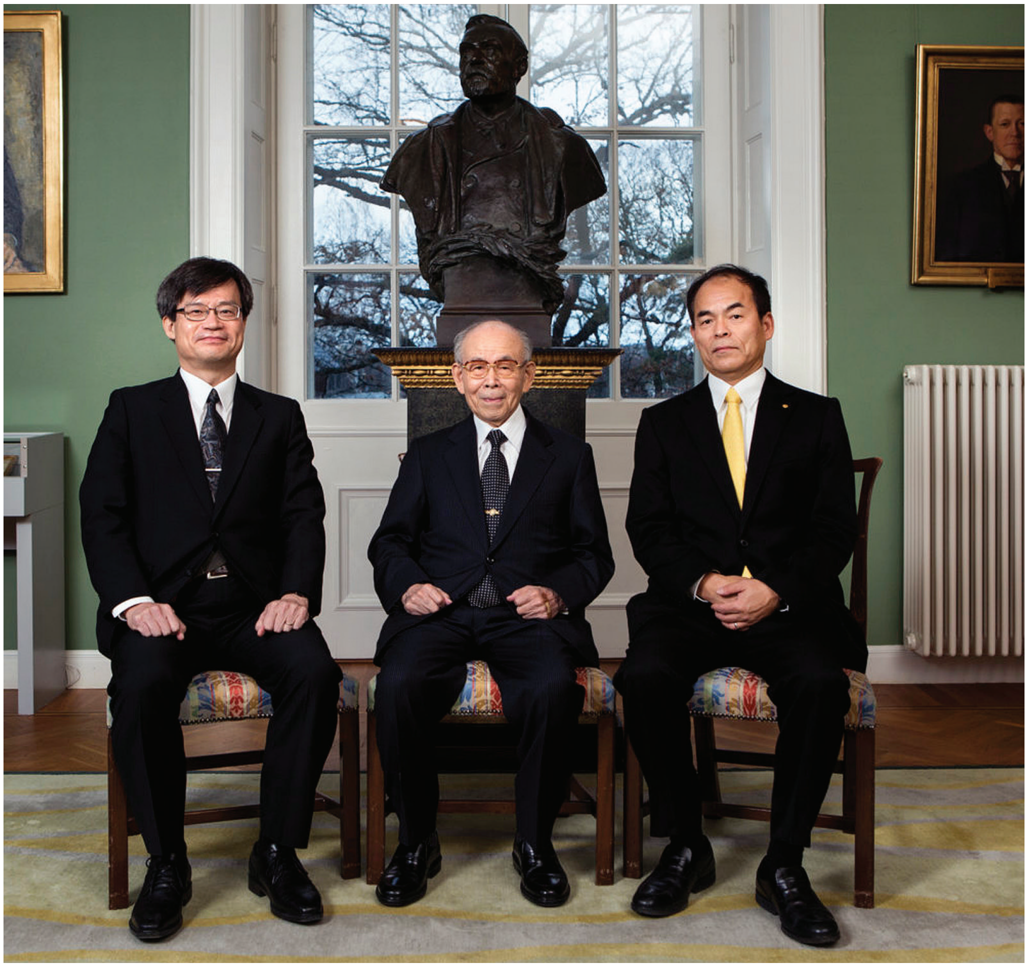


Shuji Nakamura began using blue laser pointers in talks he gave in the late 1990s, when no one else in the world had blue diode lasers. This photo was taken around 2006, when the first Blu-ray disc players became available.



Hiroshi Amano (left) and Isamu Akasaki (middle) collaborated in producing a blue-light LED. Shuji Nakamura (right) worked independently. The three were honored with the Nobel Prize for Physics in 2014.

MARKUS MARCETIC/THE ROYAL SWEDISH ACADEMY OF SCIENCES/NOBEL MEDIA

small group of semiconductors that had what was known as a wide bandgap. This feature meant it could emit photons at relatively high frequencies, in the green, blue, and purple regions of the visual spectrum. Such an optoelectronic property would eventually become the basis of multibillion-dollar industries in lighting and lasers.

GREAT PROMISE, FIENDISH CHALLENGES

The road to such riches would be a very long and twisting one. It began in 1932, when researchers at the University of Chicago synthesized gallium nitride (GaN) by reacting gallium and ammonia at temperatures above 900 degrees C. But the material's astonishing characteristics did not become clear until after James Tietjen and Herbert Paul Maruska managed to create single crystals with fewer defects, in 1969. They devised a process based on RCA's hydride vapor phase epitaxy, in which gaseous source chemicals are flowed over a heated substrate, which serves as the foundation on which the crystal will be grown. The crystal that results is in the form of a thin film, grown in layers as successive rounds of gaseous reactants are flowed over the surface of the growing crystal.

But therein was the problem. To make crystals as nearly perfect as possible, technicians use the same material for the substrate as the crystal they are trying to grow. But that wasn't possible for GaN, because bulk crystals of pure GaN did not exist—creating them would require impractically high pressures and temperatures. So GaN researchers used crystals of other substances, such as sapphire or gallium arsenide.

One problem with that approach is known as lattice mismatch. All crystals have a specific lattice structure, and growing one kind of crystal on top of a different one results in a mismatch of their lattices at the boundary between the two. This mismatch creates a variety of problems, such as flaws, called dislocations, in the crystal being grown. If that crystal is used as a semiconductor, those dislocations degrade the device's performance, whether the device is a light-emitting diode or a power transistor.

Early GaN devices had extremely high levels of defects, in the range of 10 billion per square centimeter. For comparison, commercial LED semiconductors typically have fewer than 100,000. Nevertheless, researchers persevered and were amazed to find that these early, defect-riddled GaN devices did function, even though theory suggested they shouldn't.

The reason for the perseverance was obvious enough. Red LEDs were widely available by the late 1960s (see "Seeing Red," p. 84). Researchers realized that if they could create blue and green LEDs, they could combine them with that red LED to produce white-light emitting devices that would be much more efficient than incandescent light bulbs.

They also realized that if they could produce a blue LED, then the same basic technology would probably also let them produce green LEDs, purple LEDs, and laser diodes in various colors. A blue laser was particularly sought because it would make possible optical storage systems with much higher capacity.

At RCA in 1971, Jacques I. Pankove led a team that produced the first blue-light GaN LEDs. These devices were too dim to have any practical use. Nevertheless, it was a very impressive achievement, for which Pankove was awarded the IEEE Electron Devices Society's J. J. Ebers Award in 1975.

RCA soon abandoned its efforts for lack of imminent commercial promise, as did other companies. GaN then mostly languished for more than a decade after researchers were stymied by some serious limitations of the semiconductor. Chief among these were the high defect densities and the fact that there was no reliable way to produce "p-type" gallium nitride, which has an excess of positive-charge carriers called holes. A semiconductor diode is basically a junction between two kinds of semiconductor: p-type and n-type.

Interest in GaN surged in the 1980s, thanks to three Japanese researchers, Isamu Akasaki and Hiroshi Amano from the University of Nagoya, and Shuji Nakamura at Nichia Chemical Industries.

BRIGHT BLUE LIGHT, AT LAST

After years of slow progress, Akasaki and Amano had a series of breakthroughs starting in 1986. First, they created a relatively high-quality GaN crystal using, as a substrate, sapphire topped by a layer of aluminum nitride. A few years later they also managed to create p-type GaN. Looking at the material in a scanning electron microscope, Akasaki and Amano saw that the material glowed more intensely. They deduced that this effect was caused by the microscope's electron beam, which appeared to be making the p-type layer more efficient. This discovery led, in 1989, to a process of "activating" the p-doping by irradiating it with electrons. In 1992, they built a GaN diode that emitted bright blue light.

Nakamura, meanwhile, started working on GaN in 1988 and managed to create high-quality GaN crystals in 1990 and his first blue LEDs in 1993. He realized that Akasaki and Amano's electron beam had improved the formation of p-type GaN because it removed hydrogen that had prevented the p-type layer from forming. Nakamura also improved the manufacturability of the devices by pioneering a variation of a fabrication technique called Metal Organic Chemical Vapor Deposition. Nakamura's twist, called two-flow MOCVD, improved the crystal quality and uniformity by adding an inert gas, which flowed perpendicularly to the substrate and reactant gas. This second gas flow enabled finer control of the reactant gas flow over the substrate.

Nakamura went on to produce a blue laser diode using GaN in 1995. This early laser emitted photons in pulses rather than continuously, and it required relatively high voltages to function. But within several years those problems were solved. In 2006, the first Blu-ray disc players were shipped, equipped with Nichia's 405 nanometer (blue) diode lasers.

For their inventions, Akasaki, Amano, and Nakamura have won many awards, including the Nobel Prize for Physics in 2014. Previously, in 1996, the three won the IEEE Photonics Society's Engineering Achievement Award. Akasaki was named an IEEE Fellow in 1999 and won the IEEE Edison Medal in 2011. (In November, 2020, five months before he died at 92, Akasaki was listed as a coauthor of a paper on GaN ultraviolet laser diodes published by IEEE in connection with the 2020 IEEE Photonics Conference.) Amano has been an IEEE member since 2013.

Undoubtedly, their greatest honor was the satisfaction of seeing their work change the world. According to a recent study by the International Energy Agency, the share of the global lighting market held by gallium-nitride light-emitting diodes has gone from zero to more than 50 percent in just two decades. This shift has avoided, on an annual basis, the release of hundreds of millions of tonnes of carbon-dioxide into the atmosphere, a figure that has been steadily rising as more of the world adopts LED-based white lights. ■

SEMICONDUCTORS | 2011

‘We Dug in Our Heels’

The rise of efficient electric cars and renewable energy would be hard to imagine without the silicon carbide transistor.

The yin and yang of a transistor are power and speed. For computer logic and for amplifying microwave radio signals, you mainly want speed. But for countless other applications what you really need is power. These uses include pivotal roles in some of the most important emerging technology-based industries, such as electric vehicles, renewable energy, and high-voltage electricity transmission.

For all of these, and more, a type of transistor fabricated with the semiconductor silicon carbide has jumped out to an early lead. First created around 2009 and released commercially in 2011, the silicon carbide metal-oxide semiconductor field-effect transistor (MOSFET) had by the end of 2022 created a market worth $1.4 billion annually, according to the consultancy Transparency Market Research.

And like so many technology breakthroughs of that era, the story of the SiC MOSFET is a tale of brilliant insights and intense competition, particularly among researchers in the United States and Japan. Two of the most important figures were Hiroyuki Matsunami of Kyoto University and John Palmour of North Carolina State University and later Cree Inc. (now known as Wolfspeed). Both were named IEEE Fellows for their work, Palmour in 2013 and Matsunami in 2014.

THE ALLURE OF SILICON CARBIDE

Silicon carbide (SiC), also known as carborundum, is one of the hardest known materials—if you can find it. Most natural SiC on earth comes from meteorites. To create it, for example, for use as an abrasive, technicians combine silica (SiO2), which is found in sand and is one of the most common substances on earth, and carbon in a furnace at a temperature between 1,600 degrees C and 2,500 degrees C.

However, this process does not produce crystals with nearly the purity and perfection required to fabricate semiconductor devices. So for many years, researchers worked on economical means of producing crystalline SiC with the superior characteristics needed for semiconductors.

WOLFSPEED

Cree Inc. (now Wolfspeed) introduced a 1,200-volt, 42-ampere silicon carbide power transistor in 2011.

The payoff, they all knew, would be huge. SiC is what is known as a wide-bandgap semiconductor. The wider the bandgap of a crystal, the greater the amount of energy that is released when electrons combine in the crystal with electron deficiencies called holes. In a semiconductor with a wide bandgap, the bonds between atoms are strong, and so the material is generally able to withstand relatively high voltages before the bonds break and the transistor is said to break down. The bandgap of silicon is 1.12 electron volts. For the most common type of SiC, the bandgap is 3.26 eV. This property enables a SiC transistor to block relatively high voltages—much higher than silicon—when in the "off" state.

Another key characteristic that determines how much power a semiconductor can handle is its thermal conductivity. High levels of power in a semiconductor mean high heat. So the ability to conduct that heat rapidly and efficiently is paramount. The thermal conductivity of a material is measured in watts per meter Kelvin. For silicon, the figure is 150. For SiC, it is 490.

The path to a viable SiC power transistor hit a major milestone in 1987, when Matsunami, in Kyoto, invented a process for growing SiC crystals using a process called epitaxy. Matsunami's specific breakthrough was a method called Step-Controlled (or Step-Flow) Epitaxy. To grow layers of SiC on a substrate, Matsunami tilted the substrate on which the crystal was grown by a few degrees with respect to the surface of the crystal. The procedure allowed for exceptionally pure, thin layers of SiC to be grown at relatively low temperatures, literally step by step. He described the process in a paper presented at an IEEE conference, the 10th Conference on Semiconducting and Insulating Materials, in 1998.

Largely in recognition of this invention, the IEEE awarded Matsunami its Edison Medal in 2023.

FIRST DIODES, THEN TRANSISTORS

Practical SiC devices soon followed Matsunami's breakthrough. Matsunami himself and three colleagues described a diode they fabricated and tested at voltages up to 1,100 volts in a paper published in the journal *IEEE Electron Device Letters* in 1993.

By then, many companies were also working on SiC transistors. During the 1990s, Wolfspeed (then Cree) was one of the leading companies pursuing transistors. The company had already developed the world's first SiC wafer, which can be thought of as the foundation on which devices such as transistors are fabricated.

The driving force behind Cree's work was Palmour, who had earned a Ph.D. in materials science and engineering from North Carolina State in 1988 and had founded Cree at around the same time. The prize, Cree's founders knew, was a SiC MOSFET.

A SiC MOSFET remained elusive, however. Researchers began to suspect that SiC crystals simply contained too many defects to function effectively as a conductor. In addition, there are some 200 different types of crystal structure states within SiC, a phenomenon known as crystal polymorphism. Finding the best structure for use in electronics was difficult.

Some in the industry believed that a SiC MOSFET device wouldn't work because the oxide insulator it needed could never be made reliable. Indeed some companies even dropped their SiC MOSFET-related efforts to pursue other transistor types, such as junction field-effect transistors or bipolar junction transistors.

Indeed, the first SiC transistor to come to market was a JFET, from SemiSouth Laboratories, in 2008. But the potential advantages of a commercial SiC MOSFET kept the device at the top of many R&D agendas. Basically, the JFET would have the edge in inherent reliability, but the MOSFET would lead or be at least comparable in just about every other aspect—cost, performance, and compatibility with existing circuit devices and techniques.

A huge win for SiC MOSFETs occurred in 2017, when Tesla adopted them for the onboard, or traction, inverters in its Model 3 electric vehicles.

Finally, in 2011 Cree began selling the first commercially viable SiC transistor that was superior to silicon for power applications. It could block 1,200 volts when the transistor was in the "off" state and had a respectably low resistance of 80 milliohms when conducting current in the "on" state.

A BILLION-DOLLAR INDUSTRY IN LESS THAN 10 YEARS

John Palmour, who died in 2022, lived long enough to see SiC MOSFETs become a billion-dollar industry. On the 10th anniversary of the first SiC MOSFET, he wrote a retrospective on the device's invention:

"We explored three different crystal structures. We struggled to drive down the cost while increasing ampacity...by factors of 1,000 or more! We started with a wafer the size of my pinkie nail before ultimately bringing the SiC MOSFET to market on a

IEEE AWARDS

The two people most responsible for the invention of practical silicon carbide power transistors are Hiroyuki Matsunami [opposite] and John Palmour.

WOLFSPEED

3-inch diameter wafer…We dug in our heels because we knew that the MOSFET is what the customer really wanted in the end. We believed we could create the most powerful, reliable semiconductors on the market using silicon carbide."

A major advantage of the SiC MOSFET was its similarity to existing silicon power MOSFETs. Both feature a source, a gate, and a drain. When the transistor is turned on, by applying a voltage to the gate, electrons move from a heavily doped n-type source and across a lightly doped bulk area before being "drained" via a conductive substrate.

A huge win for SiC MOSFETs occurred in 2017, when Tesla adopted them for the onboard, or traction, inverters in its Model 3 electric vehicles. In an EV, the traction inverter converts direct current from the car's batteries to alternating current for the motor. The inverter also varies the frequency of the alternating current to control the speed of the motor. Other car makers have since gone over to SiC MOSFETs or are planning to do so, including General Motors, Mercedes-Benz, Toyota, Renault, Lucid Motors, and Chinese EV maker BYD.

By 2022, SiC was beginning to face stiff competition from another wide-bandgap semiconductor, gallium nitride. Umesh K. Mishra, dean of the UC Santa Barbara College of Engineering, extolled the virtues of the two semiconductors in *IEEE Spectrum*. "SiC and GaN are going to enable far greater reductions in [greenhouse gas] emissions," Mishra wrote. "Virtually everywhere that alternating current must be transformed to direct current or vice versa, there will be fewer wasted watts…. In the effort to mitigate climate change, eliminating waste in power consumption is the low-hanging fruit, and these semiconductors are the way we'll harvest it." ■

SEMICONDUCTORS | 2017

The Death of Moore's Law, Prematurely Foretold

Extreme ultraviolet lithography has been decisive in extending the astonishing winning streak of integrated circuits—so much so that today experts are pondering the limits of silicon.

For more than half a century, Moore's Law observed that the number of transistors that would fit within a given area of silicon was doubling every year or two. Keeping Moore's Law going for all those years demanded that semiconductor researchers could, for each successive generation of integrated circuits, fabricate transistors roughly half the size of the ones in the generation before.

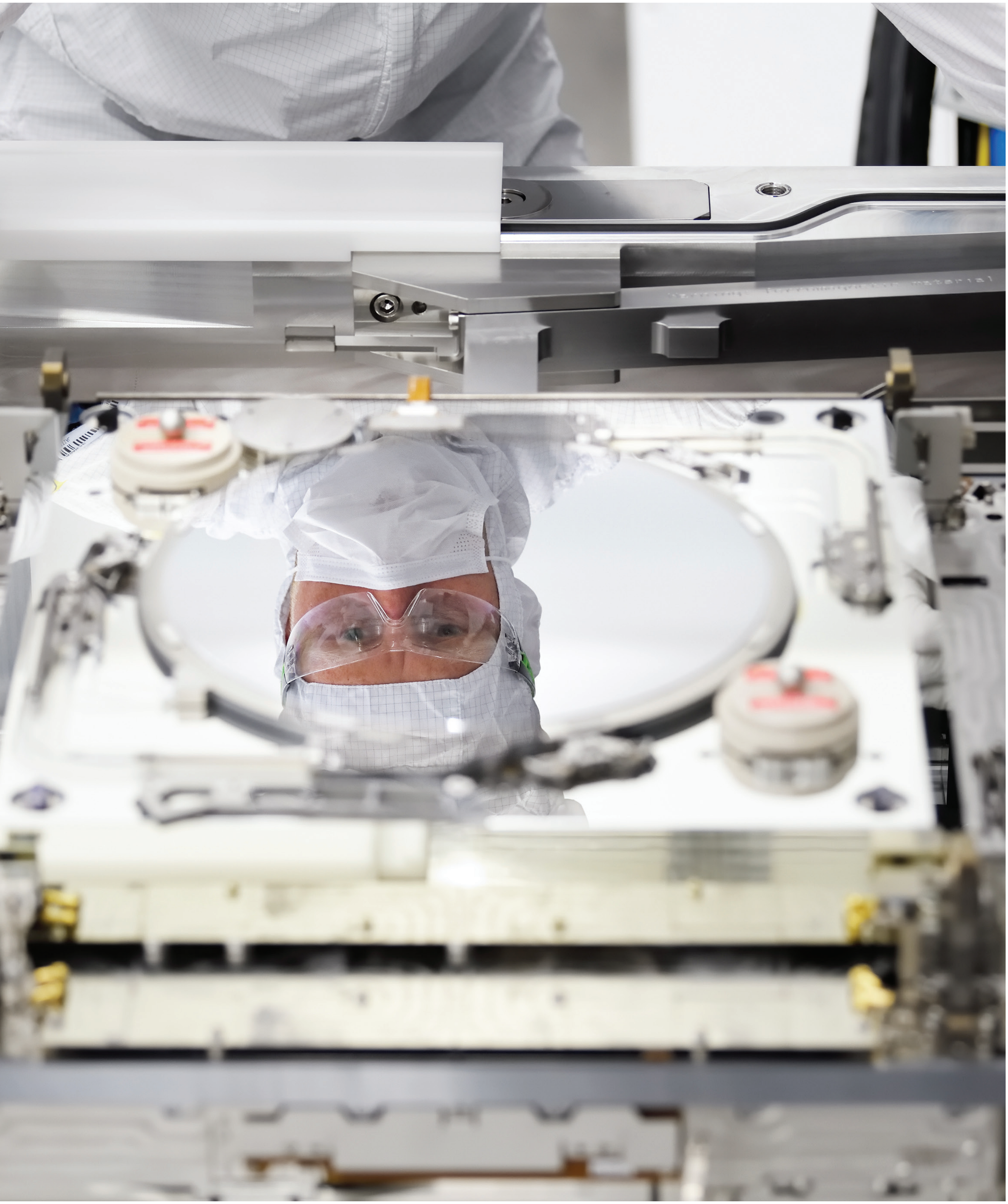
Sustaining Moore's Law became more difficult as the years went on. And in 2009 the speculation was escalating into something like a full-blown panic that Moore's Law might actually come to an abrupt end long before the physical limits of silicon could be reached.

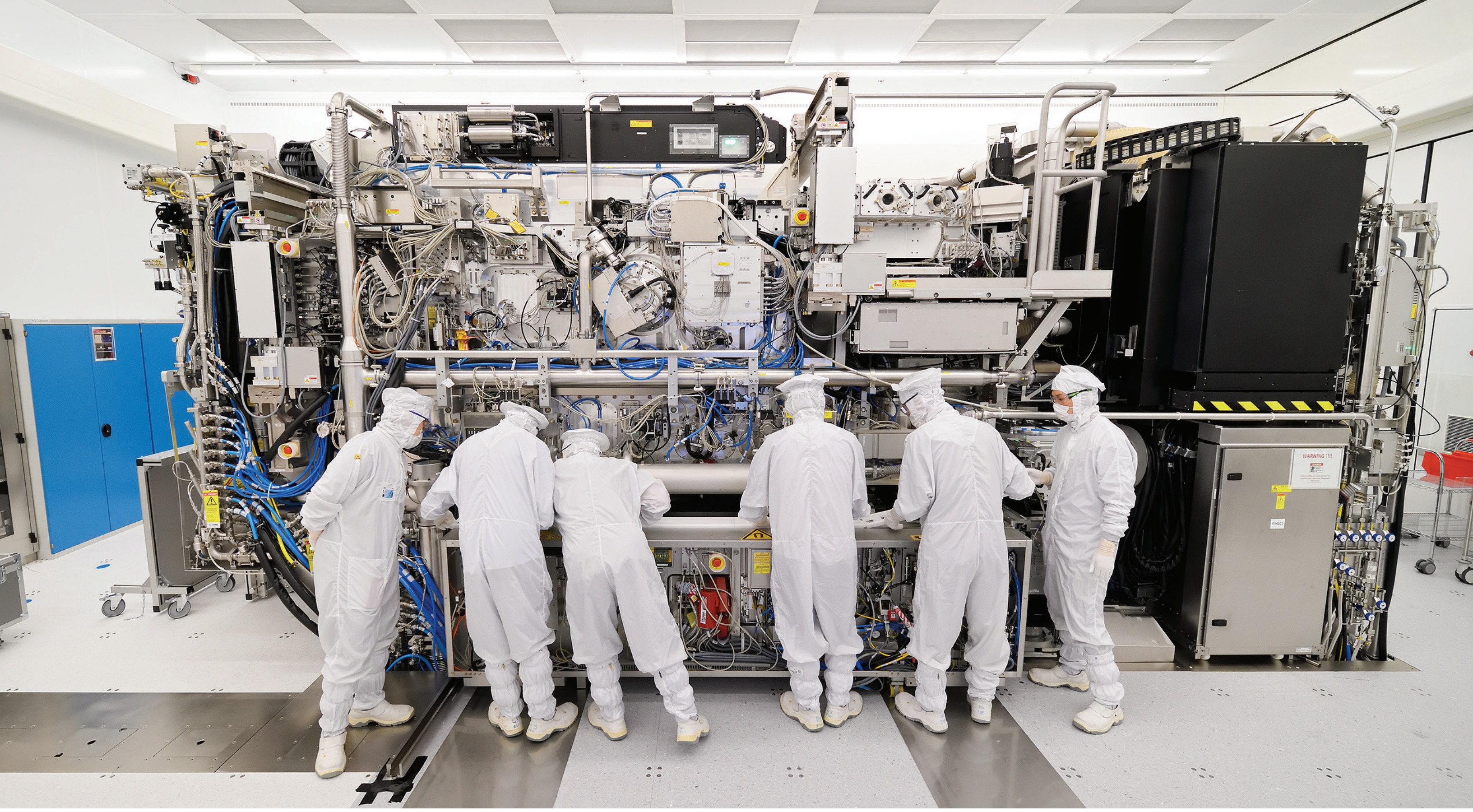
By 2009, IC manufacturers could build transistors with key features that measured as small as 32 nanometers. They were relying on highly advanced techniques, called double-patterning and immersion lithography, to project the infinitesimal circuit patterns needed to fabricate such circuits. There were proposals for methods to scale down to the next level, to keep on the Moore's Law trajectory, but none of them looked particularly promising.

The basic problem was the wavelength of the radiation needed to project these infinitesimal circuit details. The smaller the details, the shorter the wavelength of radiation needed to project the pattern. Those cutting-edge ICs in 2009 with 32-nm features were being fabricated with light at 193 nm, a wavelength in the ultraviolet part of the spectrum. Scientists and engineers knew that an emerging technology, extreme ultraviolet lithography, would in theory extend Moore's Law, but making the transition to EUVL was going to be


ASML

In a clean room at the headquarters of ASML in Veldhoven, Netherlands, a technician's face was reflected in a silicon wafer being prepared for exposure in an extreme ultraviolet lithography machine.





ASML

Most of an extreme ultraviolet lithography machine is visible in this photo taken at ASML in the Netherlands. (The only major component missing is the system that produces the soft X-rays, at a wavelength of 13.5 nanometers.)

enormously difficult. Some experts thought it might not be possible at all.

LET'S GET SMALL

To understand the magnitude of this challenge, look at the process upon which chipmaking depends. In photolithography, light is shone through a patterned mask to illuminate a light-sensitive substance—a photoresist—that has been applied to the surface of a silicon wafer. This projection transfers the mask's circuit pattern onto the photoresist. It occurs repeatedly as technicians project different patterns to create the many layers of a modern integrated circuit.

For years, while researchers were trying to solve the many steep challenges of EUV, other engineers deployed a series of increasingly dazzling breakthroughs that extended the life of regular ultraviolet lithography for far longer than anyone had thought possible. Engineers used light at shorter and shorter wavelengths, new types of masks, and new formulations for photoresists. They exposed wafers multiple times and through water rather than air (immersion lithography), and used computers to shape the waves of the exposing light. But eventually, it became clear that further progress wasn't going to be possible without EUV.

Why is "extreme" ultraviolet light so much more difficult to work with than ordinary ultraviolet? First, don't be fooled by that name. Radiation at 13.5 nm actually sits within the X-ray band of the electromagnetic spectrum, not in the ultraviolet. Photons at that wavelength are difficult to create at high intensities.

That was just one of many hurdles for those trying to make EUVL work. There was no source of extreme ultraviolet radiation powerful enough to make chips at commercial scale. Also, the wavelength selected, 13.5 nm, was in a band of radiation that was absorbed by essentially everything, including air and optical lenses of any kind. Lithography machines would have to be redesigned to expose treated wafers in a vacuum, with EUV radiation directed and focused by highly specialized mirrors rather than lenses. Adding to the challenge: there was no suitable photoresist and no inspection equipment that could verify that pretty much everything from the patterning of masks to the results of each production step had been successful.

ASML'S BRIGHT IDEA

The first prototype EUV lithography systems became available in the early 2010s, from companies such as ASML, Canon, and Nikon, as well as research institutes including

There were many hurdles for those trying to proceed to EUVL. There was no source of EUV radiation powerful enough to make chips at commercial scale. Also, the wavelength selected was in a band of radiation that was absorbed by everything.

Lawrence Livermore National Laboratory in California and Hanyang University in South Korea. But these machines were utterly inadequate for commercial-scale production. Their EUV sources were weak, which meant that each wafer needed to be exposed to the radiation for a relatively long period of time.

The best machines had EUV light sources operating at 50 to 80 watts, good enough to expose 40 wafers per hour. ASML calculated that to succeed commercially, it would need an EUV light source that could produce 250 watts of EUV light and turn out 125 wafers per hour.

In 2016, ASML announced an advance in one of the most promising technologies being pursued to generate EUV radiation. The technique involves shooting laser radiation at droplets of molten tin, just 25 microns in diameter, in a stream of such droplets. They are hit by a double laser pulse at a rate of 50,000 per second.

As the droplets are hit by the pulses, they become a plasma that emits EUV radiation. The radiation is directed and focused by means of the mirrors into a scanner, which exposes the wafers. Using this method, ASML managed to push the power of the light source to 200 watts and ASML expected it could go even higher, which it soon did.

ARRIVAL OF A FASTER FUTURE

A year later, ASML introduced the world's first full-scale commercial EUV lithography machine, the NXE:3400B. The first three buyers were three of the world's largest chipmakers: Taiwan-based TSMC, South Korea's Samsung, and Intel.

These systems are among the most complicated pieces of machinery ever created, and they don't come cheap. A commercial ASML EUVL machine has a price tag north of $150 million, approximately twice the cost of a typical 193 nm machine. It's the size of a city bus and needs to be shipped in multiple 747 aircraft. In addition, its power consumption is estimated at 1.5 megawatts, which is many times higher than other fabrication machines.

Moving EUV lithography into commercial production hasn't been without some snags. Each photon from the 13.5 nm laser-driven EUV source has 14 times the energy of photons from ultraviolet lasers at 193 nm, so these higher-energy photons demanded new photoresist materials to ensure that wafers moving through the manufacturing process were uniformly exposed.

Starting around 2021, engineers from TSMC and Samsung created 5-nm chips that demonstrated a speed gain of 15 percent over ICs produced prior to EUV's introduction, along with a 30 percent improvement in power efficiency.

EUV technology will inevitably have to be improved. Experts believe that lithography systems will soon need to produce 500 watts of EUV radiation and eventually even 1,000.

EUV lithography has been decisive in increasing the performance of ICs, but how much further can it go? By 2023 silicon was getting close to its theoretical limits. Industry analysts were arguing again that Moore's Law would soon be dead, or that the concept of "death" here was meaningless because the phrase had become a mere metaphor for technological progress in the industry, which had become staggeringly complicated to measure.

That EUV technology has brought us to this remarkable juncture is noteworthy, and the IEEE is among those taking note. In 2014, the Institute bestowed its Cledo Brunetti Award on Martin Van Den Brink, the president and chief technology officer of ASML, "For designing new lithography tool concepts and bringing these to the market, enabling micrometer to nanometer imaging." ■

COMPUTING | 2017

Attention Must Be Paid

For better or worse, transformer neural networks came on the scene in 2017, leading to new forms of artificial intelligence whose impact on civilization could be profound.

ChatGPT [right] took the world by storm in December of 2022. OpenAI chairman Sam Altman [below] attended the Sun Valley Conference in Idaho in 2016, when he was president of the technology startup accelerator Y Combinator.

LEFT: DREW ANGERER/GETTY IMAGES; RIGHT: DONATO FASANO/GETTY IMAGES

It's lunchtime at Google one day back in 2017. The topic of discussion among a group of researchers: how to make computers generate text more efficiently. This is Google, so five months later, that lunchtime conversation has inspired experiments described in one of the most influential research papers of the decade. The paper, "Attention Is All You Need," focuses on overcoming the long-term memory problems of recurrent neural networks, which for years had been the dominant form of machine learning.

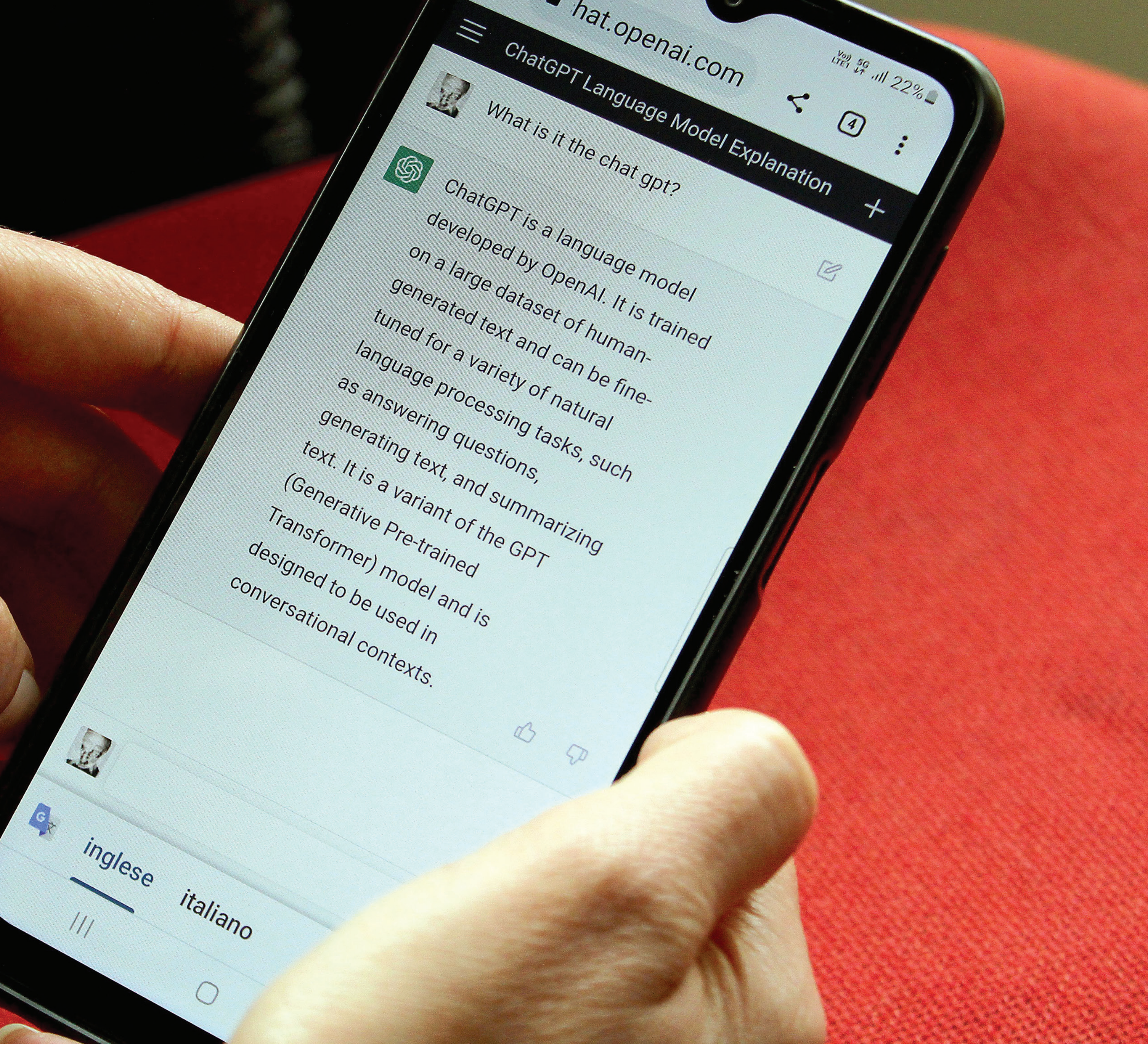
It was a major breakthrough in natural-language processing, enabling much better language input and language generation. That set the stage for the blossoming of generative artificial intelligence. Companies including OpenAI, the creator of the GPT series of large-language models, and others are using this new architecture, called transformer neural networks, to build applications capable of instantaneously producing text and images with remarkable resemblance to human works.

The stunning development reignited decades-old debates about the impact of artificial intelligence on employment, culture, politics—and even about what it will mean to be human in a world of super-capable machines.

HOW DID WE REACH THIS STARTLING JUNCTURE? LET'S BACK UP A BIT

A neural network is a type of machine-learning system based on the idea of interconnected computational units, called nodes. The system is able to improve after exposure to data, adapting to new information and getting better over time. A typical recurrent neural network is structured as layers of nodes, each of which acts on data flowing through one or more inputs.

For training purposes, these inputs are each assigned a weighting value. Based on those inputs—and their individual weights—that node either passes data on, or not, to some other nodes in the next layer. The spe-



ChatGPT Language Model Explanation

What is it the chat gpt?

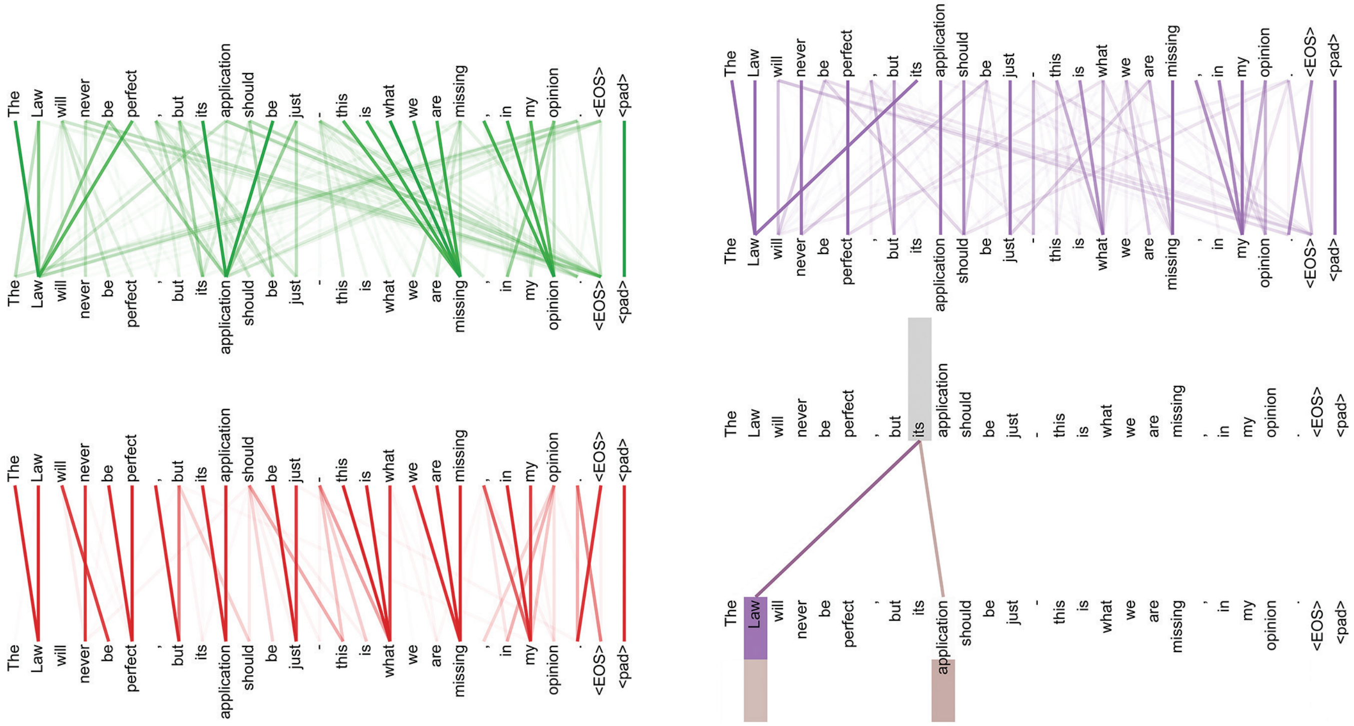
ChatGPT is a language model developed by OpenAI. It is trained on a large dataset of human-generated text and can be fine-tuned for a variety of natural language processing tasks, such as answering questions, generating text, and summarizing text. It is a variant of the GPT (Generative Pre-trained Transformer) model and is designed to be used in conversational contexts.

cific downstream nodes that get data, if any, depend on the weights.

This process of nodes communicating with other nodes based on data and weights goes on for typically many thousands of nodes across scores or hundreds of layers. At the end, the final layer of nodes comes up with a value that, for example, answers a question, such as, “Is this picture an image of a cat?”

If the neural network has answered the question correctly, the weighting values throughout the network are reinforced. But if the answer was wrong, the network downgrades the weights before the next training iteration.

This training depends on huge amounts of solved examples, called labeled datasets, because it goes on for countless iterations. Each instance makes the neural network incrementally more likely to answer the question correctly. Indeed, the accuracy for a well-trained neural network can eventually get very close to 100 percent, given sufficient training data.



One of the most important strengths of transformer neural networks is their ability to analyze long blocks of text, and thereby register dependencies between relatively distantly spaced words. Illustrations from the landmark AI research paper "Attention is All You Need" diagrammed such dependencies in a series of color-coded charts.

GOOGLE

WHY TRANSFORMERS TRIUMPHED

Although they had been commonly used for years, recurrent neural networks presented two main challenges: First, they were unable to analyze long blocks of text, and second, acquiring sufficient training data and training the neural network was very time consuming. The concept of transformer neural networks, which evolved from the Google paper, sought to address both of these challenges.

The first, called sequence transduction, limited RNNs to building only representations of each word in a sentence in a sequential manner, and without much long-term memory or the ability to analyze long blocks of text. Here, long-term memory refers to the ability to remember a long sequence of words in a piece of text. For example, in writing a sentence, an RNN would struggle to come up with the next correct word if the important, relevant words that would enable it to make the right choice were too far away (too many words distant) in the preceding text.

Transformers, on the other hand, use what are called attention mechanisms to establish the context of each word in a sentence, regardless of where the word is, which helps them to overcome the RNNs' long-term memory problem. This technique allows the model to "pay attention" to certain parts of the data and to give those parts more weight when predicting what word should come next in a sentence. This procedure allows transformers to learn the context of each word in a sentence by assigning an attention weight relative to all of the other words: in effect, learning the importance of each word in the sentence and focusing on the most relevant information. The result is much better performance on tasks that require long-range dependencies, such as machine translation and question answering.

The second major challenge addressed by transformers was the costly, time-consuming process of training a neural network on large, labeled datasets —that is, datasets that contain answers that the neural network can check at the end of a training run. Transformers can be trained on unlabeled data, which makes them much more scalable. Because they can use data that doesn't need to be labeled or otherwise prepared ahead of time, transformer neural networks can be trained on much more massive datasets—such as any piece of text on the entire internet. Training can also proceed on many pieces of text simultaneously, rather than strictly sequentially, as is the case with RNNs. This capability speeds up training enormously.

With transformers, models can not only generate text almost instantaneously, they can also be commanded in ordinary ("natural") language to produce images, in any of countless styles —the same attention mechanisms that enable them to map relationships between words also allow them to map relationships between words and visual concepts. They can also write computer code and even generate sequences of molecules, such as in proteins and drugs.

One of the most well-known early applications of transformer technology is OpenAI's Chat GPT, built on the large language model GPT-3.5. It was released on November 30, 2022, enabling anyone to interact with GPT-3.5 using natural language prompts. The response to ChatGPT was stunning. Bill Gates for example, called large-language models the most revolutionary technology in 40 years.

MIND THE "HALLUCINATIONS"

This revolutionary new architecture is not without some problems. For one, the models have had a tendency to "hallucinate," or make up information and present it as established fact, and also to get basic facts wrong sometimes.

Second, LLMs have a history of reflecting and intensifying biases in their training data, potentially yielding racist, sexist, or extremist responses. This was a particular problem with early versions of GPT, such as GPT-3. Third, the enormous amount of text that was sucked in for the purpose of training the GPT models undoubtedly included vast reams of text that was copyrighted against commercial reuse. So some have argued that OpenAI's use of the material violated laws in many countries.

The unprecedented capabilities and reach of the new models has prompted widespread concern and even anxiety in some quarters. Risks most frequently cited include disinformation, rapidly created and massively distributed, for example in service of political "dirty tricks." Another concern involves machines taking over entire categories of employment from human beings. Some pundits have gone so far as to suggest the possibility of human extinction if today's large language models lead to superintelligent AI systems whose goals are not aligned with those of humanity.

In May 2023, more than 350 people, including some well-known names in tech and science, signed a one-sentence statement published by the Center for AI Safety insisting that "mitigating the risk of extinction from AI should be a global priority alongside other societal-scale risks such as pandemics and nuclear war." The signers included Sam Altman, CEO of OpenAI; Google DeepMind CEO Demis Hassabis; Microsoft CTO Kevin Scott; and Geoffrey Hinton, who played a pivotal role in establishing recurrent neural networks as the most successful AI technology before transformers.

Not everyone took such a dire view, of course. While agreeing that there are areas of concern, Bill Gates called the risks "manageable." "This is not the first time a major innovation has introduced new threats that had to be controlled," Gates wrote in a blog post in July 2023. "We've done it before.

"It's the most transformative innovation any of us will see in our lifetimes," he added, "and a healthy public debate will depend on everyone being knowledgeable about the technology, its benefits, and its risks." ■

Which is Smarter: GPT-4 or a 7-Year-Old Child?

Despite its comparatively simple neural net structure, compared to the human brain's 100 billion neurons, the large-language model GPT-4 can emulate human language with seemingly remarkable sophistication.

But the word "emulate" here is critical. It's easy to forget that what LLMs do is apply stupendous compute power to a barrage of statistical calculations in order to compile sentences, word by word, and paragraphs, sentence by sentence. It has nothing to do with cognition and underlying it all is not even a shred of the kind of understanding that would be brought to the task by, for example, a 7-year-old child.

GPT-4 "doesn't have any underlying model of the world," said Rodney Brooks, a prominent artificial intelligence and robotics researcher and entrepreneur. "It doesn't have any connection to the world. It is correlation between language," he added. Brooks made the comments in an interview with *IEEE Spectrum* in April 2023.

"What the large language models are good at is saying what an answer should sound like," Brooks concluded. "Which is different from what an answer should be."

AI and the Next Era in Tech

There's never really been a dull era in electrotechnology. But it's safe to say some periods have been more exciting than others. And now, by almost any measure, technology is poised for an era of exceptional consequence and tumult.

As the IEEE begins its 140th year, it engages and supports technologists making enormous strides in electric vehicles, semiconductors, alternative energy and grid technologies, biomedical systems, and space exploration, among many other fields of endeavor. And yet one seems to overshadow all the rest: generative artificial intelligence.

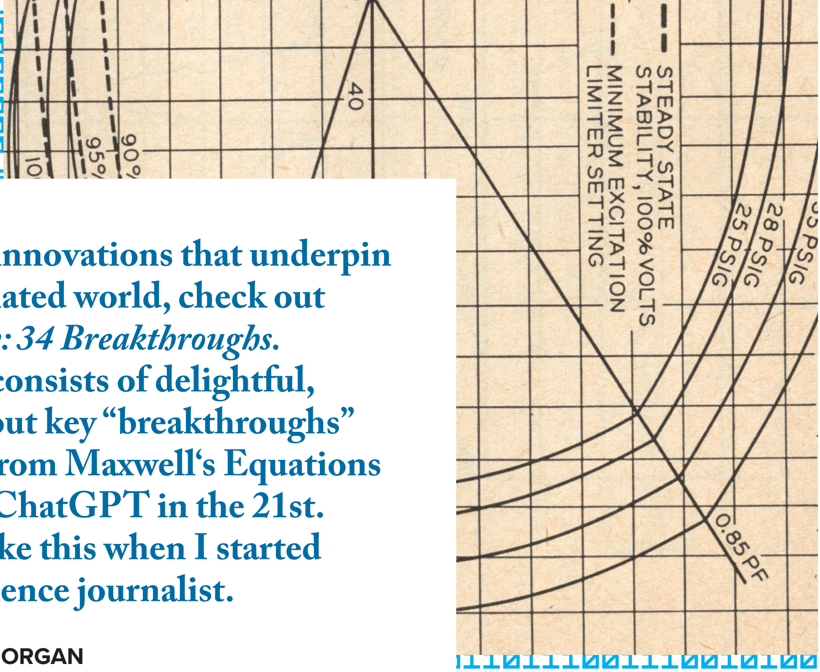
Large language models based on transformer neural networks stunned the world starting in 2022 with their ability to produce, in response to written or spoken instructions, writing, imagery, computer code, and other artifacts with a sophistication once regarded as uniquely and inherently human. And it didn't take genius-level insight to foresee long-term and widespread impacts to human employment, along with tools for generating propaganda, misinformation, and deep fakery on a massive scale.

Of course, there's plenty of upside, too. The automation of routine coding, writing, and illustration tasks will free people up for more engaging activities. Like the transistors, integrated circuits, and microprocessors that preceded it, artificial intelligence will create, enable, and transform entire industries and endeavors.

In the next decade, engineers will leverage AI and combine it with other technologies to tackle enormous and vital challenges. It will bring us great advances in manufacturing and logistics and, eventually, autonomous vehicles on land, at sea, and in the air. At the same time, we'll see the spread of power generation with drastically lower carbon emissions, and perhaps even the first permanent settlements on the moon.

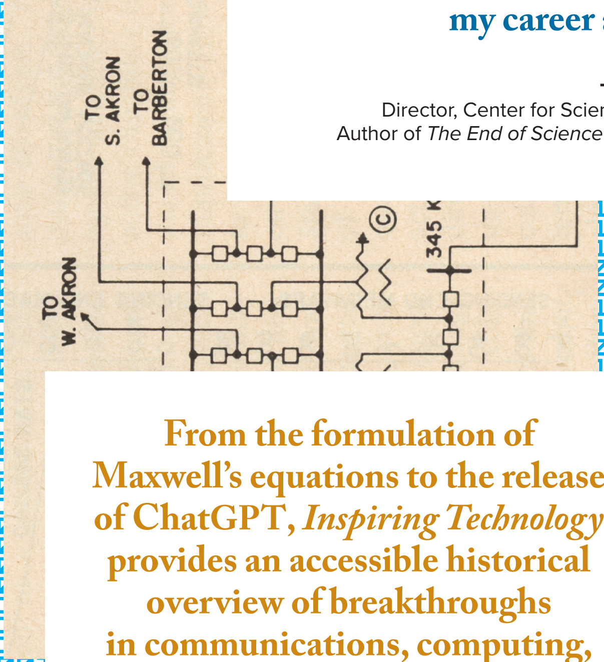
Among the people who will make this happen—who are already making it happen—will be IEEE members. Thriving communities of them, in every country on the planet, sharing technical knowledge and united in their understanding of its ability to improve the human condition. Here on Earth, and wherever humanity may go next.

—Glenn Zorpette



If you're curious about the innovations that underpin our technology-dominated world, check out *Inspiring Technology: 34 Breakthroughs*. This marvelous book consists of delightful, detail-packed stories about key "breakthroughs" in electrical engineering, from Maxwell's Equations in the 19th century to ChatGPT in the 21st. I wish I'd had a book like this when I started my career as a science journalist.

—JOHN HORGAN
Director, Center for Science Writings, Stevens Institute of Technology
Author of *The End of Science*, *The Undiscovered Mind*, and *Rational Mysticism*

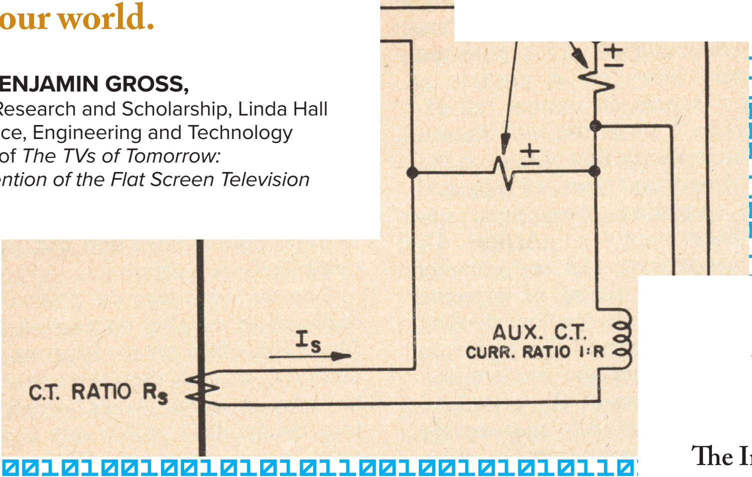


From the formulation of Maxwell's equations to the release of ChatGPT, *Inspiring Technology* provides an accessible historical overview of breakthroughs in communications, computing, and consumer electronics that have significantly transformed our world.

—BENJAMIN GROSS,
Vice President for Research and Scholarship, Linda Hall Library of Science, Engineering and Technology
Author of *The TVs of Tomorrow: RCA and the Invention of the Flat Screen Television*

The professional members of the IEEE not only witnessed history–they created it. The writers and editors of *Inspiring Technology: 34 Breakthroughs* capture the stories of the people and events that shaped the past century and a half of technological development in this deeply engaging and richly illustrated book.

—ALLISON MARSH
Professor of History, University of South Carolina
Author of *The Factory: A Social History of Work and Technology*



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