COMPUTING // HARDWARE

How Bell Labs Missed the Microchip

The man who pioneered the transistor never appreciated its full potential

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BY MICHAEL RIORDAN // DECEMBER 2006

At 4:15 a.m. on 11 December 1971, firemen extinguishing an automobile blaze in the New Jersey hamlet of Neshanic Station were shocked to discover a badly charred body slumped face-down in the back seat. It proved to be the remains of Jack A. Morton, the vice president of electronic technology at Bell Telephone Laboratories, in Murray Hill, N.J. He had last been seen talking with two men at the nearby Neshanic Inn just before its 2 a.m. closing--about 100 meters from the abandoned railroad tracks where his flaming Volvo sports coupe was spotted. Local police quickly arrested and booked the men for murder.

This gruesome slaying ended the stellar career of the man who had led Bell Labs' effort to transform the transistor from a promising but rickety laboratory gizmo into the sturdy, reliable commercial product that eventually revolutionized electronics. During the 1950s and 1960s, Bell Labs' golden age, Morton served as quarterback of the device development team, making nearly all the key calls on which technologies to pursue and which to forgo. He was a bold, forceful, decisive manager who didn't suffer fools gladly. And with some of the world's most intelligent and innovative researchers working for him, he rarely had to.

Morton didn't *always* make the right decisions, however. As one of his former colleagues observed, decisive leadership can easily become a flaw rather than a virtue [see photos, " Flawed Hero"]. On integrated circuits in particular, Morton exhibited serious blind spots that cost the parent phone company, AT&T, dearly--and may have contributed to its eventual dismemberment. But his untimely death meant that he would not be around to witness the consequences of his choices.

Like so many of the leading figures in the semiconductor industry--John Bardeen, Nick Holonyak, Jack Kilby, Robert Noyce--Jack Morton was born and raised in America's pragmatic heartland. After growing up in St. Louis, he matriculated at Wayne University, in Detroit, where he was a straight-A electrical engineering major as well as quarterback of the football team. He was avidly pursuing graduate work in the discipline at the University of Michigan, intent on an academic career, when Bell Labs research director Mervin Kelly happened to visit in 1936. Kelly offered the promising young engineer an R&D position. Morton accepted, planning to pursue a Ph.D. in physics at Columbia University simultaneously. At Bell Labs, he started the same year as John Pierce, who would go on to pioneer satellite communications; Claude Shannon, who would lay the foundations for information theory; and William Shockley, who would share the Nobel Prize for inventing the transistor.

A visionary firebrand, Kelly had directed vacuum-tube R&D at the Labs [see photos, " Early Promise"]. He was keenly aware of the limitations of the bulky, power-hungry devices and the problems with the electromechanical relays then used as switches to connect phone calls throughout the Bell System. He envisioned a future when this switching would be done completely by electronic means based on the solid-state devices that were beginning to find applications in the late 1930s. To realize his dream, he hired the best scientists and engineers he could cajole into working in an industrial laboratory.

World War II put the project on hold. Kelly played a major wartime role, heading up radar development at Bell Labs and the Western Electric Co., AT&T's manufacturing arm. Morton, too, did important military work. Having plunged into the intricacies of microwave circuit engineering just before the war, he helped design a microwave amplifier circuit that extended the range of radar systems and gave Allied forces in the Pacific a key advantage.

After the war, Morton developed a peanut-size vacuum triode that could amplify microwave signals. This triode served at the heart of the transcontinental microwave relay system that AT&T began building during the late 1940s, and it continued to be used in this capacity for decades, permitting coast-to-coast transmission of television signals.

By 1948, Morton had achieved a reputation as an imaginative engineer who knew how to get sophisticated devices into production. One day in June, Kelly tersely summoned him to his office. Such a one-on-one encounter was not to be taken lightly, for Kelly--who had risen to executive vice president--had a legendary temper. A friend of Morton's later described the meeting as follows:

"Morton," Kelly began, "You do know about the work we've been doing on the transistor?"

"Yes, sir," Morton replied a bit hesitantly. He'd heard through the grapevine about the transistor, the secret new solid-state amplifier invented the previous December by Bardeen and experimental physicist Walter Brattain, but he was unsure whether to admit it. "At least I know it's pretty important."

"Morton, I'm going to be away for the next four weeks," Kelly proceeded imperiously. "When I get back, I would like to see a report from you on the transistor. I want you to tell me how to develop it commercially."

Kelly didn't know it, but Morton had been running scared of him ever since being hired, and he was now terrified at the prospect of failing on such an enormous assignment. For the next three weeks Morton talked to the scientists and engineers working on transistors but made little progress. Then, in the last week, he somehow pulled it all together and had a 46-page report waiting on the boss's desk when he returned. Kelly read it, approved it, and immediately put Morton in charge of transistor development.

Bardeen and Brattain's point-contact transistor was a crude, fragile device consisting of two closely spaced metal points jabbed into a germanium sliver. That it worked at all was a minor miracle. Already a pilot production line at the Labs was turning out hundreds of prototypes every week for further experimentation, measurement, and testing. But the transistors were extremely noisy, variable, and unreliable. "In the very early days, the performance of a transistor was apt to change if someone slammed a door," Morton was quoted as saying in a 1953 article in *Fortune* .

In the fall of 1948, he gathered about a dozen engineers and a similar number of technicians for a meeting to launch his transistor development team [see photos, " Team Leader"]. According to two of his lieutenants, Eugene Anderson and Robert Ryder, Morton already seemed to anticipate that their work would make history: "We shall change the world," he prophesied. "In what manner I do not know, but change it we will."

The team attacked the noise and reliability problems on several fronts, and by mid-1949 they had two improved versions ready for production, one to amplify signals and the other for switching applications. Western Electric began manufacturing the transistors in 1950, and Bell System engineers soon found uses for them. The first commercial application was in a tone generator used in toll-call signaling.

Morton also had the foresight to pursue what became known as "fundamental development" of basic manufacturing processes and technologies that could have across-the-board implications for the new semiconductor industry. A prime example: when the chemist Gordon Teal could not convince his own department head to let him grow large single crystals of germanium for use in making transistors, he appealed to Morton for support. Coming from electron tube manufacturing, Morton understood that transistor action demanded a near-perfect medium--like the vacuum in a tube--and so he readily came up with the pittance required to buy or build the necessary crystal-growing equipment. Dollar for dollar, it was probably the best investment in Bell Labs' history.

Morton knew how to get research ideas and designs out of the Labs and into manufacturing at Western Electric, too. Here the groundwork had been laid by his mentor, Kelly, who during the war had recognized the obstacles to transferring technology from an isolated central lab. He felt it was crucial to have people familiar with the latest scientific and technological advances working right on the shop floor, especially when fabricating high-tech components. And so, after 1945 he established a system of branch labs at several Western Electric plants, consisting of teams of Bell Labs employees focused on production engineering and acting as liaison with their colleagues back in Murray Hill.

Morton fine-tuned this approach at the new Western Electric plant in Allentown, Pa., which produced electronic devices and components for the Bell System. He set up a semiconductor development group there and put Anderson in charge. A tube engineer who had been with Morton's Murray Hill transistor team from the outset, Anderson had a good grasp of the necessary solid-state physics and semiconductor technology.

So Morton's development team was poised to move quickly in mid-1951 when Bell Labs announced the successful fabrication of the junction transistor, much more rugged and practical than the delicate point-contact device invented by Bardeen and Brattain. Conceived by Shockley and fashioned by chemist Morgan Sparks using Teal's crystal-growing apparatus, this three-layer germanium sandwich had a much simpler structure than the point-contact transistor and far outperformed it. That the junction transistor would be the preferred path to commercialization was immediately obvious. And Morton's group led the way, getting the device into production within a year.

In the beginning, transistors were made of germanium, not silicon. Although germanium's lower melting point makes it far easier to purify, transistors crafted from it are sensitive to temperature changes. And they make lousy switches: tiny leakage currents continue to flow even when the devices are nominally off. Silicon doesn't have these problems, but it's a lot more difficult to work with. In the early 1950s, only a few farsighted researchers like Shockley recognized that silicon was the semiconductor material of the future.

In 1954 Morris Tanenbaum fabricated the first silicon transistor at Bell Labs [see "The Lost History of the Transistor," IEEE Spectrum, May 2004]. Later that year AT&T executives decided to pursue the first electronic switching system--known as ESSâ¿¿1--based on semiconductor devices rather than electromechanical crossbar switches. A trial run was set to begin in 1958.

Morton faced a crucial decision: whether to employ the (by then) well-established germanium technology or bet the house on silicon, which still had a long way to go in development and was thus far riskier. Both Sparks and Tanenbaum, who worked on the research side of the fence and didn't have to worry about manufacturing devices of extreme reliability, now say in hindsight that the choice to go with silicon was obvious. At the time, however, it was anything but.

In March 1955 Tanenbaum improved on his earlier invention by diffusing impurities into the silicon. This process allowed him to fashion a narrow base layer--the "meat" in the semiconductor sandwich--only about a micrometer thick. The device, which came to be known as a diffused-base transistor, could amplify and switch signals above 100 megahertz, into the range of FM radio and television. Best of all, such a high switching speed, about 10 times that of previous silicon transistors, meant that it could be used for electronic switching.

When he heard the news, Morton was in Europe. He immediately canceled his travel plans and rushed back to Allentown. "On a snowy, miserable day," recalled Anderson, Morton decreed that "it was to be in silicon as a material and diffusion as a technology that future transistor and diode development would move in the Bell System."

His bold decision proved correct. Bell Labs researchers soon resolved the difficulties with purifying silicon and growing crystals of it. They then discovered how to make a glassy, protective oxide layer on the silicon surface that could be used to pattern the impurity diffusions. Fairchild Semiconductor Corp., in Mountain View, Calif., led by Robert Noyce, would adapt these silicon technologies to produce the first commercial microchips in 1961. Western Electric, in turn, used Fairchild's patented planar process to make diffused-base silicon transistors for the Bell System's ESS-1, which began to show up in phone exchanges in the early 1960s [see photo, " From Lab to Factory"]. Kelly's dream of electronic switching finally became reality, thanks in part to Morton's courage and vision.

It is a remarkable historical fact that Bell Labs did not invent the microchip, despite having developed almost all the underlying technology that went into it. This puzzling failure can be attributed partly to market forces--or the lack of them. As former Bell Labs President Ian Ross once explained in an interview, the Labs focused on developing robust, discrete devices that would enjoy 40-year lifetimes in the Bell System, not integrated circuits. Indeed, the main customers for microchips were military procurement officers, who, especially after Sputnik, were willing to cough up more than US $100 a chip for this ultralightweight circuitry. But the telephone company had little need for such exotica. "The weight of the central switching stations was not a big concern at AT&T," quipped Ross, who back in 1956 had himself fashioned a precursor of the microchip.

Ultimately, though, the company would need integrated circuits. Think of the Bell System as the world's largest computer, with both analog and digital functions. Its central offices put truly prodigious demands on memory and processing power, both of which could be best supplied by microchips. And it was microchips driven by software that eventually made electronic switching a real success in the 1970s. But by then AT&T was playing an increasingly desperate catch-up game in this crucial technology.

Here Morton was partly to blame. He pooh-poohed the potential of microchips and large-scale integration. Citing his own version of the ”tyranny of numbers,” he initially argued that the manufacturing yields on integrated circuits would become unacceptably low as the number of components on a chip grew. Even though each chip component--typically a transistor--might be made with a 99 percent success rate, this number would have to be multiplied by itself many times, resulting in abominable yields, he reasoned. Tanenbaum summed up Morton’s attitude this way: ”The more eggs you put in the chip basket, the more likely it is that you have a bad one.”

And reliability would suffer, too, or so Morton thought. Due to his lofty position--he had become a vice president in 1958--this argument dominated the thinking at Bell Labs in the early 1960s. ”Morton was such a strong, intimidating leader,” observes Eugene Gordon, who worked for him then, ”that he could make incorrect decisions and remain unchallenged because of his aggressive style.” Morton’s previous string of successes probably contributed to his sense of his own infallibility.

But his tyranny hypothesis ultimately didn’t hold up. Failure rates of microchip components are an average over the entire surface of a silicon wafer. Each wafer can have unusually bad regions that pull the average down significantly, while chips in the better regions have much higher success rates, leading overall to acceptable yields. It took outsiders from the Sun Belt--at Fairchild and Texas Instruments--to overthrow the tyranny and pioneer microchip manufacturing.

Well into the 1960s, Morton continued to drag his feet on silicon-based chip technology, despite mounting evidence of its promise. He did not consider it a sufficiently ”adaptive” technology, by which he meant something that could easily respond to the evolving needs of the Bell System and gradually incorporate innovative new materials and techniques as they became available. The phone company couldn’t use a technology that was too disruptive, because the systems engineers at AT&T always had to ensure extreme reliability, compatibility with existing subsystems, and continuity of telephone service. ”Innovation in such a system,” Morton declared, ”is like getting a heart transplant while running a 4-minute mile!”

To the dismay of Gordon and others in his division, Morton squelched efforts at Bell Labs to pursue what the semiconductor industry began calling large-scale integration, or LSI, which yielded single silicon chips containing more than 1000 components. He even derided people working on LSI as ”large-scale idiots,” said one colleague. Instead, he promoted the idea of hybrid technology incorporating smaller-scale microchips, which could be manufactured with higher yields, into ”thin-film” circuits based on metals such as tantalum, in which resistors and capacitors could be etched more precisely than was possible in silicon. Morton championed this approach as the ”right scale of integration,” or RSI--another favorite phrase of his.

It proved to be a bad decision, but Morton was adamant. Tanenbaum reckons that it cost AT&T two or three years’ delay in getting microchips into the Bell System for later versions of electronic switching. Even then, the phone company had to purchase most of those chips from other companies instead of making them at Western Electric. Buying components from outsiders was something AT&T had tried to avoidï»¿ before 1968 (when forced to by a landmark decision by the Federal Communications Commission), because that made it more difficult to control their operating characteristics and reliability.

Bell Labs’ focus on robust discrete devices, almost to the exclusion of microchips, started to dissolve in the late 1960s. Engineers at Murray Hill and Allentown began working again on the metal-oxide semiconductor (or MOS) field-effect transistor, which Bell Labs had pioneered in the 1950s and then ignored for half a decade--even as companies like RCA, Fairchild, and others ran with it. In a MOS field-effect transistor, current flows through a narrow channel just under the oxide surface layer, modulated by the voltage on a metal strip above it. As the number of components per microchip swelled, the simple geometry and operation of the MOS transistor made it a better option than the junction transistor.

But Fairchild engineers had already solved most of the challenging reliability problems of MOS technology in the mid-1960s, so that company enjoyed a big technological advantage as the devices began finding their way into semiconductor memories.

Once again, it had been Morton’s decision back in 1961 not to pursue the development of MOS devices, in part because they initially exhibited poor reliability and didn’t work at high frequencies. As Anderson recalled, ”Morton, who was ever alert to spot a technology loser as well as a winner, was thoroughly convinced of the inherent unreliability of surface devices, as well as…that field-effect devices would be limited to low frequencies.” In the early 1960s, they indeed made little sense for a company already heavily committed to electronic switching based on discrete devices. But when Bell Labs and AT&T began embracing MOS transistors later that decade, they were once again playing catch-up [see ”The End of AT&T,” Spectrum, July 2005].

His dim view of microchips didn’t prevent Morton from being showered with accolades from the mid-1960s onward. In 1965, he received the prestigious David Sarnoff Medal of the IEEE for ”outstanding leadership and contributions to the development and understanding of solid-state electron devices.” Two years later, he was among the first people to be inducted into the U.S. National Academy of Engineering. In 1971, Morton published an insightful book, *Organizing for Innovation* , which espoused his ”ecological,” systems approach to managing a high-tech R&D enterprise like Bell Labs. In it, he expounded at length on his ideas about adaptive technology and the right scale of integration. Morton was also in demand as a keynote speaker at industry meetings and as a consultant--especially to emerging Japanese electronics and semiconductor companies, where his word was revered.

But there was a dark side to Morton’s personality that few of his Bell Labs colleagues ever glimpsed at work. He had a serious drinking problem, probably exacerbated by his frustration at his stagnation within the Bell Labs hierarchy. Sharing drinks with Gordon one evening, Morton confided his disappointment that he was still only a vice president after more than a dozen years at that level. Ambitious and aggressive, he yearned for the role of chief executive. Morton also had difficulties at home, and he began spending more evenings at the Neshanic Inn, a local hangout about a mile from where he lived.

Sparks vividly remembers how he was playing golf with Bell Labs president James Fisk that balmy Saturday morning in December 1971 when an anxious messenger rushed out onto the course to give them the tragic news of Morton’s death. Ashen-faced, Fisk asked Sparks to check into what had happened. Sparks went to the hospital where the autopsy was being performed. The doctor told Sparks that Morton’s lungs were singed, indicating he was still alive and breathing when the fire was ignited.

Details of what happened that fateful night came out at the murder trials of the two men, Henry Molka and Freddie Cisson, which occurred the following fall at the Somerset County Courthouse, in Somerville, N.J. According to prosecutor Leonard Arnold, Morton had just returned from a business trip to Europe and was driving back from the airport when he decided to stop by the inn for a drink. But it was nearly closing time, and the bartender refused to serve him. Molka and Cisson told Morton they had a bottle in their car and offered to pour him a drink. They walked out with him to the parking lot and mugged him there, pocketing all of $30.

Gordon figures they thought Morton an easy mark, a well-dressed man in his late 50s with a showy gold watch. But they were mistaken. Morton kept himself in good physical condition and, given his aggressive disposition, probably fought back. A violent struggle must have ensued. After knocking him unconscious, Molka and Cisson threw him in the back seat of his Volvo, drove it a block down the road, and set it on fire with gasoline they extracted from its fuel-injection system. The two men were convicted of first-degree murder and sentenced to life imprisonment, but according to Arnold, they served only 18 years.

Sadly, the world had lost one of the leading proponents of semiconductor technology, the articulate, visionary engineer who turned promising science into the extremely useful, reliable products that were already revolutionizing modern life by the time of his death. Under Morton’s leadership as head of electronics technology at Bell Labs, many other innovative devices were invented that today are ubiquitous in everyday life, including flash memory and the charge-coupled device, both derived from MOS technology. But like the microchip and the MOS transistor, they would be developed and marketed by other companies.

”Jack just loved new ideas,” said Willard Boyle, one of the CCD’s inventors. ”That’s what fascinated him, where he got his kicks.” That attitude is probably an important part of the reason that Bell Labs served as such a fount of innovative technologies under his stewardship. But AT&T could realistically pursue only a fraction of these intriguing possibilities, so the Labs focused mainly on the discrete devices and circuits that Morton and other managers considered useful in implementing their immediate, pressing goal of electronic switching. Viewed in that context, the decision to pass on yet another revolutionary, but unproven, technology made good business sense--at least in the short run.

Thus, another, more subtle tyranny of numbers was at work here. Given the seemingly infinite paths that AT&T could follow--and the legal ï»¿constraints on what it could actually make and sell--it was probably inevitable that outsiders would eventually bring these disruptive new technologies to the masses.

About the Author
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To Probe Further
An obituary of Jack Morton, written by Morgan Sparks for the National Academy of Engineering, is available on the Web at http://darwin.nap.edu/books/0309028892/html/223.html.

Chapters 9 and 10 of Michael Riordan and Lillian Hoddeson’s *Crystal Fire* (W.W. Norton, 1997) discuss the invention and development of the junction transistor at Bell Labs. A tutorial on the device, ”Transistors 101: The Junction Transistor,” appeared in the May 2004 issue of IEEE Spectrum.

Jack Morton’s *Organizing for Innovation: A Systems Approach to Technical Management* (McGraw-Hill, 1971) fleshes out his management philosophy.

Chapter 1 of Ross Knox Bassett’s *To the Digital Age: Research Labs, Start-up Companies, and the Rise of MOS Technology* (Johns Hopkins University Press, 2002) contains the definitive history of the MOS transistor.

SEMICONDUCTORS // DEVICES

How Europe Missed The Transistor

The most important invention of the 20th century was conceived not just once, but twice

BY MICHAEL RIORDAN // NOVEMBER 2005

In late 1948, shortly after Bell Telephone Laboratories had announced the invention of the transistor, surprising reports began coming in from Europe. Two physicists from the German radar program, Herbert Mataré and Heinrich Welker, claimed to have invented a strikingly similar semiconductor device, which they called the transistron, while working at a Westinghouse subsidiary in Paris.

The resemblance between the two awkward contraptions was uncanny. In fact, they were almost identical! Just like the revolutionary Bell Labs device, dubbed the point-contact transistor, the transistron featured two closely spaced metal points poking into the surface of a narrow germanium sliver. The news from Paris was particularly troubling at Bell Labs, for its initial attempts to manufacture such a delicate gizmo were then running into severe difficulties with noise, stability, and uniformity.

So in May 1949, Bell Labs researcher Alan Holden made a sortie to Paris while visiting England, to snoop around the city and see the purported invention for himself. "This business of the French transistors would be hard to unravel, i.e., whether they developed them independently," he confided in a 14 May letter to William B. Shockley, leader of the Bell Labs solid-state physics group. "As we arrived, they were transmitting to a little portable radio receiver outdoors from a transmitter indoors, which they said was modulated by a transistor."

Four days later, France's Secretary of Postes, Télégraphes et Téléphones (PTT), the ministry funding Mataré and Welker's research, announced the invention of the transistron to the French press, lauding the pair's achievement as a *"brilliante réalisation de la recherche française."* Only four years after World War II had ended in Europe, a shining technological phoenix had miraculously risen from the still-smoldering ashes of the devastation.

"This PTT bunch in Paris seems very good to me," Holden candidly admitted in his letter. "They have little groups in all sorts of rat holes, farm houses, cheese factories, and jails in the Paris suburbs. They are all young and eager." And one of these small, aggressive research groups, holed up in a converted house in the nearby village of Aulnay-sous-Bois, had apparently come through spectacularly with what might well be the invention of the century--a semiconducting device that would spawn a massive new global industry of incalculable value. Or had it?

As was true for the Bell Labs transistor, invented by John Bardeen and Walter H. Brattain in December 1947, the technology that led to the transistron emerged from wartime research on semiconductor materials, which were sorely needed in radar receivers. In the European case, it was the German radar program that spawned the invention. Both Mataré and Welker played crucial roles in this crash R&D program, working at different ends of the war-torn country.

Mataré [see photo in " Transistor Twin"], who shared his remembrances from his home in Malibu, Calif., joined the German research effort in September 1939, just as Hitler's mighty army rumbled across Poland. Having received the equivalent of a master's degree in applied physics from Aachen Technical University, he began doing radar research at Telefunken AG's labs in Berlin. There he developed techniques to suppress noise in superheterodyne mixers, which convert the high-frequency radar signals rebounding from radar targets into lower-frequency signals that can be manipulated more easily in electronic circuits. Based on this research, published in 1942, Mataré earned his doctorate from the Technical University of Berlin.

At the time, German radar systems operated at wavelengths as short as half a meter. But the systems could not work at shorter wavelengths, which would have been better able to discern smaller targets, like enemy aircraft. The problem was that the vacuum-tube diodes that rectified current in the early radar receivers could not function at the high frequencies involved. Their dimensions--especially the gap between the diode's anode and cathode--were too large to cope with ultrashort, high-frequency waves. As a possible substitute, Mataré began experimenting on his own with solid-state crystal rectifiers similar to the "cat's-whisker" detectors he had tinkered with as a teenager.

During the 1920s, he built crystal radio sets to listen to classical music on the radio waves then beginning to fill the ether. Of Belgian extraction, he was raised in Aachen, Germany, in a family immersed in music. At the heart of each of his radios was a tiny chip of semiconductor material, such as galena (lead sulfide) or silicon, with a fragile wire jabbed gingerly into its surface. For reasons nobody fully understood until the late 1930s, this detector rectified the alternating-current signal from the antenna into the direct-current signal needed to drive headphones.

Similar point-contact devices, especially those made with silicon, could be used as the rectifier required in the superheterodyne mixer circuit of a radar receiver, which shifts the received frequencies down by mixing the input signal with the output of an internal oscillator. Because the electrical action of such a crystal rectifier is confined to a very small, almost microscopic region on the semiconductor surface, the device can rectify currents at relatively high frequencies.

Theoretical work by Walther Schottky at Siemens AG, in Munich, Germany, and by Nevill F. Mott at the University of Bristol, in England, had given Mataré and other radar researchers a much better understanding of what was happening beneath the sharp metal point. When the point touched the semiconductor surface, excess electrons quickly flowed into it, leaving behind a neutral "barrier layer" less than a micrometer deep in the material just underneath it. This narrow zone then acted like an asymmetric barrier to the further flow of electrons. They could jump the barrier much more readily from the semiconductor surface to the metal point than vice versa, in effect restricting current flow to one direction.

As the war ground on, the leaders of the Berlin-based German radar establishment urged the Luftwaffe to pursue research on systems operating at wavelengths well below 50 centimeters--in what we now call the microwave range. They argued that such systems would be small enough to mount in warplanes and detect approaching enemy aircraft through dense clouds and fog.

But German military leaders, basking smugly in their early victories, ignored those pleas. Luftwaffe chief Hermann Göring, who had served as an open-cockpit fighter pilot in World War I, adamantly believed that the intrinsic fighting abilities of his Aryan warriors made electronic systems superfluous. "My pilots," he bragged, "do not need a cinema on board!"

Everything changed after February 1943, however, when a British Sterling bomber downed over Rotterdam in the Netherlands revealed how far behind the Allies Germany had fallen in radar technology. Göring ordered a thorough analysis of the bomber's 9-cm radar system and recalled more than a thousand scientists, engineers, and technicians from the front in a desperate attempt to catch up. By summer they had built a working prototype, but it was much too late. Allied bombers, aided by onboard radar systems that allowed pilots to operate even in foul weather, were pulverizing German cities with increasing impunity.

Mataré recalled the sudden urgency in an interview. He intensified his previous R&D efforts on crystal rectifiers, particularly those made of silicon, which seemed best suited for microwave reception. But the Allied bombing of Berlin was making life exceedingly difficult for Telefunken researchers. "I spent many hours in subway stations during bomb attacks," he wrote in an unpublished memoir. So in January 1944, the company shifted much of its radar research to Breslau in Silesia (now Wroclaw, Poland). Mataré worked in an old convent in nearby Leubus.

Laboring full-time to get silicon rectifiers into production, Mataré had scant opportunity to work on reducing the oscillator noise in radar receivers--an outgrowth of his doctoral dissertation. But he did manage to build and study an intriguing new device, the crystal "duodiode," in which two closely spaced metal points contact the semiconductor surface, forming two adjacent crystal rectifiers. If they possess the same resistance and capacitance, these two rectifiers can be used in a special circuit to cancel out noise from the oscillator of a superheterodyne mixer. The noise through one rectifier adds to the overall signal transmitted by the mixer, and the noise through the other rectifier subtracts from that signal. But to ensure identical electrical characteristics, the points must be extremely close--far less than a millimeter apart--so that both contact the same tiny crystal grain on the surface of the semiconductor.

Mataré worked with silicon samples provided by physicist Karl Seiler in Breslau and germanium samples from a Luftwaffe research team near Munich that included Welker, his future co-worker. Although silicon worked better for radar receivers because it rectified at higher frequencies, germanium duodiodes exhibited intriguing behavior. When the two points touched the surface less than 100 micrometers apart, Mataré claims, he occasionally noticed that by varying the voltage on one he could influence the current through the other--a phenomenon he dubbed "interference." It seemed as if one of his points could affect a region extending far beyond the narrow barrier layer predicted by Schottky's theory.

Mataré had stumbled upon a method to influence this layer, which had stubbornly blocked earlier attempts to make a solid-state amplifier. But wartime urgencies kept him from pursuing this intriguing possibility much further.

Germany's eastern front collapsed in January 1945, and the Russian Army was swiftly approaching Breslau. The Telefunken lab in Leubus was hastily abandoned, and all of Mataré's lab books and records were burned to keep them out of enemy hands. The group attempted to reconstitute its R&D program in central Germany, but the U.S. Army terminated this effort when it swept through in April 1945, mercifully sending Mataré home to rejoin his family in nearby Kassel.

Mataré's future colleague Welker wasn't spared the indignities of war, either. Allied bombs destroyed his laboratory near Munich in October 1944. Early the following year, this theoretical physicist, who during the 1930s had worked on the quantum mechanics of electrons in metals, began speculating about how to use silicon and germanium to fabricate a solid-state amplifier.

These two elements were widely regarded as metals during the 1930s, but their apparent metallic behavior was due largely to the high level of impurities in the available samples. When foreign atoms of elements in the fifth column of the periodic table--arsenic and phosphorus, for example--become lodged in the tetrahedral crystal structure of silicon or germanium, four of their five outermost electrons form strong bonds with nearby atoms, but the fifth is easily knocked away and can thus transfer current through the crystal. The much-higher-purity silicon and germanium that researchers used to build radar systems during World War II had far fewer of such current carriers and behaved more like semiconductors than like metals.

In early 1945, Welker, who was mastering the art of purifying germanium, recognized that the two semiconductors could be used to make what we now call a field-effect transistor. In fact, the device he had in mind was strikingly similar to one that Shockley was to suggest at Bell Labs a few months later.

In this scheme, an electric field from a metal plate should penetrate into a thin surface layer of a semiconductor strip beneath it, ripping electrons loose from their parent atoms to serve as current carriers. A voltage applied across the semiconductor strip would induce a current through it. Crucially, a varying voltage on the metal plate would modulate the current through the strip. Thus, small input signals would result in large output currents flowing through the strip. Or so Welker figured.

But tests he performed in March 1945 revealed no such amplification. In his logbook he recorded "only small effects," orders of magnitude less than what was predicted by Schottky's theory. Shockley, Brattain, and their Bell Labs colleagues attempted similar tests that very same spring, with similarly disappointing results.

The failures soon led Bardeen to postulate a novel idea of "surface states"--that free electrons were somehow huddling on the semiconductor surface, shielding out the field. This conjecture, and Brattain's follow-up experiments to determine the physical nature of the surface states, led to their invention of the point-contact transistor in December 1947--a month after they discovered how to overcome the shielding.

After his failures, Welker returned to research on germanium and resumed the theoretical studies of superconductivity he had reluctantly abandoned during the war. In 1946, British and French intelligence agents interrogated him about his involvement in German radar. They subsequently offered him an opportunity to work in Paris in an R&D operation set up under the auspices of a Westinghouse subsidiary, Compagnie des Freins et Signaux Westinghouse. The immediate goal was to manufacture germanium rectifiers for telecommunications and military electronics.

While teaching in Aachen at his alma mater in 1946, Mataré was also interviewed by agents. Fluent in French, he received a similar offer. He eagerly agreed to join the Paris effort, because doing research in devastated, occupied Germany was almost impossible.

Then in their mid-thirties, the two German physicists met in Paris and began organizing their operation. They found a vacant two-story stone house in the middle-class suburb of Aulnay-sous-Bois, just northwest of the city. In its basement, Welker set up his equipment to purify and crystallize germanium. Mataré's testing and measurements laboratory went on the ground floor, where later that year a production line began fabricating what soon amounted to thousands of rectifiers per month.

On the top floor the men kept offices and rooms where they often stayed overnight--especially during that frantic first year. Mataré wistfully remembers awakening now and then to the soft trills of Welker playing his violin in the adjoining room.

With the rectifiers finally in production by late 1947, Welker resumed his research on superconductivity, while Mataré began to address the curious interference effects he had seen in germanium duodiodes during the war. When he put the two point contacts less than 100 mm apart, he again occasionally could get one of them to influence the other. With a positive voltage on one point, in fact, he could modulate and even amplify the electrical signal at the other! Mataré reckons he first recognized this effect in early 1948 (perhaps a month or two after Bardeen and Brattain's breakthrough at Bell Labs). But it still happened only sporadically.

On a hunch, he asked Welker to fashion larger germanium samples, from which they could cut slivers of higher purity. Using this higher-grade material, Mataré finally got consistent amplification in June 1948, six months after Bardeen and Brattain. Encouraged by this success, they phoned PTT Secretary Eugène Thomas and invited him over for a demonstration. But Thomas was apparently too busy--or perhaps not interested enough--to come by.

About that time, Welker put aside his theoretical work and tried to analyze what was going on just beneath the shiny germanium surface of Mataré's odd contraption. In an undated, handwritten document, now in the archives of Munich's Deutsches Museum, Welker speculated that one point--which he called the *"électrode de commande,"* or "control electrode"--was inducing strong electric fields in the germanium just beneath the other electrode, altering the material's conductivity there.

But Mataré was not buying that explanation, which followed the logic of Welker's unsuccessful 1945 attempt at a semiconductor amplifier. If the phenomenon were caused by an electric field, Mataré remembers thinking, he should have witnessed a decrease in the current at the second electrode, not the increase he observed on his oscilloscope. According to this field-effect idea, a positive potential on the control electrode would induce negative charges in the germanium under the other electrode, which should reinforce the current-blocking effects of the barrier layer there.

Mataré argued instead that the control electrode must be injecting positive charges, called holes, into the germanium. And perhaps by trickling along the boundary between two crystal grains, he guessed, they reached the other electrode--many micrometers distant. There they would bolster the conductivity under this electrode and enhance the current through it. "Welker didn't really understand my measurements," Mataré says. "At the time he was too busy studying superconductivity."

But as the two men were debating the merits of their competing interpretations, surprising news arrived from across the Atlantic. In a 30 June press conference, Bell Labs suddenly lifted its six-month veil of secrecy and announced the invention of the transistor by Bardeen, Brattain, and Shockley. The breakthrough was reported in The New York Times on 1 July and published in the 15 July issue of *Physical Review* . Incredibly, the Bell Labs solid-state amplifier also had a pair of closely spaced metal points prodding into a germanium surface. [See photo, " Getting to the Point."]

Mataré soon learned Bardeen and Brattain's explanation of the curious effects he had been observing. Electrons trapped on the germanium surface induce a shallow, positively charged layer just beneath it. Holes emitted by the control electrode (which they had dubbed the "emitter") travel easily within this layer over to the output electrode (or "collector"), markedly boosting the conductivity beneath it and therefore the current flowing through it.

After the Bell Labs revelations, Mataré and Welker had little difficulty getting the PTT minister to visit their lab. Thomas urged them to apply for a French patent on their semiconductor triode; he also suggested they call it by a slightly different name: transistron. So the two physicists hastily wrote up a patent disclosure and passed it on to the Westinghouse lawyers.

On 13 August, the company submitted a patent application for a " *Nouveau système cristallin à plusieurs électrodes réalisant des effets de [sic] relais électroniques* " to the Ministry of Industry and Commerce. Its brief description of what might be happening inside the germanium mostly followed Welker's field-effect interpretation but was probably influenced by Bardeen and Brattain's explanations.

By the May 1949 press conference, the two Germans had the device [see X-ray image in " Invention and Inventors"] in limited production and were beginning to ship units for use by the PTT as amplifiers in the telephone system--initially in the line between Paris and Limoges. Speaking to the Paris press, Thomas compared these devices with vacuum tubes and demonstrated their use in radio receivers. Reporters hailed the two physicists as " *les pères du transistron* " (the fathers of the transistron). The French device "turns out...to be superior to its American counterpart," read a more measured but still favorable account in *Toute la Radio* , a technical journal [see drawing and photo in " "]. "The latter has a limited lifetime and appears to be fairly unstable, whereas the existing transistrons do not show any sign of fatigue."

According to Mataré, this superiority could be attributed to the care they employed in fabricating their devices. While observing the process with microscopes, the women working on the small assembly line would measure current-voltage curves for both metal points with oscilloscopes and fix the points rigidly on the germanium with drops of epoxy after the curves matched the desired characteristics. When Brattain and Shockley visited the Paris group in 1950, Mataré showed them telephone amplifiers made with his transistrons--which allowed him to place a call all the way to Algiers. "That's quite something," admitted Shockley a bit guardedly, Mataré recalls half a century later.

But the French government and Westinghouse failed to capitalize on the technical advantages in semiconductors that they then appeared to have. After Hiroshima, nuclear physics had emerged as the dominant scientific discipline in the public mind, and nuclear power was widely heralded as the wave of the future. France became enchanted with pursuing the nuclear genie unbottled in the 1940s, while ignorant of its promising transistron.

Mataré and Welker struggled on in Paris for two more years, but as support for their operation waned during the early 1950s, they started looking for jobs in their native land. In 1951 Welker accepted a post at Siemens in Erlangen, Germany, where he pioneered early research on III-V compound semiconductors, such as gallium arsenide. In the late 1950s and early 1960s, those materials fostered a small optoelectronics revolution in semiconductor lasers and light-emitting diodes. Welker became head of all R&D projects at Siemens in 1969 and retired in 1977. He died in 1981.

In 1952, with solid funding from a wealthy German businessman, Jakob Michael, Mataré moved to Düsseldorf, Germany, and founded a company called Intermetall. It began manufacturing germanium rectifiers and transistors similar to the point-contact devices he had made in Paris. The company bought or built equipment that helped it produce semiconductor devices of even higher quality.

The summit of Intermetall's achievements came at the 1953 Düsseldorf Radio Fair. There a young, dark-haired woman demonstrated what was probably the world's first transistor radio, built around four Intermetall point-contact transistors [see photo, " Tuning In"] more than a year before Texas Instruments Inc., in Dallas, publicly claimed that milestone for itself.

But after Michael sold the firm to Clevite Corp., then in Cleveland, later that year, its focus shifted almost exclusively to production and away from research. Discouraged by that about-face, Mataré left Germany and immigrated to the United States, where he found work in the U.S. semiconductor industry. Even today, at 93, the IEEE Life Fellow remains active, consulting from his Malibu home on such projects as a large, innovative photovoltaic array built in Southern California [see The Back Story, in this issue].

What is arguably the most important invention of the 20th century remarkably occurred twice--and independently. Given the secrecy shrouding the Bell Labs device, there is no possibility Mataré and Welker could have been influenced by knowledge of it before July 1948, when news of the revolutionary invention became widespread. And it seems clear from the still-sketchy historical record that they indeed had a working, reliable amplifier by that time.

This dual, nearly simultaneous breakthrough can be attributed in part to the tremendous wartime advances in purifying silicon and, in particular, germanium. In both cases, germanium played the crucial gateway role, for in the immediate postwar years it could be refined much more easily and with substantially higher purities than silicon. Such high-purity semiconductor material was absolutely essential for fabricating the first transistors.

But the Bell Labs team had clear priority--and a superior physical understanding of how the electrons and holes were flowing inside germanium. That advantage proved critical to subsequent achievements, such as Shockley's junction transistor [see "The Lost History of the Transistor," IEEE Spectrum, May 2004], which was much easier to mass-produce with high reliability and uniformity. By the mid-1950s, nobody was trying to make point-contact transistors any longer, and the industry was moving on to silicon.

A factor crucial to success in the nascent semiconductor industry was the *sustained* innovation that flourished at Bell Labs--as well as at Texas Instruments and Fairchild Semiconductor--leading to silicon transistors and integrated circuits.

And that required extensive infrastructure, both material and intellectual, to keep these companies at the frontiers of this fast-moving field. Such an infrastructure already existed in the United States after World War II because of its wartime radar efforts. But France had no comparable infrastructure and had to import talent from occupied Germany, which could not exploit its own radar expertise until the 1950s.

In the absence of any such advantages, it was inevitable that Europe's fledgling transistor would soon be eclipsed by other, better semiconductor devices and eventually fade from memory.

About the Author
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To Probe Further
For more details on the invention of the transistron, see "The 'French' Transistor," by Armand Van Dormael, in *Proceedings of the 2004 IEEE Conference on the History of Electronics* , Bletchley Park, England, June 2004. It is available on the Web at http://www.ieee.org/organizations/history_center/Che2004/VanDormael.pdf.