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CHAPTER FOUR

Technology as Systems, Controls, and Information

Large-scale complexity characterizes the post–World War II era of technological systems and distinguishes it from the preceding machine era. Because of this complexity, the control, or management, of technological systems becomes a major problem for engineers and other expert professionals. Finding that control is closely linked to the communication of information, they are among those who helped bring about the information revolution that took root as the twentieth century drew to a close. In the previous chapters, we have considered technology as a means of transforming a wilderness into a human-built world and as a machine for the production of goods. We will now explore its nature as systems, controls, and information and discover that managing it is a major societal challenge.

The Systems Era

The popular press portrayed Henry Ford as the creator of a massive production machine made up of large automobile factories at Highland Park and River Rouge, but Ford saw the core concept embodied in his factories as "system, system, and more system."[1]

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[1] David A. Hounshell, *From the American System to Mass Production, 1800–1932: The Development of Manufacturing Technology in the United States* (Baltimore: Johns Hopkins Uni-

The development of missile systems during the 1950s also stimulated technological and managerial changes that spread into the civil sector. The management techniques used by the U.S. Air Force and its corporate partners in developing intercontinental ballistic missiles (ICBMs) initiated a systems engineering approach stressing scheduling and coordination. It proved especially effective for projects involving thousands of contractors and subcontractors. In the 1950s, the U.S. Navy used a systems approach involving computers and software to create the Fleet Ballistic Missile (FBM) System.

The navy's Fleet Ballistic Missile Weapon System integrated a number of semiautonomous constituent components, including a Polaris intermediate-range (2,500-mile) ballistic missile (IRBM), a specially adapted atomic submarine, a missile launcher, and navigation/fire-control capability. To preside over the development of this complex array and avoid existing bureaucracy, the navy in 1955 established the Special Projects Office (SPO), which functioned as a collective systems builder and systems engineer. Staffed by the cream of navy personnel and civilians, the SPO eventually coordinated the activities of about three thousand aerospace, electronic, and instrument manufacturers, as well as university research laboratories that developed components.

In order to coordinate the countless research and development tasks, the SPO required the numerous contractors to report their progress regularly. Finding the incoming information overwhelming, the SPO, with the help of civil consultants, introduced in 1957 a mainframe-computer-based program named Program Evaluation and Review Technique (PERT). In essence, PERT graphically portrayed a flow plan, or dynamic network diagram, on a computer printout. The diagram revealed the interactive development and flow of numerous design, research, and development projects. With PERT, the SPO could observe and respond to progress and delay in each project as the FBM moved to completion. In the opinion of many who used it, PERT showed how computers and appropriate software could control complex systems, a connection that has proliferated and spread throughout the military and civil management world.

Harvey Sapolsky, an MIT political scientist, however, contends that PERT was more a public relations gimmick than a real management tool. According to Sapolsky, the navy invited members of Congress and others controlling purse strings to observe PERT computers in operation and see complex PERT charts, hoping that the inscrutable aura surrounding PERT would forestall informed criticism and justify expenditures.

The Military-Industrial-University Complex

Sapolsky is but one of many academics who criticized the military's increasing presence on the research, development, and management scene. In his farewell address to the nation in January 1961, President Dwight Eisenhower also raised doubts about the military's role and referred to a "military-industrial complex." Besides warning that a large arms industry could have undue economic, political, and spiritual influence in the councils of state, he cautioned against federal military expenditures influencing the research policies in American universities through allocations and contracts. For this reason, I add "university" to the name of the complex.

Numerous academics criticized the complex and tried to keep classified research off-campus. Seymour Melman, a Columbia University professor, in two influential books—*Pentagon Capitalism: The Political Economy of War* (1970) and *The Permanent War Economy: American Capitalism in Decline* (1985)—argued that a state economy presided over by the Department of Defense was displacing and corrupting the traditional market economy in scale and scope.

Tens of thousands of defense contracts supported both industrial corporations and universities. Between 1960 and 1967, the Department of Defense, according to Melman, awarded the Lockheed Corporation, an aerospace giant, more than $10 billion in contracts and General Dynamics $8.824 billion. In 1968 the Pentagon awarded the Massachusetts Institute of Technology $119 million; Johns Hopkins University received $57 million; the University of California, $17 million; Columbia University, $9 million;

Stanford University, $6 million; the University of Michigan, $9 million; and the University of Illinois, $8 million. Military-industrial-university expenditures, according to Melman, were drying up the government's appropriations for physical infrastructure, health, and welfare. As a result, the nation's economy, especially its once-dynamic free market, was in decline. Melman feared that the United States was becoming a garrison state.

Paul Forman, a curator and researcher at the Smithsonian Institution in Washington, rejected the military's claim that it was disinterestedly supporting basic physics research. On the contrary, he decided that the military supported basic research of a kind that gave some promise of military application. Forman contended that American physics during the period from 1940 to 1960 underwent a qualitative change in its purposes and character—an enlistment and integration into the nation's pursuit of military security. In support of his thesis, he cited physicist Merle Tuve, head of the Carnegie Institution of Washington, who said in spring 1959 that government expenditures for basic research in science contributed little to the really basic core of scholarly achievement. Forman concluded that the scientific talent flows where national priorities place incentives of money, prestige, and excitement.

Spread of Systems Approach

Despite the attacks upon the military-industrial-university complex, it has had a lasting influence upon the character of American technology and its management. Tens of thousands of engineers, scientists, and managers who took part in building weapons systems in the 1950s acquired from this learning experience a systems approach to projects. They and other professionals influenced by them increasingly conceptualized the world around them in terms of systems. Formerly, they might have seen an airplane in isolation; now they saw it as part of a system involving airfields, air controllers, fuel depots, and maintenance facilities. Formerly they might have conceived of a highway in isolation; now they placed it in a network of facilities, including automobiles, service stations, and traffic controls.

To manage the creation of large weapons systems, engineers, scientists, and managers developed a family of systems-based managerial techniques known variously as systems engineering, operations research, and systems analysis. Systems engineering usually referred to the management of the design and development of systems, operations research involved the use of quantitative techniques to analyze deployed weapons systems, and systems analysis compared, contrasted, and evaluated proposed projects. In practice, usage varies from these definitional norms.

Influential organizations and a number of universities cultivated a systems approach. The RAND Corporation in Santa Monica, California, a nonprofit think tank founded in 1948, used air force funding to assemble a staff of experienced mathematicians, natural scientists, and social scientists who impressively developed an interdisciplinary approach to systems analysis. RAND proved especially effective in advising the military about proposed weapons projects. Acting as a collective systems engineer for the first Intercontinental Ballistic Missile Project, the Ramo-Wooldridge Corporation, founded in 1953, developed the systems engineering approach essentially as practiced today. MIT's Lincoln Laboratory, the MITRE Corporation, the Systems Development Corporation, the Air Corps Systems Command, and the U.S. Navy Special Projects Office also cultivated systems approaches in the 1950s.

Academics in leading research universities codified and rationalized the practical field experience of these and other organizations. University courses about a systems approach trained a host of professionals in operations research and systems engineering. Advocates of the approach during the 1960s contended that it made possible the control of vast and complex physical and social structures not only of the military, but also of the industrialized civil world. They held that a systems approach offered a rational response to growing complexity.

Urban Systems: Promise and Failure

In the 1960s, alleviating deteriorating urban infrastructures and housing became a priority for the administration of President Lyndon Johnson. It turned to systems-approach experts who believed they could respond to urban problems as they had to military ones. In 1968 Vice President Hubert Humphrey eloquently expressed the administration's enthusiasm for the systems approach when he predicted that techniques used to manage the creation of large weapons systems and space exploration projects could solve pressing urban problems.

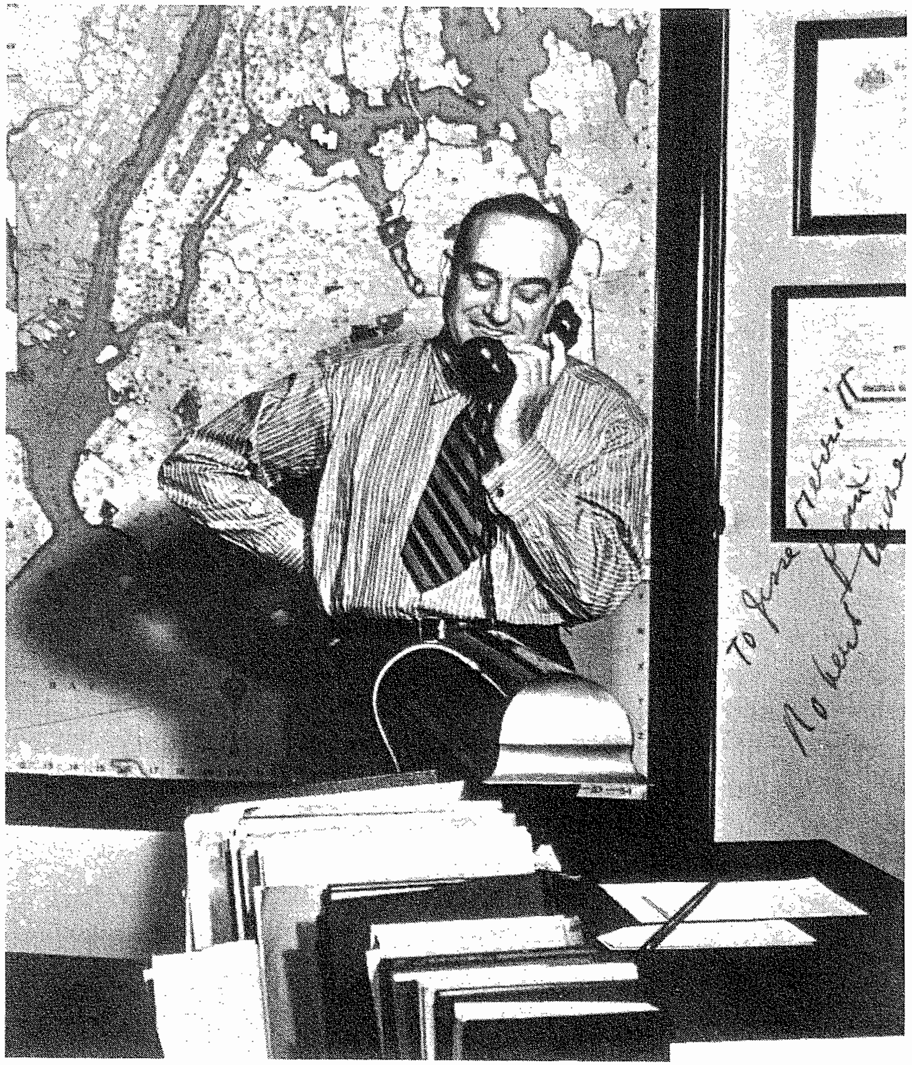
Infrastructure systems have long shaped cities, and cities have come to depend upon them. In late-nineteenth-century America, railroad, telegraph, and telephone networks stimulated the growth of cities. Centralized water supply and waste disposal, as well as urban transit networks, added to infrastructure density. By 1900 the networked city had a downside that has become more serious over time. Since infrastructures are interdependent, the failure of one can cascade throughout the networked complex. For example, a loss of electric power will, in some cities, suspend urban transit systems, automobile traffic controls, elevators, and, in some instances, water-supply pumps. The breakdown of telephone service can interrupt many communication networks dependent upon it, including air-traffic control and the stock exchange. Cascading failures can paralyze a city.

Called upon to respond to urban problems by the Johnson administration, a number of aerospace corporations and consulting engineers familiar with the systems approach floundered as they tried to move the systems approach from the military to the urban sector. In their efforts to introduce new or improved infrastructure, the systems experts found that local governments often would not cooperate when a planned system had to spread over several political jurisdictions. Having customarily given priority to technical and economic factors, they had difficulty in accepting and adjusting to political ones. Coping with the city of Philadelphia proved far more difficult than coping with the Department of Defense.

The systems approach also fell into disrepute because managers and engineers designing and deploying large systems, especially urban transportation systems, did not sufficiently take into account the traditional and delicate social fabric of urban communities. Critics cite Robert Moses, New York State and New York City park commissioner and city construction coordinator, as representative of the insensitive system builder. Yet supporters saw him as brilliantly presiding over the construction of parks, parkways, expressways, strategic bridges, public buildings, playgrounds, public beaches, and public housing in the New York City region from the 1930s to the 1960s. Moses set an example that influenced the destiny of countless twentieth-century American cities. Driven by a bold vision, Moses used public works to structure the life of an urban region.

A Yale Phi Beta Kappa and an honors man at Oxford, the physically imposing Moses began his public service as an idealist and ended it, according to biographer Robert Caro, as a ruthless user of power to fulfill his egotistical vision. Moses masterly framed legislation and established organizational structures, especially public authorities that gave him the freedom to function as an autocrat independently of elected officials and their traditional bureaucracy. Posing as a man of reason acting above politics, Moses functioned as a masterful power broker who maneuvered mayors and other public officials from an awesome power base funded by bond issues and highway and bridge tolls.

Other Moses critics focus upon his rude and high-handed taking of houses, destruction of neighborhoods, arbitrary seizure of rights-of-way, and violation of green environments. Moses believed that overconcern about nontechnical matters could paralyze engineering; in other words, his vision took precedent over the interests of ordinary citizens standing in his way. Moses argued that in laying out urban highways, he removed ghettos, but critics contended that he violated living communities by forcing hundreds of thousands of



15. First celebrated for his New York public works projects, Robert Moses later fell out of favor because his projects autocratically violated the physical integrity of neighborhood communities. Photograph of Moses courtesy of the Nassau County Museum, Long Island Studies Institute.

inhabitants from their homes, many into banal massive high-rise housing. He predicted that the high-rises would provide clean, safe, and efficient living spaces, but inhabitants often found the housing cold and forbidding, as well as isolating them from neighbors.

Yet Lewis Mumford, an insightful and frequently negative critic of his beloved Manhattan's architecture and landscaping, found much good to say about Moses in the 1930s. Writing regularly for the *New Yorker Magazine* in a series of "Sky Line" columns, Mumford declared that all around Manhattan the energetic and astute Moses was creating the framework of a new and improved city. Mumford really liked Moses's playgrounds, marine parks, and landscaped highways, especially those that connected to Moses-designed Jones Beach. Mumford found that the landscaping of Jones Beach left him in a state of ecstatic admiration. The beach architecture, however, left Mumford far less than enthusiastic.

Systems Discredited: Vietnam War and the Counterculture

Popular books and articles by scientists and social scientists heightened the reaction against large technological systems. Writing for the *New York Review of Books* with its large influence among academics and liberal intellectuals, John McDermott drew a memorable analogy between civil systems of production and military systems of destruction that the United States deployed in the Vietnam War. Rachel Carson's *Silent Spring* (1962) calls attention to the loss of natural sounds, smells, and vistas as human-built systems of production with their toxic substances displace nature. Biologist Barry Commoner, in *Science and Survival* (1966) and *The Closing Circle* (1971), writes of an environmental crisis caused by industrial pollution of the environment.

In the title of his book *Small Is Beautiful* (1973), economist E. F. Schumacher found an expression that epitomized the reaction, especially among young adults, against large-scale systems of production. The popularity of the *Whole Earth Catalog* (1968) demonstrated the enthusiasm for small-scale appropriate technology. It identified the hand tools of a benign technology useful for shaping a new environment. Many practitioners of the *Whole Earth Catalog*'s philosophy were trying, like the Amish people in Lancaster County, Pennsylvania, to reduce their dependence on large manufacturing and utility systems.

In his book *Soft Energy Paths: Toward a Durable Peace* (1979), physicist Amory B. Lovins persuasively argues that small power plants using renewable energy sources, such as wind, sun, and water, could more efficiently supply energy than regional power plants with their lengthy transmission and distribution lines. Influential interest groups, however, heavily invested with capital and with engineering and managerial skills in existing systems resisted new technologies that would destroy established ones. Innovative environment-sustaining systems lacked the capital and political influence needed to establish themselves in the face of this momentum.

Lewis Mumford railed repeatedly against the military-industrial complex, which he labeled a "megamachine." Megasystems and their elite experts, according to him, deadened the humanistic aspects of life and took society to the brink of catastrophe. In *The Pentagon of Power* (1970), he describes the massive, centrally controlled military-industrial complex as dependent on a priestly, or scientific, elite, monopolizing knowledge in order to ensure its power, glory, and material well-being.

In *Men, Machines, and Modern Times* (1966), Elting Morison, an MIT history professor, eloquently expresses with a biblical cadence his views about large systems. He holds that they have acquired an intricacy, mass, scale, and rate of change making it extremely difficult for individuals to cope. He sees the irony of industrial society mastering the natural environment, but in so doing making a second creation so complex that it defies control. We are no longer, like Job, struggling with God, but struggling, he laments, in a network of our own godlike powers that we have not mastered.

Perry Miller, a Harvard professor of American literature, in an article aptly titled "The Responsibility of Mind in a Civilization of Machines" (1979), ventures that humans face a tragic dilemma as they find themselves in a universe of their own manufacture with which they are unable to deal. He recalls that Gloucester in Shakespeare's *King Lear* could blame the gods for his predicament, but whom, asks Miller, can we blame for the physical corruption of Gary, Indiana, but ourselves. Numerous other academics and professional writers similarly considered omnipresent technological systems out of control.

The Failure of Controls

While the anti-technology values of post–World War II intellectuals influenced a limited segment of the public, well-publicized technological catastrophes heightened anxieties about the functioning of the human-built world. Large coastal oil spills and the urban smog alerts of the 1960s stimulated a rising tide of public sentiment that brought passage of federal environmental laws modifying industrial practices. The nuclear-reactor catastrophe at Three Mile Island in 1979 heightened public concern and stimulated regulations and controls that dampened the spread of nuclear power. The *Challenger* shuttle tragedy of 1986 temporarily derailed the National Aeronautics and Space Administration's bold program of space exploration.

Technological catastrophes raised serious doubts about the capability of engineers and scientists to control technology, a capacity that they claimed to have had during the machine age. Public anxiety heightened during the cold war as engineers, scientists, and managers presided over massive technological projects culminating in the production of thousands of nuclear-warhead-tipped intercontinental ballistic missiles. Furthermore, the memory of the awful destructiveness of the atom bombs dropped on Hiroshima and Nagasaki created in the public mind a specter of technology running amok. Engineers were displaying creative powers beyond the imagination of Faust and Mephistopheles.

There were disturbing failures in combat operations centers designed to detect enemy and to control friendly intercontinental missiles and aircraft. Constructed in 1961, the U.S. Air Force's underground combat operation center inside Cheyenne Mountain, Colorado, experienced alarming software failures. For eight tense minutes in 1979, Cheyenne mistook a test scenario for an actual missile attack, a mistake that could have triggered a nuclear holocaust. In 1980 a computer-chip failure mistakenly alerted the Strategic Air Command against attack. False alerts continued, especially following the installation of new computers.

Sociologist Charles Perrow in *Normal Accidents: Living with High-Risk Technologies* (1984) has called such failures in complex systems "normal accidents." These are most likely, he argues, in tightly coupled systems in which various components interact quickly over rigid connections. An intercontinental ballistic missile, for instance, with propulsion tightly coupled to its guidance system is prone to "normal accidents." In the case of the *Challenger* spacecraft tragedy, a cascading series of failures involved interacting physical components and humans in management agencies. The near-catastrophe at the Three Mile Island nuclear plant resulted from interacting operator and hardware failures. Likewise, the Chernobyl disaster in the Ukraine can be classified as a "normal accident," as well. And unintended electric-supply-system blackouts have followed upon unanticipated cascading interactions involving operator and hardware failures.

Controls and Information

Aware of the failure of controls and the frequency of "normal accidents," engineers and scientists sought to improve control theory and practice. As early as 1948, Norbert Wiener, an MIT mathematical prodigy, explored the close linkage between controls, information, and communication. In his 1948 book *Cybernetics; or, Control and Communication in the Animal and the Machine,* he declares that the

16. MIT faculty member Norbert Wiener understood the interconnection of control, communication, and information and helped pave the way for the information revolution. Photograph of Wiener courtesy of the MIT Museum.

seventeenth and early eighteenth centuries were the age of clocks; the later eighteenth and the nineteenth centuries, the age of the steam engines; and the twentieth century, the age of communication and control.

Wiener conceived his influential cybernetic theory when designing and analyzing gunfire-control devices during World War II. He and his contemporaries designed electromechanical and electronic systems that communicated information electrically to control devices at a distance. They then defined communication as the transmission of information that controls and orders.

Feedback was a central concept in Wiener's control theory. Along with his close friend Arturo Rosenblueth of the Harvard Medical School and Julian Bigelow, an MIT engineer who built mechanical models to demonstrate Wiener's concepts, Wiener defined feedback in a seminal essay entitled "Behavior, Purpose, and Teleology" (1943). Negative feedback, they explain, is the use of controlling signals to modify the output, or behavior, of a machine or organism so that it will reach its goal. Comparison of a machine's or organism's interim state with the path to its eventual goal generates the controlling, or error, signals.

Often feedback signals must be dampened to prevent the machine or organism from oscillating excessively about the path to its goal. Rosenblueth, a neurobiologist, used as an example of undamped oscillations a patient with cerebella disease waveringly and unsuccessfully attempting to raise a glass of water to her mouth. Rosenblueth, Wiener, and Bigelow compared predictive and nonpredictive behavior in feedback systems. An amoeba seeking a moving goal does not extrapolate the path of its goal; a cat, on the other hand, does extrapolate the future position of a running mouse and moves toward that future intersection. Predictive behavior is divided into orders of complexity: the cat predicts the path of the mouse; a person throwing a stone at a moving target makes a second-order prediction by foreseeing the paths of the target and the stone.

Predictive behavior requires at least two coordinates—a temporal and a spatial. Prediction is raised to a third, fourth, and so on order, if the machine or animate organism has additional sensors that discriminate a number of spatial axes. A bloodhound, for instance, does not evince predictive behavior, for it follows only smell. Because humans employ a number of sensors, their behavior can be of a higher order of prediction.

Several years before the publication of *Cybernetics,* Wiener's ideas had already greatly impressed a small interdisciplinary group of scientists, engineers, and social scientists who joined him in several seminars. This interdisciplinary group of "cyberneticians," as described by Steve Heims in *The Cybernetics Group* (1991), worked its way through cybernetic, or control, concepts and took a leading role in disseminating them by an ingenious use of analogy. They believed that cybernetic concepts had general applicability for researchers in a number of fields, including the human sciences. The cyberneticians' discourse about control and feedback and their imaginative analogies anticipated the information revolution. They probed the relationship between control, communication, and information.

Members of the interdisciplinary group included, besides Wiener, Rosenblueth, and Bigelow, John von Neumann, the Hungarian mathematician who helped introduce game theory and later designed a seminal scientific computer; Claude Shannon of Bell Laboratories, who with Wiener pioneered in the development of information theory; Warren McCulloch, a neurobiologist at the University of Illinois Medical School; Walter Pitts Jr., McCulloch's protégé; and Rafael Lorente de Nó of the Harvard Medical School, who brought a background in neurobiology to the interdisciplinary metaphor-generating discussions.

Other notables in attendance included anthropologist Margaret Mead and her husband, Gregory Bateson, a psychological anthropologist. Mead recalls that the interdisciplinary discussions about feedback controls made a strong impression—precise enough to be used in problem solving, but abstract enough to cross disciplinary boundaries. In May 1942 in New York at the seminar's first gathering, Rosenblueth gave such an engrossing and stimulating presentation on feedback controls that Mead did not notice she had broken a tooth.

Rosenblueth's presentation drew on conversations with Wiener and Bigelow about analogies between machines and organisms, especially their common characteristic of purpose. Traditionally, scientists are reluctant to explain actions in terms of purpose, for this assumes knowledge of actions in the future and placing the effect before the cause. Rosenblueth related purpose to negative feedback, or circular causality and control, another approach scientists avoided because the associated math is so difficult. For Wiener, Rosenblueth, and Bigelow, teleology is purpose controlled by feedback, as distinct from the common association of teleology with final causes.

A Flood of Control, Communication, and Feedback Metaphors

Because they realized that analogic metaphors provide connective bridges, the seminar group used control, communication, and feedback metaphors as well as computer ones to find similarities among their various disciplines. They generated a flood of metaphors. Wiener continued to stress analogies between machines and humans. Von Neumann suggested the analogous behavior of electrons in vacuum tubes with neurons in organisms. And Lorente de Nó saw similarities between the firing of an impulse from an individual neuron and the digital binary processes of computing machines. Their metaphors and talk anticipated the discourses of the information age.

Others seminar members imaginatively found analogies between machines and organisms. McCulloch in association with the younger Pitts conceived of analogies relating machines and the functional organization of the cerebral cortex. In 1943 they described a model of neural nets that soon proved a useful metaphor for describing digital computers. Their model involved idealized neurons capable of generating an excitatory or an inhibitory impulse. Separated from other neurons by synaptic gaps, the electrical controlling impulses do not fire across a gap unless the voltage of nerve fibers exceeds the threshold voltage of the neuron. When this occurs, a neuron will then fire electric impulses in a chainlike reaction to other neurons with which it is in contact through nerve fibers across synaptic gaps. The process suggests the digital switches of an electronic computer.

Known for his study of Balinese culture and language and his appreciation of metaphors and analogies, Bateson found the cybernetics approach richly thought provoking for social scientists. Years later he recalled cybernetic ideas as more profound and dramatic than the concepts associated with the double helix model of Francis Crick and James Watson. He also believed that cybernetics provides an organizing principle for the social sciences as powerful as Darwinian biology. On another occasion, he wrote that the Treaty of Versailles and the discovery of cybernetics were the two most important historical events in his life. He took as his special responsibility the transfer, by means of analogy, of cybernetics concepts from mathematics and engineering to the social sciences, a transfer leading to an emphasis by scientists and social scientists upon systems and information.

Molecular and Developmental Biology

Because some molecular biologists, especially those with physics backgrounds, left feedback out of their explanations for organic growth and reproduction, Bateson considered their approach reductionist. He found them wrongly assuming that a linear flow of control information moved from DNA genes to the human's protein manufacturing "factory." Like Bateson, Evelyn Fox Keller, a historian of science, found many molecular biologists and geneticists taking a reductionist linear approach and avoiding the tough intellectual demands required when analyzing the simultaneous interactions within complex biological systems.

In contrast to reductionist molecular biologists, developmental biologists introduced the circularity of systems, control, and information to explain growth. They conceived of information sources distributed throughout the human organic network, or system. They took their metaphors from cybernetic systems, such as computer networks, instead of the simpler mechanical machine metaphor used by many molecular biologists. In "The Cybernetics of Development" (1957), C. H. Waddington discusses the feedback needed to ensure the stability of human developmental pathways.

He refers to the self-directing systems from which Wiener drew his cybernetic theories. Michael Apter, a psychologist with computer experience, also conceived of developing organisms as exceedingly complex, feedback-laden systems. These and like-minded scientists in essence argued that genes alone do not explain embryogenesis; a self-organizing and self-steering system should be the explanatory model. In so arguing in the 1970s, they were making potentially serious inroads into the central dogma of unidirectional gene action expounded by Crick in the 1950s.

Molecular biologists later resorted to information metaphors. They used terms such as "inscription," "transcription," "translation," "expression," and "transformation." They referred to bits of genetic text and to the transmission, accumulation, and storage of information. Using a biblical metaphor, historian Lily Kay predicted that the master of the DNA molecule will be the one who reads the book of genetic scripture. Yet even resorting to information metaphors did not free molecular biologists from accusations that their approach was reductionist.

Origins of the Information Revolution

Information theory and metaphors not only pervaded biology, but also increasingly infiltrated scientific, engineering, and managerial discourse about communication and control. This discourse in the 1950s and '60s signaled a forthcoming information revolution, which was soon brought about by a confluence of conceptual, technological, scientific, and organizational developments. Like earlier industrial revolutions, the information revolution has multifaceted origins involving unanticipated confluences.

In *The Control Revolution: Technological and Economic Origins of the Information Society* (1986), sociologist James R. Beniger associates an incipient information revolution with the interaction of controls and information, thus recalling Wiener. Crises of control brought by rapid industrialization, the spread of larger and more complex technological, managerial, and business systems, and an increase in "normal accidents" stimulated a quest for control devices that were information dependent.

Other scientists and social scientists also observed the rise of an information-dependent industrial society, especially in the United States. In the 1960s, historian of science Derek J. de Solla Price called attention to the exponential growth of information in the realm of natural sciences. Anticipating the use of computers as information processors, in 1945 Vannevar Bush, a renowned MIT academic engineer and science policy maker, published his plans for the "memex," a memory and retrieval device designed to help academics, lawyers, and business executives awash in information to organize and retrieve it. As wartime head of the Office of Scientific Research and Development, Bush observed the wartime federal government increasing the value of printing and reproducing equipment from $650,000 to $50 million within a year.

Economist Fritz Machlup pointed out that as early as 1958 the information sector of the U.S. economy accounted for 29 percent of the gross national product and 31 percent of the labor force. In the 1960s and '70s, books and articles appeared with titles such as "Production and Distribution of Knowledge," "Age of Information," and "Information Revolution." In the 1980s, the Smithsonian National Museum of American History organized a major exhibition featuring computers called *The Information Age.* Information was becoming a driver of far-flung and deep social and cultural changes, much as energy had been during earlier industrial revolutions. Contemporaries were observing and defining the information revolution.

The Revolution's Technical Core

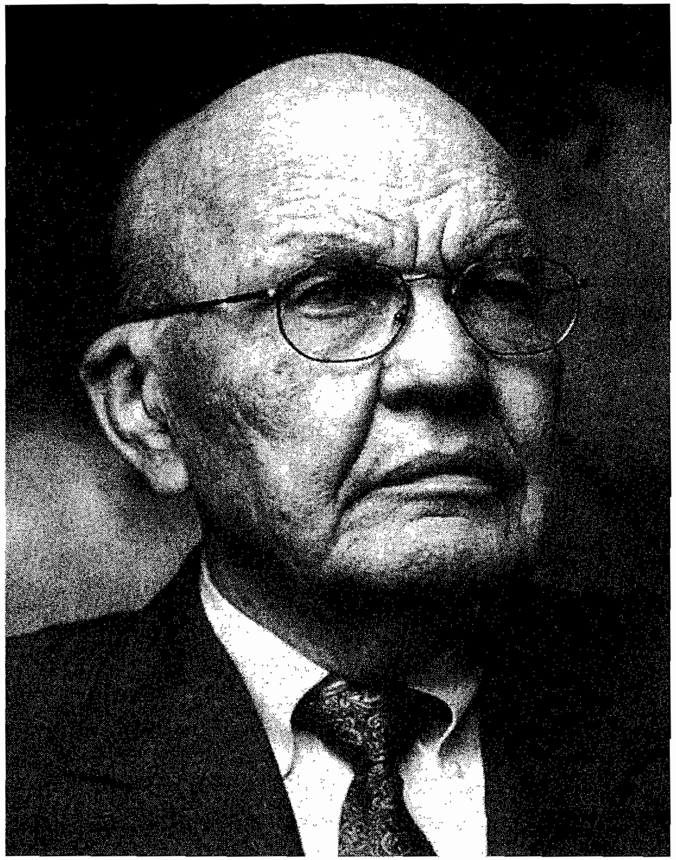
Like the second industrial revolution, the information revolution involves the spread of new pervasive technology and its interaction with existing technological systems. The introduction of electric power, a new form of energy, generated cascading effects as it displaced steam engines in numerous energy-dependent systems including transportation and production. Similarly, numerous technological systems depend on information, especially for communication and control. Introducing a new means of transmitting information also has cascading effects as digital information displaces older forms of information in various systems. Information and electric energy have similar effects and generate comparable developments because both are means of transmission and distribution, in one case, energy and, in the other, information.

The origins of the information revolution have yet to be thoroughly explored by historians, yet even now it appears that the interactive development of computers, semiconductors, and software nurtured the spread of digital information, which in turn led into the revolution. Just as early inventors and developers of electric dynamos, motors, and lamps did not anticipate that these would interact to cause changes so varied and widespread, the early inventors of semiconductors, computers, and software forged ahead without foreseeing that they were involved in a nascent information revolution.

In 1947 Walter Brattain, John Bardeen, and William Shockley at Bell Laboratories patented a small semiconductor transistor to displace the omnipresent large vacuum tube in military and civil communication and control devices. Saying that he wanted to make a million dollars and see his name in the *Wall Street Journal,* not only in the *Physical Review,* Shockley left Bell Labs in 1955 to start a company to develop, manufacture, and market transistors. By establishing a research-and-development start-up company in Stanford University's research park in Palo Alto, California, he initiated a trend the consequences of which he could not have possibly foreseen.

Nor did Jack Kilby of Texas Instruments and Robert Noyce, who in 1959 independently invented an integrated circuit, realize that this would contribute to the information revolution. The device allowed resistors and capacitors to be combined with transistors in an electronic circuit on a single silicon wafer. Another major breakthrough came in 1971 with the invention of a microprocessor by Marcian (Ted) Hoff, an engineer at the Intel Corporation. More complex than the integrated circuit, the microprocessor incorporated hundreds of thousands of circuit components dedicated to the logic of calculating or control, thus becoming a computer on a chip.

The information revolution began to take shape as integrated



17. Inventor of an integrated circuit, Jack Kilby displayed the creativity that represents the present-day interaction of technology and science. For his innovation, he received the Nobel Prize in 2000. Photograph of Kilby © The Nobel Foundation.

circuits and microprocessors interacted with the development of computers and software. Microprocessors allowed designers in the 1970s to introduce computers smaller than mainframes, first minicomputers, still large by comparison with today's desktop computers, and then personal computers. Initially having limited use by scientists as giant calculators, computers soon served as control devices for weapons and industrial systems and spread into the civil realm as information processors. In the 1970s, production of transistors, integrated circuits, microprocessors, and computers skyrocketed in California's Silicon Valley centered upon Stanford University. Research and development start-up companies proliferated; their innovations fueled the information revolution.

Personal computing took a giant step in the 1970s when engineers and scientists at the Palo Alto Research Center of the Xerox Corporation designed and built the Alto computer. It featured icons, a mouse, and a pull-down menu designed by Douglas Engelbart, as well as a laser printer. For complex reasons, Xerox's commercial design of this innovative computer was not successful. In Silicon Valley in 1977, Steve Jobs and Steve Wozniak introduced the Apple II computer and later a Macintosh with Alto features, a floppy drive, and an elegant and simple architecture.

Initially mistakenly considered peripheral to computer, or hardware, development, software soon became a major component in the evolving information revolution. After IBM introduced a personal computer with spreadsheet software and word processing, *Time* magazine named the computer "Machine of the Year" in 1983. The IBM machine used William Gates's MS-DOS operating system, and his Microsoft Corporation soon became the world's leading software producer.

Designers of minicomputers and personal computers did not intend them to function interconnected, but the Advanced Research Projects Agency (ARPA) of the U.S. Defense Department funded their interconnection in a system named the ARPANET. After 1971 it became the core of interconnected computer networks called the Internet. Use of the Internet expanded dramatically after Tim

Berners-Lee, a scientist at CERN, the European particle physics laboratory, in 1991 made available the prototype for what has become known as the World Wide Web. The usefulness of the Web increased greatly when Marc Andreesen, a student at the University of Illinois, and Eric Bina in 1982 composed a program for a Web browser that allows users to search the Internet effectively.

As in earlier industrial revolutions, inventor-entrepreneurs such as Brattain, Jobs, and Engelbart, pursuing independent ends, were the immediate causes of the information revolution. Like their predecessors, these inventor-entrepreneurs presided over the development of an inventive idea until development culminated in a marketable product. They often established a start-up company to develop, manufacture, and market their invention. Like the independent inventors of the past, they have been responsible for radical innovations through the launch of new systems.

Managerial, Organizational, and Social Changes

Tightly coupled to technological change, managerial practices and organizational forms have evolved during the information revolution. Hierarchy, specialization, standardization, centralization, expertise, and bureaucracy became the hallmarks of management during the second industrial revolution. Flatness, interdisciplinarity, heterogeneity, distributed control, meritocracy, and nimble flexibility characterize information-age management. The organizational culture of Silicon Valley at the epicenter of the revolution has been described as information sharing, collective in learning, informal in communication, fast moving, flexible in adjustments, entrepreneurial, start-up inclined, and thoroughly networked.

Virtual corporations that focus upon management and that outsource manufacturing and other functions to contractors also display the information-revolution organizational style. Because of its rapid and deep interconnectedness, the Internet allows a virtual corporation to function like a systems engineer presiding over a project by scheduling and coordinating subcontractors. Not invested in facilities to manufacture components made by its contractors, a virtual corporation can nimbly shed its contractors and move to another domain.

The information revolution, like the second industrial revolution, locates in particular cities and regions and brings demographic change. New York and Berlin attracted innovators during the second industrial revolution. Silicon Valley, Boston-Cambridge, Austin, North Carolina's Research Triangle, and northern Virginia have become information revolution sites. Futurists have predicted that the home computer and the Internet will also accelerate the movement of population out of the cities and away from transportation nodes into the suburban home. Work can often be done in the isolated home as well as in centrally located offices. During the second industrial revolution, there was a demographic shift away from the coal-rich regions into those with water and electric power. Because computers are not as energy dependent as is heavy industry, computer and software manufacturers tend to locate in campuslike environments, such as Silicon Valley, where young university-trained engineers and managers prefer to live and work.

On the other hand, the information revolution homogenizes places and transforms them into spaces. Places, be they cities or villages, have history, traditions, and local characteristics stemming from physical and human geography. Cities that lose their unique characteristics become spaces. Today cities throughout the world are losing their architectural identity and moving toward becoming spaces because architects are responding to the siren song of globalism, which they believe to be driven by information-revolution technology. They easily resort to a homogeneous global style. Because technology provides unprecedentedly low-cost transportation and communication, architects and planners are not constrained to using local materials and energy sources. Singapore, Kuala Lumpur, and Dallas resemble one another. They have high-rise office buildings, shopping malls selling similar products, fast-food franchises, villas for the wealthy, condominiums for young middle-class professionals, and traffic congestion reaching into the suburbs.

Reactions to the Information Revolution

Humanists, public intellectuals, and artists lamented the constraining influences of large technological systems upon individual freedom and associated them negatively with the Vietnam War and the deterioration of the environment. In contrast, reactions to the information revolution have been decidedly positive. George Gilder has been the most enthusiastic and influential of the celebrants of the computer-driven information age. Before becoming a prophet of the new age, he made a name for himself writing about supply-side economics in his book *Wealth and Poverty* (1981). President Ronald Reagan's speeches reveal that he quoted Gilder more than any other living author. With the publication of *Microcosm: The Quantum Revolution in Economics and Technology* (1989), he changed from a supply-side evangelist to a technoprophet. *Microcosm* caught the attention of the then congressional Speaker of the House Newt Gingrich, whose enthusiasm for computer technology resembled Gilder's.

Before the collapse of many dot-com companies at the turn of the century, Gilder's newsletter in which he singled out highly innovative dot-coms led his devoted and trusting readers to invest in droves in companies about which Gilder spoke glowingly. For a number of years, Gilder held an annual conference called Telecosm at Lake Tahoe, California. His talks about the religious meaning of the emerging information revolution highlighted the meetings. He believes that the revolution is driven by his and other's faith in the future of technology.

Microcosm established a litany for the faithful, a line of prophecy that has shaped later books and articles of those sharing his enthusiasm. Gilder declares that the industrial age has passed and the

United States and Japan have entered upon the quantum age. Isaac Newton's laws describing the macro physical world are now transcended by those of Max Planck and others who explored and explained a microworld of quantum physics consisting of particles and waves. The result, for Gilder, is that machines and material things, which have been the measure of wealth, are being displaced by creative human minds as the measure and source of wealth. He points out that Japan, a barren group of islands with a scarcity of material resources, has become a leading economic power because of the creativity of its entrepreneurs. In the United States, Silicon Valley is similarly a great resource rich in creative minds.

For Gilder, the microchip made mostly of dirt-cheap sand and computer software devoid of material substance are the prime examples of embodied creativity characteristic of the quantum era, or the information revolution. He is fascinated by the fact that the cheap material in the microchip is given great value by the creativity of designers. In celebrating the newness of the new age, he chooses to ignore the fact that for centuries engineers have transformed inert natural materials into economic resources.

The designers of microchips and the other technology of the new age, he delights in saying, are not Ivy League graduates in gray flannels and button-down blue shirts, but outsiders, nerds, science wonks, and upwardly mobile engineers. The acne-faced, ponytailed young people who work seventy hours a week have carried the United States into the information age. Alongside them are the immigrants from Madras, Israel, and Malaya.

The creators of the new age who generate wealth by creativity are becoming not only the masters of the economy, but also of politics and social life. Using computer telecommunications, they are the destroyers of large bureaucratic government and industrial organizations. One entrepreneur sitting at a computer workstation, according to Gilder, exercises more world-transforming power than the captains of heavy industry sitting atop a massive hierarchical structure.

Gilder's appeal to the young hackers, virtual-reality denizens,

Net surfers, multimedia artists, and other information-age enthusiasts is understandable. As he observes, they are not Ivy League corporate aspirants: they are the outsiders who are becoming the insiders who live, or perish, by their skill in developing new hardware and software. They, like Gilder, dismiss the past as irrelevant and believe that their world is entirely new under the sun. They fervently believe that computer-driven technology will change everything. Vested interests in the status quo are ignored.

Gilder's messianic and technically informed style engages the new age creators. Manuel Castells's *The Rise of the Network Society* (1996), a denser study, influences the way in which social scientists and humanists understand and react to the information revolution. After acknowledging the hype surrounding the majority of books and articles about the information-technology revolution, he, nevertheless, equates its impact with that of the British industrial revolution. A professor of sociology at the University of California, Berkeley, Castells argues that both revolutions in a period of several decades thoroughly transformed the material basis of society and changed its culture.

Castells focuses upon the networked global economy emerging in the last quarter of the twentieth century. Interconnected computers throughout the world enable producers and consumers, borrowers and lenders, investors and brokers, to instantaneously exchange information. The exchanges transcend national boundaries, so the constraints of national economies give way to an interdependent global economy. Because of the primacy of information as the new raw material and creator of wealth, world regions prosper or decline not so much because of natural resources, but because of the capacity of their managers, engineers, scientists, and workers to harvest knowledge as raw material. The global economy supports an international division of labor that locates regional manufacturing of computer components where knowledge and skill reside. Regions without these assets languish.

Castells's most original ideas deal with what he calls the space of flows. He imagines a global electronic network superimposed upon the world, a network along which digital information consisting of texts, images, and voice flows instantaneously. Interactions are often simultaneous rather than sequential. This network supersedes the railways, highways, and communication linkages of the pre-information age. Global manufacturing, commercial, and financial firms function within this space of flows.

Besides the network, nodes exist in the space of flows. Global cities in which information is generated and managed become network nodes. They are losing their local connections and becoming spaces that resemble one another. Elites presiding over organizations and institutions that control flows on the network choose to live and work in the global cities. Their high-rise business centers, luxury hotels, and airports all tend to resemble one another.

In *The Closed World* (1996), media historian Paul Edwards provides an enlightening perspective on Castells's space of flows. Edwards defines the closed world, or cyberspace, as an artificial space inside a computer or a computer network. In this space, nothing exists except abstract nonphysical information. The action in science-fiction books such as William Gibson's *Neuromancer* and films such as *Blade Runner* and the *Star Wars* trilogy take place in a closed world, such as cities and space stations, which are devoid of animals and plants, in short, devoid of nature. Humans and cyborgs inhabit the spaces. Cyborgs (cybernetic organisms) are integrated humans and machines, especially computers, that usually have the forms of either robots or humans. Dramatic tension in the books and films often involves conflict between cyborgs and humans. A computer network, not unlike Castells's space of flows, often provides a constraining structure within which action takes place. Edwards argues that these fictional closed worlds distill and simplify our anxieties and aspirations in the so-called real world.

Both Castells's space of flows and Edwards's closed world share a disconnection from nature, or what Edwards calls the green world. Humans sometimes try to escape from the closed world into the green one. While rationality prevails in the closed world, natural forces, emotions, community, and even mystical, magic powers prevail in the green world. The space of flows and the closed world, on the other hand, are human-built, human-imagined worlds completely disconnected from physical nature and completely controllable.

Tom Forester's *High-Tech Society* (1987), like so many other books on the subject, breathlessly characterizes the information technology revolution as dramatically transforming society. *High-Tech Society* is representative of the hype to which Castells alludes and that Edwards avoids. Forester, an author or editor of five books on technology and society, approvingly quotes others who describe developments in computer hardware as the most remarkable technology ever confronted by humankind and the digitalization of information as the twentieth century's most fascinating development.

Technological developments in conjunction with deregulation and privatization have resulted, Forester believes, in new companies and new products emerging as never before in history. New telecommunications systems involving computers, digitalization, and fiber optics, Forester is assured, will bring changes as momentous as the railroad and highway systems. Computers in the factory will revolutionize industrial production; in marketing and finance, the changes will be comparable. He ventures that the speed of the high-tech revolution is much faster than that of the industrial revolution. After surveying high-technology developments in the United States and Japan, Forester predicted in 1990 that Japan would become the world's leading economic power by 2000.

Bill Gates, the head of the software giant Microsoft Corporation, touts the bright future of the information revolution. In *The Road Ahead* (1995), he shares his vision of a future for which, he says, he can hardly wait. He confides that he has been doing all he can to bring it closer. Not surprisingly, Gates, as a successful marketer, stresses that the revolution promises a huge market for goods, services, and ideas. It will change what all of us buy and how we invest. It will also determine who our friends will be and how we will spend our time with them. The workplace and education will be transformed beyond recognition. If that were not enough, the information age will create a new human identity. In short, he concludes, almost everything will be different.

In *Being Digital* (1995), MIT professor Nicholas Negroponte, the founding director of the MIT Media Laboratory, is fascinated by the transformation of various kinds of information into a common digital form. He is apparently unaware that electrical power during the second industrial revolution similarly transformed various forms of energy, such as steam, water, and chemical, into a common electron form. He compares bits, the unit of digitalization, with the atoms of the past. More appropriately, he might have compared bits with electrons, but then the digital revolution he is describing would not seem as dramatic and unprecedented.

Negroponte optimistically embraces the information revolution. After acknowledging that jobs may be lost to computerized automation, that individual privacy may be violated, that digital vandalism will occur, and that large sectors of the population will feel disenfranchised, Negroponte moves on to predict that like an irresistible force of nature, digitalization will decentralize, globalize, harmonize, and empower. A new generation of "kids," unconstrained by the need to be in geographic proximity, will collaborate over digital networks to increase global harmony. Like so many technological optimists in the past, Negroponte believes that people who know each other better will like one another better, too.

He concludes that the digitized tomorrow will exceed people's "wildest" predictions—a statement that can be taken several ways. To temper Negroponte's enthusiasm, we should recall Thoreau's gentle reminder that the dappled sunlight falling across the path of the poet provokes joy beyond that which technology can bring. The gentle wind cooling the heated brow fills the poetic mind with profit and happiness equal to that which inventions supply.

Enthusiastic authors arguing that the information revolution would change everything for the better helped alter public attitudes toward technology. Having gone along with humanists and social scientist who damned systems in the 1960s, the public now viewed technology more favorably. The profits being taken from technology stock did nothing to dampen their ardor. Because weapons technology employed during the heavily televised Gulf War of 1991 seemed to be the major reason for a low-casualty U.S. military victory, memories of ineffectual, stalemated technology during the Vietnam War apparently faded into the past. Time will tell how the crash of dot-com stocks and terrorism will affect attitudes toward technology. Dramatic swings in attitudes stimulated by passing events have long characterized history.