tions on the bestowment of honorary degrees and awards. Sometimes letter writers asked, would Dr. Shannon consider contributing to a new book? And sometimes he would actually send back a typewritten response. "Unfortunately," he would say, "I am currently completely snowed under with a googol of other jobs."[22] When he did answer a letter it was more likely to be about juggling than mathematics.

At first, Shannon visited Murray Hill occasionally. He would come to talk with his old colleagues like Slepian and Hagelbarger about his most recent ideas, and to hear about theirs and perhaps offer a suggestion or two. Shannon and his supervisors at Bell Labs agreed that he would stay on the Labs payroll as a part-time employee, so he still maintained an office there. But eventually the visits to Murray Hill grew less and less frequent. And then, finally, he would not come at all. Shannon's office, its nameplate burnished and its door always closed, stood in wait. He remained in the Bell Laboratories telephone book. Those who phoned his office discovered they would instead be directed to a Bell Labs secretary, who would inform them that no, no, unfortunately, Dr. Shannon wasn't in today.[23]

Nine

FORMULA

In the late winter of 1950, Mervin Kelly embarked on a whirlwind trip through France, Switzerland, Sweden, Holland, Belgium, and England. Kelly had gone to Europe just a few years before—in 1948, not long after the invention of the transistor, for a monthlong excursion. At that time, he had made his way through a continent that was broken not only socially and politically, but technologically as well. Repairs to the havoc wrought by World War II were only beginning. Now, two years later, Kelly was keenly interested in seeing how much Europe's laboratories and communications systems had rebounded.

But he had come across the Atlantic with another purpose as well.[1] Over the past year he had prepared a lengthy presentation about Bell Labs, and in Europe he intended to lecture on an organization that he now described as "an example of an institute of creative technology." He was a missionary with a gospel to preach. On the same trip during which British engineers were urging Kelly to send Claude Shannon to Europe to talk about Shannon's new theory of information, Kelly was meanwhile offering them a broader context into which they could place Shannon's work, or for that matter Bill Shockley's. Kelly wanted to explain how their efforts were enmeshed within the vast machinery of ideas at Bell

Labs. Listeners who hadn't before seen or heard Kelly reacted to his habitual manner—speedy, impatient, assertive—with surprise. "The remark was made that never before were so many words said in 1.5 hours in England," Kelly wrote to Ralph Bown, his deputy, about one of his speeches. "So I apparently was talking at my home speed."[2]

In London, late in the afternoon on March 23, 1950, Kelly gave a polished version of the lecture about Bell Labs in front of the Royal Society, making every effort to speak more slowly. Even sixty years after the fact, it is worth pausing to consider what Kelly was trying to do in the London speech, for he not only tried to explain the empire he was building, but why he was building it. Only good manners kept him from suggesting to a packed auditorium that Bell Labs was the world's foremost example of a place where scientists pursued creative technology. Echoing Shannon's ideas on the subject, Kelly told his audience in London that "the telephone system of the United States could be viewed as a single, integrated, highly technical machine in which electrical currents that are very small and complex in wave form are sent from any one of more than 40 million points to any one of all the others."[3] Bell Labs helped maintain and improve that system, he said, by creating an organization that could be divided into three groups. The first group was research, where scientists and engineers provided "the reservoir of completely new knowledge, principles, materials, methods and art." The second group was in systems engineering, a discipline started by the Labs, where engineers kept one eye on the reservoir of new knowledge and another on the existing phone system and analyzed how to integrate the two. In other words, the systems engineers considered whether new applications were possible, plausible, necessary, and economical. That's when the third group came in. These were the engineers who developed and designed new devices, switches, and transmissions systems. In Kelly's sketch, ideas usually moved from (1) discovery, to (2) development, to (3) manufacture.

To look at the process in more concrete terms, Kelly explained, one might imagine the kernel of new knowledge that arose from the Labs' solid-state research team just two years before The transistor moved

from there to development and manufacture. At the same time, the systems engineers began to consider how to insert it into the phone system. Though its impact on technology was still only speculative, the transistor validated in Kelly's mind everything he had done in his management career, along with everything he thought America's industries (and now Europe's, too) should be doing in the years to come.

In truth, the handoff between the three departments at Bell Labs was often (and intentionally) quite casual. Part of what seemed to make the Labs "a living organism," Kelly explained, were social and professional exchanges that moved back and forth, in all directions, between the pure researchers on one side and the applied engineers on the other. These were formal talks and informal chats, and they were always encouraged, both as a matter of policy and by the inventive design of the Murray Hill building. Researchers and engineers would find themselves discussing their respective problems in the halls, over lunch, or they might be paired together on a project, either at their own request or by managers. Or a staffer with a question would casually seek out an expert, "whether he be a mathematician, a metallurgist, an organic chemist, an electromagnetic propagation physicist, or an electron device specialist." At the Labs this was sometimes known as going to "the guy who wrote the book." And it was often literally true. The guy who wrote the definitive book on a subject—Shockley on semiconductors, John Tukey on statistics, Claude Shannon on information, and so forth—was often just down the hall. Saddled with a difficult problem, a new hire at Bell Labs, a stuttering nobody, was regularly directed by a supervisor toward one of these men. Some young employees would quake when they were told to go ask Shannon or Shockley a question. Still, Labs policy stated that they could not be turned away.

Physical proximity, in Kelly's view, was everything. People had to be near one another. Phone calls alone wouldn't do. Kelly had even gone so far as to create "branch laboratories" at Western Electric factories so that Bell Labs scientists could get more closely involved in the transition of their work from development to manufacture.

Kelly never mentioned the word "innovation" in his speech. It would be a few more years before the executives at Bell Labs—especially Jack Morton, the head of transistor development—began using the word regularly.[4] What he went on to describe in London, though, was a systematized approach to innovation, the fruit of three decades of consideration at the Labs. To Kelly, inventing the future wasn't just a matter of inventing things for the future; it also entailed inventing ways to invent those things. In London, Kelly seemed to be saying that Bell Labs' experience over the past few years demonstrated that the process of innovation could now be professionally fostered and managed with a large degree of success—and even, perhaps, with predictability. Industrial science was now working on a scale, and embracing a complexity, that Edison could never have imagined. Please listen, Kelly was telling the Europeans. He had a formula.

In technology, the odds of making something truly new and popular have always tilted toward failure. That was why Kelly let many members of his research department roam free, sometimes without concrete goals, for years on end. He knew they would fail far more often than not. To gather new knowledge in real time, as Kelly had done all his life—even back to those early days in his career, when he counted oil drops in Millikan's lab, or when he shared an office on West Street with the slow-moving and specter-thin Clinton Davisson—was to see how difficult and faltering the process was. So how was one to make something truly innovative every year? "There is a certain logic in the reasoning that methods which have produced much new knowledge are likely to be the best to produce more new knowledge," the science historians Ernest Braun and Stuart Macdonald wrote some years after Kelly's 1950 speech. "Though there is also something paradoxical in the thought that there should be established methods of creating the revolutionary."[5]

Here, then, was the dilemma: Just because you had made something new and wondrous didn't mean you would make something else new and wondrous. But Bell Labs had the advantage of necessity; its new inventions, as one of Kelly's deputies, Harald Friis, once said, "always originated because of a definite need." In Kelly's view, the members of the technical staff had the great advantage of working to improve a system where there were always problems, always needs.

Sometimes innovations sprang from economic needs—making something cheaper, for instance, such as a long-distance phone call, by efficiently combining many different conversations on a single cable, interleaving them at different frequencies or at different time intervals (or both), and then pulling apart those conversations at the receiving end. Sometimes innovations sprang from operational needs—making something that worked better and faster, such as direct dialing so subscribers wouldn't need to use an operator to complete a phone call. Sometimes, apparently, innovations sprang from cultural necessity—making something that appealed to an evolving society, such as a cross-country phone link or, by 1950, a new Bell product like the car phone. And sometimes they sprang from military necessity—an invention such as radar or automatic gun controllers, which were urgent for national defense.

To innovate, Kelly would agree, an institute of creative technology required the best people, Shockleys and Shannons, for instance—and it needed a lot of them, so many, as the people at the Labs used to say (borrowing a catchphrase from nuclear physics), that departments could have a "critical mass" to foster explosive ideas. What's more, the institute of creative technology should take it upon itself to further the education and abilities of its promising but less accomplished employees, not for reasons of altruism but because industrial science and engineering had become so complex that it now required men and women who were trained beyond the level that America's graduate schools could attain. In 1948, Bell Labs began conducting a series of unaccredited but highly challenging graduate-level courses for employees known as the Communications Development Training Program, or CDT. But nobody at Bell Labs really called it CDT. The program was informally known—much to Kelly's discomfort—as "Kelly College," because that's what it was.

An institute of creative technology needed to house its critical mass close to one another so they could exchange ideas; it also needed to give them all the tools they needed. Some of these tools took the form of expensive machinery or furnaces for the laboratories. Some of them were human, however. Bell Labs employed thousands of full-time technical assistants who could put the most dedicated graduate students to shame. Such assistants sometimes had only a high school diploma but were dexterous enough, mentally and physically, that PhDs would often speak of them with the same respect they gave their most acclaimed colleagues. The TAs, as they were known, formed a large subculture—a stratum parallel to the one formed by the Labs' esteemed scientists—where they would exchange valuable information among themselves over lunch. "They were the keepers of practical information," John Rowell, an experimental physicist, recalls.[6] "They knew secrets, tricks. And they knew all this lore about what had been done in the early days." The best of the assistants had the same talents that Walter Brattain and other physicists would idealize, a natural ability to take apart car engines or radios and put them back together, an ability that at Bell Labs might translate into a gift for growing crystals, preparing the surface of a metal for a contact, or constructing experiments.[7]

An institute of creative technology required a stable stream of dollars. "Never underestimate the importance of money," the physicist Phil Anderson says—and it was true.[8] Thanks to the local phone companies, AT&T, and Western Electric, Bell Labs had ample and dedicated funding. Plans could thus be made for the near term as well as for the far future—five, ten, and even twenty years away.

Perhaps most important, the institute of creative technology needed markets for its products. In the case of Bell Labs, there were markets for consumers (that is, telephone subscribers) as well as for manufacturing (with Western Electric). There was no precise explanation as to why this was such an effective goad, but even for researchers in pursuit of pure scientific understanding rather than new things, it was obvious that their work, if successful, would ultimately be used. Working in an environment of applied science, as one Bell Labs researcher noted years later, "doesn't destroy a kernel of genius—it focuses the mind."[9]

Finally, something else seemed important. "A new device or a new invention," Kelly once remarked, "stimulates and frequently demands

other new devices and inventions for its proper use."[10] Just as the invention of the telephone had led to countless developments in switching and transmission, an invention like the transistor seemed to point to even more developments in switching, transmission, and computer systems. Or to put it another way, the solution to a technological problem invariably created other problems that needed solutions. So making something truly new seemed to ensure that you would be making something else truly new before too long. The only trouble was, this rule suggested that your competitors—that is, if you weren't a regulated monopoly like the American Telephone and Telegraph company, and you actually had competitors—could do the same.

He had always been in a rush, ever since his Missouri childhood, but in the late 1940s and early 1950s Kelly became even busier, a blur of a man. Robert Oppenheimer and several other scientists remarked that he seemed to be working himself to death, but that at least he didn't look quite as exhausted as he did during the war.[11]

His days were long. "He would read at night until 12 o'clock," Kelly's wife would recall.[12] But in the mornings, at 5 a.m., Kelly would rise and dress and make his way down the stairs of his big Dutch colonial house and out into the backyard toward the garden. His neighborhood in Short Hills, New Jersey, was a leafy maze of streets flanked by the homes of the wealthy and the very wealthy. Kelly's house was among the more modest—six bedrooms instead of ten, his lot comprising a single landscaped acre as opposed to neighbors who had two or three.[13] It was his backyard gardens—ornate, multitiered, shrieking with color—that might be called extravagant. They were a private indulgence. Each year Kelly supervised the arrangement of tens of thousands of tulip and daffodil bulbs, some of which he ordered from Holland—"1,000 bulbs every year just to keep it going," his wife recalled—but most of which he would store during the winter in the corners of a basement room, secreted under piles of sand and sorted according to a complex color classification system of his own devising.[14] For a hobby, it was almost absurd in its meticulousness. Then again, this was Kelly. In the yard he would turn the dirt himself, impatiently, before the gardeners arrived, working methodically in the cool near-dark.

When he was finished, he would shower and eat breakfast and dress for work.[15] The uniform was almost always the same: a pinstriped double-breasted suit, white shirt, and patterned tie; his dark hair, slightly gray now, combed straight back; his round-rimmed glasses softening the severity of his face and giving him a vaguely scholarly air. Kelly worked out of two offices, one at Murray Hill and one at the old West Street building in Manhattan. His rush began on the way to work. "He had one official driver for his car, a company car," Brock McMillan, the Bell Labs mathematician, says. "And he would beat on this guy—'drive faster, drive faster, get going, get going.'" When Kelly once hectored the driver so intently that he hit a car pulling out of the company lot, Kelly left the wreck without pause. He walked back to the office to get another car.

"You get paid for the seven and a half hours a day you put in here," Kelly often told new Bell Labs employees in his speech to them on their first day, "but you get your raises and promotions on what you do in the other sixteen and a half hours."[16] He seemed to live by his own advice. In 1950, Kelly was still the executive vice president of the Labs, serving as Oliver Buckley's deputy, but it had been arranged that Kelly would succeed Buckley upon his retirement in 1951.[17] Buckley had Parkinson's disease. The fact was not publicly known.[18] Ostensibly, Buckley was in charge; in truth, Kelly was. And with his 1950 speech in London, Kelly began to move from manager to statesman, an emissary of industrial science who took every opportunity to consider, in speeches to academic audiences and professional groups all over the United States, how Bell Labs' work fit into the future of American science. His pace was grueling, and the frenetic schedule sometimes resulted in fits of distemper. "Twice he submitted his resignation to the president of AT&T, stating that important work at Bell Laboratories was not being adequately funded," a colleague would recall. "In each case, he got the funds."[19] The constant travel and constant meetings and constant speaking engagements—and almost certainly, too, his constant chain-smoking—sometimes resulted in bouts

of utter exhaustion, requiring him to take time off and convalesce near his tulip gardens.[20] But within a week or two he would come roaring back.

By 1950, too, Kelly was involved in military and government affairs to such a degree that it required half of his working hours.[21] He now served as a scientific consultant to the United States Air Force and as a frequent advisor on government science commissions; in turn, he enjoyed the same level of security clearance as the head of the CIA. This was in large part a consequence of Bell Labs' work on radar and gun control during World War II, and on the Labs' electronics breakthroughs in the years since: The success of the work had thrust Kelly, willingly, into a shadow society of wise men—people like Frank Jewett, or Vannevar Bush—whose scientific training and large social networks allowed them to move smoothly between the elite circles of industry, academia, military intelligence, and public policy. Truman advisor William Golden visited Kelly and Oliver Buckley in 1950 and early 1951 seeking advice on who might serve as a science advisor to President Truman because Kelly and Buckley were on a short list of the elite. ("While Mervin Kelly was courageous," Golden pointed out later, reaffirming his belief that Kelly was his first choice, "Buckley was timorous.")[22] But Kelly wasn't interested in the job, preferring instead to move into the presidency of the Labs after Buckley's retirement. He directed Golden to friends of his in the scientific elites: Lee DuBridge (president of Caltech), James Conant (president of Harvard), James Killian (president of MIT), and Robert Oppenheimer, now at the Institute for Advanced Study in Princeton, who had successfully managed the Manhattan Project.[23]

Why was an office in the White House so unappealing to Kelly? For one thing, he was already immensely influential at the highest military and policy levels. The tightening alignment between a handful of the largest American corporations and the armed forces—"the huge industrial and military machinery of defense," as President Dwight D. Eisenhower would call it when he left office a decade later—had already become an enormous business for AT&T, which entrusted its Bell Laboratories and manufacturing divisions at Western Electric to design and manufacture a vast array of secret equipment for the Army, Navy, and Air Force. Most of the industrial work orders related to radar and communications equipment; these were considered vital for national defense.

These contracts earned AT&T more than revenue; they gave the company strong allies within the government that the company would need as the twentieth century reached its midpoint. In 1949, Thomas Clark, Harry Truman's attorney general, filed a complaint against AT&T alleging that it and Western Electric, the phone company's equipment manufacturing arm, had "unlawfully restrained and monopolized trade and commerce in the manufacture, distribution, sale and installation of telephone equipment."[24] In effect, the government sought to break the bond between Ma Bell and its factories—cleaving the companies in two and then again cleaving Western Electric into three separate businesses, so that AT&T could buy phone equipment more cheaply through a competitive bidding process. Clark's belief, shared by many in the government, was that telephone costs were being inflated by the cozy arrangement between AT&T and Western. It may well have been true, but the data and accounting records were extremely difficult to penetrate. A countervailing belief, however, little noted at the time but discussed privately among military leaders and AT&T executives—and eventually with Attorney General Clark and President Truman—was that a company that the U.S. government depended upon to help build up its military during the cold war was arguably worth far more intact than apart.[25] In a private letter, Leroy Wilson, the president of AT&T, pointed out the contradiction. "We are concerned by the fact that the anti-trust suit brought by the Department of Justice last January seeks to terminate the very same Western-Electric–Bell Laboratories–Bell System relationship which gives our organization [its] unique qualifications." The Attorney General's office, in other words, seemed to be fighting to break up AT&T at the same time the Department of Defense was moving to capitalize on its broad expertise. If that was in fact true, then Wilson—and Kelly, too—realized they had some leverage. They could make AT&T indispensable in the affairs of government. Kelly had long been willing to do anything necessary to preserve Bell Labs' existing structure, size, and influence. If he had to work even harder to do so, he would.

. . . .

The Chief, the passenger train that rumbled southwest from Chicago through Kansas City and on to the Pacific, brought Mervin Kelly and Jim Fisk to Albuquerque, New Mexico, on March 6, 1949. The trip had been Fisk's idea.[26] On leave from Bell Labs, the physicist Kelly had hired in 1939 and had put in charge of the radar magnetron work at Bell Labs was doing a stint as the research director for the Atomic Energy Commission in Washington. Earlier that year, Fisk had been informed that the University of California, which had been running the government's Sandia Labs in New Mexico, wanted to stop managing the facility.[27] Sandia was Los Alamos' less glamorous sister. Whereas Los Alamos' famous scientists were charged with researching and developing the nuclear components inside America's missiles and bombs, Sandia's fifteen hundred employees built all the non-nuclear components of those weapons. Sandia's scientists and engineers tested new ballistic shapes and designed sophisticated fuses for detonation. They also trained the troops who would ultimately handle the weapons.

Managing Sandia required extraordinary expertise in research, development, and manufacturing. And some in the military felt the job was beyond the capabilities of any university. Fisk had proposed a solution to his superiors at the Atomic Energy Commission: If the University of California could no longer manage the lab, some other organization would have to take charge. Fisk suggested that Mervin Kelly would be an excellent person to assess Sandia and advise the commission about possible replacements for Cal. Kelly could visit the lab, gather information, and then make an informal report to the AEC about how to improve its operations and administration.

The commission readily accepted Fisk's suggestion and Kelly traveled twice to Sandia that year. Hour after hour, he sat in meetings, eyes closed, as was his habit, listening to managers explain their work. When he made a lengthy report in early May 1949, Kelly unsurprisingly concluded that the AEC should place Sandia under the management of "an industrial contractor with experience, professional know-how, and a sense of public responsibility."[28] By the middle of the month, the AEC had determined that Bell Labs and AT&T would be the best contractor for Sandia. "This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction," President Truman wrote to AT&T president Leroy Wilson.[29] He urged Wilson and Bell Labs president Oliver Buckley to take on the job (Kelly had apparently recused himself from the negotiations, owing to the fact that he had been hired as an impartial assessor). In early June, following a meeting at Wilson's home with AEC chairman David Lilienthal, the two parties sealed the deal, on the condition that AT&T would not profit from the management of Sandia. In July, Lilienthal wrote Kelly an effusive note of thanks for his work. "It was a splendid job," he noted, "and a real contribution to the atomic energy program."[30]

Despite its distance from New Jersey, Sandia soon became a frequent stopover for Bell Labs managers moving up through the executive ranks—a place where they could be rotated in or out, like a pitcher on a minor league baseball team, depending on the needs of the parent organization. With its focus on the development of missiles and bombs, Sandia fit into the Labs' expanding portfolio of military work. In the final days of World War II, for instance, the Army's Ordnance Department, along with the Air Force, had selected the Labs "to determine the practicability of developing a ground based guided-missile system." The results—a concerted effort of the Army, Air Force, Bell Labs, Western Electric, and the Douglas Aircraft Company—were code-named Nike, after the Greek goddess of victory, and put into operation in 1953. "Essentially a defensive weapon," the *Bell Laboratories Record* explained, "the Nike system will provide defended areas with a far greater degree of anti-aircraft protection than was ever before possible with the more limited ranges and altitudes of conventional anti-aircraft guns."[31] Nike "systems," essentially clusters of missiles poised for flight, were sited on the outskirts of major U.S. cities and near strategic locations, including Bell Labs' Murray Hill offices. The first missiles were known as Nike-Ajax; each was twenty feet long and about a foot in diameter, with a serration of sharp fins surrounding the white tube containing the propellant fuel and explosives. Ajax missiles were not nuclear. But the next iteration of larger Nike rockets—the Nike-Hercules, which in the late 1950s offered "increased lethality"—were. Later still came the even more sophisticated Nike-Zeus.

What made the Labs essential to the Nike program was an expertise in radar and communications. "Telephone technology has much in common with that of new weapons systems," Kelly remarked as the Nike installations were being built.[32] The new missiles, outfitted with several antennas, were guided by a complex control system, both in the air and on the ground, that involved radio detection and guidance and required, according to one assessment, approximately 1.5 million parts. Though nuclear arms and communications were often perceived as distinct phenomena—one was military, the other was civilian; one was deadly, the other benign—it was becoming increasingly difficult to separate the atomic age from the information age. Indeed, at the military's request, Bell Labs and Western Electric also began designing and building a string of remote radar installations in the frozen wastes north of the Arctic Circle from Canada's Baffin Island to Alaska's northwestern coast; these installations, "the arctic eye that never sleeps" (as the *Bell Laboratories Record* put it), were meant to warn North America of a Soviet nuclear attack. Named the DEW—for Distant Early Warning—line and made possible by a string of nonmilitary discoveries years earlier at the Labs regarding microwave communications,[33] the defensive systems were sister projects to the Labs' military work that included BMEWS (Ballistic Missile Early Warning System) and White Alice, which connected radio sensors in Alaska to Air Force command headquarters in Colorado.

Sandia, Nike, DEW—"All that is part of our good citizenship and, I think, fully meets the obligation imposed by the unique place that we have in our society," Kelly said.[34] He wanted to limit the Labs' military contracts so that they would not get in the way of its communications business, yet he harbored no apparent qualms about such endeavors. All were either strategically or financially important to the phone company; all were potentially useful in keeping at bay the antitrust regulators, who still sought to break up the Bell System. The military work could easily be construed as part of the implicit pact between the phone company and the government that allowed it a monopoly.

To counter communist intransigence, Kelly remarked, would require a "two-front defense," each as important as the other. Americans "are faced with maintaining a military strength adequate to deter the Russians from a general war, while at the same time maintaining a civilian economy that provides our people with an increasingly abundant life." Both pursuits were to him necessary, and so he decided to split his lab, and his career, between the two.

Ten

SILICON

On the civilian front at Bell Labs, there was still the business of semiconductors. Slowly, in the five years since the unveiling of Bardeen, Brattain, and Shockley's discoveries, Jack Morton, the transistor's development chief, had shepherded the device through the Labs' development process to the point that it had begun to infiltrate the mainstream economy. It had also moved outside of Ma Bell. The company's executives—wary of the regulatory implications of hoarding the technology to itself, and also convinced that production costs of transistors would decrease much faster if the semiconductor industry was large and competitive—had licensed its patents to a number of other companies, including Raytheon, RCA, and GE. They were poised to join Western Electric in the transistor business. The year 1953, *Fortune* magazine proclaimed, would be "the year of the transistor," when the "pea-sized time bomb," fashioned from a sliver of purified germanium, finally went into volume production and thus began to erode the electronics industry's dependence on the vacuum tube.[1] The doubts that had dogged the invention after its unveiling had since vanished. The transistor, Francis Bello wrote in *Fortune*, in what seemed an uncanny echo of Mervin Kelly's own thoughts, "will almost certainly stimulate greater changes in commerce and industry