8 Electronics

A third area in which research begun during World War II became transformed by the actions of the military–industrial–academic complex and big science into technoscience during the Cold War, was the field of electronics which led to the development of digital computers, transistors and integrated circuits. All of these inventions can be traced to the great impact that electronics had on World War II, particularly the ways in which the military became dependent upon radar, computers and communication systems. Although funding from the Office of Scientific Research and Development (OSRD) ended after the war, individual branches of the military, such as the Office of Naval Research (ONR) and the Army Signal Corps, continued to fund research into electronics at universities, such as M.I.T., Harvard, Stanford, Columbia, the University of Pennsylvania, as well as at private industries, such as Bell Labs, IBM, Hughes Aircraft Company and American Optical Company.[1] By the 1950s additional government funding for electronics research came from the newly created National Science Foundation, NASA and the Defense Department's Advanced Research Projects Agency (ARPA or later DARPA).

General purpose computers

One of the most significant developments to arise from government-sponsored academic and industrial research into electronics was the computer. Originally the term computer referred to a person, most often a woman, who carried out long tedious calculations, either by hand or with the aid of an adding machine.[2] As we have seen, early work on computers was done during World War II with the development of the British Colossus for code breaking and the U.S. Electronic Numerical Integrator and Computer (ENIAC) which was developed to do ballistic calculations.

Even before ENIAC was completed there was planning for a greatly improved electronic computer that would serve as a basic model for computer architecture for much of the rest of the century. One of the most significant limitations of ENIAC was that in order to do a different calculation, the machine had to be physically rewired by rearranging cables into plug boards. Although the machine could do a calculation in a few minutes, it could often take hours, or even days, to configure the machine to do that calculation.[3] The idea that broke the bottleneck in computing was the principle of the stored program, in which the instructions for doing calculations or manipulating information would be stored in the memory of the computer along with the data.[4] This would allow the machine to work much faster, since it would not have to be physically reconfigured in order to do different types of operations. A number of individuals contributed to the idea of a stored program.[5] Some claim that the idea can be traced to Babbage's idea of feeding both operational and variable cards into the store of his Analytical Engine. Another important contributor was George Boole, who in the middle of the nineteenth century developed an algebraic system that could represent the rules of logic.[6] An important characteristic of Boolean algebra was that it could be represented by a binary system of 0s and 1s, or yeses and nos. In his 1936 paper "On Computable Numbers," Alan Turing showed that if instructions could be written in a binary code like Boolean algebra, his ideal Turing machine could do any calculation that could be done by any specialized computer. This idea combined with Claude Shannon's demonstration in 1937 that logical statements in the form of Boolean algebra could be represented by electronic switches and circuits that existed in either an on or off condition, meant that instructions, in the form of Boolean statements, could be stored in a computer in the same way as data and then could control a calculation by changing the internal configuration of the computer without having to reconfigure the actual wiring of the machine.

It was while ENIAC was being constructed that John Mauchly and Presper Eckert began to realize the potential of a stored program, but the idea of a stored program became most closely associated with the Hungarian refugee mathematician, John von Neumann.[7] For much of the war, von Neumann had worked on the atomic bomb at Los Alamos where he was concerned with doing hydrodynamic calculations associated with the implosion mechanism for the plutonium bomb. During 1944 von Neumann first heard of ENIAC and saw its potential for solving ballistic equations. He also came to realize that in order to solve the partial differential equations that he faced on the Manhattan project it would require an improved memory as well as a more efficient method of programming.[8]

By late summer of 1944, von Neumann became a regular consultant to the ENIAC group and he began to work on plans for a new computer called EDVAC (Electronic Discrete Variable Automatic Computer) that would attempt to overcome the limitations of ENIAC, especially the problem of programming it.[9] The result of the work was von Neumann's *A First Draft of a Report on the EDVAC*, published on June 30, 1945. A major problem with ENIAC was its limited memory which relied on vacuum tubes, but Eckert's experience with radar led him to propose using a mercury delay line as a memory device for the new computer. With the possibility of a new expanded memory, von Neumann recognized that the computer memory could hold both data and instructions that would determine what operations were to be applied to the data. Although von Neumann's *Report* did not focus on the actual hardware of the new computer, it did outline its logical structure – what became known as the von Neumann architecture, even though others, such as Mauchly and Eckert contributed to the idea.[10] As outlined by von Neumann, a computer would follow a linear and serial process in which instructions would be transferred from the memory to a control unit where those instructions would be used to execute some set of instructions on some data that was also transferred from the memory to an arithmetic unit. After these instructions were executed on the data, they were placed back in the memory and a new set of instructions and data would be transferred from the memory to the control and arithmetic units.[11] Later the arithmetic unit would be called the central processing unit and the control unit would be the codes that control the machine.

Although the actual EDVAC would not be completed until 1952, von Neumann's *Report* served as a model for the design of a number of new stored program computers, several of which were completed before EDVAC.[12] The United Kingdom had been a leader in the development of computers, having built the electronic Colossus code-breaking computer two years before ENIAC was operational. A small test computer, called the "Manchester Baby Machine," built at Manchester University in 1948 by Frederic Williams, a radar engineer, proved that the concept of a stored program could work in an actual machine.[13] Two years earlier, Maurice Wilkes, a Cambridge mathematician, had visited the Moore School and on his return to England began work on EDSAC (Electronic Delay Storage Automatic Calculator) which was based on the EDVAC idea of a stored program and the idea of a delay line as a memory. Drawing on his knowledge of mathematics and on the work he did on radar during the war, Wilkes completed his machine in May 1949, making it the first full-scale stored program computer.

By 1946 Eckert and Mauchly had left the University of Pennsylvania to establish the Electronic Control Company and began designing an EDVAC stored program computer aimed at the general business market.[14] Up until this point, all electronic computers had been designed to do mathematical or scientific calculations, but Mauchly had come to realize that electronic computers could also be useful at such things as sorting and collating data. As we have seen, the Mark I had made use of IBM electromechanical tabulating and sorting machines, but adapted them to do scientific calculations. Now Mauchly and Eckert were proposing to take the computer back to its roots. During the war the two had discussions with the Bureau of the Census concerning the use of computers as data processing machines. By 1946 the Bureau agreed to purchase a computer and Mauchly and Eckert, using the basic outline of the EDVAC report, began work on the UNIVAC (Universal Automatic Computer).[15] A significant innovation was the use of a magnetic tape system, adapted from sound recording, to replace the data contained on millions of punched cards. Before the machine was completed they also had orders from the A. C. Nielson marketing firm and the Prudential Insurance Company. Although Mauchly and Eckert had several orders for UNIVACs, by 1950 financial considerations led them to agree to sell their company to Remington Rand, the typewriter producer which had begun moving more and more into high technology areas after the war.

By March 1951 UNIVAC was completed and gained widespread publicity when in 1952 it was used by CBS television on election night to predict the outcome of the presidential election. While the first UNIVACs were purchased by the Census Bureau and by private industry for billing, payroll, inventory and accounting, they soon became used by the military to solve logistical and inventory problems and they were eventually used for technical problems associated with weapons design.[16]

IBM had initially been reluctant to enter the commercial computer market, but the development of UNIVAC led it to change its strategy and to begin work developing the 701 Defense Calculator and the 702 Electronic Data Processing Machine.[17] Since stored program electronic computers could easily do either scientific calculations or data processing simply by changing the program, the two IBM computers were, in fact, quite similar.[18] Although it entered the electronic computing field after UNIVAC, IBM soon became the leader in the computing industry. Part of IBM's advantage over Remington Rand's UNIVAC was the development of new computer memories. Unlike the UNIVAC which used mercury delay lines, the 701 and 702 used "Williams Tubes" which were large television-like tubes invented by Frederic C. Williams at Manchester University. These turned out to be faster and more reliable than mercury delay line memories.[19] Around the same time, IBM began work on a memory that used a rotating magnetic drum.[20] The idea had originated with John V. Atanasoff in the 1930s but had not been perfected until after World War II. Although the magnetic drum memory was much slower than delay lines or Williams Tubes, they were much cheaper as well as more reliable. This allowed IBM to market the 650 computer in 1953 at one quarter the cost of its 700 series computers and this helped IBM to begin its dominance of the computer market.

By the mid-1950s the use of computers for both scientific calculations and data processing was growing significantly, but even the most advanced computers had some significant limitations. First, computer memories were still quite small and either unreliable or slow and this limited the speed at which operations could be done and it limited the amount of data that could be processed. Second, the use of large numbers of vacuum tubes in computers made them unreliable since the tubes had a finite life resulting in frequent failures. Third, vacuum tubes were large, delicate, and produced significant amounts of heat which meant that computers had to be quite large, filling an entire room; had to be kept in a controlled environment; and were in need of constant attention. The introduction of core memories and transistor circuits during the second half of the 1950s would overcome these limitations and help to revolutionize computing. But both of these changes would come from research done outside of the area of digital computing.

The development of what became known as core memory emerged from Project Whirlwind; a wartime project at M.I.T. to design what would later be called an airplane simulator.[21] The "aircraft trainer" used a set of electromechanical devices, or servomechanisms, to simulate the movements of an airplane in flight, allowing pilots to gain experience without risking losing a real airplane. Near the end of the war, the designers of Project Whirlwind began to picture a single simulator that could mimic a wide range of airplanes, but the existing analogue devices were too slow and of limited accuracy. This led Jay Forrester, the leader of M.I.T.'s Servomechanism Laboratory, to begin to focus on a more general digital system that could function in real time. At the time, except for the classified Colossus, no other digital or stored program computer existed, but Forrester began development of a digital computer that could function in real time.

The biggest problem in designing such a computer was creating a reliable storage, or memory, system that could be accessed in real time.[22] Such a system would have to run up to 100 times faster than computers that were on the drawing board. Forrester quickly discovered that delay lines and storage tubes were unsuitable for the speeds that he needed. With the end of World War II, the ONR no longer saw as great a need for flight simulators, but Forrester began to reconceive Project Whirlwind as a much grander scheme. He now saw it as a general military information system that would be responsible for command and control of a battlefield, including aircraft control, air defense and submarine warfare.[23] In 1949 Forrester began working on a new storage system. During the war, Germany had used magnetic materials for some of their fire control systems, and Forrester began to investigate how such materials might be used for a computer memory.[24] By using doughnut-shaped ceramic magnetic materials with wires passing vertically and horizontally through the cores, he discovered that such a system could be magnetized and demagnetized, depending on the current running through the wires, and therefore it could store binary information. Such a memory, which was perfected by William Papian, could be compact, did not need electrical power to hold information, and could provide random access to any bit of information, unlike delay lines and drum memories which had to go through a certain amount of memory before a specific bit of information could be accessed.

By 1950 the ONR began to lose interest in Project Whirlwind and severely cut back its funding, but the testing of the Soviet Union's first atomic bomb in August of 1949 raised concerns within the Air Force that the United States might become vulnerable to attack and it began a program to upgrade the United States' air defense system.[25] What emerged was an idea for a computerized nation-wide air defense system that could control and coordinate radar, antiaircraft artillery, surface-to-air missiles and fighter interceptors. Soon the Project Whirlwind computer, with its new magnetic core memory, became the centerpiece of what would later become known as SAGE (Semi-Automatic Ground Environment). The work on SAGE was first done by Lincoln Laboratory, which was created by M.I.T. as a research laboratory. Eventually IBM was contracted to build the computers, based on the Project Whirlwind prototype, for the 23 Direction Centers of SAGE.[26] By the time the system was completed in 1963 at a cost of $8 billion, much of its original purpose was made moot by the development of ICBMs which could not be defended against. But the project has been called "the single most important computer project of the postwar decade."[27] As a result of SAGE, the Project Whirlwind computer, with its core memory that could handle real-time computing, became the industry standard. This new standard would lead to such developments as the SABRE (Semi-Automatic Business Research Environment) airline reservation system in 1960 and to the Universal Product Code (or bar code) the emerged in the 1970s.[28] Real-time computing would also be fundamental to the emergence of the internet. Project Whirlwind and SAGE also played an important role in turning the area around Boston, known as Route 128, into one of the first high-tech centers in the world.[29]

The transistor

The second major change that would revolutionize computers was the replacement of vacuum tubes with transistor, and later, integrated chips. The origins of the transistor lie outside of the computer industry but like the computer emerged out of World War II electronics.[30] As early as 1874 the German physicist, Ferdinand Braun, discovered that a crystal of galena would only allow electricity to flow in one direction, and by the 1920s such crystals were used in radio sets to rectify the alternating current created by oscillatory radio waves, into direct current that produced sound in the earphones.[31] But scientists had little understanding of how such crystals functioned. The development of quantum mechanics began to provide some insights into how certain crystals could rectify an electric current.[32] Classical physics had pictured the behavior of electrons in a metal as similar to a gas confined within the metal but allowed to move freely through the metal. This explained why metals were conductors. But quantum mechanics tended to treat electrons as wave phenomena, and since quantum mechanics restricted electrons to only certain energy levels, in a solid these energy levels would constitute energy bands in which the electrons were confined. In 1931 British theorist Alan Wilson argued that in materials that are insulators, all of the energy bands are filled to what is called the Fermi level, but in a conductor, like a metal, the top energy band is only partially filled, allowing electrons room to flow through the metal. This new quantum theory of solids helped to explain the recently discovered category of solids labeled semiconductors. In the 1920s and 1930s researchers discovered that certain materials, like copper oxide and selenium, were not insulators, like glass and rubber, but they did not conduct electricity as easily as metals. Wilson speculated that semiconductors contained impurities whose electrons' energy level fell between the material's filled bands and its unfilled bands. If some energy is applied to such a semiconductor, in the form of heat or light, the electrons from the impurities will be able to move to the unfilled band and conduct electricity.

In 1938, just before the beginning of World War II, Mervin Kelly reorganized the Bell Labs Physical Research Department by focusing on "fundamental research work on the solid state."[33] Previously, researchers had discovered that when a semiconductor, like copper oxide, was layered onto pure copper, it acted as a rectifier, allowing electricity to pass only in one direction. In 1938

Walter Schottky and Nevill Mott explained this in terms of the difference in Fermi levels between the semiconductor and the metal which made it easier for electrons to flow from the semiconductor to the metal but made it difficult for electrons to flow from the metal to the semiconductor. At Bell Labs, William Shockley, a theoretical physicist who had studied quantum mechanics at M.I.T. with John Slater, one of the leading solid state theorists, and Walter Brattain, a leading experimentalist, began to consider the possibility of creating a solid state amplifier by somehow applying a voltage to the barrier between the semiconductor and the metal so that it would act like a valve, similar to a vacuum tube triode.

Around the same time, Russell Ohl, a researcher on radio at Bell Labs, discovered that silicon might make an even better semiconductor than copper oxide. Ever since 1906, silicon had been used as a crystal detector in radios, and operators came to recognize that only certain spots on the crystal provided good reception. Ohl began to speculate that the "hot spots" in radio crystals had something to do with impurities, and in testing samples of silicon he found some samples only allowed electricity to flow in one direction while in others it would only flow in the opposite direction. He also discovered that in some samples, shining light on the silicon generated an electric current. Ohl concluded that different types of impurities were producing the different types of behavior in the silicon. Impurities, such as boron or aluminum, all of which were in the third column of the periodic table, on the left side of silicon, produced P-type silicon, named because the impurity created an excess of positive charge. On the other hand, impurities, such as phosphorus, which was in the fifth column of the periodic table on the right side of silicon, produced N-type silicon, named because the impurity created an excess of negative charge. Often the two types were mixed together and when a sample was cut it contained what became known as a P-N junction, and if light fell on the junction it would cause electrons to move into the unfilled bands. But the junction allowed the free electrons to move only in one direction, acting like a rectifier. Researchers realized that if a voltage could be applied to the P-N junction it might be an even better amplifier than copper oxide. But with the beginning of World War II most work on semiconductors was put aside in favor of research on radar and submarine detection.[34]

After the end of World War II, Bell Labs returned to its interest in developing a solid state substitute for the triode vacuum tube. In a triode a grid is placed between the cathode and the anode. Any small change in current on the grid will cause a much larger change in the current flowing from the cathode to the anode and thus act as an amplifier. Wartime work on silicon as rectifiers for radar at the Rad Lab and at Purdue led to a new understanding of how impurities affected silicon's behavior and it also led to new methods of producing impurities in the silicon.[35] Researchers discovered that doping silicon with a material like phosphorus, which has five electrons that can be shared, produces an excess of electrons, since it can only bond with four silicon atoms. On the other hand, doping with a material such as boron, which has only three electrons to share with four silicon atoms, creates a "hole" which according to the rules of quantum mechanics can move through the crystal, behaving like a positive charge.

Using the model of wartime mission oriented research, Kelly created an interdisciplinary team of researchers to develop a solid state amplifier. The team included William Shockley, who was primarily a theorist, Walter Brattain, who was primarily an experimentalist, and John Bardeen, who had a Ph.D. in physics but also an M.S. in electrical engineering.[36] The team also included physical chemists and metallurgists. Using quantum mechanics to predict the energy bands in P and N types of silicon, Shockley believed that a strong electrical field across a P-N junction could be used to control the flow of electrons and holes inside silicon and act like a triode. By November 1947 Bardeen suggested that a metal point pushed into a piece of silicon might create an electrical field that could control such a flow, and a month later he suggested that germanium, another semi-conducting material, might work better than silicon. On December 23, 1947, Brattain and Bardeen demonstrated to Shockley and the rest of Bell Labs a solid state device made of germanium that functioned like an amplifier or a triode tube. Six months later, on June 30, 1948, Bell Labs announced to the public the invention of the transistor (so named because it was a resistor that could amplify signals transferred through it). While the device was a significant technical success, it was a long way from being a practical device that could be used in electronic equipment. First, the prototype that was demonstrated was almost as large and delicate as the triode that it was designed to replace. Second, the device was not well understood.[37] Although the quantum theory of solids explained what happened inside a solid, the first transistor was based on surface phenomena that were not well understood. The manufacturing of such devices was more of an art than a science and only 20 percent of the devices passed inspection.

One month after Brattain's and Bardeen's first demonstration at the end of 1947, Shockley had the idea that a P-N-P, or N-P-N sandwich could also imitate the action of a triode. Instead of relying on poorly understood surface phenomena, such a transistor would rely on the linear flow through the interior of a semi-conducting material. But while Shockley's junction transistor seemed simpler to understand, no one knew how it could be manufactured. On the other hand, Brattain's and Bardeen's point-contact transistor had actually been built but its physics was poorly understood. As a result, during 1948 and 1949 Bell's work on semiconductors was divided into two sometimes hostile groups.[38] Even though a prototype of the point-contact transistor had been built and demonstrated, Bell faced significant problems trying to develop either transistor into a practical device that could be mass produced. Kelly turned much of the development work on the point-contact transistor to a separate group headed by Jack Morton, but the transistor continued to have problems, including high noise levels and a narrow power and frequency range.[39] In early 1950 Gordon Teal and Morgan Sparks, two researchers in Bell's Chemical Research Department, developed a technique of doping N-type germanium first with gallium, to create a P-type layer, and then with antimony to create an N-type layer. This resulted in a method to produce an N-P-N sandwich. Using Spark's and Teal's technique, Shockley demonstrated his new junction transistor to the public on July 4, 1951. The new transistor was a major improvement over the point-contact transistor. It needed much less power to operate and soon the junction transistor replaced the point-contact transistor.

A major force behind the development of the transistor was the role of the military. The Army Signal Corps was particularly interested in miniaturizing communication devices.[40] During World War II the development of the walkie-talkie allowed infantrymen to communicate without setting up phone lines or carrying heavy radios, but the device still weighed six pounds and often did not stand up to battlefield conditions since it relied on vacuum tubes. A week before the public announcement of the transistor in June 1948 Bell Labs briefed representatives from the military on the device. Since the Army's Ballistics Lab was developing some of the first computers, there was also interest in the transistor as a switching device for digital computers. By June 1949 all three military services entered into a contract with Bell Labs to study the military applications of the transistor. One of the first applications was to transistorize a Navy war simulator computer. In the early 1950s the beginning of the Korean War and the development of the much simpler junction transistor led to significant increased funding from the military into transistor research and development. The Army was especially interested in using transistors in its new Nike ground based anti-aircraft and anti-ballistic missile system. The military also encouraged Bell to hold a series of symposia to disseminate knowledge of the transistor to the military, industry and universities. One result of the 1952 symposium was the development of an important new technique, called zone refining, which allowed the manufacture of exceedingly pure germanium crystals which led to significant improvements in junction transistors.[41] By the mid-1950s several techniques emerged for producing transistors, including General Electric's and RCA's alloy junctions in which indium was alloyed on both sides of germanium, creating a P-N-P alloy junction. Later Bell Labs introduced a new diffusion-based transistor in which a vapor of doping material was diffused, under heat, into semiconductor crystals.

As Thomas Misa argues, the role of the military was crucial to the transistor's ultimate success.[42] By 1953 50 percent of Bell's budget for transistors was coming from the military. Especially during the early 1950s the high cost of transistors limited their civilian applications, but during that period the Army provided funding for new production facilities and pushed for establishing basic operating standards for transistors. Military requirements also pushed the electronics industry to develop silicon rather than germanium transistors. Although silicon transistors cost more than germanium, the fact that they could operate at much higher temperatures and they were resistant to radiation made them suitable for jet aircraft, guided missiles and nuclear-powered ships. The growth in demand of silicon transistors helped to make Texas Instruments a leading competitor in the electronics field. Begun as Geophysical Services, Inc. which built electronic seismographic equipment, it became involved in submarine detection during World War II and by 1951, renamed Texas Instruments, it began to focus on military electronics, especially silicon transistors.[43] By the second half of the 1950s, with the military market for transistors declining because of the end of the Korean War and Eisenhower's attempt to cut or limit defense spending, new civilian markets began to emerge. In 1954 companies such as Texas Instruments began manufacturing transistors for hearing aids and for the Regency TR1, the first mass-produced commercial transistor radio. By 1957 Texas Instruments had also signed a contract with IBM to produce transistors to replace vacuum tubes in computers. Around the same time, the electronics firm Philco completed a computer named SOLO for the National Security Agency that was one of the first all-transistor computers. This led to what has become known as the second generation of computers.[44] During the same period new semiconductor firms began to emerge. In 1954 Western Electric, Bell's manufacturing arm, provided a license to manufacture transistors to Totsuko, a small Japanese firm.[45] Since the peace agreement ending World War II forbid Japan from having a military, the Japanese electronics firms had to focus on developing a commercial market for transistors. Akio Morita and Masaru Ibuka began to design and manufacture small transistor radios and soon renamed their company SONY (for *sonus*, the Latin word for sound). This commercial use of transistors served as the basis for the future development of the Japanese electronics industry.

In the United States during this period, Bell's original Nobel Prize-winning team of Shockley, Brattain and Bardeen were breaking up over personality conflicts and differences over developing the junction transistor versus the point-contact transistor. Bardeen decided to leave the company and return to academic research at the University of Illinois where he would win a second Nobel Prize for work on the phenomenon of superconductivity.[46] Even though Shockley's junction transistor had won out over the point-contact transistor, he was no longer happy at Bell. His personality made it difficult for him to get along with the Bell management and staff. Years later he would become a great center of controversy when he supported the idea of a connection between race and intelligence, arguing that blacks were genetically inferior to whites.[47] By 1956 Shockley had left Bell and formed his own company, Shockley Semiconductor Laboratory, in the Stanford Industrial Park which had been created by Stanford Provost Frederick Terman to encourage cooperation between the university and private research, especially in the area of electronics.[48] Until the mid-1950s research in the area had focused on microwave technology which had been developed at Stanford during World War II, but with the arrival of Shockley Semiconductor, the region began its emergence into what would become Silicon Valley. Shockley attracted around him a group of researchers, including Robert Noyce, a M.I.T. physicist who worked at Philco; Gordon Moore, a Cal Tech chemist who worked in the Applied Physics Lab at Johns Hopkins; William Happ from Raytheon; Leo Valdes from Bell Labs; Sheldon Roberts from Dow Chemical; Victor Jones from Berkeley; and Jay Last from M.I.T.[49] Many of these individuals, especially Noyce and Moore, would help to place Silicon

Valley on the map. Shockley's company developed some major improvements in the transistor, including a four layer P-N-P-N diode, but Shockley's personality again began to cause problems and by September 1957 eight of Shockley's leading researchers, known as the Shockley 8, including Noyce and Moore, resigned.[50] Under the leadership of Noyce, the eight received financial backing from Fairchild Camera and Instruments and established Fairchild Semiconductor which would become another leader in the success of Silicon Valley.

With the emergence of new markets for transistors, along with the establishment of new firms, there began a series of new developments in semiconductors. The popularity of transistor AM radios and the possibility of transistor radios capable of picking up higher frequency FM broadcasts as well as the possibility of transistorized TV sets which would function in the VHF (Very High Frequency) or UHF (Ultra High Frequency) range, led to a push to develop transistors capable of operating at such frequencies.[51] In the mid-1950s Bell Labs used a new double diffusion technique which allowed the fabrication of transistors with a very thin gap between the emitter and the collector. This allowed the manufacture of transistors that would function at the much higher frequencies needed for FM radios and TV.

The integrated circuit

The most significant new innovation, one that would bring about a revolution in electronics, was the development of the integrated circuit.[52] As with the transistor, the integrated chip emerged from two different research groups. As transistorized circuits became more complex and as miniaturization became more of a goal, the problem of interconnecting a large number of transistors within a small space became a significant problem. Often the connections had to be soldered by hand which slowed down the process and raised questions of quality control. In particular, the military, which saw great advantages in miniaturization, funded several projects to try to create a reliable small circuit that could be mass produced. Also NASA needed new miniaturized electronic systems for satellites and for manned space missions. One of the first researchers to produce an integrated circuit was Jack Kilby who was working at Texas Instruments in the late 1950s.[53] He had previously worked at Centralab in Milwaukee which had developed a method during World War II of silk screening portions of circuits for proximity fuses onto ceramic wafers in order to speed up production. After the war, Kilby began to apply the technique to radio and television circuits. After attending some of the transistor symposia at Bell Labs, he became interested in silicon transistors and began work at Texas Instruments in 1958. In July of that year, Kilby had the breakthrough idea that it might be possible to place an entire electronic circuit on a single silicon chip if resistors and capacitors could be made out of silicon along with the transistors and diodes.[54] He also realized that new techniques that allowed the transfer of photographs to stone in order to produce lithographs would give much finer control than silk screens. Using such a photographic technique, he was able to etch away certain portions of silicon and deposit gold or aluminum on other portions, creating a pattern of resistors and capacitors. By February 1959 Texas Instruments filed a patent on "miniaturized electronic circuits."[55] While Kilby had found a way to place different circuit elements on a single chip of silicon, the elements still had to be wired together by hand using small gold wires.

At the same time that Kilby was working on his miniaturized electronic circuit at Texas Instruments, Robert Noyce had a similar idea. At Fairchild Semiconductor, he had begun producing transistors through a "planar" process in which P-N silicon was covered with a protective covering that could be etched away using photolithography.[56] In January 1959, while Texas Instruments was filling its patent, Noyce had the idea that his planar technique could be used to produce entire circuits, not just transistors. But unlike Kilby, Noyce had the idea of also fabricating the electrical connections between the components by using photolithography to deposit fine lines of aluminum to take the place of wires. By July 1959 Noyce had also filed a patent for a "Semiconductor Device-and-Lead Structure." The almost simultaneous invention of the integrated circuit by Kilby and Noyce led to a continual debate over who should be credited with its invention. Kilby seems to have had the idea first (he would eventually be awarded the Nobel Prize but it was after Noyce had died so he could not receive the prize), but in 1961 the U.S. Patent Office granted Noyce the basic patent on the integrated circuit. A key advantage of Noyce's idea was that the connections along with circuit components could be produced in the fabrication process, and Texas Instruments would eventually use the idea in the manufacture of its chips.[57]

The invention and development of the integrated circuit brought about another revolution in the electronics industry. Even the earliest integrated circuits had the equivalent of dozens of transistors, resistors and diodes, all in a chip the size of a grain of rice.[58] With President Kennedy's announcement of the race to the Moon in May 1961, NASA became a major market for integrated circuits. Also, the Air Force was seeking to upgrade the Minuteman missile's guidance system which required a major investment in integrated circuits.[59] But the most significant impact of integrated circuits may have been in bringing about the "third generation" of computers. As early as 1961 Texas Instruments introduced a computer that it developed for the Air Force that used integrated circuits and weighed less than a pound, but it had the same capacity and calculating power as a transistorized computer 150 times as large and more computing capacity than the room-sized ENIAC.

The most significant use of integrated circuits in computers was for random access memories (RAM) and for microprocessors. During the second half of the 1960s a number of computer firms, including Digital Equipment Corporation and Data General built small minicomputers around the integrated circuit.[60] By 1971 Data General introduced its Super Nova computer using an integrated circuit for its random access memory. The idea of using an integrated circuit as a memory device originated in 1970 with Fairchild Semiconductor's Illiac IV chip that had been developed for a supercomputing project at the University of Illinois. Although the project's attempt to find an alternative to the von Neumann architecture did not succeed, its development of a semiconductor memory played an important role in the use of semiconductors for a computer's core memory. Just before Fairchild's development of the Illiac IV, Robert Noyce and Gordon Moore left the company and established Intel (Integrated electronics) in 1968 and by 1971 it had become one of the dominant firms in the production of memory chips.

One of Intel's major innovations was the microprocessor.[61] In 1969 the Japanese calculator company Busicom asked Intel to design a set of custom chips for its line of calculators. Marcian (Ted) Hoff decided to design a more general chip that had many of the characteristics of an all-purpose computer, particularly the ability to use subroutines. Such a chip could be programmed to carry out the various calculations required by Busicom, but it could also be programmed to do almost anything a typical computer could do, and therefore it could be used in a wide variety of markets. The programs for the chip would be stored in Intel's memory chips. By 1971 Hoff had developed the 4004, the first "microprogrammable computer on a chip."[62] The combination of the semiconductor memory chip and the microprocessor opened the door to the personal computer.

Computer science

At the same time that transistors, core memories, integrated circuits, semiconductor memories and microprocessors were transforming computer hardware, significant changes were taking place in the development of computer software.[63] The earliest computers had to be programmed by hand in such a way that instructions understandable to humans would be translated by some technician into a binary code that could be understood by the computer. During the late 1940s and early 1950s a number of researchers, including Heinz Rutishauser in Zurich and Maurice Wilkes in Cambridge, realized that since computers essentially manipulate numbers and symbols, the "coding" of human instructions into a machine code could be done by the computers themselves.[64] In the mid-1950s some of the first compilers, as they came to be known, were developed for UNIVAC and the Project Whirlwind computer, but these early compilers were often slower than individual coders and they were usually limited to solving algebraic problems rather than general purpose applications. By the later 1950s, as libraries of instructions, or subroutines, were built up, the idea of higher level programming languages began to be developed, such as FORTRAN (Formula Translation) in 1957 and COBOL (Common Business Oriented Language) in 1959.[65] Such languages took statements written in symbols similar to algebra, in the case of FORTRAN, or in ordinary English, in the case of COBOL, and then translated those symbols into machine codes. Along with software, such as programming languages that made it easier for a user to solve a specific problem, researchers were also developing programs that would automatically control how a computer scheduled the various tasks that it needed to accomplish, especially when several different users were running programs on a single computer or when a single user wished to run more than one program. These programs became known as operating systems, one of the earliest of which was MAD (Michigan Algorithmic Decoder) developed at the University of Michigan in 1959. By the 1970s and 1980s operating systems, such as UNIX, developed by Bell Telephone and MS-DOS, developed by Microsoft, would come to dominate the industry.

The combination of new computer hardware based on the integrated circuit and new language and operating systems led to the idea that a series of diverse workstations could be networked together. Beginning in 1963 the Advanced Research Projects Agency (ARPA) of the Department of Defense sponsored a project called ARPANET which linked together defense contractors so that they could share information. By the 1970s the use of techniques such as store and forward packet switching that had been developed from the nineteenth-century telegraph system, and the idea of the Interface Message Processor (IMP), which used a minicomputer at each node in the network to modify information from different software systems and then pass it on through the network, made it possible for local area networks (LAN) to connect to the ARPANET. The result was a much broader system that became known as the Internet which is in reality not a single network but a connection of a variety of local area networks.[66]

As Paul Ceruzzi has argued, the developments taking place in computer hardware and software beginning in the mid-1970s also led to the emergence of a new discipline that in North America came to be known as computer science.[67] At first computer science tended to focus on developing general rules concerning the specific functioning of computers, such as the size and speed of memories or the times required to do certain procedures. In 1967 Herbert Simon, Alan Perlis and Allen Newell, all of Carnegie Institute of Technology, put forward the argument that computer science was "the study of computers," similar to the way that astronomy is the study of stars.[68] The only difference was that stars were natural objects while computers were humanly constructed artifacts, but as Simon would argue in a series of lectures, a "science of the artificial" could be just as scientific as a science of natural objects.[69] As such, computer science was to be seen as what had been called an engineering science.

Ironically the attempt to make computer science into a science led it away from Simon's science of the artificial and closer to what some would call a pure science. As early as 1959 Louis Fein was arguing that in computer science "too much emphasis has been placed on the computer equipment," and he argued that computer science "should be possible *without* any computer equipment at all, just as a first-rate program in certain areas of physics can exist without a cyclotron."[70] By 1968 many in the field of computer science were focusing on the issues and problems surrounding the notion of computation as the fundamental characteristic of a true science of computing. This idea drew on the 1930s work of Alan Turing who proved that his ideal Turing machine could carry out the calculations of any specially designed computer. It also drew on Alanzo Church's thesis that a computer could accomplish any task that could be described by a precise set of instructions or algorithms.[71] If computer science was defined as the study of algorithms, it meant that it could be independent of the nature of any specific computer and would be closer to the nature of a pure science. As Ceruzzi notes, "the algorithm is as fundamental to computing as Newton's Laws of Motion are to physics."[72] This new definition of computer science received intellectual support in 1968 when Donald Knuth published his *Fundamental Algorithms* as the first volume in a series on *The Art of Computer Programming*.[73] Using mathematical theorems and principles, the book established a theoretical foundation for computer science. In the same year the idea that computer science was the study of algorithms gained important institutional support when the Association for Computing Machinery, the leading professional society in the field, published a new recommended curriculum for computer science. In what became known as Curriculum '68, courses on computer hardware were completely dropped and replaced with courses in mathematics, logical design and switching theory and on algorithmic processes.[74]

The focus of computer science on the problem of computation helped to erase the boundaries between science and technology. Computation could be seen as either a human construction and therefore technological, or as a branch of mathematics and therefore a science. At the same time that computer scientists were arguing that a study of computers should be considered a science, scientists, in a variety of disciplines, began to try to understand the natural world in terms of a computer. During the second half of the twentieth century, researchers discovered that they could use the digital computer to solve not only scientific problems but that the computer could serve as a model for understanding scientific phenomena.

One of the earliest areas in which the computer served as a model for science was cognitive science. During World War II Norbert Weiner, a mathematician, and Julian Bigelow, an engineer, worked on a project to improve the accuracy of anti-aircraft guns.[75] Since both the anti-aircraft gun and the airplane were controlled by humans, they realized that they needed to develop a mathematical theory of the control of machines. In doing so they recognized the importance of the idea of feedback in which the actual performance of a machine is fed back as an input in order to control the machine. Their discovery of the importance of feedback in the control of machines led Weiner and Bigelow, along with Arturo Rosenblueth, a physiologist at Harvard Medical School, to speculate that it might also play a role in the control of human beings.[76] A result of this research was the conclusion that communication and control in machines and animals were similar and depended more on issues of information theory than on electrical engineering. These ideas were brought together in Weiner's 1948 book *Cybernetics: or Control and Communication in the Animal and Machine* where he used the Greek term for steersman to coin the word cybernetics.

The close connection between the functioning of a machine, like a computer, and the actions of the nervous system in the human body led researchers to investigate the possibility that a computer might imitate human intelligence.[77] In 1950 Turing, influenced by Weiner, wrote an article entitled "Computing

Machinery and Intelligence," in which he proposed that if an interrogator could not tell whether a machine or a person was answering his questions, the machine would have passed a "Turing test" and would have to be considered as having intelligence. In 1956 the Rockefeller Foundation with support from the ONR sponsored a conference at Dartmouth which brought together scientists, engineers, and physiologists, such as John McCarthy, Claude Shannon, Marvin Minsky, Allen Newell and Herbert Simon.[78] The conference helped to coin the term artificial intelligence and it played an important role setting the agenda for future research in the field. A significant breakthrough occurred when Newell and Simon began to view the computer as a symbol-processing machine rather than simply a mathematical calculator.

During the 1960s and 1970s researchers in artificial intelligence developed a number of "expert systems" programs that allowed a computer to pass a Turing test in very limited areas associated with human intelligence, such as playing chess or diagnosing diseases. The so-called "rule-driven AI" attempted to reproduce human intelligence by discovering the basic rules of human thought. A second approach to artificial intelligence attempted to model a computer on the neural networks of the human brain. In 1943 Warren McCulloch and Walter Pitts did research on the nervous system which showed that the actions of neurons could be explained in terms of a mathematical model similar to the Boolean logic used in information theory.[79] In late 1949 Donald Hebb suggested that neurons could learn by changing the strength of the connections between them when they were excited. During the 1950s and 1960s these ideas led to the development of so-called "emergent AI" or connectionism. Instead of assuming that intelligence could be programmed into the computer through a set of rules, emergent AI assumed that if a computer was designed with technological equivalents of neurons and neural networks, intelligence would emerge as the system was exposed to new series of inputs which would lead to new strengths of connections between elements of the network. The idea of connectionism led to the introduction of a new computer architecture during the 1980s. Instead of the von Neumann architecture in which all calculations were done sequentially in a large central processor, W. Daniel Hillis created his Connection Machine which processed information using 65,000 small processors, doing so-called parallel processing.

While the practical achievements of parallel processing has been limited by the problem of writing software for such an architecture, and while some of the more optimistic claims for artificial intelligence were not achieved during the twentieth century, the concept of artificial intelligence, both rule-based and emergent, played an important role as a new model of understanding for cognitive science and psychology at the end of the twentieth century.[80] Howard Gardner argues that the overthrow of behaviorism and its replacement with a new cognitive science began in 1956 and was brought about by a meeting on information theory held at M.I.T.[81] At that meeting Newell and Simon showed that a computer could carry out a logical proof; Noam Chomsky demonstrated that language had the formal precision of mathematics; and George Mill argued that human short-term memory was limited to seven bits of information. The idea that the computer could serve as a model for cognitive science was given added support in 1958 when von Neumann published his series of lectures, *The Computer and the Brain*, in which he talked about computers in terms of memory and the ability to reproduce themselves.[82] Two years later, in 1960, George Miller, along with Eugene Galanter and Karl Pribram, published *Plans and the Structure of Behavior*, which brought together cybernetics, communication theory, linguistics, and computer theory in order to develop a theory of cognition. Although the computer model of cognitive science also highlighted ways in which human beings differed from computers, it also erased the boundaries between science and technology, especially since the early development of artificial intelligence in the 1940s and 1950s was based upon models drawn from studies of neurology while the later development of cognitive science in the 1950s and 1960s was based on computer models that had been previously derived from neurology.[83] As we shall see later, the computer also provided a new model for understanding not only the cognitive sciences but much of biology. Much of the modern interpretation of genetics and DNA has been influenced by computers and information theory and the recent development of systems biology has led researchers to use ideas derived from information theory and engineering networks to describe how a single fertilized egg can develop into a complex organism.[84]

Another area in which computer science is erasing the boundaries between science and technology is in the field of physics and cosmology. With the widespread use of computers in science and with increased memory and speeds of computing, many physicists began to realize that insights into previously unsolvable problems, such as problems in meteorology or in cosmology, could be gained by simulating those problems on a digital computer. To some degree this was similar to the earlier use of analog computers, such as the differential analyzer that was used to solve ballistics problems during World War II, but now the simulation of some physical phenomenon was done digitally rather than by some servomechanical or electrical analog.

The success of what became known as computational physics led a number of researchers to conclude that computation was not simply a methodology for solving problems in physics, but that the universe was, at its base, essentially computational and could be best understood in terms of computation or information processing. A typical digital computer represents information, or data, as a string of 0s and 1s, or bits. Computation or information processing simply involves changing some of the bits from 0s to 1s or from 1s to 0s or leaving them unchanged. Modern theories of physics, especially quantum mechanics, have a similar binary aspect in which a particle, like an electron when measured or observed, can exist at a certain location or state or not exist at that location or state. This led some researchers, such as theoretical physicist John Archibald Wheeler, to argue that the entire universe is the result of a series of binary yes or no choices that take place when measurements or observations are made at the quantum level and can be summarized by the phrase "it from bit."[85]

Seth Lloyd, a pioneer in quantum computing, made a controversial claim in an article in *Physical Review Letters*, that the universe could be understood as functioning in terms of information processing.[86] He argued that at a simple level a series of coins can be either heads or tails and therefore represent information the same way that a computer represents information with a series of 0s and 1s. If some of the coins are then flipped, they will represent a new pattern of information which can be interpreted as changing or processing the original information that was represented. But if a simple coin can represent information and flipping it can process information, then the position and state of every piece of matter in the universe could also represent the storage of a huge amount of information and the motion, or changing states, of those pieces of matter could represent information processing. Lloyd argues that the fact that we have actual computers which are composed of the material of the universe and governed by the same physical laws that apply to the entire universe, indicates that at least a small part of the universe is obviously capable of carrying out computation and information processing. Such new interpretations, arising from computational physics that the universe is comprised primarily of information and that computation is the fundamental process of the universe, have further erased the boundaries between science and technology and reflect more the notion of a technoscience.[87]

The development of electronics and computer science became a prime example of the new concept of technoscience. First, these two areas virtually did not exist before the twentieth century. But more importantly they were fields in which distinctions between science and technology almost did not exist. The focus of research in these fields was not some object of pure nature, rather they were truly "sciences of the artificial," in that the focus of research was humanly created artifacts such as transistors, integrated circuits, computer hardware and computer software. In fact with a new focus on computation, science began to become modeled on the technology of the computer. Not only did the computer begin to serve as a model for physical processes but it also came to be a model for biological processes, with the idea that life itself was governed by an informational genetic code and human thought and consciousness arose from information processing and computation.[88] Therefore technoscience not only began to erase the boundaries between science and technology but between living and non-living things.

Notes

1 Joan Lisa Bromberg, *The Laser in America, 1950–1970* (Cambridge, MA: M.I.T. Press, 1999), Ch. 1.
2 Paul E. Ceruzzi, *A History of Modern Computing*, 2nd ed. (Cambridge, MA: M.I.T. Press, 2003), 1–2.
3 Ceruzzi, *A History of Modern Computing*, 21.
4 Ibid., 20–24; Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (New York: Basic Books, 1996), 87–95; and Herman H. Goldstine, *The Computer: From Pascal to von Neumann* (Princeton, NJ: Princeton University Press, 1972), Ch. 7.

5 Goldstine, *The Computer*, 256.
6 David F. Channell, *The Vital Machine: A Study of Technology and Organic Life* (New York: Oxford University Press, 1991), 119–120.
7 Goldstine, *The Computer*, Ch. 6; Ceruzzi, *A History of Modern Computing*, 21–24; and Campbell-Kelly and Aspray, *Computer*, 89–95.
8 Campbell-Kelly and Aspray, *Computer*, 89–93; and Goldstine, *The Computer*, 179–83.
9 Campbell-Kelly and Aspray, *Computer*, 92–95; and Goldstine, *The Computer*, 186–188.
10 Ceruzzi, *A History of Modern Computing*, 23–24.
11 Ibid., and Campbell-Kelly and Aspray, *Computer*, 94.
12 Paul Ceruzzi, "Electronics Technology and Computer Science, 1940–1975: A Coevolution," *IEEE Annals of the History of Computing* 10 (1988): 257–275, esp. 262.
13 Campbell-Kelly and Aspray, *Computer*, 100–104.
14 Ibid., 24–27; and Campbell-Kelly and Aspray, *Computer*, Ch. 5.
15 Campbell-Kelly and Aspray, *Computer*, 105–119.
16 Ceruzzi, *A History of Modern Computing*, 30–31.
17 Ibid., 34–36; and Campbell-Kelly and Aspray, *Computer*, 123–128.
18 Ceruzzi, *A History of Modern Computing*, 36.
19 Campbell-Kelly and Aspray, *Computer*, 126.
20 Ceruzzi, *A History of Modern Computing*, 38.
21 Ibid., 49–53; Campbell-Kelly and Aspray, *Computer*, 157–164; and Paul N. Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America* (Cambridge, MA: M.I.T. Press, 1996), 76–83.
22 Campbell-Kelly and Aspray, *Computer*, 161.
23 Edwards, *Closed World*, 79–80.
24 Ceruzzi, *A History of Modern Computing*, 49–50; and Campbell-Kelly and Aspray, *Computer*, 164.
25 Campbell-Kelly and Aspray, *Computer*, 165–169; and Edwards, *Closed World*, 81–90.
26 Campbell-Kelly and Aspray, *Computer*, 167.
27 Edwards, *Closed World*, 75.
28 Campbell-Kelly and Aspray, *Computer*, 169–180.
29 Ibid., 158; and Ceruzzi, *A History of Modern Computing*, 140.
30 See Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information* Age (New York: W.W. Norton & Company, 1997); and Thomas J. Misa, "Military Needs, Commercial Realities, and the Development of the Transistor, 1948–1958," in *Military Enterprise and Technological Change: Perspectives on the American Experience*, ed. Merritt Roe Smith (Cambridge, MA: M.I.T. Press, 1985), 253–288.
31 Riordan and Hoddeson, *Crystal Fire*, 19–20.
32 Ibid., 60–70.
33 Ibid., 84.
34 Ibid., 102–106.
35 Misa, "Military Needs, Commercial Realities," 256.
36 Riordan and Hoddeson, *Crystal Fire*, 108–165.
37 Misa, "Military Needs, Commercial Realities," 261.
38 Riordan and Hoddeson, *Crystal Fire*, 155–156.
39 Ibid., 180–194.
40 Misa, "Military Needs, Commercial Realities," 262–270.
41 Riordan and Hoddeson, *Crystal Fire*, 198–223.
42 Misa, "Military Needs, Commercial Realities," 273–280.
43 Riordan and Hoddeson, *Crystal Fire*, 206–212.
44 Ceruzzi, *A History of Modern Computing*, 65.
45 Riordan and Hoddeson, *Crystal Fire*, 214–217.
46 Ibid., 191.
47 Ibid., 277.

48 Ibid., 233–253; and Stuart W. Leslie, *The Cold War and American Science: The Military–Industrial–Academic Complex at MIT and Stanford* (New York: Columbia University Press, 1993), 68–72.
49 Riordan and Hoddeson, *Crystal Fire*, 237–240.
50 Ibid., 251–252.
51 Ibid., 218–224.
52 Ibid., Ch. 12; and Ceruzzi, *A History of Modern Computing*, 182–189.
53 Riordan and Hoddeson, *Crystal Fire*, 256–261; and Ceruzzi, *A History of Modern Computing*, 182–183.
54 Riordan and Hoddeson, *Crystal Fire*, 258–259.
55 Ibid., 260.
56 Ibid., 262–265; and Ceruzzi, *A History of Modern Computing*, 184–187.
57 Ceruzzi, *A History of Modern Computing*, 186.
58 Riordan and Hoddeson, *Crystal Fire*, 272.
59 Ceruzzi, *A History of Modern Computing*, 182.
60 Ibid., 190–198.
61 Ibid., 218–221; and Campbell-Kelly and Aspray, *Computer*, 236–237.
62 Ceruzzi, *A History of Modern Computing*, 220.
63 Ibid., Ch. 3; Ceruzzi, "Electronics Technology and Computer Science," 263–274; Campbell-Kelly and Aspray, *Computer*, Ch.8; and Goldstine, *The Computer*, Ch. 9.
64 Campbell-Kelly and Aspray, *Computer*, 184; and Ceruzzi, *A History of Modern Computing*, 84–86.
65 Ceruzzi, *A History of Modern Computing*, 90–101.
66 Ibid., 291–294; and Campbell-Kelly and Aspray, *Computer*, 288–294.
67 Ceruzzi, *A History of Modern Computing*, 101–104; and Ceruzzi, "Electronics Technology and Computer Science," 263–272.
68 Ceruzzi, "Electronics Technology and Computer Science," 267.
69 Herbert A. Simon, *The Sciences of the Artificial* (Cambridge, MA: MIT Press, 1969).
70 Quoted in Ceruzzi, "Electronics Technology and Computer Science," 267.
71 Channell, *Vital Machine*, 120.
72 Ceruzzi, "Electronics Technology and Computer Science," 267.
73 Ceruzzi, *A History of Modern Computing*, 102–103.
74 Ceruzzi, "Electronics Technology and Computer Science," 268–269.
75 Channell, *Vital Machine*, 121–122.
76 Edwards, *Closed World*, 180–182.
77 Channell, *Vital Machine*, 122–123.
78 Edwards, *Closed World*, 252–259.
79 Ibid., 188; and Channell, *Vital Machine*, 121.
80 Edwards, *Closed World*, Ch. 6.
81 Howard Gardner, *The Mind's New Science: A History of the Cognitive Revolution* (New York: Basic Books, 1985), 28–30.
82 Edwards, *Closed World*, 190–233.
83 Gardner, *Mind's New Science*, 384–388.
84 Elizabeth Pennisi, "Tracing Life's Circuitry," *Science* 302 (2003): 1646–1649; Uri Alon, *An Introduction to Systems Biology: Design Principles of Biological Circuits* (Boca Raton, FL: Chapman & Hall/CRC, 2006).
85 John Archibald Wheeler, with Kenneth Ford, *Geons, Black Holes and Quantum Foam: A Life in Physics* (New York: W.W. Norton & Company, 1998), 340–341.
86 Seth Lloyd, "Computational Capacity of the Universe," *Physical Review Letters* 88 (June 2002): 237901.
87 David F. Channell, "The Computer at Nature's Core," *Wired Magazine* 2 (February 2004): 79–80.
88 Channell, *Vital Machine*, Ch. 7.