CHAPTER
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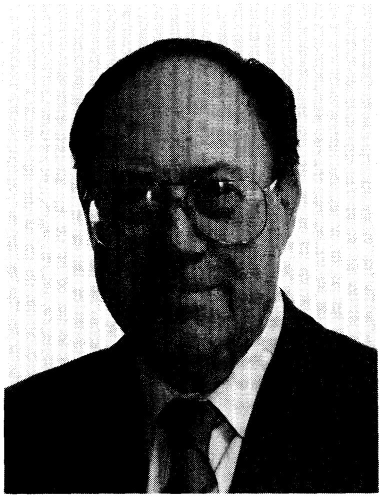

AMOS JOEL

Figure 1. Amos Joel, recipient of the Kyoto Prize, member of the National Academy of Engineering, winner of the IEEE Medal of Honor, and current resident of South Orange, New Jersey.

"The Magic of Your Dial"
Amos Joel and the Advent of Electronic Telephone Switching

In 1928 the Joel family of Atlantic City, New Jersey, was paid a visit by a technician from the local telephone company. Ten-year-old Amos, the Joels' only son, watched as the repairman installed a new telephone in the living room. He recalled later that "at that time we had a desk-stand telephone, so they replaced it with one with a dial, and after a certain day you were supposed to start using the dial. I got very curious about this. I said to myself, 'well, how does this thing work?' I wrote a letter to the New Jersey Bell and got a booklet back—*The Magic of Your Dial*. But it didn't tell me enough to satisfy me."[1]

That precocious curiosity persisted, leading Joel to a career in telephone research and engineering. By the time he retired in 1983, he was a leading international figure in one of the most important areas of telecommunications: electronic telephone switching. This new technology emerged from Bell Telephone Laboratories, the corporate research and development facilities of American Telephone and Telegraph, where Joel spent his entire professional career. At Bell Labs, engineers inspired by the promise of electronics guided the development of new electronic switching networks from simple prototypes to computerized central offices of massive scale. Joel rose from a fabricator of electromechanical switchgear in the late 1930s to become one of the leading architects and designers of AT&T's first regular-production electronic switching network in the 1960s.

A prolific inventor with over seventy patents, he contributed to the evolution of electronic switching at each stage of its development. Throughout his career, he also promoted the study of switching as a formal field of engineering science in his technical articles, teaching, and volunteer activities for his professional society. Later in his career, he became an accomplished historian; his publications include a comprehensive history of switching in the Bell System and a more recent book that he coauthored on the international development of electronic switching. This chapter examines Joel's career and concentrates on the process by which electronic switching technologies developed at Bell Labs.

Joel's Early Years

Amos Joel, Jr., was born in Philadelphia on 12 March 1918. During his childhood, his family moved several times, and his earliest memories date from the period after his father moved the family to the seaside town of Atlantic City, New Jersey. His father worked as a traveling salesman for a clothing manufacturer in Philadelphia and was frequently on the road. In 1929 he took a position working for a relative at the famous New York City clothier, the A. Sulka Company, where he eventually became an executive vice president. Young Amos attended public schools in Atlantic City and later at the famous DeWitt Clinton High School in the Bronx when the family moved to New York City.

Amos became interested in electromechanical technologies early in life. As a youth, he played with electric trains and an Erector Set, and experimented with a crystal radio. Model railroads became a consuming hobby, and he constructed elaborate track layouts and signaling circuits. In his teens, he also played the saxophone and clarinet.

His early curiosity about the new dial telephone began at the family home, but it did not stop there. His imagination followed the wires out to the telephone pole and down the streets of Atlantic City, straight to the central switching office. At age ten, he began to pursue his engineering career by querying the New Jersey Bell Company for information about how the dial telephone system worked. He was disappointed that they did not invite him to visit the telephone exchange, but his interest continued undiminished. In 1929 his family moved to an apartment on West 86th Street in Manhattan, and there he set up a private telephone system to connect him to his neighborhood friends. At each end of his block, Joel built a crude manual switchboard from knife switches. He strung wires along the fences in back of the 86th Street high-rises and into his friends' apartments.

The long arm of the telephone company inevitably caught up with Joel. While attending the switchboard one day, the telephone rang. A voice, louder and clearer than was usual on his network, announced "this is the telephone man. Where are you located?" The Depression had left many apartments empty in New York, although they were still equipped with leased telephones. These telephones, "liberated" by Joel, had been put to work in his private network. According to Joel, New York Telephone did not take kindly to his private service, but he maintained that "it was fun building it."[2]

With an ever-growing interest in the telephone system, Joel wrote at age thirteen to American Telephone and Telegraph in regard to one of their newly developed switching systems. An employee referred him to the relevant patent literature. Thus Joel began another hobby: collecting patents and technical information about telephone switching. At the local library he discovered the monthly journal of patent announcements, the Patent Office *Official Gazette*, and began to order copies of every switching patent he could identify.

Joel's knowledge of switching systems grew, and in 1931 he decided to design his own system. The product, which he called the Joel All-Relay Dial System, utilized small, general-purpose electromechanical relays. When he started to build his prototype, however, he learned an important lesson: the cost of relays—about a dollar each—made the system prohibitively expensive.

> *There was one opportunity I had a little later, just before I went to college, which was in 1936. I had acquired a copy of a little pamphlet put out by the New York Telephone Company for their people. Part of a training course or something. It was a beautifully done pamphlet about the panel dial system, which was one of the major dial systems at the time. It was written by a man by the name of Ellsworth H. Goldsmith. I remember that. I got curious and wrote him a letter. He invited me down to the Telephone Company, and I met him. He didn't take me through the telephone office or anything, but I had a chance to talk to him about it and learn more. I learned that he was a horologist, interested in clocks. He put clocks together. That was his hobby. But he happened to have a job in the Telephone Company writing course material.*
>
> *That was the only time I ever had any contact with people from the Telephone Company other than writing to them and trying to get information, which, I would say, on the whole, was not very satisfactory. In fact, it led me later to try to do something about this. Later on in my career I felt that switching got the short end when it came to telecommunications. Everybody talked about transmission, and they did a great job of teaching it in colleges and schools. Transmission had been reduced to at least a quasi-science so that you could express mathematically the various relationships that take place in transmission. But you couldn't do this in switching. And I wondered why. Why couldn't we do a better job of it? I felt that part of this was not enough dissemination of what goes on in the business of switching.*[3]

Joel at MIT: The Making of an Engineer

In 1933, as Joel considered high-school graduation, he began to plan for college. He had his sights set firmly on becoming an electrical engineer. He wanted to go to the Massachusetts Institute of Technology (MIT), but worried that his parents would not be able to afford it. His parents did, however, manage to find the resources, and he matriculated in the autumn following his high school graduation in 1936.

At MIT Joel found that the electrical engineering department was in the process of instituting changes to the curriculum, using a new series of textbooks to shift part of the instruction from power engineering to some of the leading-edge electronics fields, especially communications. He met a professor, Carleton Tucker, who was interested in telephone transmission and who gave him encouragement. Joel even got the chance to prove his facility with switching systems by repairing the electrical engineering department's telephone equipment. Through Tucker, Joel made his first contacts in the telephone industry and gained hands-on exposure to a variety of telephone equipment.[4]

Electromagnetic theory, important in telephone communications, was part of the engineering curriculum at MIT, but other communications-related topics like switching were not offered. Many electrical engineering courses were concerned with electrical power, and lectures on the telephone system concentrated on the transmission of signals. One reason may have been that there was no real theoretical basis for switching, a problem that Joel would address later in his career.

Joel made many friends among the faculty and students. One acquaintance he remembers particularly well was Claude Shannon. They frequently walked the streets of Boston (and later Manhattan, when they both worked at Bell Laboratories) by night, talking "shop." Shannon recalls that these talks with Joel were the inspiration for the subject of his master's thesis, the application of Boolean alegebra to the design of relay and switch circuits. Shannon went on to make fundamental contributions to the information theory that underlies much subsequent research on switching theory and work with digital circuit design.[5]

Joel earned money in college by working in the office at one of the dormitories. To his delight, his duties included running the dorm switchboard. He was on this job one day when he met his future wife, a student at a nearby women's college who came to MIT with a friend. Joel asked her for a date on the spot and, in his words, "one thing led to another."[6] Joel took his date to his dorm room, where he attempted to explain some of the switching patents that he had posted on his wall. "She went home and told her father I was crazy," Joel recalls, but that did not stop her from eventually marrying him.[7]

As a senior, Joel began thinking seriously about employment after graduation. He had long since set his sights on Bell Telephone Laboratories. But with the lingering Depression, the job market was extremely tight, and Joel's first letters to Bell did not receive a positive response. His professors tried unsuccessfully to pull strings for him. He finally put aside his highest hope and contacted a smaller manufacturer, the Automatic Electric Company.

Automatic Electric, which manufactured telephone equipment in competition with AT&T's Western Electric Company, brought Joel to its Chicago facility for a job interview. Unbeknownst to him, things were finally stirring back at Bell Labs. One of Bell's patent attorneys had recommended Joel at the insistence of his son, who was Joel's classmate at MIT. Toward the end of a day of interviewing in Chicago, Joel received a telephone call from the manager of the local A. Sulka store. He was told not to accept any offer from Automatic Electric until he had spoken privately to him. Joel made haste to the store, where he received the unexpected good news that Bell Labs now wanted to speak to him.

Bell Labs had finally noticed Joel's unusual qualifications and experience and contacted Carleton Tucker at MIT. Tucker informed Bell about Joel's trip to Automatic Electric in Chicago. This was enough to spur Bell's eleventh-hour call for an interview. Joel was overjoyed with the opportunity and went immediately from Chicago to New York for an interview at the Labs. Both companies offered him jobs, but Automatic Electric initially offered a higher salary. When Bell Labs matched the offer, Joel gladly accepted.

Early Years at Bell Labs: The Switching Art in Transition

In July 1940 Joel reported for work at Bell Laboratories on West Street in New York City. At that time there was only one major Bell Labs site, though during the next few years the new labs opened in Murray Hill, New Jersey. Formed in 1925, Bell Labs had become one of the largest and most prestigious private research and development organizations in the world by 1940. The organization had a hierarchical structure of management that followed the model of American manufacturing companies. The Labs employed a large number of engineers and scientists, who might be assigned to work on individual projects, direct those projects, or manage large groups of projects referred to as "laboratories."[8]

Despite the impressive knowledge of switching he brought with him to Bell Labs, Joel was assigned to the same training program as the other new engineers, which involved being moved from department to department to get a feel for the entire operation. His first assignment was in a shop that assembled equipment. The work was tedious, and after a few days he pleaded with his supervisor for reassignment. After another week, he was moved to the relay section, where he built and adjusted special-purpose relays. This work proved to be more rewarding, although within a short time he was relieved to be sent to another lab to work on the design of relays. He discovered that one of his new bosses, F. J. Scudder, was someone whose work he already knew well from his patent collection. He soon met many of the other Bell Labs engineers named in telephone switching patents.[9]

Bell Laboratories played a major role during World War II in the development of electronics and communications technologies for the military, and during this period Joel cut his teeth in the fields of electronics and computers. The Labs' contributions to the war actually began in a very modest way in the late 1930s with a small radar project. Radar research expanded greatly in the early 1940s, but by then it was only one of many military projects at Bell Labs. The number of staff members working under military contract grew explosively from 200 in 1940 to over 2000 (of the 2500 employees) in 1943. Bell research eventually ranged over a whole landscape of electrical and electronics technologies, from radar and sonar, to improved radio and wire communications, to proximity fuzes and fire-control computers.[10]

Shortly after the United States declared war in 1941, developmental work on telephone switching and other civilian telephone technologies virtually ceased. Joel joined a project working on military cryptographic systems that used electromechanical relays and complex switching circuits. He recalled his relish at working on something "really brand new."[11] His first assignment was the development of a machine to transmit and receive coded teletype messages. Standard teletype machines transmitted information in the form of pulses, and the Bell Labs' design made these pulses unintelligible to any receiving station not equipped with the proper decoding equipment. Early in the war, the Army Signal Corps and the Navy adopted this technology for secret communications.[12]

Joel also participated in a project sponsored by the National Research Council to develop a voice encryption system, so that secure voice transmissions could be made by wire from the battlefield. The resulting device filtered out several narrow bands of frequencies from the signal and transmitted them in jumbled order. Only a specially equipped receiver could reorder the encrypted message properly. Since such machines were also well-known to the Germans, the coding could generally be broken after only a few hours of expert analysis. For this reason, these machines were used only for applications such as relaying battlefield instructions, where the secrecy of the transmissions had value for only a short time.

Joel's group later became involved in an effort to digitize speech for the top secret scrambled-signal voice transmission system known as Project X. Bell Labs researchers in the 1930s had already developed the Vocoder, a device for splitting speech signals into a multitude of different frequency bands. Now Bell designed electronic circuits to digitize these discrete channels and combine them with other, randomly generated signals. As in the earlier Teletype devices, receiving and transmitting equipment contained matching versions of the code used to encrypt and decipher the signal.[13]

The original version of the Project X system used phonograph recordings of the decoding information, with just two copies pressed before the master was destroyed. Joel and other researchers designed a relay-based version that, while less secure than the phonograph type, could be used to set up and test the equipment (saving the records for actual operations) or in installations requiring less stringent security.

Later Joel worked on another enciphering system that employed a technique called "pulse code modulation." He received one of his first patents for this work, a solution to the crucial problem of synchronizing the digital data at each end of the system. This project gave him an opportunity to become much more familiar with electronics, a subject that he had studied only briefly at MIT but which played an important role in his later career.[14]

In January 1940 Bell Labs placed into operation an electromechanical complex number calculator built from ordinary telephone relays by two of its engineers, George Stibitz and Samuel Williams. It was used for multiplying and dividing complex numbers in connection with research and development.[15] Because of this experience, Bell Labs was contracted by the government to build a series of electromechanical calculating machines for the war effort. Three such machines—the Relay Interpolator, the Model III, and the Model IV—were built to aid in the design and simulation of automatic aiming devices for antiaircraft guns. Near the end of the war, Bell Labs was contracted to build a much larger and more complex relay calculator, the Model V, for use in producing artillery firing tables. The first one was delivered to the Army in 1946. Rather than having arithmetic circuits for doing calculations, it made extensive use of look-up on hardwired addition tables.[16]

Joel was assigned to work on the Model V computer. He was given the task of designing the most complicated circuit, which had to do with trigonometric functions, logarithms, and tape block searching—a very unusual circuit that contained its own memory. Because of this experience, once the war was over Joel was assigned to designing computing equipment for the Automatic Message Accounting system being developed for implementation with the first Crossbar System in Philadelphia. Joel's wartime experience in digital electronics and computing was extremely valuable to his postwar work on electronic telephone switching.

Joel and Electronics: The Automation of Long Distance Dialing

Joel's first assignment after the war returned him to the design of switchgear.

Bell Labs engineers and managers were enthusiastic about the possibilities of the new technologies developed during the war, including computers and improved relays and vacuum tubes. Further, within a few years the Labs announced the invention of the transistor, and speculation ran high regarding the opportunities presented by electronics. Switching was one area in which Bell pursued those opportunities, resulting in rapid technological innovation during the three decades following 1945. During these years Joel advanced from a designer in large projects to a systems engineer, and thus had an increasingly important role in both the promotion of new switching technologies and in their realization. He eventually became instrumental in a revolution in telephone technology, the introduction of electronic switching. Its revolutionary aspects are evident in the changes occurring in the telephone industry today. As older equipment has been replaced by electronic switchgear that is computer-controlled, the range of services, flexibility, reliability, and speed of the telephone network has vastly improved.

For AT&T the road to the new technology was marked by experimentation, false starts, and temporary reversals—just as in most technological innovation. The company experimented with a number of transitional technologies before attempting a fully electronic system. Joel contributed at every step of the way, either in the design of particular machines or in the management of projects leading to new technological systems. One of the first large postwar projects to which Joel was assigned resulted in his first major computer project, the Automatic Message Accounting Computer.

AT&T had long been interested in automating the routing of long-distance telephone calls as much as possible, and by the late 1940s the drive to automate steered research toward electronics. The introduction of the dial telephone in the 1920s was matched by innovations in electromechanical switching machines that could operate as automatic switchboards. The first generation of automatic switching technology, called the Step-By-Step System, consisted of a machine with sectors of electrical contacts and a small number of moving contacts. These contacts interconnected incoming and outgoing lines, which converged at central offices. When a customer dialed a number, the telephone set sent electrical pulses to the switchgear at the central office. Those pulses controlled the movement of the switchgear directly, causing it to connect the incoming line with the appropriate outgoing set of contacts. Each number that was dialed acted upon a particular set of switches, establishing a complete connection through a series of steps. This system worked well for small, self-contained communities, but it could not be easily or economically expanded to serve large cities, nor could it be modified for automatic long-distance use.

In the 1920s and 1930s, two new generations of switching technology emerged to address these problems. The first was the Panel System, so named because its automatic components moved up and down along contacts mounted on a long panel. Panel machinery, which was used experimentally as early as 1915, was built by Western Electric until 1950 and used until 1982. (See Figure 2.) A second type of electromechanical switch was the Crossbar System, first used in 1938. Unlike the previous two generations of equipment, the Crossbar relied on a matrix of contacts, rather than contacts that moved through large distances. The Crossbar could handle more connections per machine and was designed to make connections faster and more quietly.[17] With the Panel and Crossbar systems, Bell engineers also developed the concept of "Common Control," a method for controlling the system that employed various ancillary devices to store dial pulses temporarily and make more effective decisions on call routing. Common Control became the central focus in switching design, resulting by the 1950s in highly complex and specialized machines such as markers, registers, and senders.[18] The complexity of these machines increased with the size of the network, creating problems with cost, reliability, speed of operation, and physical size. All of these problems pointed the Labs toward the development of new component technologies. However, the concept of Common Control carried over into the electronic era, becoming the foundation of specialized switching computers.[19]

The need for even faster, more sophisticated switching equipment was more keenly felt in the postwar period when AT&T established the goal of nationwide direct long-distance dialing. Toll calls previously had passed through central long-distance exchanges, where human operators manually established connections to exchanges near the call destination and wrote charge tickets for billing. The first step, the institution of a national, uniform numbering system with area codes (so that geographic areas could be accessed by automatic switches), was followed by the installation of automatic equipment to make direct long-distance dialing technically feasible. This, in turn, required expensive modifications to many local exchanges, so that the switching systems could deal with the extra dialed digits representing area code numbers.[20]

The new switching system, or modifications to older ones that allowed direct dialing, was accompanied by an automatic machine to record information about long-distance calls for billing purposes. During the war, a Bell researcher named W. W. Carpenter had proposed a system for automatic message accounting (AMA) that could record information about long-distance calls in a machine-readable form.[21] Carpenter's AMA recorder punched on a paper tape a coded message providing a record of the origin, destination, and elapsed time of telephone calls. Joel was assigned the task of designing a complementary accounting computer to process this information so that callers could be billed.

The AMA computer resulted in a very lengthy US patent with over 250 claims. Over 100 of these computers were installed in centralized AMA installations, called accounting centers, dispersed across the country. The punched-tape output of the AMA machines was eventually converted to magnetic tape, and the accounting computers went out of service. The electromechanical AMA system was a useful technology for a time and contributed significantly to the ongoing drive toward full long-distance automation.[22]

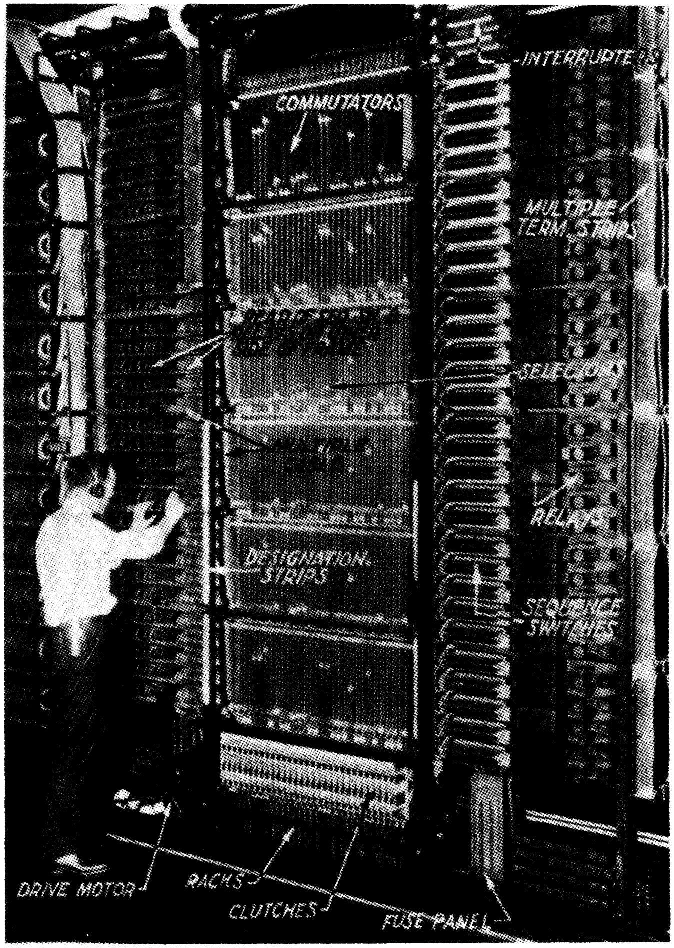

Figure 2. Photograph of a panel switching frame.

When in the late 1940s it became a goal at Bell to apply electronics to switching, three basic lines of inquiry emerged. The first was to replace the mechanical relays used in the switching machines with electronic relays, which were thought to be faster, more reliable, less bulky, and perhaps less expensive. The second, and more challenging, goal was to design electronic

Common Control devices that would replace electromechanical equivalents and increase the efficiency and flexibility of the system. Third, the computer technology under development at Bell Labs and in research institutions around the world seemed to be the key to a fully electronic network. Engineers began to adapt computer technology to suit the requirements of telephone switching.

After the war Bell Labs expanded its investigations of the application of electronics to switching. Vacuum tubes had been brought to a high level of development at Bell in the 1920s and were already used widely in long-distance amplifiers. In the early 1940s Bell researchers, experimenting with gas-filled diode tubes, began to appreciate the increases in switching speed possible by employing electronics in place of mechanical relays. Because of the mass of their moving contacts, relays had inherent physical limitations on their maximum speed.[23] New switching devices demanded high-speed electronics in order to be useful. Interest in electronics grew after the war, as many Bell Labs employees returned to civilian work with experience in military radar and communications electronics. During the 1940s and 1950s, Joel and his colleagues found that electronics was the key to improved Common Control and switching devices. Other technologies developed for computers, including magnetic drum, cathode-ray tube, and ferrite memory, were adopted by Bell Labs researchers for use in a range of switching machines.[24]

In 1951 C. E. Brooks, an engineer at Bell's West Street laboratories in New York City, proposed an electronic replacement for Panel and Step-by-Step central offices. The new system was to consist of three main sections: first, the switching network and control circuits; second, an accounting facility, which was envisioned as being located some distance away from the central office; and third, a Remote Line Concentrator, a small automatic switching machine similar in function to the a Private Branch Exchange (PBX).[25]

Whereas PBXs had usually been marketed to companies in office buildings, the Line Concentrator was intended for somewhat smaller buildings, such as apartment complexes. It was usually installed on the outside of a building in contrast to the PBX, which was mounted in a special room, often in a basement. In addition to filling a special market niche, the Line Concentrator was also a test case for the use of new switching technologies and physical design techniques. The high cost of maintenance, a chronic problem for switching equipment installed on a customer's premises, was addressed in part through the placement of critical circuits on plug-in circuit boards, which could easily be replaced when circuits failed.[26]

The function of the Line Concentrator was to allow a large number of telephones to be connected to a central office over a much smaller number of trunk lines. Taking into account the calling characteristics of its customers, AT&T determined the number of trunk lines based upon the number of telephones in use and the average volume of usage. This increased the efficiency of the network and eliminated some of the cost of stringing new lines. In prototype form, the Line Concentrators served sixty customers with only ten lines to the central office.

The switches in the Concentrator used a special switching device consisting of a reed relay and gas tube, several of which were built into a plug-in module. Telephone companies installed concentrators in LaGrange, Illinois, Englewood, New Jersey, and Freeport, Long Island, and the system proved to be reliable.[27]

In addition to the equipment at the customer's premises, special electronic Common Control machines with magnetic drum memories were used at the central office in conjunction with the Concentrator. Though not invented at AT&T, magnetic drums were incorporated into a series of early Bell Labs designs. Despite its technical success, the Remote Line Concentrator was not implemented in the Bell System. According to Joel, the additional development was needed to guarantee its reliability in long-term service. AT&T also decided that the small potential market for the Concentrator did not justify the additional development costs that would have been incurred in preparing the design for production. The Line Concentrator nonetheless demonstrated the possibilities of the gas-tube reed relay, which was used in later switching equipment.[28]

JOEL: *. . . At the same time that Chet Brooks sold this originally, the idea of exploring electronic switching when the transistor was first invented, there were other people at high levels in Bell Labs who wrote similar memos: Now is the time we ought to be doing something about switching . . . getting away from electromechanical. So there were other people thinking along that line. But Chet was the one who was pushing so hard that he wanted to set up a group to do the whole thing. The other people were just writing memos about it.*

ASPRAY: ***What were the limitations on transistors at the time? They weren't reliable, you couldn't manufacture them and attain stable characteristics.***

JOEL: *They were awful! In fact, one of the things that came out of this first two years of our exploratory work was [the realization that the new technology] was so poor, so unreliable, so unpredictable, that we should get some smaller project moving first. Indeed, in my group we started two different projects that were only tangentially related to a completely electronic switching system. [One project was an] electronic remote concentrator that we could apply to [the existing] electromechanical systems.*

ASPRAY: *What is a remote concentrator?*

JOEL: *The idea is that with an apartment building or a housing development, instead of running a pair of wires from every apartment or house to the central office and there picking up the first point in the switch, have the first point in the switch out there.... It had been a dream of switching people for years, but they had no technology that would do it well.... Here we had transistors that we thought could do a lot better. We [built the transistorized remote concentrator and] actually put three of them in service.*

ASPRAY: *But this never became a widely-distributed technology?*

JOEL: *No, not for a long time. In fact, we did so much to prove the idea that remote concentrators were good that the electromechanical people went out and designed an electromechanical remote concentrator that was a lot cheaper than the electronic one. They sold their design, and it was placed into production and service.*[29]

Joel contributed to a series of other transitional switching devices employing electronics technology during the 1950s. Implementing direct-dialing of long distance numbers required significant changes in the various switching networks in use around the country. Beyond the standardizing of area codes, Bell Labs engineers had to find ways for Step-By-Step, Panel, and Crossbar switches then in use to work in the new system, which supplanted 7-digit telephone numbers with 10-digit numbers (7 digits plus an area code) and long-distance access codes. Even in the Step-By-Step system, where dial pulses controlled the switching directly, Bell engineers felt that something resembling Common Control would have to be added to the machines. The space- and time-saving possibilities offered by electronic components presented opportunities to make compact new devices that could add more automatic controls for switching machines, and Joel conducted exploratory development in this area.

The introduction of Direct Distance Dialing (DDD) necessitated the use of an access code, originally 211 but later just 1, to initiate a long-distance call. Joel's group worked on a "translator," a kind of automatic control device to adapt existing switching systems to the new long-distance dialing procedure. They devised a machine called the Magnetic Drum Auxiliary Sender (MDAS), which recorded incoming digits, made decisions about where to send them, and replayed the recording into the proper lines. One novel feature of MDAS was its ability to scan electronically the telephone lines for incoming information. When the device detected an incoming call, the dialed numbers were stored as magnetized regions on the magnetic drum memory while the Common Control made decisions about call routing.

The MDAS replaced a large number of conventional registers (electromechanical common-control devices) by using magnetic memory. The pulse information constituting a dialed number could be stored on about a square inch of the drum surface. The ability to store a number in this way eliminated about fifty relays and several cubic feet of space in an electromechanical register. The MDAS was a hybrid electronic device representing the transition from vacuum tube to semiconductor electronics, employing logic circuits built with transistors and semiconductor diodes but with read-write circuits that used conventional vacuum tubes.[30]

Joel carried the development of the MDAS through to the point of drawing up detailed plans for production. When in 1954 AT&T determined that the design would not be economically feasible, development ceased. One economic issue that doomed the MDAS was its potential unreliability in service, expressed in terms of "maintainability," reflecting AT&T's traditional high standards of engineering. The vacuum tubes and roller bearings used in the drum assembly had maximum expected life spans of only one or two years, which the company deemed unacceptable. Yet the MDAS proved valuable as a demonstration of the use of magnetic recording in telephone switching, which reappeared in later systems.[31]

Despite these abortive efforts, AT&T remained committed to implementing electronic equipment in the telephone network. The application of semiconductors in electronic switching equipment at Bell Labs began shortly after the invention of the transistor and took place alongside work with vacuum tube electronics. Joel's first exposure to transistors came as he was finishing up the AMA computer in 1947. In that year there came a "fateful day," when "they got . . . all the members of the technical staff that they could fit in . . . the auditorium and told us about the transistor. And then they sent us back and said, 'What can you do with it?' Then I started thinking, boy, this is really the opportunity."[32]

One of the central problems in lowering the cost of switching networks, and thus making it more feasible to construct larger ones, was the cost of relays and related components. Joel had learned this at an early age, when his "Joel All Relay Dial System" proved too expensive to build. Another factor was speed: A faster switching device could obviously be more productive in a given amount of time than a slower device. A third issue was reliability. One approach to the high cost of switching equipment was to make it reliable enough to operate for decades without requiring replacement. Bell researchers hoped that similar standards of reliability could be built into semiconductor-based machines.

Finally, perhaps the most important advantage of the transistor was its low power and heat dissipation. Bell Labs engineers perceived a substantial savings in operating costs to be possible with compact transistorized switching networks. As semiconductor-based switching came on line in the 1970s and 1980s, Bell System Companies greatly reduced the number of its leased buildings in many cities, which reflected the smaller size of the new systems.

Semiconductor Switching in the Public Network: Joel and the Making of the ESS

Bell Labs research in semiconductor switching dated to the 1930s, when researchers experimented with rectifiers made from copper oxide and other metals. By the mid 1940s, projects were underway to use germanium to construct a solid-state amplifier. When the transistor emerged in 1947, it was immediately apparent that it had uses as both an amplifier and a switch. Although the first transistors were unreliable and expensive, they captured an influential cadre of supporters. The weight of over a decade of research and the enthusiasm of certain key engineers and administrators overcame the reluctance of some designers, particularly those in switching, to adopt this new technology.[33]

When Bell Labs began to produce experimental transistors in quantity after 1948, Joel (having moved from product development to systems engineering) was asked to join a "browser" group on transistor applications. Bell Labs regularly assembled browser groups to investigate opportunities presented by new technologies and suggest long-range strategies for the company. The ideas suggested by Joel's browser group were predictions rather than practical design proposals. But to Joel and other researchers these investigations served to reveal the wide scope of possibilities for the transistor in switching. Joel joined a growing party of Bell Labs researchers enamored of these possibilities. In the early 1950s, these researchers went to great lengths to lobby for transistor development projects. In the case of electronic switching, the support of upper management helped ensure that the projects continued to be funded over a long period of product development.[34]

In the early 1950s, the ascendancy of semiconductor electronics in the telephone system was not at all apparent. The transistorized-switching exploratory group, of which Joel became a member, was not the only group "browsing" new switching ideas. Other researchers were simultaneously developing ideas such as gas-tube switching and improved electromechanical relays. Additional competition came from the existing development groups, inasmuch as many engineers in the switching field opposed electronics research because it encroached on the electromechanical art, which they believed was superior in reliability and cost. When Joel's group began to campaign for large sums of exploratory development money, opposition from these other groups mounted. In response, a member of Bell Labs' Systems Engineering section and an ardent supporter of electronics, Chester Brooks, drafted a long and apparently influential memo promoting the application of transistors in switching and forecasting a great future for them in the Bell system.[35]

With support at high levels within AT&T, including that of Bell Labs President Mervin J. Kelly, the labs established a new Exploratory Department in 1952, headed by Joel's associate Bill Keister. Joel was chosen to supervise the architectural design of a new transistorized switching system. This included the Remote Line Concentrator and the MDAS. The projects were moved from New York to the laboratories in Whippany, New Jersey, some thirty miles away. About thirty people were brought in to work on the project, with Joel as one of four supervisors. The group ran into problems early on with Chester Brooks, whose visionary ideas had only scant grounding in knowledge of electronics. The publicity that would accompany the opening of the new office made the choice of its location political. Brooks chose Morris, Illinois, a small city in the jurisdiction of the Illinois Bell company where he had friends. At his insistence, the mission of the switching project was changed from an experimental investigation to the construction of a working prototype, to be called the Electronic Central Office (ECO).

When the basic architecture was laid out, Bell Labs brought in engineers from Western Electric to assist in the construction of the first ECO. Because Western Electric was to be AT&T's manufacturer of commercial electronic switchgear, the Labs began working with them on the system prototype. This ensured that the final form of the new switching system would be designed with production in mind.[36]

Several months of work resulted in the group's earliest transistorized switching devices. They were "so poor, so unreliable, so unpredictable," that the group began revising earlier deadlines for the Morris project.[37] In the meantime, the work of other Bell Labs researchers was steadily improving the reliability of transistors. By 1953 the company decided to fund the construction of laboratory models of an electronic central office, with services comparable to a Panel- or Crossbar-equipped central office plus Remote Line Concentrators. The work was assigned to the department at the Whippany Lab, where Joel had now been promoted to head.[38]

As the ECO laboratory model emerged, it came to be known as the "pre-Morris" system, as distinct from the much more elaborate installation planned for Morris, Illinois. The model would employ an electronic device to scan telephone lines for originating calls and a central control unit capable of storing call information and sending out commands to the distribution network. The network unit was made from a matrix of gas tubes that formed the electrical connections between telephone lines accessed through remote line concentrators. It was modularly constructed, consisting of plug-in circuit boards holding computer-style "building block" circuits such as logic gates. The system also incorporated stored-program control utilizing a cathode-ray tube memory, instead of the older method of controlling the machines' functions with hard-wired circuits.[39]

While Joel worked on the system plan as a whole, other designers engineered the memories, the gas tube switching network, and the trunk circuits. Initial studies recommended borrowing from digital computer technology either the magnetic drum or the Williams cathode-ray tube (CRT). Bell Labs designers instead developed a new type of cathode-ray tube memory. The Williams tube employed an internal phosphor (which glowed when bombarded with electrons) and an external capacitance-coupled plate. Bell Labs researchers placed a capacitance plate inside the tube, resulting in greater speed, capacity, and reliability. This device, named the Barrier Grid Store, was used as short-term memory for storing call data.

For longer-term memory, Ray Ketchledge, leader of the subsystems design team, proposed another type of CRT memory, the Flying Spot Store (FSS). In this tube, the electron beam struck a phosphor-coated plate, causing it to give off light at each storage location. (See Figure 3.) The light then passed through a special photographic plate holding information in the form of opaque or transparent regions that passed or blocked the light. Light passing through the plate was detected by photomultiplier tubes. Lenses inside the FSS could direct the light to several photographic plates simultaneously, making it possible for the device to manipulate words of 32 bits in parallel.

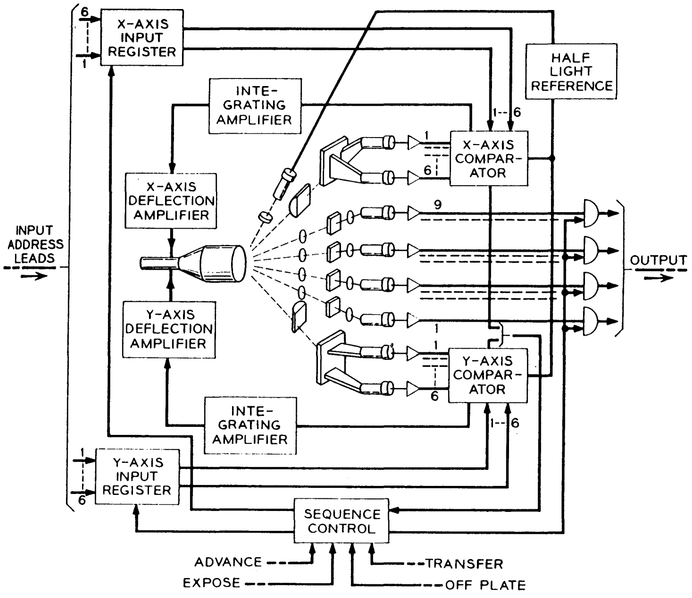

Figure 3. Simplified schematic of the Flying Spot Store.

Initially the FSS was intended to store semi-permanent information such as the directory number associated with a switching network terminal. As Ketchledge continued his work, an expanded capability of the FSS became apparent. By adding servo control to the cathode ray beam location, he was able to add considerably more storage locations (words) and increase reliability. The photographic plates used to store information were made using the FSS itself.[40]

Work on the Common Control circuits initially proved troublesome. The group started out with the goal of completely eliminating relays but discovered that the logic circuits required to do so were inordinately complex. One engineer in Joel's department, W. A. Budlong, suggested the use of a stored program, an idea from the computer field that seemed possible given the increased capability of the flying spot store. The architecture that the group devised was unusual for its day. It was designed to allow the switching equipment to deal with a very large number of inputs (incoming telephone calls) simultaneously.[41] This real-time design demanded a large amount of fast memory and high-speed logic. The size of the planned switching system was such that it could handle at least 50,000 individual lines (more than twice the capacity of a standard Crossbar system), and the engineers expected about 50,000 simultaneous call attempts during busy hours. In addition to his work on architecture, Joel was the major contributor to the overall system development and design coordination for this project, which was demonstrated in 1955.[42] (See Figure 4.)

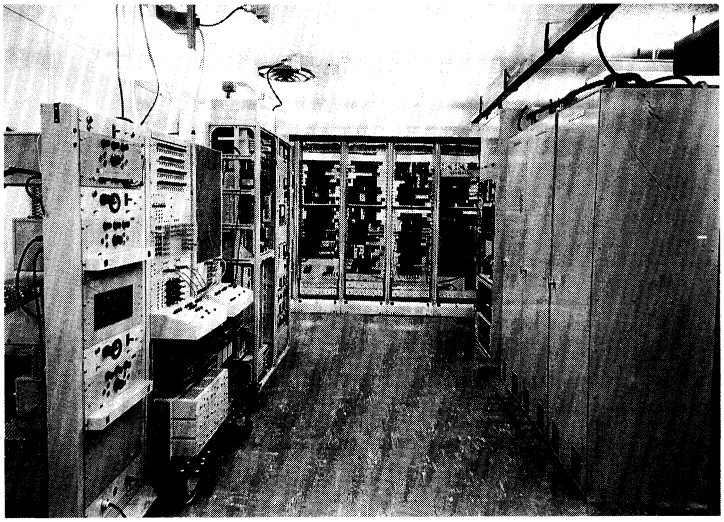

Figure 4. The "pre-Morris" system: a laboratory model electronic switching system that incorporated stored-program control.

The actual Morris system was a greatly enlarged version of the pre-Morris laboratory apparatus, reflecting the rapid pace of change in computer and electronics technologies as well as the lessons learned in the building of the pre-Morris system. The switching network used a special cold-cathode neon tube as the "crosspoint" or connecting element, rather than the anticipated transistors, because transistors had proven incompatible with the high currents used in the existing network. The crosspoint tubes operated both as switches and amplifiers. The normal 90-volt signal used to ring a subscriber telephone could not be passed through the gas tubes, so the company designed special equipment for this purpose, including a device to send an audio frequency ringing signal to the subscriber's telephone and a special telephone with a transistor amplifier and miniature loudspeaker. Other components in the system made extensive use of semiconductor diodes and transistors.

The Morris system used a much larger and faster cathode-ray (also known as the "flying spot") memory, providing 2.2 million bits of storage. A new comparator-based feedback system substantially increased the speed and accuracy of the memory tube. The electron beam in the memory tube se-quentially scanned a developed photograph plate, which represented the program and other semipermanent information requirements, passing through it and striking photodetectors on the far side. Another CRT memory, called the Barrier Grid Store, was used as an electronic "scratchpad" to retain briefly instructions and telephone number information before dialing telephone numbers.[43]

The program used at Morris had 50,000 words of 25 bits each. This was larger than many computers of the day, but somewhat smaller than the other major real-time computer application of the era, the SAGE air defense system developed for the Air Force, which had a program of 75,000 words.[44] A third of the program was devoted to telephone operation, while the remainder was used for maintenance and administration functions.

The Morris equipment could, for example, self-diagnose equipment failures. Previous generations of electromechanical equipment had addressed the problems of fault diagnosis and maintenance, two major operating expenses in switchgear. Since the introduction of Common Control, it had been possible for electromechanical switchgear to automatically identify technical problems and indicate or otherwise make a record of those problems for the purposes of maintenance. As much more sophisticated electronic equipment began to be used, maintenance problems grew. The new electronic system carried self-diagnosis to a new level of sophistication, obviating much of the skill necessary to maintain electromechanical switches. At Morris, the task of the maintenance personnel was only that of looking up a printed trouble report in a maintenance dictionary to find out the location of a defective plug-in package in order to replace it.[45] (See Figure 5.)

During the development of this system, the group had to defend and justify its work continuously. One of the major selling points of the programmed system was that it would make future changes in the system as easy as changing the program. But, as Joel recalls, "We didn't tell them how hard it was going to be to change the memory. And how many people it took to write the program or anything like that." In fact, he says, "we didn't know [that] ourselves at that time."[46]

In March 1958 the design groups visited the pre-Morris installation for the inaugural tests of the system. A series of carefully determined tests was planned to check each stage in the system before it underwent further system tests. Casting all this planning aside, one of the supervisors in charge of the system tests instead turned to Joel and said, "Well, dial! Dial! Dial the number and see if the call goes through!" It did, and the era of electronic, stored-program switching began.[47]

In June 1960 Bell Labs tested the Morris facility by placing it in service on the public network. The cost of the Morris installation was much higher than originally anticipated. When the experimental version had been completed, the project leaders had asked for an additional $10 million from AT&T. By the time the first lines had been "cut over" in Morris, the cost had exploded to over $100 million. Based upon these demonstrations and the project management's predictions of the potential for service improvement, increased revenue, and reduced operating expenses, AT&T continued to fund the stored program electronic switching effort even though its development costs had increased tenfold.

At its peak, the Morris system serviced 434 telephones, but it remained in service only until early 1962. The new switching system proved highly reliable, but almost all of its major components were obsolete even before it went into service.[48] This was because Bell Labs and other institutions continued to develop new component technologies at a rapid pace in the late 1950s and early 1960s. One was the twistor memory,[49] an inexpensive semi-permanent magnetic memory component made of a permalloy tape wrapped in a spiral around a conductor which replaced the FSS. Another technology addressed the problem of integrating voltage-sensitive electronics into the rest of the existing telephone network, which used a 90-volt ring signal. When semiconductor switching research began in the early 1950s, a transistor capable of withstanding high voltages was thought to be within reach. But at the end of the decade a cost-effective transistor switch was still not available. In response, the Ferreed switch,[50] a nonelectronic system, was developed for the electronic switching system, ESS, described below. However, semiconductor diodes and junction transistors were used extensively in the low-voltage circuits in control devices, such as the machines used to scan lines and detect dialing pulses.[51] The next generation of electronic switchgear control retained the concept of a stored program, which had proven highly efficient, but used the new magnetic twistor hardware in place of the Flying Spot Store. The twistor used cards with magnetic spots to store semipermanent information such as the program and translations.

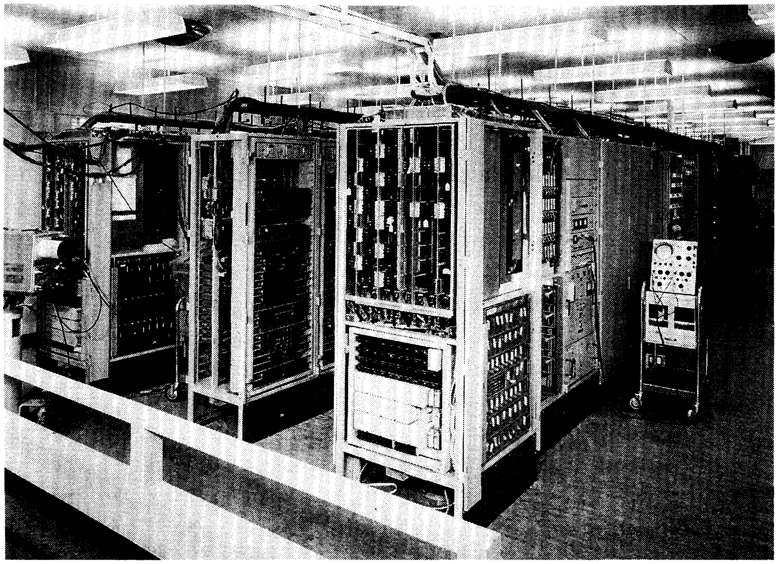

Figure 5. The concentration and distribution networks of the Morris system.

Development of the model Number 1 Electronic Switching System (ESS), the first commercial version of the electronic central office, began in 1958 just after the pre-Morris system had been successfully operated and new technology had been chosen for the commercial system. Joel was in charge of the architecture of this new system. The emphasis was not only on the new technology, but also the cost of the system compared with the electromechanical systems it was to replace. In 1962 Western Electric began to manufacture the ESS equipment, and testing of the systems began early the following year. In the spring of 1965, a small Number 1 ESS went into service in Succasunna, New Jersey, and 200 of the town's 4,300 subscribers enjoyed the benefits of new services such as call waiting, call forwarding, conference calls, and greater speed of connection. These new services, while simple for customers to use, represented a leap forward in the complexity and sophistication of switching equipment.[52]

Even with the new ESS system in production at Western Electric, Joel and his colleagues still had to sell the idea of electronic switching. During the first few years of ESS production he was frequently called upon to meet with representatives of the local Bell operating companies to encourage them to buy these machines. By 1967 each of the twenty-four Bell operating companies in the United States had installed one or more of the model Number 1 ESS.[53]

In the spring of 1962, the electronic switching laboratory moved to a new location in Holmdel, New Jersey. Instead of following his colleagues there, Joel accepted a new position at the old West Street lab in New York City. There he was put in charge of designing the many new ancillary devices needed to keep older switching technologies working in conjunction with newer telephone services. The thrust of this research was to find some way using electronics to allow Step-By-Step and Panel equipment, which represented a huge capital investment, to remain in service and fit into changing nationwide service plans. The coming of Direct Distance Dialing (including automatic identification of the calling line number), automatic pay telephone operation, Touch Tone service, and other features, made it necessary to continue to modify older switching equipment. Joel and his team devised machines that would store and manipulate incoming and outgoing information and control the older switching devices. One of Joel's missions during these years was to move the switchboard laboratory into the electronic switching era. The laboratory had already made some halting efforts in electronic switching, such as creating an electronic control module for one of the oldest of the electromechanical systems. However, Joel found that many of the existing staff were old-guard types with only electromechanical experience, a fact that caused many of the projects to continue to be based on electromechanical technology.

Joel soon changed this situation. The advent of Direct Distance Dialing technology automated about sixty percent of long-distance calls nationally. In early 1950s the company studied ways to automate the remaining forty percent. Calls requiring certain special procedures, such as collect calls or person-to-person calls, posed especially difficult problems for the designers of automatic switching. The studies commissioned by Bell Labs concluded that instead of attempting full automation, a more economical approach would be to develop a new kind of operator-attended switchboard, combined with Automatic Message Accounting.[54]

The Traffic Service Position (TSP), an earlier Bell Labs innovation, allowed an operator to manually enter data about operator-assisted, long-distance calls to Automatic Message Accounting devices. About twenty-one of these machines were installed beginning in 1963. They were integrated into the common control design of the No. 5 Crossbar system. In effect, the TSP was another Common Control device, this time in a semi-automatic form.

Joel faced the problem of adapting the TSP for use with the antiquated Step-By-Step system. Dick Jaeger, one of Joel's coworkers, suggested giving the engineers in the department, especially the newly hired younger men, some experience with electronics. The two proposed the idea of a stored-program control system to assist telephone operators. With it, AT&T could modify older switching systems to accept this new technology to expand the availability of the new national long-distance scheme. It provided automatic direct dialing while retaining the option of operator-assisted calls. Customers dialed the prefix "0" on special calls that required operator intervention or credit call number recording.

AT&T was soon persuaded of the merits of this idea and the system was renamed the Traffic Service Positions System (TSPS).[55] It became a major new component of the telephone network. TSPS was based loosely on the control unit in the Number 1 ESS, but used a new writable twistor memory. The first version of the TSPS, installed at Morristown, New Jersey, in 1969, served 3000 trunks with 320 operators. TSPS was adopted nationally, and by 1976 about half of all operator-assisted calls passed through TSPS offices. This new equipment resulted in a great reduction in the number of operators needed.[56]

TSPS presented new service opportunities as well. With it, for example, Bell could provide real-time toll-charge data to hotels for the purpose of billing patrons, and telephone credit-card numbers could be dialed and checked for fraud. It also allowed Bell customers to begin direct dialing to foreign countries from nonelectronic switching offices. Equipment was later added to TSPS offices to announce charges automatically to payphones using a 1949 invention of Joel's. These new services, instituted in the mid-1970s, proved highly profitable to the company by lowering operating costs for toll and long-distance calls. For this work, Joel and Jaeger received an Outstanding Patent award from the New Jersey Council for Research and Development.[57]

During these years, Joel's laboratory explored the possibilities of automatic directory assistance and intercept systems to provide information on number changes. For a while, the group experimented with an electromechanical switching device controlling a magnetic drum. The drum stored recorded messages about new and changed telephone numbers so that when someone called information to get the number of a new customer, or reached a changed number, the machine would automatically announce the new number. At the time this device proved not to be economically feasible, and it was not until later that such devices came to be installed in the network. Semiautomatic systems of this type, made by other manufacturers, appeared in 1965. It was not until Joel devised a way to use the line identification arrangements in electromechanical offices that it became possible to introduce a fully automatic intercept system in 1967. Like some other projects Joel worked on, automatic directory assistance technology experienced a long period of development and experimentation before being deemed sufficiently reliable and cost-effective for commercial service.[58]

ASPRAY: *Throughout your career at Bell Labs, do you feel that there was some sort of engineering style that characterized your personal work?*

JOEL: *I've always been motivated by wanting to invent, wanting to create something new. I always wanted to do something different. . . .*

ASPRAY: *Did you have a stock of tools that you used over and over?*

JOEL: *No, I had no tools. I had no one approach.... Ideas come to you in all different ways and different conditions. But in switching, it's usually combinations of things that trigger you off. I think it's important for people to know about history, because sometimes just thinking about how they did things way back, a century ago maybe [can give you ideas]. Doing that with modern technology may not be a bad idea.... I stress in my classes that people should always look back. It's not really re-inventing the wheel that you worry about, but people do tend to get certain things from relooking at old ideas with new technology. It can make a big difference. It may not just be the wheel, but getting a rubber tire on it and a few of those things that make it really worthwhile to have a wheel.*[59]

After several years of directing this switching laboratory, Joel tired of the routine of budgeting and management, desiring to use his technical rather than his managerial skills. He approached his boss, who reassigned him as a "director without portfolio." Thus, in 1967, Joel began circulating from laboratory to laboratory, making contributions to various projects when he felt he had something to add. After a short time, Joel was officially reclassified as a consultant within the company. Because he was free to exercise his creativity without the burden of administrative duties, he found his new status at Bell Labs invigorating. He appreciated the fact that Bell Laboratories allowed creative people to be creative.

One of the results of this freedom was his contribution to the early development of mobile telephones. After examining the cellular work in progress at Bell Labs, he realized that the engineers working on the new system had not yet designed suitable switching techniques. He offered his expertise in electronic switching, and this work brought him one of the basic patents on cellular communication in 1972. (See Figure 6.)

Bell Labs encouraged the participation of switching engineers in professional and teaching activities, and Joel took advantage of this opportunity. He promoted the idea of a special section of the American Institute of Electrical Engineers (AIEE) devoted to switching, and with a small group of experts he helped form the Switching Committee in the late 1940s. In the 1950s he became more involved with the AIEE looking for other ways to address the profession's failure to recognize properly the field of switching. He was active in initiating the International Switching Symposia and chaired the program committee of the 1972 meeting.

His involvement in education was no less extensive. In college, he noticed that switching was not part of the training in communication engineering as was telephone transmission. The latter had been elevated to an organized body of engineering theory, with textbooks written on the subject, while in the US switching was ignored. Based on the research he conducted for his master's thesis at MIT, Joel felt confident that the technology of switching could be taught at a college level. Before and during World War II he petitioned the top management at Bell Labs to let him try his ideas. When the war was over, it was recognized that the teaching of switching would be necessary as new engineers were added to the staff. As a result, a school Bell Labs established included a new switching curriculum in 1946, with Joel as one of the founding instructors. These educational opportunities, along with his collaboration on a switching textbook, allowed him to demonstrate the teaching of switching principles, rather than simply the description of switching systems.[60]

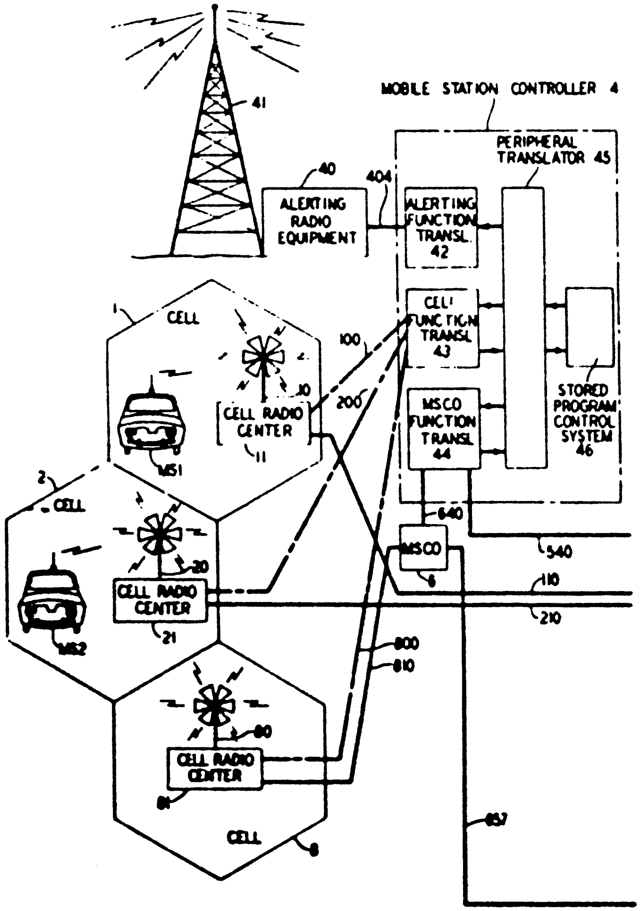

Figure 6. Illustration from the first page of Joel's 1972 patent on a cellular phone system.

Throughout his career, Joel continued to encourage young switching engineers to study the principles of switching, and he promoted the scientific approach to the subject through publications. His courses and textbooks went beyond the existing work on communications, or traffic theory, looking for the generalized principles of switching system architectures. This approach has been paralleled in the field of computer architecture. Although he left the project soon after establishing it in order to pursue other interests, Bell Labs engineers continued to offer these courses for many years and published a textbook based on the course. Joel's efforts in promoting and developing this course are recognized in the preface to this text.

> *The greatest engineering challenge has not been the specific inventions. . . . The greatest challenge to me has been trying to fit together the state of the art of switching and to make something of this. . . . We were able to show there are certain principles—what switching is all about—that we can teach and explain to succeeding generations. And as new switching techniques evolve, we can continue to do that. I think we've put the framework down for doing that. Of course, my big disappointment is we haven't been able to formalize it more. We haven't been able to formalize it to the degree of putting some mathematics with it that would allow one to evaluate and synthesize the various architectures and so on. But at least I think people now understand the principles pretty well. When I started out, there were no such things as identified principles. I couldn't go to the vice president or even the engineer that had been working the longest on switching systems at Bell Labs and say, "What kinds of switching systems are there?" He'd tell me there was step-by-step and panel and manuals, but he wouldn't be able to tell me the principles upon which they were based. I think we've done an awful lot over the period of my career to do that. Today you can classify the technologies and architectures that are used in switching.*[61]

After several years of relatively independent engineering as consultant at large within Bell, Joel's idyll came to an end. Periodically since its founding, AT&T had been investigated by the federal government on charges of unfair practices related to the company's monopoly position. In early 1972 the Federal Communications Commission, the body formally charged with regulating AT&T, began investigating anew. Because Joel was an expert on the technologies of the telephone network and was not tied down with other duties, company executives chose him to help with the technical side of the company's defense.

In looking for instances of monopolistic practices, the FCC's gaze fell upon the development of electronic switchgear, which AT&T dominated. Joel was asked to provide information to defend against charges that AT&T purposefully delayed the development of ESS in order to maintain its near monopoly in the American market for central office equipment. This he did until 1974, when the Justice Department initiated another investigation and filed a new antitrust case against the company. Joel continued his duties as an aid to the legal department, but ironically he was now defending the company against charges that such new technologies as ESS were introduced prematurely.[62]

In early 1983 the government concluded its presentation of the case, as AT&T reached a consent agreement with the Justice Department stipulating the divestiture of the Bell Operating Companies. This same year, Joel also reached his mandatory retirement age of sixty-five, so his somewhat frustrating research duties for the company came to a close.[63] In retirement, he still works with Bell Labs as a part-time consultant, and he also acted as a consultant to the then newly formed AT&T International. He also became a consultant to IBM, Continental Telephone, and some of the Bell operating companies.

In the course of his career, Joel published numerous technical articles and two historical monographs. In celebration of the centenary of the invention of the telephone in 1976, AT&T commissioned a series of books on the history of Bell Laboratories. Joel edited the volume on switching in the Bell System, which was published in 1983.[64] Just about that time, he also began work on another book, written with Robert Chapuis, on the history of electronic switching at Bell and internationally.

For his inventive and professional activities, Joel has been repeatedly honored by the engineering and scientific communities. His international recognition includes the Alexander Graham Bell Medal of the Institute of Electrical and Electronics Engineers (IEEE) and the Kyoto Prize Laureate in Advanced Technology by the Inamori Foundation. Local organizations honored him as well, including the New Jersey Congress of Inventors and the city of Genoa, Italy, which in 1984 awarded him a Columbian Medal and named him "Mr. Switching." His other honors include the IEEE Communications Society Achievement Award (1972), membership in the National Academy of Engineering (1981), the Franklin Institute's Stuart Ballantine Medal (1981), the International Telecommunication Union's Centenary Prize (1983), and AT&T's patent recognition award, the Charles E. Scribner Trophy (1992). In 1992 he received IEEE's highest award, the Medal of Honor.

Amos Joel, Electronic Switching, and the Innovation Process at Bell Laboratories

During the half century from the 1930s to early 1980s, Amos Joel devoted his professional career to the design of telephone switching systems. "Knowing a lot about one thing, namely switching," worked better for him than knowing "a little about a lot of things" like some other engineers.[65] But Joel was also constantly adapting himself to emerging new technologies, and he had the ability to see switching as part of a larger technological system. He continued to demonstrate this perspective even in retirement, as for example his recent patent on the emerging technology of photonic switching.

During the postwar period, Bell Labs carried forward its drive for greater speed, automation, and flexibility in switching and established a great many research projects in electronics. Although electronic switching appeared to emerge suddenly in the 1970s and 1980s, this revolution actually began quietly in the 1950s. Joel was instrumental in producing the series of innovations that proved the concept of electronic switching, even though they sometimes had little immediate impact on the public network. The accumulated knowledge gleaned from such experiments as the MDAS and the Remote Line Concentrator contributed directly to the full-scale Number 1 ESS. From an engineering perspective, electronic telephone switching also represented a number of technical breakthroughs:

> The [Morris] system proved that large numbers of new electronic devices could be assembled and operated reliably. It also demonstrated the feasibility and forecast public acceptance of some of the new services that the low cost memory and the flexibility of stored program control made practicable. These services included call transfer, add-on conference, abbreviated dialing, code calling of extension telephones, series completion of calls to non-consecutive line numbers.[66]

Joel's career illustrates several important features of Bell Labs. AT&T's special position, when it had a virtual monopoly, helped to reinforce the tendency toward long-term, company-wide planning for technological change. This high degree of organization and long-term planning did not preclude competition among different projects at Bell Labs. More than once, electronic equipment devised by Joel vied for sponsorship with electromechanical and other electronic equipment performing the same functions. Bell Labs had the financial wherewithal to investigate, often simultaneously, several different answers to technical problems in a way that probably would not have been possible in a less secure, free-market situation. Even after some of Joel's innovations successfully passed from design to field test, the company had the ability to reject—and sometimes did reject—them as being "impractical" or "not economical at present." AT&T, though it felt compelled to respond to the public's demand for improved service at a lower cost, set its own pace of technological innovation and its own high standards of reliability for implementation.[67]

The development of electronic switching tells much about the politics of innovation at Bell Laboratories. Those like Joel who believed in the promise of electronics faced numerous obstacles above and beyond technical difficulties, including resistance from the supporters of competing technologies both inside and outside the Labs. Electromechanical switching represented the accumulated knowledge of decades of invention and innovation, and had repeatedly proven its viability. It was not surprising that many Bell Labs engineers, AT&T managers, and telephone customers resisted the relatively unproven electronic technology. On the other hand, Joel's experience shows how the sponsorship of laboratory directors and managers could ease the way for a controversial technological change. In many ways, electronic switching was the vision of upper managers and engineers at the department head or director level. The process of creating the first ESS involved communicating this vision down the hierarchical ladder. Joel's involvement in the engineering, planning, and selling of electronics at Bell demonstrates this process at every level.[68]

My family life has been, I think, a very important contributor to my ability to do the things that I've done. . . . it's been a very tranquil family life. . . . My wife and I are celebrating our 50th anniversary this year, and we've had a very good life together. . . . Our three children have all been a joy.

As far as my hobbies are concerned, I've always been interested in music. . . . I did have a period when I was rather ill . . . and the doctor found out that I was a workaholic. He said, "You've got to have hobbies." So I decided I would like to play the organ. . . . my wife went out and rented an organ, and once we had an organ in the house, we never let it go. Kept buying newer and bigger and better. Right now I just got a new gadget for my birthday that's coming up. I just enjoy playing the organ. For the last 15 years or so, every night after supper I sit down and play the organ for at least a half hour. I get a lot of relaxation and pleasure out of that. I wouldn't say I play well, but it's a good hobby. Of course, I get involved in the technology of it, and so I've got all kinds of gadgets to go with it. I don't just play straight, I play these other things as well—unfortunately, my wife doesn't like this.

Through the last 20 years at Bell Labs, I always had access to computers, and have used them a great deal in forming databases and doing research and writing papers. . . . I've spent a lot of time keeping up to date with computers and enjoy that as a hobby, too.

It was hard to get me to take a vacation for many years. Since I've been retired, I have enjoyed taking vacations—particularly cruising. I like to take a boat. I don't take my work with me, and so I enjoy it much more that way. My wife says it's because there are no telephones to answer.[69]

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[1] For this chapter, the principal source of personal information about Amos Joel is an extended oral history interview of Joel conducted by William Aspray 4 and 18 February 1992 (referred to here as Interview 1992). An edited transcript is held at the IEEE Center for the History of Electrical

Engineering. (The passage quoted here is from page 3.) The author wishes to thank the following people who contributed to this chapter either by providing factual information or by offering critique and commentary: Amos Joel, William Aspray, Andrew Goldstein, Frederik Nebeker, and Steven Vallas.

[2] Interview 1992, p. 6.

[3] Interview 1992, pp. 8–9, slightly edited.

[4] During these years, many top engineering schools modernized their electrical engineering curriculums in a similar way. See Frederick Terman, "A brief history of electrical engineering education," *Proceedings of the IEEE*, vol. 64, 1976, pp. 1400–1401.

[5] John Horgan, "Claude E. Shannon," *IEEE Spectrum*, vol. 29, no. 4, 1992, p. 72.

[6] Interview 1992, p. 25.

[7] Ibid.

[8] The formation of the Bell Laboratories is discussed in Leonard Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876–1926* (Cambridge: Cambridge University Press, 1985), pp. 153–154; R. F. Rey, ed., *Engineering and Operations in the Bell System* (Murray Hill NJ: AT&T Bell Laboratories, 1983), p. 24. It should be noted that Bell's employment figures for technical personnel do not represent the true number of persons employed. Technicians and those without engineering degrees were counted only half, while degreed engineers and other "full" members of the technical staff were each counted once. [M. D. Fagan, ed., *A History of Engineering and Science in the Bell System: National Service in War and Peace 1925–1975* (Bell Telephone Laboratories, Inc.; 1978), p. 11.]

[9] By the late 1930s, the practice of training engineers by moving them from department to department was well-established at many large American manufacturing companies. AT&T and other large manufacturers also maintained strong ties to major engineering institutions and often provided the faculty for specialized engineering courses. See Ronald R. Kline, "Origins of the issues," *IEEE Spectrum*, vol. 21, no. 11, 1984, pp. 38–43; and Kline, "The General Electric Professorship at Union College, 1903–1941," *IEEE Transactions on Education*, vol. 31, 1988, pp. 141–147.

[10] Fagan, *A History of Engineering and Science*, pp. 9–14.

[11] Interview 1992, p. 46.

[12] This machine was based on the World War I–era work of another Bell Labs researcher, G. S. Vernam, and undertaken as a collaboration between AT&T and the Teletype Corporation. Teletype machines of the day transmitted a letter or number by converting it into a five-bit binary code. Vernam's plan called for both transmitting and receiving Teletype machines to have matching copies of a special punched tape, which supplied a random, nonrepeating source of additional code pulses. The machine added the two pulses to produce the coded message and transmitted it just as with an uncoded Teletype message. At the receiving end, the machine could synchronize itself to the incoming message, combine the incoming pulses with the pulses supplied by the matching punched tape, and print the deciphered message. See Fagan, *A History of Engineering and Science*, pp. 244–246; and E. F. Watson, "Fundamentals of teletypewriters used in the

Bell System," *Bell System Technical Journal*, vol. 17, 1938, pp. 620–639. AT&T purchased the Teletype Corporation in 1930, and it is currently a subsidiary of Western Electric [Rey, *Engineering and Operations in the Bell System*, p. 5].

[13] Fagan, *A History of Engineering and Science*, pp. 298–306; Homer Dudley, "The carrier nature of speech," *Bell System Technical Journal*, vol. 19, 1940, pp. 495–515.

[14] Fagan, *A History of Engineering and Science*, p. 308. Interestingly, the patents filed between 1941 and 1945 on this coded transmission system were kept secret, some for over three decades. See US Patent 3,967,067 (29 June 1976), Ralph K. Potter, "Secret telephony"; and US Patent 3,985,958 (12 October 1976), Homer W. Dudley, "Secret telephony"; Rather similar work was conducted by the US Army Signal Security Agency on machines used to analyze and decipher telegraphic messages sent by German Enigma machines. See David J. Crawford and Philip E. Fox, "The Autoscritcher and the Superscritcher: Aids to cryptanalysis of the German Enigma Cipher Machine, 1944–1946," *IEEE Annals of the History of Computing*, vol. 14, 1992, pp. 9–22. Joel's work on secrecy systems resulted in several other patents which were kept secret for over 25 years. One of these included the basic idea of creating a long key code by the use of prime number generators [Joel, private communication, 10 February 1993].

[15] See Fagan, *A History of Engineering and Science*, p. 170; and E. G. Andrews, "Telephone switching and the early Bell Laboratories computers," *Bell System Technical Journal*, vol. 42 , 1962, pp. 341–354.

[16] For more information on this so-called CADET (Can't Add, Doesn't Even Try) architecture or on the specifications of the various Bell Labs relay computers, see chapter 6 of Michael R. Williams, *A History of Computing Technology* (Englewood Cliffs NJ: Prentice-Hall, 1985). These developments should not be confused with other wartime work at Bell Labs on electric analog calculators used in the field for gun-aiming.

[17] William Keisler, et al., *The Design of Switching Circuits,* (Princeton NJ: D. Von Nostrand, 1951), pp. 194–199.

[18] F. A. Korn, "The Number 5 Crossbar System," *Transactions of the AIEE*, vol. 69, 1950, pp. 244–254; and Keister, *The Design of Switching Circuits*, pp. 446–449.

[19] F. J. Scudder and J. N. Reynolds, "Crossbar dial telephone switching systems," *Bell System Technical Journal*, vol. 18, 1939, pp. 76–118.

[20] A. B. Clark and H. S. Osborne, "Automatic switching for nationwide telephone service," *Bell System Technical Journal*, vol. 31, 1952, pp. 823–831; W. H. Nunn, "National numbering plan," *Bell System Technical Journal*, vol. 31, 1952, pp. 851–859; F. F. Shipley, "Automatic toll switching systems," *Bell System Technical Journal*, vol. 31, 1952, pp. 861–862. The national numbering plan also signaled the abandonment of the old mnemonic devices once used by AT&T to make it easier for Americans to remember telephone numbers. Whereas telephone numbers were previously identified using a combination of letters and digits (e.g., PEnnsylvania 6-5000), in combinations of up to seven digits, eventually (in the period between 1958 and 1977) they were uniformly composed solely of a 3-digit area code plus seven digits [Richard Brodsky, "Your evolving phone number," *American Heritage of Invention and Technology*, vol. 6, 1991, p. 64].

[21] In taking this project, Joel inherited the results of several years of research on automatic accounting. Bell researchers had been tinkering with such devices since the late 1930s and had developed a device that could automatically produce cards printed with information about individual calls, such as the originating number, the number called, and the duration of the call. In 1944 AT&T installed this experimental automatic ticketing machine in the Los Angeles network. See A. E. Joel, et al., *A History of Engineering and Science in the Bell System: Switching Technology 1925–1975* (Bell Telephone Laboratories; 1982), pp. 132–135; and Joel, "Tracing time backward in AMA," *Bell Laboratories Record*, vol. 30, 1952, pp. 422–429.

[22] Joel, *A History of Engineering and Science*, pp. 142–143; G. V. King, "Centralized automatic message accounting system," *Bell System Technical Journal*, vol. 33, 1954, pp. 1331–1342. Joel also worked on a number of other devices in the immediate postwar years. He received a patent for improvements to coin-operated calling for a system that would automatically register the value of coins inserted into a pay telephone. Previously, the operator had to listen to the sound of the coins as they were inserted. However, this idea was left on the shelf until the 1970s, when it was revived and modified for use with the new long-distance pay station direct dialing service. See page 259 of this chapter and Interview 1992.

[23] Even the earliest AT&T electronic switchgear gave an indication of the speed increases possible through the use of electronics. Vacuum tube diodes were 10 times faster than the best electromechanical relays, while transistors were 1000 to 10,000 times faster. See Joel, "An experimental switching system using new electronic techniques," *Bell System Technical Journal*, vol. 37, 1958, pp. 1098–1099.

[24] Joel, *A History of Engineering and Science*, pp. 43–44, 200–201.

[25] One Bell engineer in 1965 stated succinctly AT&T's public justifications for adopting electronic switching, saying that postwar work in this area was motivated by the company's desire to "improve service, reduce costs, and provide greater flexibility while retaining high reliability." See W. H. C. Higgins, "A survey of Bell System progress in electronic switching," *Bell System Technical Journal*, vol. 44, 1965, p. 938. The electromechanical Private Branch Exchange was also in use at this time. This class of switch, still in use, is put into large buildings and offices to distribute incoming and outgoing calls between a multitude of different telephones and a smaller number of wires to the central office. Its value is that it removes the necessity to supply a separate pair of wires from the central office to each telephone, and therefore the PBX saves money. When a PBX is installed in an office building, there is the assumption that not all the telephones in the building will be in use simultaneously. A telephone call to any telephone in the building is transmitted from the central switching office through a common pair of wires (the number of physical lines to the building is based on the number of telephones in the building and the expected traffic) and then distributed to the proper telephone by the PBX. Similarly, when the PBX detects an outgoing call, it automatically makes a connection between one of the large number of telephones in the building and one of the small number of lines to the central office.

[26] Joel, *A History of Engineering and Science*, pp. 214–215. Joel's 1956 technical paper on the Line Concentrator explained the objections that AT&T had regarding decentralized switching; the largest concern was the difficulty of maintenance and the cost of controlling switchgear at a distance

[Joel, "Experimental remote controlled line concentrator," *Bell System Technical Journal*, vol. 35, 1956, p. 250].

[27] Joel, *A History of Engineering and Science*, p. 215.

[28] Ironically, the line concentrator idea was so successful that another laboratory built an electromechanical version of it. This device, called the Universal Concentrator, used a miniature, modified crossbar switching system. It was of a scale similar to Joel's concentrator, serving 50 to 100 individual lines over ten trunk lines to the central office. Unlike the Remote Line Concentrator, the Universal Concentrator was widely used. In all, about 4,300 of these devices were installed around the country, beginning in 1961. Most were in use only temporarily, allowing local exchanges to delay the installation of additional telephone lines. In the end, maintenance costs proved to be too high to justify permanent installation.

Still, the Universal Concentrator demonstrates the ingenuity that Bell's electromechanical switching designers displayed in reaction to an unfamiliar new technology, electronics. According to Joel, many of them felt that their jobs were threatened by electronics, and lobbied against it within the organization. Joel encountered this resistance repeatedly, and it contributed to the problems AT&T encountered as it tried to convert the network to electronic switching. [Joel, *A History of Engineering and Science*, p. 384; "Telephone interview with Amos E. Joel, Jr., by David L. Morton, Jr.," 17 October 1992 (hereafter Morton, "Joel Interview")].

[29] Interview 1992, pp. 88–91, slightly edited.

[30] Joel, *A History of Engineering and Science*, pp. 222–223; Robert J. Chapuis and Amos E. Joel, Jr., *100 Years of Telephone Switching*, vol. 2, *Electronics, Computers and Telephone Switching* (Amsterdam: North-Holland Publishing Company, 1990), p. 44.

[31] Chapuis and Joel, *100 Years*, p. 191; Joel, *A History of Engineering and Science*, p. 24. As in the case of the Remote Line Concentrator, an electromechanical version of the MDAS emerged. This was the Auxiliary Sender, a machine that enabled older electromechanical systems to handle the extra digits used in Direct Distance Dialing. Starting in 1957, Auxiliary Senders were added to many such systems. These were in place for about ten years before finally being superseded in 1967 by an entirely new electronic device.

[32] Interview 1992, p. 73.

[33] Charles Weiner, "How the transistor emerged," *IEEE Spectrum* vol. 30, no. 1, 1973, p. 30.

[34] Joel's first opportunity to join a browser group was in late 1941, when he was invited to join a group interested in new switching technologies. Before he was able to begin this work the US entered World War II and Joel was reassigned to war work. See Interview 1992.

[35] Chapuis and Joel, *100 Years*, p. 48.

[36] Bell Labs and Western Electric worked together on many projects. See McKinsey and Co., Inc., *A Study of Western Electric's Performance* (New York: American Telephone and Telegraph, 1969), p. 72.

[37] Interview 1992, p. 89.

[38] Joel, *A History of Engineering and Science*, p. 225.

[39] Ibid., pp. 225, 229; Joel, "Experimental electronic switching system,"

Bell Laboratories Record, vol. 36, 1958, pp. 359–363.

[40] C. W. Hoover, Jr., R. E. Staehler, and R. W. Ketchledge, "Fundamental concepts in the design of the Flying Spot Store," *Bell System Technical Journal*, vol. 37, 1958, pp. 1161–1194; Joel, *A History of Engineering and Science*, pp. 239–240.

[41] In the ESS, the function allowing multiple inputs was called "scheduling." See Chapuis and Joel, *100 Years*, pp. 113–114. One of the few multiple-input, real time computers of the day was the Whirlwind, developed in the late 1940s at MIT. This machine, infamous in its day for its cost and complexity, was later incorporated into the SAGE radar air defense system, developed in the early 1950s by the US Air Force. In its experimental form, the SAGE system accepted data from several radar sets, interpreted it, and formed a composite radar image on a cathode-ray tube display. See George E. Valley, Jr., "How the SAGE development began," *Annals of the History of Computing*, vol. 7, 1985, pp. 196–226.

[42] Joel, "Experimental Switching System," pp. 1091–1124.

[43] Ibid., p. 240.

[44] R. R. Everett, et al., "SAGE—a data processing system for air defense," *Annals of the History of Computing*, vol. 5, 1983, pp. 330–339.

[45] Joel, *A History of Engineering and Science*, pp. 14–15, 238, 240.

[46] Interview 1992, p. 96.

[47] Interview 1992, p. 97.

[48] During the Morris trials, machine-related "errors" affected about 7.5 percent of all calls at the time of start-up, dropping to less than 1 percent after 7 months. The customers whose telephones were connected to the Morris switch were given the opportunity to experiment with abbreviated dialing (a 2-digit speed dialing system for frequently called numbers), code dialing (a household intercom feature using the telephone), and call forwarding. On average, 15 percent of all calls were placed using the abbreviated dialing, and in some households that figure was as high as 50 percent. See Higgins, "Survey," pp. 942–943.

[49] Another ferromagnetic memory device, called the ferrite sheet, was used for a time before the magnetic core memories were developed. By the mid-1950s, most computer builders had begun to use magnetic core memories. Western Electric did not want to use cores because they could not make them at a price competitive with the rest of the industry (which was having them assembled in Japan). Instead, Bell Labs opted to develop the ferrite sheet, which functioned in a similar fashion but was designed to be made economically by Western Electric. See Chapuis and Joel, *100 Years*, p. 155.

[50] The Ferreed was, according to Joel, "a major bridge between electronics and electromechanical contacts," in that they "responded to short pulses, they operated rapidly (less than one millisecond), they magnetically latched, [and] they required no holding power . . . " [Chapuis and Joel, *100 Years*, p. 154]. The Ferreed had contacts sealed in a small glass tube, with an electromagnet around the tube. A pulse of current in the electromagnet closed the contacts. Initially there was an external permanent magnet; later the reeds stayed "latched" due their own magnetic attraction. When a subsequent path conflicted with operated contacts, a pulse of opposite polarity in the electromagnet reopened the contacts. See Chapuis and Joel, *100 Years*, pp. 54–55; A. Feiner, C. A. Lovell, T. N. Lowry, and P. G. Ridinger,

"The Ferreed—a new switching device," *Bell System Technical Journal*, vol. 39, 1960, pp. 1–30.

[51] Joel, "Electronics in telephone switching systems," *Bell System Technical Journal*, vol. 35, 1956, p. 994. The computing logic used in the ESS was adapted from an earlier project, the Electronic PBX (EPBX). These circuits required more expensive silicon diodes and transistors, but were faster. See Chapuis and Joel, *100 Years*, pp. 248–249.

[52] The *Bell System Technical Journal* for September 1964, comprising over 700 pages, was devoted entirely to the Number 1 ESS. Scanning the 19 articles on the various ESS subsystems reveals that dozens of engineers made technical contributions. Many other contributors are not named. The special issue of the *Journal* demonstrates the extent to which the ESS was a corporate effort. It is interesting to note that by the time the issue appeared, Joel had been moved to other projects and his name did not appear in connection with the system he had done so much to bring about.

[53] Chapuis and Joel, *100 Years*, p. 158; Morton, "Joel Interview."

[54] Joel, *A History of Engineering and Science*, pp. 307–308.

[55] "Traffic" refers to incoming and outgoing calls, and "position" refers to where the human operators are seated.

[56] In 1970, when the rate of installation of electronic switchgear was beginning to increase, Joel wrote that "eliminating the human element in these large networks has not only accelerated their growth, but has in many cases resulted in their being engineered on a non-delay basis." See Joel, "Twenty-five years of switching system innovation," *Proceedings of the National Electronics Conference,* 1970, p. 883.

[57] Joel, *A History of Engineering and Science*, pp. 311–315.

[58] Ibid., pp. 322–324.

[59] Interview 1992, pp. 149–150, edited.

[60] The first AT&T switching textbook to which Joel contributed has been cited previously as William Keister, et al., *The Design of Switching Circuits*. Joel also contributed to the later "Orange Books," including *Switching Circuits and Systems* (New York: American Telephone and Telegraph Company, 1961).

[61] Interview 1992, pp. 175–176, edited.

[62] United States District Court for the District of Columbia, Civil Action 74–1698, *United States vs. AT&T et al.*, Plaintiff's third statement of contentions and proof, reprinted in Christopher H. Sterling, et al., eds., *Decision to Divest: Major Documents in U.S. vs. AT&T, 1974–1984* (Washington, D.C.: Communications Press, 1986), pp. 1578–1724.

[63] Joel felt that his creative role in the company was nearly overwhelmed by the duties of his last years at Bell Labs, describing those duties as "onerous." His friends often commented, "Think how many additional inventions he might have made if he had not been given these assignments." [Joel, private communication, 10 February 1993.]

[64] A. E. Joel, et al., *A History of Engineering and Science in the Bell System: Switching Technology 1925–1975* (Bell Telephone Laboratories; 1982).

[65] Interview 1992, pp. 176–177.

[66] Chapuis and Joel, *100 Years*, p. 53.

[67] Many Bell Labs projects were expensive and involved long-term commitments to research before any economic return was realized by the company. One example, the development of the transistor, is discussed in Ernest Braun and Stuart McDonald, *Revolution in Miniature* (Cambridge: Cambridge University Press, 1978), p. 40.

[68] The same sort of process seems to have been at work in the development of semiconductors at Bell. Historian Charles Weiner writes of Bell Laboratories' executive vice president Mervin J. Kelly's crucial role in promoting semiconductor research within the organization. See Weiner, "How the transistor emerged."

[69] Interview 1992, pp. 178–181, edited.