Hughes, Thomas P. 1987. The evolution of large technological systems. In *The social construction of technological systems. New directions in the sociology and history of technology*, edited by W. E. Bijker, T. P. Hughes and T. Pinch. Cambridge, Massachusetts & London, England: MIT Press, 51-82.

Bath, and by Harvey and Pickering at the Science Studies Unit, University of Edinburgh. See, for example, the references in note 7.

29. See, for example, Bijker and Pinch (1983) and Bijker (1984 and this volume). Studies by Van den Belt (1985), Schot (1985, 1986), Jelsma and Smit (1986), and Elzen (1985, 1986) are also based on SCOT.

30. Constant (1980) used a similar evolutionary approach. Both Constant's model and our model seem to arise out of the work in evolutionary epistemology; see, for example, Toulmin (1972) and Campbell (1974). Elster (1983) gives a review of evolutionary models of technical change. See also Van den Belt and Rip (this volume).

31. It may be useful to state explicitly that we consider bicycles to be as fully fledged a technology as, for example, automobiles or aircraft. It may be helpful for readers from outside notorious cycle countries such as The Netherlands, France, and Great Britain to point out that both the automobile and the aircraft industries are, in a way, descendants from the bicycle industry. Many names occur in the histories of both the bicycle and the autocar: Triumph, Rover, Humber, and Raleigh, to mention but a few (Caunter 1955, 1957). The Wright brothers both sold and manufactured bicycles before they started to build their flying machines—mostly made out of bicycle parts (Gibbs-Smith 1960).

32. There is no cookbook recipe for how to identify a social group. Quantitative instruments using citation data may be of some help in certain cases. More research is needed to develop operationalizations of the notion of "relevant social group" for a variety of historical and sociological research sites. See also Law (this volume) on the demarcation of networks and Bijker (this volume).

33. Previously, two concepts have been used that can be understood as two distinctive concepts within the broader idea of stabilization (Bijker et al. 1984). *Reification* was used to denote social existence—existence in the consciousness of the members of a certain social group. *Economic stabilization* was used to indicate the economic existence of an artifact—its having a market. Both concepts are used in a continuous and relative way, thus requiring phrases such as "the *degree* of reification of the high-wheeler is *higher* in the group of young men of means and nerve than in the group of elderly men."

34. The use of the concepts of interpretative flexibility and rhetorical closure in science cases is illustrated by Pinch and Bijker (1984).

35. Advertisements seem to constitute a large and potentially fruitful data source for empirical social studies of technology. The considerations that professional advertising designers give to differences among various "consumer groups" obviously fit our use of different relevant groups. See, for example, Schwartz Cowan (1983) and Bijker (this volume).

36. The concept of translation is fruitfully used in an extended way by Callon (1980b, 1981b, 1986), Callon and Law (1982), and Latour (1983, 1984).

37. A model of such a "stage 3" explanation is offered by Collins (1983a).

38. Historical studies that address the third stage may be a useful guide here. See, for example, MacKenzie (1978), Shapin (1979, 1984), and Shapin and Schaffer (1985).

The Evolution of Large Technological Systems

Thomas P. Hughes

Definition of Technological Systems

Technological systems contain messy, complex, problem-solving components. They are both socially constructed and society shaping.[1] Among the components in technological systems are physical artifacts, such as the turbogenerators, transformers, and transmission lines in electric light and power systems.[2] Technological systems also include organizations, such as manufacturing firms, utility companies, and investment banks, and they incorporate components usually labeled scientific, such as books, articles, and university teaching and research programs. Legislative artifacts, such as regulatory laws, can also be part of technological systems. Because they are socially constructed and adapted in order to function in systems, natural resources, such as coal mines, also qualify as system artifacts.[3]

An artifact—either physical or nonphysical—functioning as a component in a system interacts with other artifacts, all of which contribute directly or through other components to the common system goal. If a component is removed from a system or if its characteristics change, the other artifacts in the system will alter characteristics accordingly. In an electric light and power system, for instance, a change in resistance, or load, in the system will bring compensatory changes in transmission, distribution, and generation components. If there is repeated evidence that the investment policies of an investment bank are coordinated with the sales activities of an electrical manufacturer, then there is likely to be a systematic interaction between them; the change in policy in one will bring changes in the policy of the other. For instance, investment banks may systematically fund the purchase of the electric power plants of a particular manufacturer with which they share owners and interlocking boards of directors.[4] If courses in an engineering school shift emphasis from the study of direct current (dc) to alternating current (ac) at about the same time as the physical artifacts in power systems are changing from dc to ac, then a systematic relationship also seems likely. The professors teaching the courses may be regular consultants of utilities and electrical manufacturing firms; the alumni of the engineering schools may have become engineers and managers in the firms; and managers and engineers from the firm may sit on the governing boards of the engineering schools.

Because they are invented and developed by system builders and their associates, the components of technological systems are socially constructed artifacts. Persons who build electric light and power systems invent and develop not only generators and transmission lines but also such organizational forms as electrical manufacturing and utility holding companies. Some broadly experienced and gifted system builders can invent hardware as well as organizations, but usually different persons take these responsibilities as a system evolves. One of the primary characteristics of a system builder is the ability to construct or to force unity from diversity, centralization in the face of pluralism, and coherence from chaos. This construction often involves the destruction of alternative systems. System builders in their constructive activity are like "heterogenous engineers" (Law, this volume).

Because components of a technological system interact, their characteristics derive from the system. For example, the management structure of an electric light and power utility, as suggested by its organizational chart, depends on the character of the functioning hardware, or artifacts, in the system. In turn, management in a technological system often chooses technical components that support the structure, or organizational form, of management.[5] More specifically, the management structure reflects the particular economic mix of power plants in the system, and the layout of the power plant mix is analogous to the management structure. The structure of a firm's technical system also interacts with its business strategy.[6] These analogous structures and strategies make up the technological system and contribute to its style.

Because organizational components, conventionally labeled social, are system-builder creations, or artifacts, in a technological system, the convention of designating social factors as the environment, or context, of a technological system should be avoided. Such implications occur when scholars refer to the social context of technology or to the social background of technological change. A technological system usually has an environment consisting of intractable factors not under the control of the system managers, but these are not all

organizational. If a factor in the environment—say, a supply of energy—should come under the control of the system, it is then an interacting part of it. Over time, technological systems manage increasingly to incorporate environment into the system, thereby eliminating sources of uncertainty, such as a once free market. Perhaps the ideal situation for system control is a closed system that does not feel the environment. In a closed system, or in a system without environment, managers could resort to bureaucracy, routinization, and deskilling to eliminate uncertainty—and freedom. Prediction by extrapolation, a characteristic of system managers, then becomes less fanciful.

Two kinds of environment relate to open technological systems: ones on which they are dependent and ones dependent on them. In neither case is there interaction between the system and the environment; there is simply a one-way influence. Because they are not under system control, environmental factors affecting the system should not be mistaken for components of the system. Because they do not interact with the system, environmental factors dependent on the system should not be seen as part of it either. The supply of fossil fuel is often an environmental factor on which an electric light and power system is dependent. A utility company fully owned by an electrical manufacturer is part of a dependent environment if it has no influence over the policies of the manufacturer but must accept its products. On the other hand, ownership is no sure indicator of dependence, for the manufacturer could design its products in conjunction with the utility.[7] In this case the owned utility is an interacting component in the system.

Technological systems solve problems or fulfill goals using whatever means are available and appropriate; the problems have to do mostly with reordering the physical world in ways considered useful or desirable, at least by those designing or employing a technological system. A problem to be solved, however, may postdate the emergence of the system as a solution. For instance, electrical utilities through advertising and other marketing tactics stimulated the need for home appliances that would use electricity during hours when demand was low. This partial definition of technology as problem-solving systems does not exclude problem solving in art, architecture, medicine, or even play, but the definition can be focused and clarified by further qualification: It is problem solving usually concerned with the reordering of the material world to make it more productive of goods and services. Martin Heidegger defines technology as an ordering of the world to make it available as a "standing reserve" poised for problem solving and, therefore, as the means to an end. This challenging of man to order the world and in so doing to reveal its essence is called enframing (Heidegger 1977, p. 19).

Technological systems are bounded by the limits of control exercised by artifactual and human operators. In the case of an electric light and power system, a load-dispatching center with its communciation and control artifacts and human load dispatchers is the principal control center for power plants and for transmission and distribution lines in the system. The load-dispatching center is, however, part of a hierachical control system involving the management structure of the utility. That structure may itself be subject to the control of a holding company that incorporates other utilities, banks, manufacturers, and even regulatory agencies. An electric utility may be interconnected with other utilities to form a regional, centrally controlled electric light and power system. Regional power systems sometimes integrate physically and organizationally with coal-mining enterprises and even with manufacturing enterprises that use the power and light. This was common in the Ruhr region in the years between World War I and World War II. Systems nestle hierarchically like a Russian Easter egg into a pattern of systems and subsystems.

Inventors, industrial scientists, engineers, managers, financiers, and workers are components of but not artifacts in the system. Not created by the system builders, individuals and groups in systems have degrees of freedom not possessed by artifacts. Modern system builders, however, have tended to bureaucratize, deskill, and routinize in order to minimize the voluntary role of workers and administrative personnel in a system. Early in this century, Frederick W. Taylor's scientific-management program organized labor as if it were an inanimate component in production systems. More recently, some system builders have designed systems that provide labor with an opportunity to define the labor component of a system. The voluntary action does not come to labor as it functions in the system but as it designs its functions. A crucial function of people in technological systems, besides their obvious role in inventing, designing, and developing systems, is to complete the feedback loop between system performance and system goal and in so doing to correct errors in system performance. The degree of freedom exercised by people in a system, in contrast to routine performance, depends on the maturity and size, or the autonomy, of a technological system, as will be shown. Old systems like old people tend to become less adaptable, but systems do not simply grow frail and fade away. Large systems with high momentum tend to exert a soft determinism on other systems, groups, and individuals in society.

Inventors, organizers, and managers of technological systems mostly prefer hierarchy, so the systems over time tend toward a hierarchical structure. Thus the definer and describer of a system should delimit the level of analysis, or subsystem, of interest (Constant, this volume). For instance, interacting physical artifacts can be designated a system, or physical artifacts plus interacting organizations can be so designated. The turbogenerators in an electric power system can be seen as systems with components such as turbines and generators. These artifacts can, in turn, be analyzed as systems with components. Therefore the analyzers of systems should make clear, or at least be clear in their own minds, that the system of interest may be a subsystem as well as one encompassing its own subsystems. In a large technological system there are countless opportunities for isolating subsystems and calling them systems for purposes of comprehensibility and analysis. In so doing, however, one rends the fabric of reality and may offer only a partial, or even distorted, analysis of system behavior.

The definer or describer of a hierachical system's choice of the level of analysis from physical artifact to world system can be noticeably political. For instance, an electric light and power system can be so defined that externalities or social costs are excluded from the analysis. Textbooks for engineering students often limit technological systems to technical components, thereby leaving the student with the mistaken impression that problems of system growth and management are neatly circumscribed and preclude factors often pejoratively labeled "politics." On the other hand, neoclassical economists dealing with production systems often treat technical factors as exogenous. Some social scientists raise the level of analysis and abstraction so high that it does not matter what the technical content of a system might be.

A technological system has inputs and outputs. Often these can be subsumed under a general heading. For instance, an electric light and power system has heat or mechanical energy as its primary input and electrical energy as its output. Within the system the subsystems are linked by internal inputs and outputs, or what engineers call interfaces. An electrical-manufacturing concern in the system may take electrical energy from the utility in the system and supply generating equipment to the utility. The manufacturing concern may also take income from the profits of the utility and from sale of equipment to the utility and then reinvest in the utility. Both may exchange information about equipment performance for purposes of design and operation. An investment bank may take profits from its investments in a manufacturing company and a utility and then also invest in these enterprises. Financial and technical information about light and power systems is also interchanged. In the examples given, one assumes interlocking boards of directors and management and control.

Pattern of Evolution

Large, modern technological systems seem to evolve in accordance with a loosely defined pattern. The histories of a number of systems, especially the history of electric light and power between 1870 and 1940, display the pattern described in this chapter. The sample is not large enough, however, to allow essentially quantitative statements, such as "most" or "the majority," to be made. Relevant examples from the history of modern technological systems, many from electric light and power, support or illustrate my arguments. I also use a number of interrelated concepts to describe the pattern of evolution. The concept of reverse salient, for instance, can be appreciated only if it is related to the concept of system used in this chapter. The concept of technological style should be related to the concept of technology transfer. The term "pattern" is preferable to "model" because a pattern is a metaphor suggesting looseness and a tendency to become unraveled.

The pattern suggested pertains to systems that evolve and expand, as so many systems originating in the late nineteenth century did. With the increased complexity of systems, the number of components and the problems of control increased. Intense problems of control have been called crises of control (Beniger 1984). Large-scale computers became a partial answer. An explanation of the tendency of systems to expand is offered here. The study of systems contracting, as countless have through history, would by comparison and contrast help explain growth. Historians of systems need among their number not only Charles Darwins but also Edward Gibbons.

The history of evolving, or expanding, systems can be presented in the phases in which the activity named predominates: invention, development, innovation, transfer, and growth, competition, and consolidation. As systems mature, they acquire style and momentum. In this chapter style is discussed in conjunction with transfer, and momentum is discussed after the section on growth, competition, and consolidation. The phases in the history of a technological system are not simply sequential; they overlap and backtrack. After invention, development, and innovation, there is more invention. Transfer may not necessarily come immediately after innovation but can occur at other times in the history of a system as well. Once again, it should be stressed that invention, development, innovation, transfer, and growth, competition, and consolidation can and do occur throughout the history of a system but not necessarily in that order. The thesis here is that a pattern is discernible because of one or several of these activities predominating during the sequence of phases suggested.

The phases can be further ordered according to the kind of system builder who is most active as a maker of critical decisions.[8] During invention and development inventor-entrepreneurs solve critical problems; during innovation, competition, and growth manager-entrepreneurs make crucial decisions; and during consolidation and rationalization financier-entrepreneurs and consulting engineers, especially those with political influence, often solve the critical problems associated with growth and momentum. Depending on the degree of adaptation to new circumstances needed, either inventor-entrepreneurs or manager-entrepreneurs may prevail during transfer. Because their tasks demand the attributes of a generalist dedicated to change rather than the attributes of a specialist, the term "entrepreneur" is used to describe system builders. Edison provides a prime example of an inventor-entrepreneur. Besides inventing systematically, he solved managerial and financial problems to bring his invention into use. His heart, however, at least as a young inventor, lay with invention. Elmer Sperry, a more professional and dedicated inventor than Edison but also an entrepreneur, saw management and finance as the necessary but boring means to bring his beloved inventions into use (Hughes 1971, pp. 41, 52–53).

Invention

Holding companies, power plants, and light bulbs—all are inventions. Inventors, managers, and financiers are a few of the inventors of system components. Inventions occur during the inventive phase of a system and during other phases. Inventions can be conservative or radical. Those occurring during the invention phase are radical because they inaugurate a new system; conservative inventions predominate during the phase of competition and system growth, for they improve or expand existing systems. Because radical inventions do not contribute to the growth of existing technological systems, which are presided over by, systematically linked to, and financially supported by larger entities, organizations rarely nurture a radical invention. It should be stressed that the term "radical is not used here in a commonplace way to suggest momentous social effects. Radical inventions do not necessarily have more social effects than conservative ones, but, as defined here, they are inventions that do not become components in existing systems.

Independent professional inventors conceived of a disproportionate number of the radical inventions during the late nineteenth and early twentieth centuries (Jewkes et al. 1969, pp. 79–103). Many of their inventions inaugurated major technological systems that only later came under the nurturing care of large organizations; they then stabilized and acquired momentum. Outstanding examples of independent inventors and their radical inventions that sowed the seeds of large systems that were presided over by new organizations are Bell and the telephone, Edison and the electric light and power system, Charles Parsons and Karl Gustaf Patrik de Laval and the steam turbine, the Wright brothers and the airplane, Marconi and the wireless, H. Anschütz-Kaempfe and Elmer Sperry and the gyrocompass guidance and control system, Ferdinand von Zeppelin and the dirigible, and Frank Whittle and the jet engine.[9] Even though tradition assigns the inventions listed to these independent inventors, it should be stressed that other inventors, many of them independents, also contributed substantially to the inauguration of the new systems. For instance, the German Friedrich Haselwander, the American C. S. Bradley, and the Swede Jonas Wenström took out patents on polyphase systems at about the same time as Tesla; and Joseph Swan, the British inventor, should share credit with Edison for the invention of a durable incandescent filament lamp, if not for the incandescent lamp system.

Even though radical inventions inaugurate new systems, they are often improvements over earlier, similar inventions that failed to develop into innovations. Historians have a rich research site among the remains of these failed inventions. Elmer Sperry, who contributed to the establishment of several major technological systems, insisted that all his inventions, including the radical ones, were improvements on the earlier work of others (Sperry 1930, p. 63). The intense patent searches done by independents reinforces his point.

The terms "independent" and "professional" give needed complexity to the concept of inventor. Free from the constraints of organizations, such as industrial or government research laboratories, independent inventors can roam widely to choose problems to which they hope to find solutions in the form of inventions. Independent inventors often have their own research facilities or laboratories, but these are not harnessed to existing systems, as is usually the case with government and industrial research laboratories. Not all independent inventors are "professional"; professional inventors support their inventive activities over an extended period by a series of commercially successful inventions. They are not salaried employees, although they might take consulting fees. Many independents who were not professionals, such as Alexander Graham Bell, gained immense income from several major inventions and then chose to live, or enjoy, life other than as inventors. Elmer Sperry, Elihu Thomson, Edward Weston, Thomas Edison, and Nikola Tesla are outstanding examples of inventors who persisted as professionals for an extended period during the late nineteenth and early twentieth centuries.

The independents who flourished in the late nineteenth and early twentieth centuries tended to concentrate on radical inventions for reasons both obvious and obscure. As noted, they were not constrained in their problem choices by mission-oriented organizations with high inertia. They prudently avoided choosing problems that would also be chosen by teams of researchers and developers working in company engineering departments or industrial research laboratories. Psychologically they had an outsider's mentality; they also sought the thrill of a major technological transformation. They often achieved dramatic breakthroughs, not incremental improvements. Elmer Sperry, the independent inventor, said: "If I spend a life-time on a dynamo I can probably make my little contribution toward increasing the efficiency of that machine six or seven percent. Now then, there are a whole lot of arts that need electricity, about four or five hundred per cent, let me tackle one of those" (Sperry 1930, p. 63). To achieve these breakthroughs, the independents had the insight to distance themselves from large organizations. They rightly sensed that the large organization vested in existing technology rarely nurtured inventions that by their nature contributed nothing to the momentum of the organization and even challenged the status quo in the technological world of which the organization was a leading member. Radical inventions often deskill workers, engineers, and managers, wipe out financial investments, and generally stimulate anxiety in large organizations. Large organizations sometimes reject the inventive proposals of the radicals as technically crude and economically risky, but in so doing they are simply acknowledging the character of the new and radical.

In the 1920s several of the world's major oil companies rejected the proposals made by the French inventor Eugene Joules Houdry for a radically different way of refining gasoline with catalytic agents. The engineering staffs of the established companies justified their rejections by citing the lack of refined engineering detail and the engineering problems not solved in the process as then developed by Houdry. Apparently they did not take into account that this was indeed a characteristic common among radical inventions in the development phase. After development in the 1930s by Sun Oil Company, an innovative, relatively small independent US refiner, the Houdry process brought substantially increased yields of the gasoline fraction from a given amount of crude oil and became the envy of, and model for, the petroleum industry (Enos 1962, pp. 137, 140–141).

Independent inventors such as Houdry have more freedom but consequently more difficulty in identifying problems than inventors and scientists working in large-company engineering departments or industrial research laboratories. On several notable occasions academics stimulated the problem choices of independent inventors who flourished in the late nineteenth and early twentieth centuries. Charles Hall heard his professor of science say that the world awaited the inventor who could find a practical means of smelting aluminum; a professor at the Polytechnic in Graz, Austria, stimulated Nikola Tesla to embark on the search that culminated in his polyphase electrical system (Hughes 1983, p. 113); Professor Carl von Linde of the Munich Polytechnic defined a problem for his student Rudolf Diesel that eventually resulted in Diesel's engine (Diesel 1953, p. 97); and physics professor William A. Anthony of Cornell University outlined several problems for young Elmer Sperry that climaxed in his first major patents.[10] Perhaps the academics' imaginations ranged freely because they, like independent inventors, were not tied to industry but at the same time were broadly acquainted with technical and scientific literature.

Inventors do publish, despite widespread opinion to the contrary. They publish patents, and they often publish descriptions of their patented inventions in technical journals. The technical articles, sometimes authored by the inventors, sometimes by cooperating technical journalists, brought not only recognition but also publicity of commercial value. Whether patent or article, the publication informed the inventive community about the location of inventive activity. This alerted the community about problems that needed attention, for rarely was a patent or invention the ultimate solution to a problem, and experienced inventors realized that a basic problem could be solved in a variety of patentable ways, including their own. So, by keeping abreast of patents and publications, inventors could identify problem areas. This helps explain why patents tend over a period of several years to cluster around problem sites.

Professional inventors have other reasons for their problem choices. In avoiding problems on which engineering departments and industrial research laboratories were working, independents narrowed their problem choice. The challenge of sweet problems that have foiled numerous others often stimulates the independents' problem choices. They believe their special gifts will bring success where others have failed. Not strongly motivated by a defined need, they exhibit an elementary joy in problem solving as an end in itself. Alexander Graham Bell, a professor of elocution and an authority on deafness, seeing the analogy between acoustic and electrical phenomena, pursued the goal of a speaking telegraph despite the advice of friends and advisers who urged him to continue to concentrate on the problem of multiplexing wire telegraphy, a conservative telegraph-industry-defined problem. Another independent, Elisha Gray, who was also working on multiplexing and who also saw the possibility of a speaking telegraph, made the conservative decision and concentrated on multiplexing (Hounshell 1975).

The independent professionals had not only freedom of problem choice but also the less desirable freedom from the burden of organizational financial support. Their response has been ingenious. At the turn of the century they often traded intellectual property for money. In an era before a patent became essentially a license to litigate and before the large companies amassed the resources to involve an independent in litigation to the point of financial exhaustion, independent professionals transformed their ideas into property in the form of patents. Having done this, they sold their intellectual property to persons with other forms of property, especially money. Sometimes the inventor and the financier would each deposit so many patents and so much cash and divide the stock of a new company founded to exploit the patent. In democratic America the ability of a self-made inventor to match wits with the presumedly ill-gotten gains of financiers was believed wonderfully meritocratic.

As the armaments race, especially the naval one, increased in intensity before World War I, inventors turned to the government for development funds. These came as contracts to supply airplanes, wireless, gunfire control, and other high technology artifacts of the day. Governments contracted for a few models that were in essence experimental designs. With income from these contracts the inventors invested in further development. In order to contract with the armed services, many of the inventors allied with financiers to form small companies. The possibility existed that the company would flourish, and then the inventor would be harnessed to a burden of his own making; but many of the companies collapsed, leaving the inventor to savor independence again. The independents also raised funds by setting up as consultants or by organizing small research and development companies that would develop their own and others' inventions. Perhaps the ideal of funding and freedom came when the inventor had licensed sufficient patents over the years to bring a steadily mounting income that could be reinvested in invention. The investment was often in workshop, laboratory facilities, and staff, for contrary to myth independent inventors were not necessarily "lone" inventors.

An aspect of radical invention less understood than problem choice and funding lies at the heart of the matter: the times of inspiration or "Eureka!" moments. There exists a helpful body of literature on the psychology of invention and discovery, but it lacks richly supported and explored case histories of invention.[11] The inventors themselves have rarely verbalized their moments of inspiration. Some promising but unexplored leads to follow exist, however. Frequently, inventors speak of their inventions in terms of metaphor or analogy. An analogy is an invention that carries its creator from the known to the unknown. Inventors often develop a particular mechanism or process that they then formulate as an abstract concept, probably visual, that subsequently becomes a generalized solution. So prepared, the inventor becomes a solution looking for a problem. These clues, however, only tantalize. Historians and sociologists of technology should join psychologists in exploring the act of creation.[12]

Development

Radical inventions, if successfully developed, culminate in technological systems. One inventor may be responsible for most or all of the inventions that become the immediate cause of a technological system; the same inventor may preside over the development of the inventions until they result in an innovation, or a new technological system in use. If one inventor proves responsible for most of the radical inventions and the development of these, then he or she fully deserves the designation inventor-entrepreneur.

Development is the phase in which the social construction of technology becomes clear. During the transformation of the invention into an innovation, inventor-entrepreneurs and their associates embody in their invention economic, political, and social characteristics that it needs for survival in the use world. The invention changes from a relatively simple idea that can function in an evironment no more complex than can be constituted in the mind of the inventors to a system that can function in an environment permeated by various factors and forces. In order to do this, the inventor-entrepreneur constructs experimental, or test, environments that become successively more complex and more like the use world that the system will encounter on innovation. Elmer Sperry, for instance, having written, or having had written for him, the equations of his concept of a gyro ship stabilizer gave the concept material form in a model of a rolling ship consisting of a simple pendulum and a laboratory gyroscope. In the next step he redesigned the invention, making it more complex, and experimented with it in an environment incorporating more ship and sea variables than the simple pendulum could provide. In time the model reached a level of complexity that in Sperry's opinion allowed it to accommodate to use-world variables. He tested the ship stabilizer on a destroyer provided by the US Navy. The testing of inventions as mathematical formulas and as models stripped down to scientific abstractions permits small investments and small failures before the costly venture of full-scale trial and ultimate use is attempted.

There are countless examples of independent inventor-entrepreneurs providing their inventions with the economic, political, and other characteristics needed for survival. Edison's awareness of the price of gaslight deeply influenced his design of a competitive electric light system. In the early 1880s in England, Lucien Gaulard and John Gibbs invented a transformer with physical characteristics that allowed the transformer's output voltage to be varied as required by the Electric Lighting Act of 1882 (Hughes 1983, pp. 34–38, 89–90). The Wright brothers carefully took into account the psychology and physiology of the pilots who would have to maintain the stability of their flyer. According to David Noble, digital machine tool systems have built into them the interests of the managerial class (Noble 1979).

Because new problems arise as the system is endowed with various characteristics, radical inventor-entrepreneurs continue to invent during the development period. Because problems arise out of the systematic relationship of the system components being invented, the choice of problems during the development process becomes easier. If, for instance, during development the inventor varies the characteristics of one component, then the other interrelated components' characteristics usually have to be varied accordingly. This harmonizing of component characteristics during development often results in patentable inventions. An entire family of patents sometimes accompanies the development of a complex system.

A large organization inventing and developing a system may assign subprojects and problems to different types of professionals. When the Westinghouse Corporation developed Tesla's polyphase electric power transmission system, it used him as a consultant, but ultimately a talented group of Westinghouse engineers brought the system into use (Passer 1953, pp. 276–282). Physicists, especially academic ones, have sometimes proven more adept at invention than engineers, who often display a preference and a capability for development. Until World War II academic physicists were relatively free of organizational constraints, and during World War II this frame of mind survived, even in such large projects as the Radiation Laboratory in Cambridge, Massachusetts, the Manhattan Project laboratory in Chicago under Arthur Compton, and the Los Alamos laboratory under Robert Oppenheimer. Since the end of the nineteenth century, engineers have been associated with large industrial corporations, or, in the case of academic engineers, they have tended to look to the industrial sector for definition of research problems (Noble 1977, pp. 33–49).

The relationships between engineers and scientists and between technology and science have long held the attention of historians, especially historians of science. From the systems point of view the distinctions tend to fade. There are countless cases of persons formally trained in science and willing to have their methods labeled scientific immersing themselves fully in invention and development of technology.[13] Engineers and inventors formally trained in courses of study called science have not hesitated to use the knowledge and methods acquired. Persons committed emotionally and intellectually to problem solving associated with system creation and development rarely take note of disciplinary boundaries, unless bureaucracy has taken command.

Innovation

Innovation clearly reveals technologically complex systems. The inventor-entrepreneur, along with the associated engineers, industrial scientists, and other inventors who help to bring the product into use, often combines the invented and developed physical components into a complex system consisting of manufacturing, sales, and service facilities. On the other hand, rather than establishing a new company, the inventor-entrepreneur sometimes provides specifications enabling established firms to manufacture the product or provide the service. Many of the independent professionals of the late nineteenth and early twentieth centuries, however, founded their own manufacturing, sales, and service facilities because, in the case of radical inventions, established manufacturers were often reluctant to provide the new machines, processes, and organizations needed for manufacture. Independent inventor-entrepreneurs chose to engage in manufacture because they wanted to introduce a manufacturing process systematically related to the invention. They often invented and developed the coordinated manufacturing process as well as the product. If, on the other hand, the invention was a conservative one, in essence, an improvement in an ongoing system, the manufacturer presiding over this system would often be interested in manufacturing the invention.

George Eastman, for instance, concentrated on the invention and development of machinery for the photography devices invented by him and his partner William Hall Walker. Eastman, while developing a dry-plate system, obtained a patent in 1880 for a machine that continuously coated glass plates with gelatin emulsion. With Walker, Eastman then turned to the invention of a photographic film and a roll holder system to replace the one using glass plates. Later, Eastman concentrated on the design of production machinery while Walker directed his attention to the invention and development of cameras. In the fall of 1884 the two had developed, along with the holder mechanism and the film, the production machinery. Eastman also dedicated his inventive talents to production machinery in the development of the Kodak system of amateur photography (Jenkins 1975).

Edison also provides a classic example of the inventor-entrepreneur presiding over the introduction of a complex system of production and utilization. Edison had the assistance of other inventors, managers, and financiers who were associated with him, but he more than any other individual presided over the intricate enterprise. The organizational chart of 1882 of Edison-founded companies outlines the complex technological system. Among the Edison companies were The Edison Electric Light Company, formed to finance Edison's invention, patenting, and development of the electric-lighting system and the licensing of it; The Edison Electric Illuminating Company of New York, the first of the Edison urban lighting utilities; The Edison Machine Works, founded to manufacture the dynamos covered by Edison's patents; The (Edison) Electric Tube Company, established by Edison to manufacture the underground conductors for his system; and the Edison Lamp Works (Jones 1940, p. 41). When Edison embarked on the invention of an incadescent lighting system, he could hardly have anticipated the complexity of the ultimate Edison enterprise.

System builders, such as Eastmen and Edison, strive to increase the size of the system under their control and to reduce the size of the environment that is not. In the case of the Edison system at the time of the innovation, the utilities, the principal users of the equipment patented by The Edison Electric Light Company and manufactured by the mix of Edison companies, were being incorporated into the system. The same group of investors who owned the patent-holding company owned The Edison Electric Illuminating Company of New York, the first of the Edison urban utilities. The owners of the Edison companies accepted stock from other utilities in exchange for equipment, thereby building up an Edison empire of urban utilities variously owned and controlled. Similar policies were followed later by the large manufacturers in Germany. The manufacturers absorption of supply and demand organizations tended to eliminate the outside/inside dichotomy of systems, a dichotomy avoided by Michael Callon in his analysis of actor networks (Callon, this volume).

Once innovation occurs, inventor-entrepreneurs tend to fade from the focal point of activity. Some may remain with a successful company formed on the basis on their patents, but usually they do not become the manager-entrepreneurs of the enterprise. Elihu Thomson (1853–1937), a prolific and important American inventor who acquired 696 patents over five decades, became head of research for the Thomson-Houston Company, an electrical manufacturer founded on the basis of his patents. Afterward he served as principal researcher and inventor for the General Electric Company, formed in 1892 by a merger of Thomson-Houston and The Edison General Electric Company. Thomson's point of view remained that of an inventor, and the contrasts between it and the views of the manager-entrepreneurs taking over the General Electric Company became clear. Diplomatic negotiations on the part of managers such as Charles A. Coffin, early head of GE, reconciled the laboratory with the front office (Carlson 1983). The manager-entrepreneur, after innovation, gradually displaced the inventor as the responder to the principal reverse salients and the solver of critical problems associated with them.

Technology Transfer

The transfer of technology can occur at any time during the history of a technological system. Transfer immediately after innovation probably most clearly reveals interesting aspects of transfer, for the technological system is not laden with the additional complexities that accrue with age and momentum. Because a system usually has embodied in it characteristics suiting it for survival in a particular time and place, manifold difficulties often arise in transfer at another time or to a different environment. Because a system usually needs adaptation to the characteristics of a different time or place, the concepts of transfer and adaptation are linked. Besides adaptation, historians analyzing transfer have stressed the modes of transfer.[14]

Aspects of adaptation can be shown by episodes drawn from the early history of the transformer. As noted, Lucien Gaulard and John Gibbs introduced a transformer with characteristics that suited it to British electric lighting legislation. They organized several test and permanent installations of their transformer in the early 1880s. In 1884 Otto Titus Blàthy and Charles Zipernowski, two experienced engineers from Ganz and Company, the preeminent Hungarian electrical manufacturer, saw the transformer on exhibit in Turin, Italy. They redesigned it for a Ganz system and for Hungarian conditions, under which electrical legislation did not require the complex characteristics embodied in the Gaulard and Gibbs device. The resulting transformer has been designated the world's first practical and commercial transformer (Halacsy and Von Fuchs 1961, p. 121). But such a designation is misleading because the transformer was practical for Hungary, not for the world. In the United States the Westinghouse Company also learned of the Gaulard-Gibbs transformer, acquired the rights to the patent, and had it adapted to American conditions. Westinghouse employed William Stanley, an independent inventor, to develop a transformer system of transmission on the basis of the Gaulard-Gibbs device. Subsequently, the engineering staff at Westinghouse gave the system an American style by presuming a large market and adapting the transformer and the processes for manufacturing it for mass production (Hughes 1983, pp. 98–105).

The case of the Gaulard-Gibbs transformer reveals legislation and market as critical factors in transfer and adaptation, but there are other factors involved, including geographical and social ones (Lindqvist 1984, pp. 291–307). The Gaulard and Gibbs case involves a physical object being transferred and adapted; when a technological system is transferred, organizational components are as well. There are numerous cases of the transfer, successful and unsuccessful, of companies as well as of product so whether the agent of transfer is an inventor, an engineer, a manager, or some other professional depends on the components being transferred and the phase of development of the technological system.

Technological Style

Exploration of the theme of technology transfer leads easily to the question of style, for adaptation is a response to different environments and adaptation to environment culminates in style. Architectural and art historians have long used the concept of style. When Heinrich Wölfflin in 1915 wrote about the problem of the development of style in art, he did not hesitate to attribute style in art and architecture to individual and national character. The concept of style can, on the other hand, be developed without reference to national and racial character, or to *Zeitgeist*. Historians of art and architecture now use the concept of style warily, for "style is like a rainbow. . . . We can see it only briefly while we pause between the sun and the rain, and it vanishes when we go to the place where we thought we saw it" (Kubler 1962, p. 129).

Historians and sociologists of technology can, however, use the notion of style to advantage, for, unlike historians of art, they are not burdened by long-established and rigid concepts of style, such as those of the High Renaissance and the Baroque that can obfuscate perceptive differentiation. Historians and sociologists can use style to suggest that system builders, like artists and architects, have creative latitude. Furthermore, the concept of style accords with that of social construction of technology. There is no one best way to paint the Virgin; nor is there one best way to build a dynamo. Inexperienced engineers and laymen err in assuming that there is an ideal dynamo toward which the design community Whiggishly gropes. Technology should be appropriate for time and place; this does not necessarily mean that it be small and beautiful.[15]

Factors shaping style are numerous and diverse. After the traumatic Bolshevik Revolution of 1917 and during the shaky beginnings of the new state, the Soviets needed the largest and the fastest technology, not for economic reasons but in order to gain prestige for the regime (Bailes 1976). After comparing the gyrocompass he invented with German ones, Elmer Sperry decided that his was more practical because the Germans pursued abstract standards of performance, not functional requirements. His observation was a comment on style. Charles Merz, the British consulting engineer who designed regional power systems throughout the world, said in 1909 that "the problem of power supply in any district is . . . completely governed by local conditions" (Merz 1908, p. 4).

The concept of style applied to technology counters the false notion that technology is simply applied science and economics, a doctrine taught only a decade or so ago in engineering schools. Ohm's and Joule's laws and factor inputs and unit costs are not sufficient explanation for the shape of technology. The concepts of both the social shaping of technology and technological style help the historian and the sociologist, and perhaps the practitioner, to avoid reductionist analyses of technology.

The concept of style also facilitates the writing of comparative history. The historian can search for an explanation for the different characteristics of a particular technology, such as electric power, in different regions. The problem becomes especially interesting in this century when international pools of technology are available to the designers of regional technology because of the international circulation of patents, internationally circulated technical and scientific literature, international trade in technical goods and services, the migration of experts, technology transfer agreements, and other modes of exchange of knowledge and artifacts. Having noted the existence of an international pool of technology and having acknowledged that engineering science allows laws to be stated and equations to be written that describe an ideal, or highly abstract, electrical system made up of electromotive forces, resistances, capacitors, and inductances that are internationally valid and timeless, we come upon the fascinating problem: Why do electric light and power systems differ in characteristics from time to time, from region to region, and even from nation to nation?

There are countless examples in this century of variations in technological style. A 1920 map of electricity supply in London, Paris, Berlin, and Chicago reveals remarkable variation from city to city in the size, number, and location of the power plants (Hughes 1983, p. 16). The striking variation is not the amount of light and power generated (the output in quantitative terms) but the way in which it is generated, transmitted, and distributed. (Focusing on the quantitative, the economic historian often misses variations in style.) Berlin possessed about a half dozen large power plants, whereas London had more than fifty small ones. The London style of numerous small plants and the Berlin style of several large ones persisted for decades. London, it must be stressed, was not technically backward. In the London and Berlin regulatory legislation that expressed fundamental political values rests the principal explanation for the contrasting styles. The Londoners were protecting the traditional power of local government by giving municipal boroughs authority to regulate electric light and power and the Berliners were enhancing centralized authority by delegating regulatory power to the City of Berlin (Hughes 1983, pp. 175–200, 227–261).

Natural geography, another factor, also shapes technological style. Because regions as traditionally defined are essentially geographical and because geography so deeply influences technology, the concept of regional technological style can be more easily identified than national style. When regulatory legislation applies on a national level, however, regional styles tend to merge into national ones. Before 1926 and the National Grid in Great Britain, for example, there were distinctive regional styles of power systems—London in contrast to the northeast coast; but the grid brought a more national style as legislation prevailed over other style-inducing factors.

Regional and national historical experiences also shape technological style. During World War I a copper shortage in Germany caused power plant designers to install larger and fewer generators to save copper. This learning experience, or acquired design style, persisted after the war, even though the critical shortage had passed. After World War I the Treaty of Versailles deprived Germany of hard-coal-producing areas and demanded the export of hard coal as reparations, so the electric power system builders turned increasingly to soft coal, a characteristic that also persisted after the techniques were learned. Only history can satisfactorily explain the regional style of Ruhr and Cologne area power plants with their post–World War I dependence on lignite and large generating units (Hughes 1983, pp. 413–414).

Technological style is a concept applicable to technologies other than electric light and power and useful to professionals other than historians. Louis Hunter pointed out fascinating contrasts between Hudson River and Mississippi River steamboats (Hunter 1949). Eda Kranakis has written about the French "academic style" of engineering (Kranakis 1982, pp. 8–9), and Edwin Layton has contrasted the US and the French approaches to water-turbine design in the nineteenth century (Layton 1978). In the 1950s the American public became familiar with contrasting American and European styles of automobiles and even with Soviet and US space vehicles of contrasting designs.[16] Recently, Mary Kaldor identified a Baroque style of military technology—in the twentieth century (Kaldor 1981). Aware of the richness and complexity of the concept of style and the possibility of using it to counter reductionist approaches to engineering design, Hans Dieter Hellige has urged the introduction of style into the education of engineers (Hellige 1984, pp. 281–283).

Growth, Competition, and Consolidation

Historians of technology describe the growth of large systems but rarely explore in depth the causes of growth. Explanations using such concepts as economics of scale and such motives as the drive for personal power and organizational aggrandizement can mask contradictions. If by economies of scale one means the savings in material and heat energy that come from using larger containers, such as tanks, boilers, and furnaces, then the economy can be lost if the larger container is not used to capacity. If by economy of scale one simply refers to the number of units produced or serviced, then plant or organization capacity and the spread of the output over time are not taken into account and economy is not adequately measured. For instance, a power plant scaled up to generate twice as many kilowatt-hours per month would increase its unit cost if the increased load were concentrated during a few peak load hours a day. If a larger organization is assumed to bring greater influence and control for the managers, then the distinct possibility that individual initiative will be lost in bureaucratic routine is ignored. Long ago, Leo Tolstoy argued in *War and Peace* that the overwhelming momentum of the huge French army and the image of the all-powerful and victorious Emperor gave Napoleon during the invasion of Russia less freedom of action than the common foot soldier. Small firms and armies are not as likely to smother initiative.

Some designers of technological systems have taken these contradictions into account. Designers of electric power plants decide whether to build a large plant or to construct a number of smaller ones over an extended time. The latter choice often matches growing capacity to increasing load. Utility managers and operators also manage the load to avoid extreme peaks and valleys in output that signify unused capacity. In the past managers of small electric utilities often fought the absorption of their systems by larger ones because they anticipated that in the larger organization bureaucracy would reduce their exercise of authority. The small, technically advanced, and profitable power plants and utilities that flourished in London from about 1900 to the implementation of the National Grid after 1926 give evidence that large-scale output and organizational size are not necessary for profitability and personal power (Hughes 1983, pp. 259–360). Most of the top managers of the small utilities that have been absorbed into larger ones were destined to play subordinate roles in the bureaucratic recesses of middle management.

Yet in modern industrial nations technological systems tend to expand, as shown by electric, telephone, radio, weapon, automobile production, and other systems. A major explanation for this growth, and one rarely stressed by technological, economic, or business historians, is the drive for high diversity and load factors and a good economic mix. This is especially true in twentieth century systems in which accountants pay close attention to, and managers are informed about, interest on capital investment. The load factor, a concept now applied to many systems, originated in the electrical utility industry in the late nineteenth century. The load factor is the ratio of average output to the maximum output during a specified period. Best defined by a graph, or curve, the load factor traces the output of a generator, power plant, or utility system over a twenty-four-hour period. The curve usually displays a valley in the early morning, before the waking hour, and a peak in the early evening, when business and industry use power, homeowners turn on lights, and commuters increase their use of electrified conveyance. Showing graphically the maximum capacity of the generator, plant, or utility (which must be greater than the highest peak) and tracing the load curve with its peaks and valleys starkly reveal the utilization of capacity. Because many technological systems now using the concept are capital intensive, the load curve that indicates the load factor, or the utilization of investment and the related unit cost, is a much relied on indicator of return on investment.

The load factor does not necessarily drive growth. A small technological system can have a high load factor, for example, if the load, or market, for output is diversified. The load of an electric power system becomes desirably diverse if the individual consumers make their peak demands at different times, some in the late evening, some in the early morning, and so on. When this is not the case, the managers of a technological system try to expand the system in order to acquire a more desirable load or diversity. The load can also be managed by differential pricing to raise valleys and lower peaks. In general, extension over a larger geographical area with different industrial, residential, and transportation loads provides increased diversity and the opportunity to manage the load to improve the load factor. During the twentieth century expansion for diversity and management for a high load factor have been prime causes for growth in the electric utility industry. The load factor is, probably, the major explanation for the growth of capital-intensive technological systems in capitalistic, interest-calculating societies.[17]

The managers of electric power systems also seek an improved economic mix. This results, for instance, in the interconnection of a power plant located in the plains near coal mines with another in

distant high mountains. The Rheinisch-Westfälisches Elektrizitätswerk, a utility in the Ruhr Valley of Germany, expanded in the 1920s hundreds of miles until the system reached the Alps in the south. Then, after the spring thaws, it drew low-cost hydroelectric power from the Alps and at other times from the less economical coal-fired plants of the Ruhr. The outputs of the regional plants could also be mixed, the less efficient carrying the peak loads on the system and the more economical carrying a steady base load. The intellectual attraction—the elegant puzzle-solving aspect—that the load factor, economic mix, and load management had for the engineer-managers of rapidly expanding electric power systems becomes understandable. For those more concerned with the traditional drive for power and profit, elegant problem solving was coupled with increased profits, market domination, and organization aggrandizement.

As the systems grew, other kinds of problem developed, some of which can be labeled "reverse salients." Conservative inventions solved these problems, whereas radical ones brought the birth of systems. A salient is a protrusion in a geometric figure, a line of battle, or an expanding weather front. As technological systems expand, reverse salients develop. Reverse salients are components in the system that have fallen behind or are out of phase with the others. Because it suggests uneven and complex change, this metaphor is more appropriate for systems than the rigid visual concept of a bottleneck. Reverse salients are comparable to other concepts used in describing those components in an expanding system in need of attention, such as drag, limits to potential, emergent friction, and systemic efficiency. In an electrical system engineers may change the characteristics of a generator to improve its efficiency. Then another component in the system, such as a motor, may need to have its characteristics—resistance, voltage, or amperage—altered so that it will function optimally with the generator. Until that is done, the motor remains a reverse salient. In a manufacturing system one productive unit may have had its output increased, resulting in all the other components of the system having to be modified to contribute efficiently to overall system output. Until the lagging components can be altered, often by invention, they are reverse salients. During the British Industrial Revolution, observers noted such imbalances in the textile industry between weaving and spinning, and inventors responded to the reverse salients by inventions that increased output in the laggard components and in the overall system. In a mature, complex technological system the need for organization may often be a reverse salient. In the 1920s manager-entrepreneurs saw the need for an organizational form that could preside over the construction, management, and financing of horizontally and vertically integrated utilities. The invention of an appropriate holding-company form corrected the reverse salient.

Entrepreneurs and organizations presiding over expanding systems monitor the appearance of reverse salients, sometimes identifying them by cost-accounting techniques. Having identified the reverse salients, the organization assigns its engineering staff or research laboratory to attend to the situation, if it is essentially one involving machines, devices, processes, and the theory and organized knowledge describing and explaining them. The staff or laboratory has the communities of technological practitioners possessing the traditions of relevant practice (Constant, this volume). Communities of inventors congregate at reverse salient sites, for a number of companies in an industry may experience the reverse salient at about the same time. The inventors, whether engineers or industrial scientists, then define the reverse salient as a set of critical problems, which when solved will correct it. Reverse salients emerge, often unexpectedly; the defining and solving of critical problems is a voluntary action. If the reverse salient is organizational or financial in nature, then the individuals or communities of practictioners who attack the problem may be professional managers or financiers who come forth with their inventive solutions. In each stage in the growth of the system the reverse salients elicit the emergence of a sequence of appropriate types of problem solver—inventors, engineers, managers, financiers, and persons with experience in legislative and legal matters (Hughes 1983, pp. 14–17).

Industrial research laboratories, which proliferated in the first quarter of this century, proved especially effective in conservative invention. The laboratories routinized invention. The chemist Carl Duisberg, a director of Bayer before World War I, aptly characterized the inventions of industrial research laboratories (*Etablissementserfindungen*) as having "Von Gedankenblitz keine Spur" (no trace of a flash of genius) (Van den Belt and Rip, this volume). Unfortunately for the understanding of technological change, the public relations departments and self-promoting industrial scientists persuaded the public, managers, and owners that industrial laboratories had taken over invention from independent inventors because the independents were less effective. Considerable evidence shows, to the contrary, that radical inventions in disproportionate number still come from the independents.[18] A mission-oriented laboratory tied to an industrial corporation or government agency with vested interest in a growing system nurtures it with conservative improvements or with inventions that are responses to reverse salients.

The early problem choices of the pioneer industrial laboratories suggest this rigid commitment to conservative inventions and relative disinterest in radical ones. After the Bell Telephone System in 1907 consolidated its research activities in the Western Electric Company and in American Telephone & Telegraph, its staff of scientists and engineers concentrated on reverse salients that arose out of the decision to build a transcontinental telephone line. Attenuation, or energy loss, proved a major reverse salient. The invention of the loading coil reduced attenuation. By 1911 the introduction of improved repeaters for transmission lines became a major problem for the research and development staff.[19] Reverse salients in electric light and power systems attacked by engineers and scientists at the General Electric Research Laboratory at about the time of its founding in 1900 included improved filaments and vacuum for incandescent lamps and improvements in mercury vapor lamps. Even Irving Langmuir, a distinguished GE scientist who was given exceptional freedom in his choice of research problems, did not neglect highly practical problems encountered by the General Electric Company as it expanded its product lines. Willis R. Whitney, laboratory director, pursued the policy of "responsiveness to business needs" (Wise 1980, p. 429).

When a reverse salient cannot be corrected within the context of an existing system, the problem becomes a radical one, the solution of which may bring a new and competing system. Edward Constant has provided an example of the emergence of a new system out of an established one in which a "presumptive anomaly" was identified. Constant states that presumptive anomalies occur when assumptions derived from science indicate that "under some future conditions the conventional system will fail (or function badly) or that a radically different system will do a much better job" (Constant 1980, p. 15). A presumptive anomaly resembles a presumed reverse salient, but Constant rightly stresses the role of science in identifying it. A notable presumptive anomaly emerged in the late 1920s when insights from aerodynamics indicated that the conventional piston engine–propeller system would not function at the near-sonic speeds foreseen for airplanes. The inventors Frank Whittle, Hans von Ohain, Herbert Wagner, and Helmut Schelp responded with the turbojet engine, the first three working as independents when they conceived of the new engine (Constant 1980, pp. 194–207, 242).

Edison and others presiding over the growth of the dc electric lighting system in the early 1880s failed to solve a reverse salient and saw other inventors and engineers respond to it with radical inventions that inaugurated the ac system. A "battle of the systems" then ensued between the two, culminating in the 1890s, not with victor and vanquished, but with the invention of devices making possible the interconnection of the two systems. These motor-generator sets, transformers, and rotary converters interconnected heterogeneous[20] loads, such as incandescent lamps, arc lamps, induction motors for industry, dc motors for streetcars, or trams, into a universal system[21] supplied by a few standardized polyphase generators and linked by high-voltage transmission and low-voltage distribution lines. The design and installation of universal power systems in the 1890s is comparable to the introduction by AT&T a decade or so later of a universal telephone network and is similar to the recent design by computer manufacturers of large interconnections for diverse systems. These physical linkages were accompanied by the organizational linkages of utilities and manufacturers who had nurtured the competing systems. The Thomson-Houston Company, with its ac system, merged in 1893 with the Edison General Electric Company with its dc system.[22] Consolidation of electric light and power systems occurred throughout the industrial world until the interwar period, when two large manufacturers in the United States (General Electric and Westinghouse) and two in Germany (Allgemeine Elektrizitäts-Gesellschaft and Siemens) dominated electrical manufacturing. Similarly, large regional utilities prevailed in electrical supply. At about the same time industry-wide standardization of technical hardware created, for instance, standard voltages, frequencies, and appliance characteristics. Similar mergers and standardization took place in the telephone and automobile-production systems during the early twentieth century.

Momentum

Technological systems, even after prolonged growth and consolidation, do not become autonomous; they acquire momentum. They have a mass of technical and organizational components; they possess direction, or goals; and they display a rate of growth suggesting velocity. A high level of momentum often causes observers to assume that a technological system has become autonomous.[23] Mature systems have a quality that is analogous, therefore, to inertia of motion. The large mass of a technological system arises especially from the organizations and people committed by various interests to the system. Manufacturing corporations, public and private utilities, industrial and government research laboratories, investment and banking houses, sections of technical and scientific societies, departments in educational institutions, and regulatory bodies add greatly to the momentum of modern electric light and power systems. Inventors, engineers, scientists, managers, owners, investors, financiers, civil servants, and politicians often have vested interests in the growth and durability of a system. Communities of practitioners, especially engineers maintaining a tradition of technological practice, sometimes avoid deskilling by furthering a system in which they have a stake (Constant, this volume). Actor networks, as defined by Michel Callon, add to system momentum (Callon, this volume). Concepts related to momentum include vested interests, fixed assets, and sunk costs.

The durability of artifacts and of knowledge in a system suggests the notion of trajectory,[24] a physical metaphor similar to momentum. Modern capital-intensive systems possess a multitude of durable physical artifacts. Laying off workers in labor-intensive systems reduces momentum, but capital-intensive systems cannot lay off capital and interest payments on machinery and processes. Durable physical artifacts project into the future the socially constructed characteristics acquired in the past when they were designed. This is analogous to the persistence of acquired characteristics in a changing environment.[25]

The momentum of capital-intensive, unamortized artifacts partially explains the survival of direct current after the "battle of the systems," despite the victory of the competing alternating current. The survival of high-temperature, high-pressure, catalytic-hydrogenation artifacts at the German chemical firm of Badische Anilin- und Soda-Fabrik (BASF) from about 1910 to 1940 offers another example of momentum and trajectory (Hughes 1969). In the BASF case a core group of engineers and scientists knowledgeable about the hydrogenation process through the design of nitrogen-fixation equipment during World War I subsequently deployed their knowledge and the equipment in the production of methanol during the Weimar period and of synthetic gasoline during the National Socialist decade.

From 1910 to 1930 system builders contributed greatly to the momentum of electric light and power systems in the industrialized West. Combining complex experiences and competence, especially in engineering, finance, management, and politics, Hugo Stinnes, the Ruhr magnate, Emile and Walther Rathenau, the successive heads of Germany General Electric (AEG), and Oskar von Miller, who helped create the Bayernwerk, the Bavarian regional utility, built large German systems. Walter von Rathenau, who was especially fascinated by the aesthetics of system building, said approvingly in 1909 that "three hundred men, all acquainted with each other [of whom he was one], control the economic destiny of the Continent" (Kessler 1969, p. 121). In 1907 his AEG system was "undoubtedly the largest European combination of industrial units under a centralized control and with a centralized organization." In Great Britain consulting engineer Charles Merz presided over the growth of the country's largest electric supply network, the Northeastern Electric Supply Company. In the United States Samuel Insull of Middle West Utilities Company, S. Z. Mitchell of Electric Bond and Share, a utility holding company associated with General Electric, and Charles Stone and Edwin Webster of Stone & Webster ranked among the leading system designers.

Stone and Webster's became an exemplary system. Just graduated from the Massachusetts Institute of Technology in 1880, they founded a small consulting engineering company to advise purchasers of electric generators, motors, and other equipment. Knowing that the two young men were expert in power plant design and utility operation, J. P. Morgan, the investment banker, asked them to advise him about the disposition of a large number of nearly defunct utilities in which he had financial interest. From the study of them, Stone and Webster identified prime and widespread reverse salients throughout the utility industry and became expert in rectifying them. Realizing that money spent prudently on utilities whose ills had been correctly diagnosed often brought dramatic improvement and profits, Stone and Webster in about 1910 were holistically offering to finance, construct, and manage utilities. As a result, a Stone and Webster system of financially, technically, and managerially interrelated utilities, some even physically interconnected by transmission lines, operated in various parts of the United States. In the 1920s Stone and Webster formed a holding company to establish closer financial and managerial ties within the system (Hughes 1983, pp. 386–391). Similar utility holding companies spread throughout the Western world. Some involved the coal-mining companies supplying fuel for the power plants in the system; others included electrical manufacturers making equipment for the utilities. Others established linkages through long-term contractural relations, interlocking boards of directors, and stock purchases with manufacturing firms and transportation companies that were heavy consumers of electricity. In Germany local government sometimes shared the ownership of the utilities with private investors. Brought into the system, thereby, local government became both regulator and owner.

Such mammoth, high-momentum systems were not limited to the electrical utility field. The system of automobile production created by Henry Ford and his associates provides a classic example of a high-momentum system. Coordinated to ensure smooth flow from raw material to finished automobile ready for sale, interconnected production lines, processing plants, raw material producers, transportation and materials-handling networks, research and development facilities, and distributors and dealers made up the Ford system. Interconnection of production and distribution into systems with high flow or throughput also took place in the chemical industry early in this century.[26]

The high-momentum systems of the interwar years gave the appearance of autonomous technology. Because an inner dynamic seemed to drive their course of development, they pleased managers who wished to reduce uncertainty and engineers who needed to plan and design increased system capacity. After 1900, for instance, the increasing consumption of electricity could be confidently predicted at 6 percent annually. Such systems appeared to be closed ones, not subject to influence from external factors or from the environment. These systems dwarfed the forces of the environment not yet absorbed by them. Subject to the power brokering, the advertising, and the money influence of the system, those who controlled forces in the environment took on the values and objectives of the system.

Appearances of autonomy have proved deceptive. During and immediately after World War I, for instance, the line of development and the characteristics of power systems in England changed appreciably. Before the war the British systems were abnormally small compared to those in the United States and industrial Germany. Utility operators elsewhere called the British system backward. In fact, the British style accorded nicely with prevailing British political values and the regulatory legislation that expressed them. Traditionally, the British placed a high value on the power of local government, especially in London, and electrical utilities were bound within the confines of the small political jurisdictions.[27] World War I in particular and the increasingly apparent loss of industrial preeminence in general brought into question the political and economic values long prevalent in Great Britain. During the war Parliament overrode local government sensibilities and forced interconnection of small electrical systems to achieve higher load factors and to husband scarce resources. With victory the wartime measures could have been abandoned, but influential persons questioned whether the efficiency achieved during the war was not a prerequisite for industrial recovery in peacetime. As a result, in 1926 technological change in electric power systems was given a higher priority than tradition in local government. Parliament enacted legislation that created the first national interconnection, or grid. The political forces that were brought to bear more than matched the internal dynamic of the system.

After World War II, utility managers, especially in the United States, wrongly assumed that nuclear power reactors could easily be incorporated in the pattern of system development. Instead, nuclear power brought reverse salients not easily corrected. Since World War II changes such as the supply of oil, the rise of environmental protection groups, and the decreasing effectiveness of efficiency-raising technical devices for generating equipment have all challenged the electrical utility managers' assumptions of momentum and trajectory.

These instances, in which the momentum of systems was broken, remind historians and sociologists to use such concepts and patterns of envolving systems as heuristic aids and system managers to employ them cautiously as predictive models. Momentum, however, remains a more useful concept than autonomy. Momentum does not contradict the doctrine of social construction of technology, and it does not support the erroneous belief in technological determinism. The metaphor encompasses both structural factors and contingent events.

Conclusion

This chapter has dealt with the patterns of growing or evolving systems. Countless other technological systems in history have arrived at a stage of stasis and then entered a period of decline.[28] In the nineteenth century, for instance, the canal and gas light systems moved into stasis and then decline. Historians and sociologists of technology should also search for patterns and concepts applicable to these aspects of the history of technological systems.

Notes

The Wissenschaftszentrum (Berlin) and the Wissenschaftskolleg zu Berlin provided support for the preparation of this chapter, which is part of a long-term study of technological change.

1. The concept of technological system used in this essay is less elegant but more useful

to the historian who copes with messy complexity than the system concepts used by engineers and many social scientists. Several works on systems, as defined by engineers, scientists, and social scientists, are Ropohl (1979), von Bertalanffy (1968), and Parsons (1968). For further references to the extensive literature on systems, the reader should refer to the Ropohl and the Bertalanffy bibliographies. Among historians, Bertrand Gille has used the systems approach explicitly and has applied it to the history of technology. See, for instance, his *Histoire des techniques* (1978).

2. In this chapter "technical" refers to the physical components (artifacts) in a technological system.

3. A coal mine is analogous to the wind in John Law's Portuguese network, for the winds are adapted by sails for use in the system. See Law (this volume).

4. Most of the examples of systems in this essay are taken from my *Networks of Power* (1983). For the relation between investment organizations and electrical manufacturers, for instance, see pp. 180–181 and 387–403 of that book.

5. I am grateful to Charles Perrow of Yale University for cautioning me against acceptance of the contingency theory of organization, which holds that an organization simply reflects the pattern of hardware, or artifacts, in a system. Perrow has contributed to the clarification of other points in this essay.

6. In contrast to Alfred D. Chandler, Jr. (1966, pp. 15–19), who locates technological (technical) changes as part of a context, including population and income, within which an organization develops strategy and structure, I have treated technical changes as part of a technological system including organizations. Borrowing from architectural terminology, one can say not only that in a technological system organizational form follows technical function but also that technical function follows organizational form.

7. The manufacturer, Allgemeine Elektrizitäts-Gesellschaft and the utility Berliner Electrizitäts-Werke were linked by ownership and cooperated systematically in design and operation of apparatus (Hughes 1983, pp. 175–200).

8. For an extended set of cases histories supporting the phase and system builder sequence suggested, see my *Networks of Power* (1983).

9. Existing telephone and telegraph companies played a minor role in the early history of the wireless; existing compass makers did not take up the gyrocompass; and existing aircraft manufacturers provided little support for early turbojet inventive activities.

10. Anthony told Sperry that there was a need for an automatically regulated constant-current generator (Hughes 1971, p. 16).

11. See, for instance, Arieti (1976) and the appended bibliography.

12. Arthur Koestler provides imaginative insights in *The Act of Creation* (1964). Arieti (1976) is also stimulating.

13. See, for example, Hoddeson (1981), Wise (1980), and Hughes (1976b). For an analysis of positions taken in the journal *Technology and Culture*, see Staudenmaier (1985, pp. 83–120).

14. An issue of *Technikgeschichte* (1983, vol. 50, no. 3) with articles by Ulrich Troitzsch, Wolfhard Weber, Rainer Fremdling, Lars U. Scholl, Ulrich Wengenroth, Wolfgang Mock, and Han-Joachim Braun, who has written often on transfer, is given over to *Technologietransfer im 19. und 20. Jahrhundert.*

15. Compare the concept of technological frame proposed by Bijker (this volume).

16. I am indebted to Edward Constant for information on style in automobiles and to Alex Roland for information on contrasting styles of Soviet and US space technology.

17. For a further discussion of load— and diversity—factors, see Hughes (1983, pp. 216–222). Alfred Chandler labels a similar but less graphic concept applied to manufacturing and chemical industries as "throughput" (1977, p. 241).

18. Jewkes et al. (1969) persuasively argue the case for the independents in the past and present.

19. For more on invention (conservative) and the expanding telephone system, see Hoddeson (1981).

20. See Law (this volume) on heterogeneous entities and engineers.

21. I am indebted to Robert Belfield for the concept of universal system, which he encountered in the Charles F. Scott papers at Syracuse University.

22. On the "battle of the systems," see Hughes (1983, pp. 106–135). See also Bijker (this volume).

23. Langdon Winner (1977) has analyzed the question of whether or not technology is autonomous. For a sensible discussion of the questions of autonomy and technological determinism, see the introduction to MacKenzie and Wajcman (1985, pp. 4–15).

24. For a discussion of trajectory, see Van den Belt and Rip (this volume).

25. Edward Constant has explored and explained communities of practitioners. See, for instance, his chapter in this volume.

26. A recent study of the Ford and other systems of production is provided by Hounshell (1984). Chandler (1977) analyzes and describes the integration of production and distribution facilities in several industries, including the chemical industry.

27. For an extended account of the electric utility situation in Great Britain before and after World War I, see Hughes (1983, pp. 227–261, 319–323, 350–362).

28. I am indebted to Richard Hirsh of Virginia Polytechnic Institute and State University for calling my attention to stasis in the post–World War II electrical utilities. Hirsh explores the concept in his unpublished manuscript, "Myths, Managers, and Megawatts: Technological Stasis and Transformation in the Electric Power Industry."

Society in the Making: The Study of Technology as a Tool for Sociological Analysis

Michel Callon

Social scientists, whether they are historians, sociologists, or economists, have long attempted to explain the scope, effects, and conditions of the development of technology. They consider technology a specific object that presents a whole range of problems that these experts have tried to solve using a series of different methods available to the social sciences.[1] But at no point have they judged that the study of technology itself can be transformed into a sociological tool of analysis. The thesis to be developed here proposes that this sort of reversal of perspective is both possible and desirable. Not only would it enlarge the methodological range of the social sciences but it would also facilitate the understanding of technological development. To bring this reversal about, I show that engineers who elaborate a new technology as well as all those who participate at one time or another in its design, development, and diffusion constantly construct hypotheses and forms of argument that pull these participants into the field of sociological analysis. Whether they want to or not, they are transformed into sociologists, or what I call engineer-sociologists.

Seeing the process of technological innovation and the role played by engineers in this way defies certain accepted ideas. By taking this perspective I am not simply repeating the already countless criticisms of the notion of innovation as a linear process. This notion describes technological development as a succession of steps from the birth of an idea (invention) to its commercialization (innovation) by way of its development. Everyone now recognizes that the to and fro's or coupling processes that continuously occur between technology and the market are extremely important.[2] Nor in this chapter do I challenge the notion that claims that the role and importance of financial backing or organizational structure varies considerably between periods of elaboration and development of an innovation.[3] What I am questioning here is the claim that it is possible to distinguish during the process of innovation phases or activities that are distinctly technical or