[14]

ORGANIZATIONAL DETERMINANTS OF TECHNOLOGICAL CHANGE:

TOWARD A SOCIOLOGY OF TECHNOLOGICAL EVOLUTION

Michael L. Tushman and Lori Rosenkopf

ABSTRACT

This paper employs organization literature and concepts to help understand the nature of path of technological progress. Our premise is that since technological progress is underdetermined by factors internal to the technology, it is the interaction of technical options with organization and interorganization dynamics that shapes the actual path of technological progress. Rather than reviewing technology as an autonomous force or as driven by an elite set of organizations, we argue that technologies evolve through the combination of random events, the direct action of organizations shaping industry standards, and the invisible hand of multiple competing organizations in a technological community. We suggest that the greater a product's technical uncertainty, the greater the intrusion of non-technical factors in the product's evolution. Two fundamental factors shape technological uncertainty: the stage of the technology's evolutionary cycle and uncertainty: the stage of the technology's evolutionary cycle and the technological complexity of the product itself. During periods of

Research in Organizational Behavior, Vol. 14, pages 311-347.

ISBN: 1-55938-242-2.

technological ferment, uncertainty is substantial. During these periods, organizational and interorganizational processes emerge to close on industry standards. Technological uncertainty is, however, minimized during periods of incremental technical change. We also suggest that technology can be described as systems ranging from non-assembled closed systems to complex, open systems. The more complex a product, the greater the number of subsystems, interfaces, dimensions of merit and linking requirements. The more complex and/or open the product, the greater the technical uncertainty and the greater the intrusion of organizational dynamics in technological evolution. Technological cycles and complexity together affect the relative importance of organizational processes in shaping the path of technological change. As technology is an ever more important determinant of organization outcomes, the time is ripe to open up the black box of technological evolution; to use organization theory and research to understand the social, political, and organizational roots of technological change.

Organization theory has long considered technology and technological change as influential determinants of organizational phenomena (e.g., Perrow, 1967; Thompson, 1967; Woodward, 1965). There is extensive literature on the effects of technology on organizations at the individual (Hulin & Roznowski, 1985), organization (Burkhardt & Brass, 1990), population (Tushman & Anderson, 1986) and community (Astley, 1985) levels of analysis. While we have extensive knowledge of the effects of technology on organizations, we know very little about the determinants of technology (Tushman & Nelson, 1990). Technology is treated as a black box—as either a contextual fact or as an outcome of stochastic processes driven by unpredictable individual genius (Arthur, 1988; Rosenberg, 1982). This primitive view of technology minimizes the impacts that organizations have on technological progress and, in turn, stunts theory and research on innovation processes within organizations, industries and communities[1] (Astley & Fombrun, 1983).

This paper's purpose is to get inside the black box of technological change. Our premise is that technological progress is underdetermined by factors internal to the technology. It is the interaction of technical options with organization and interorganization dynamics that shapes the actual path of technological progress. We borrow from sociology history of technology, economics, and organization theory to build a community-level model of technological progress and a systems perspective on technology. We explore the relative impacts of chance, individual genius, as well as organization and interorganization action in shaping technological change. We find that at critical junctures, organization action (and inaction) dramatically affects the shape and direction of technological change. This approach to technological change suggests that technological evolution is driven by a combination of technical, economic, social, political, and organizational processes and, as such, deserves more sustained attention from organizational scholars.

Both scientific and technological progress are affected by social and organizational dynamics. Historians and sociologists of science and technology find that the conduct of scientific and technological progress is not coldly rational, but is infused with value (Constant, 1987; Kuhn, 1962). Science is drive by core norms and values that are carried, interpreted and defined by the community of scientific practitioners. Discipline oriented scientists define locally agreed on status distinctions, problem areas, methodologies, and legitimate solutions (Crane, 1972; Kuhn, 1962; Merton, 1973).

Social dynamics are accentuated in technological change because of the underlying nature of technology. Unlike science, technology almost always involves interdependence between disciplines (Laudan, 1984). For example, where physics is executed by interactions among physicists, jet engines require interactions between aerodynamic, metallurgical, combustion, and mechanical engineers. The conduct of technological evolution involves more uncertainty and dissensus as there are normative and knowledge based differences across engineering and scientific functions.

Further, the nature of satisficing is different between science and technology. Where science is focused on understanding some phenomena, technology is focused on doing a task in a given context (Constant, 1987, 1989). Where criteria for satisficing in science are defined within disciplines, technology must satisfy cross-disciplinary performance and sociopolitical contextual criteria. Thus those engineers developing digital switches must satisfy electrical, mechanical, and computer science constraints, constraints embedded in the telephone network and sociopolitical constraints in the community. As the network of interdependencies is more complex in technology than science, technological progress involves a greater array of uncertainties than science. These complex uncertainties associated with technological progress can only be adjudicated by social, political, and organizational dynamics at the community level. Given the underlying nature of technology, technological progress can be seen as driven by interdisciplinary and interorganizational community dynamics and by the systemic nature of the technology itself.

This paper is organized into four sections. The first section provides several examples of the phenomenon of technological change and the intrusion of nontechnical factors in technological evolution. The second section explores technology as an outcome of community dynamics. We build a model of technical change that is driven by sociocultural processes of variation, selection, and retention. Technical change is driven by both random technological jolts and by social, political, and organizational action in adjudicating between alternative technical regimes. Selection of an industry standard, in turn, anchors a period of incremental technical progress. This period of incremental, puzzle-solving, technical progress enhances the community's competence within the technical paradigm but stunts openness to technical approaches outside the paradigm.

The third section explores technology as systems composed of component and linking technologies. Technological progress occurs at the subsystem and system levels of analysis and is shaped by both technical capabilities and by the actions of technical practitioners constrained by suppliers, customers and the larger socioeconomic community. The more complex the system, the greater the technical uncertainties, and the greater the impact of sociopolitical processes in shaping technical advance. Thus, while the technical system itself may suggest logical evolutionary paths, as the system gains complexity, nontechnical forces weigh more heavily on the process of technological evolution.

In the final section, we synthesize our community and systems perspectives on technological evolution. If the evolution of technological systems is fundamentally underdetermined by technical forces, then it is the interaction of community dynamics with technological systems that should interest students of organizations and technology. By viewing the process of technological change as determined through the interaction of communities and technical systems, we can begin to identify hierarchies of actors shaping technological evolution and in turn, deepen our understanding of the sociology of technological evolution.

ON THE NATURE OF TECHNOLOGICAL EVOLUTION

Consider these examples of technological evolution:

1. In cement manufacture, there were four revolutionary technological advances between 1890 and 1980 (Anderson & Tushman, 1990). In each case, new technology substituted for the prior technology, and resulted in new industry standards, within eight years. Similarly, in container glass, there were four technological discontinuities between 1893 and 1950. As in cement, in each case the new technology substituted for the prior technology and resulted in new industry standards within 15 years of the discontinuity (Anderson & Tushman, 1990). In each industry, competence-destroying discontinuities were initiated by new entrants while competence-enhancing discontinuities were initiated by a combination of veterans and new entrants. In the American photographic industry, technological progress between 1839 and 1925 was characterized by four technological discontinuities which demarked different periods of incremental technical change. In these industries, the breakthrough technology quickly substituted for the prior film technology, and was initiated by firms outside the existing film industry (Jenkins, 1975).
2. In the diagnostic imaging industry there were at least four competing technologies between 1963-1973 (X-ray, nuclear, sound, computed tomography). In this product class there was technological uncertainty within and between each diagnostic mode (Mitchell, 1989). Within ultrasound alone,

no clear technical regime dominated relevant dimensions of merit. In the absence of a technologically dominant regime, negotiations between powerful producers and users led to the emergence of CT scanners as the dominant technological form through the early 1970s (Yoxen, 1987).

At the turn of the century, the choice between gas, electric and steam technologies for automobile engines could not be driven by technical criteria since each technology dominated on different dimensions of merit (e.g., cost, safety, range, noise, power, etc.; see Abernathy, 1978). Internal combustion engines became the industry standard only after Ford invested in mass production technology and mass distribution administrative systems (Hounshell, 1984). Similarly, even though cast-iron stoves dominated openhearth stoves along every technological dimension of merit (e.g., fuel efficiency, comfort, safety, and cleanliness), they were dominated by openhearth stoves until process innovation reduced the price per unit (Cowan, 1987).

In the technological competition between the QWERTY and DVORAK typewriter keyboards, the technologically inferior technology (QWERTY) dominated partly due to chance events and partly due to technical constraints in the typewriter as a technical system (David, 1985). Finally, technological competition between alternative machine tool technologies and alternative inertial guidance systems could not be settled on technical grounds. In both industries, collaboration between the Air Force, MIT and a few powerful organizations led to the emergence of industry standards (MacKenzie, 1987; Noble, 1984).

3. In 1904, during a major fire in Baltimore, Maryland, reinforcements were called from Washington, DC, New York, and Philadelphia. While there was plenty of water, reinforcements were of no use since screw couplings for "foreign" fire hoses would not fit Baltimore hydrants (Hemenway, 1975). Similarly, interstate railway commerce was severely restricted as long as each state had different gauge track (Chandler, 1977). While there were clearly no technologically determined best fitting couplings or railway gauge, for these systems to operate effectively, sociopolitical processes must decide between alternative interface standards and technologies.

Similarly, in communication, radio, TV, or in information systems, there are a myriad of competing technical subsystems and linking technologies whose differences are not amenable to simple technical analyses. Given these substantial technical uncertainties, technical decisions are driven by sociopolitical dynamics shaped by technological constraints (David, 1987). Indeed, in the battle of alternative power systems in the late nineteenth century, neither AC nor DC dominated each other on technical grounds. While individual, political and organizational factors led to AC in the United States, similar social and political dynamics led to DC being the standard in England through World War I (Hughes, 1983).

These technological histories demonstrate three aspects of the phenomenon of technological evolution. Evidence from the cement, glass, and photography industries suggests that technical progress is characterized by incremental change punctuated by discontinuous advance. In these industries, the new technologies rapidly replaced prior technological regimes. Furthermore, while technological discontinuities transform industries, the technological breakthroughs are most frequently driven by organizations outside the existing technical order.

In the second collection of examples, technological competition among diagnostic imaging systems, automobile engines, stoves, typewriter keyboards, machine tooling technologies, and inertial guidance systems suggest that while it is possible for technical advance to be driven by clear technical dominance, it is much more common that no technological variant is dominant over all dimensions of merit. In these technically underdetermined cases, economic, social, political, and organizational processes determine which technical options survive.

The third collection of historical phenomena highlights the role of sociopolitical influences on technical evolution for complex technological systems. Complex systems, whether for firefighting, transportation, communication, or transmission, require consensus by multiple actors so that technological subsystems are compatible. The more complex the technology, the more important linking technologies become. For complex technical systems, sociopolitical and interorganizational processes emerge to shape technical progress.

A CYCLICAL MODEL OF TECHNOLOGICAL CHANGE: TECHNOLOGY AS COMMUNITY

Building on work in sociology, history, economics, and industrial engineering, Anderson and Tushman (1990) argue that technological change can be characterized by sociocultural evolutionary processes of variation, selection and retention (Basalla, 1988; Campbell, 1969). Variation is driven by stochastic technological breakthroughs. Technological discontinuities initiate substantial technological rivalry between alternative technological regimes. Because technical rivalry is often not settled by technical logic, social and organizational dynamics select from among technological opportunities, single industry standards or dominant designs. Positively selected variants then evolve through retention periods marked by incremental technical change and increased interdependence and enhanced competence within and between communities of practitioners (Constant, 1987). These periods of incremental technical change may be broken by subsequent technological breakthroughs (Jenkins, 1975).

A technology cycle has four components: technological discontinuities, eras of ferment, dominant designs, and eras of incremental change. Technological discontinuities and dominant designs are events that mark the transitions between eras of ferment and eras of incremental change, as illustrated in Figure 1.

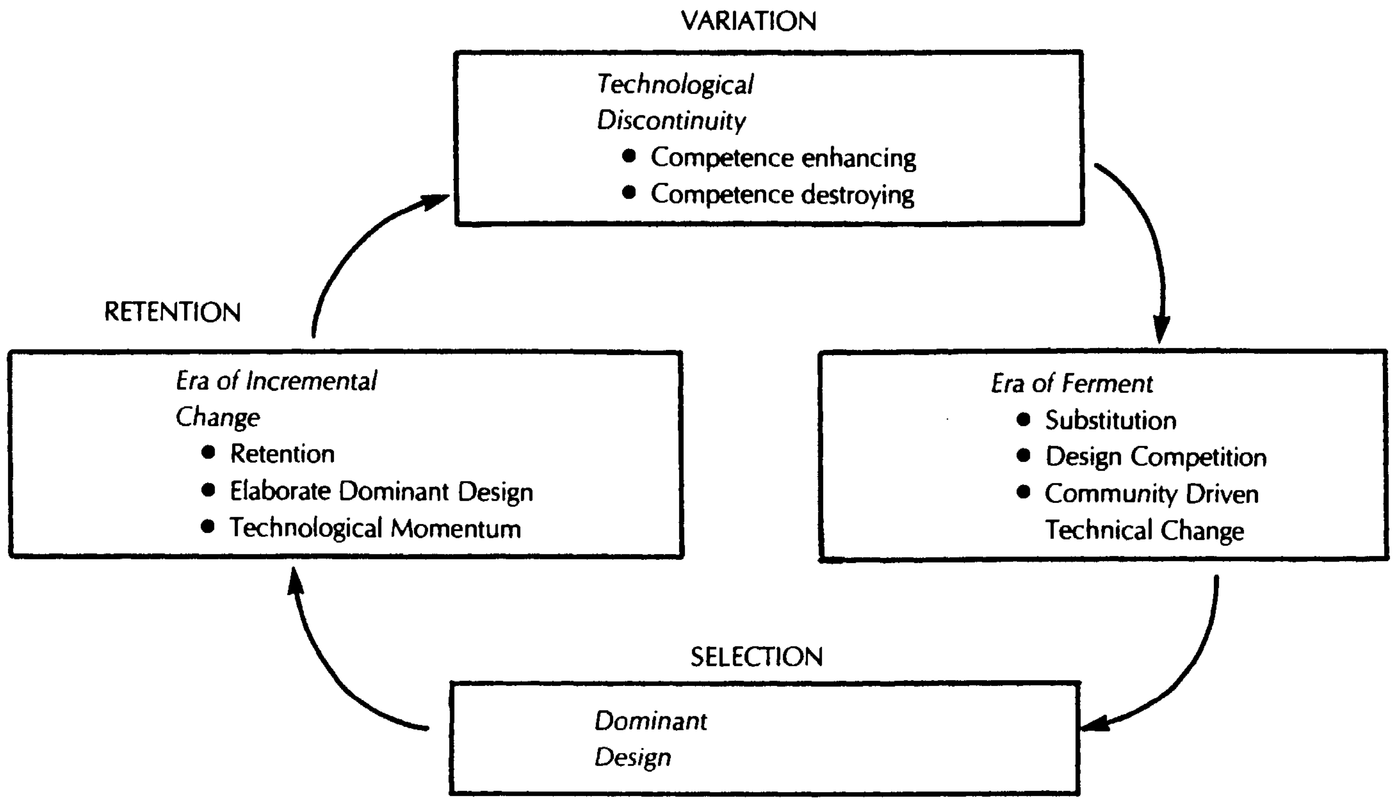


Figure 1. A Technology Cycle

Technological advance is, then, driven by the combination of chance events (variation), direct social and political action of organizations in selecting between rival technical regimes (artificial selection), as well as by incremental, competence-enhancing, puzzle-solving actions of many organizations learning-by-doing (retention). This retention stage provides a context for the subsequent technological discontinuity. We briefly examine each element of this technology cycle, stressing the roles of social, political, and organizational actors in the course of technological evolution.

Technological Discontinuities

Technological discontinuities are those rare, unpredictable innovations which advance a relevant technological frontier by an order-of-magnitude *and* which involve fundamentally different product or process design (Anderson & Tushman, 1990). Product discontinuities are fundamentally different product forms which command a decisive cost, performance or quality advantage over prior product forms (e.g., jet engines, diesel locomotives, quartz oscillation, electronic typing). Process discontinuities are fundamentally different ways of making a product which are reflected in order-or-magnitude improvements in the cost or quality of the product (e.g., Bessemer steel, float glass).

Not all technological discontinuities are alike. Tushman and Anderson (1986) characterize technological discontinuities as competence destroying or enhancing. Competence destroying discontinuities are based on fundamentally different technological knowledge or concepts and, as such, obsolete expertise required to master existing technology. For example, mechanical watch making skills were rendered irrelevant by quartz movements. Similarly, drawing-machine knowhow was not transferable to the float-glass process in glass manufacture. Competence-enhancing discontinuities, on the other hand, build on existing knowhow. In watch technology, for example, automatic mechanical movements represented a fundamentally different way of providing energy to the spring, but built on prior mechanical competence. Competence-enhancing innovations introduce a new technical order while building on, not obsolescing, the existing technical regime.

Eras of Ferment—Community-Driven Technologies

Technological discontinuities open eras of ferment, as radical technical advances increase variation in a product class. Technological discontinuities usher in an era of experimentation as organizations struggle to absorb (or destroy) the innovative technology. This era of ferment is characterized by two distinct processes: competition between old and new technological regimes, and competition within new technical regimes. This period of substantial product class variation and, in turn, uncertainty, is closed by the emergence of a dominant design (Anderson & Tushman, 1990; Utterback & Kim, 1985).

Eras of ferment are characterized by substantial uncertainty as rival technologies and communities compete for dominance. Competition between old and new technologies is fierce; older technological orders seldom vanish quietly (Foster, 1986). The response of the existing community of practitioners is often to increase the innovativeness and efficiency of the existing technical regime. For example, mechanical typewriters, piston jets, spark gap radio transmission, gas lighting, and mechanical watches all experienced sharp performance advances in response to technological threat (Aitken, 1985; Bright, 1949; Cooper & Schendel, 1976; Hughes, 1983; Landes, 1983). Given the innovative response of practitioners rooted in the existing technical order, technological discontinuities do not always dominate (e.g., bubble memory, wankel engines, quadraphonic sound systems; see Postrel, 1990).

Concurrent with competition between technical orders is the process of design competition within a technological order. Several, often incompatible, versions of the breakthrough appear both because the technology is not well understood and because each pioneering firm has an incentive to differentiate its variant from rivals. For example, in electric power generation, AC systems competed with DC systems. Indeed, even within AC systems there was competition among alternative frequencies (David, 1987; Hughes, 1983). Similarly, in medical imaging, there was technical competition between and within fundamentally different imaging technologies (i.e., nuclear, ultrasound, X-ray; see (Yoxen, 1987).

During eras of ferment, substitution processes and design competition are associated with substantial technical and market uncertainty (Clark, 1985). Technological variants compete along functional dimensions of merit. Competition exists both for which dimensions of merit are important and how each technology fares along these functional parameters. For example, in the opening of the automobile product class, electric, internal combustion, and steam powered automobiles competed against each other (and against the bicycle and carriage) on safety, range, noise, economy, power, and convenience dimensions of merit (Leslie, 1904). Similarly, in watch manufacture in the 1960s, quartz, tuning fork and escapement mechanisms competed with each other on size, stability, durability, complexity and frequency dimensions of merit (Landes, 1983).

During eras of ferment, critical dimensions of merit are unclear because users themselves are not certain of the product's critical characteristics (Teubal, 1979). For example, early in CT scanners, doctors were not clear on the relative priorities of scan time vs. resolution (Yoxen, 1987). Further, during this period of design competition, it is not clear which technology will dominate on what technical parameters. Initially, substitute technologies dominate on a single (typically a new) dimension of merit, but lag considerably behind the technical frontier on other critical dimensions of merit (Utterback & Kim, 1985). Substitute technologies will dominate existing technologies only if they add an important functional parameter and do as well on existing parameters, or if they dominate existing parameters. However, during eras of ferment, neither dimensions of merit nor subsequent technical performance are clear.

The degree of uncertainty during eras of ferment may be contingent on the type of discontinuity. When a technology builds on a completely new knowledge base, it may take longer for technical and market forces to sort out rival designs than for competence-enhancing technical change. Similarly, firms and/or communities of organizations confronted with the choice of abandoning existing know-how in the face of competence-destroying technical change will defend older technology more stubbornly, prolonging uncertainty about whether the new technology will become dominant (Anderson & Tushman, 1990).

Dominant Designs—Community-Driven Technological Selection

For variation and selection to cumulate in an evolutionary process, there must be a retention mechanism; a successful variation must be preserved and propagated (Campbell, 1969). A dominant design is the second watershed event in a technology cycle, demarking the end of the era of ferment. A dominant design is a single architecture that establishes dominance in a product class (Abernathy, 1978; Sahal, 1981). Once a dominant design emerges, future technological progress (until the next discontinuity) consists of incremental improvements elaborating the standard. For example, in the early automobile and airplane industries, technological variation between fundamentally different product designs remained high until standard designs emerged to usher in periods of incremental technical change (i.e., the internal combustion engine, open automobile and the DC-3 airplane; see Abernathy, 1978; Miller & Sawers, 1968).

Dominant designs emerge across diverse product classes (Sahal, 1981; Utterback & Abernathy, 1975). Whether in sewing machines or rifles (Houndshell, 1984), VCRs (Rosenbloom & Cusimano, 1987), bicycles (Bijker, Hughes, & Pinch, 1987), synthetic dyes (Van de Belt & Rip, 1987), radio transmission and receiving (Aitken, 1985), reprographic machines (Dessaur, 1975), or photolithography (Henderson & Clark, 1990), single designs emerge to dominate rival designs. These designs remain dominant until the next technological discontinuity. While only known in retrospect, dominant designs reduce variation and, in turn, uncertainty in the product class (Anderson & Tushman, 1990).

Once dominant designs emerge, technological uncertainty decreases. Uncertainty associated with substitute or design competition decreases as critical dimensions of merit are settled and critical technical problems (or reverse salients) get defined (Hughes, 1983). For example, by 1972, quartz movements dominated both the tuning fork and escapement movements for watches. Technical problem solving then focused on the size, cost, and stability of quartz oscillation and on linking quartz technology to other watch subsystems. Similarly, only after VHS dominated beta format for cassette recorders did intensive effort begin to increase the resolution and quality of VHS technology (Rosenbloom & Cusumano, 1987).

After dominant designs emerge, technical uncertainty decreases and the nature of technical change shifts from variation to incremental change. Technical clarity and convergence on a set of technical parameters permit firms to design standardized and interchangeable parts and to optimize organizational processes for volume and efficiency (Hounshell, 1984). Practitioner communities develop industry-wide procedures, traditions and problem solving modes that permit focused, incremental technical puzzle-solving (Constant, 1987). Dominant designs permit more stable and reliable relations with suppliers, vendors, and customers. From customers' perspectives, dominant designs reduce product class confusion and promise dramatic decreases in product cost. Finally, if the product is part of a larger system, industry standards permit system-side compatibility and integration (David, 1989; Farrell & Saloner, 1985).

A dominant design emerges in several ways. For simple or nonassembled products, dominant designs emerge from technological logic. For example, suspension preheating cement manufacture became the industry standard because it was a significantly more fuel efficient method of producing high volumes of cement (Anderson & Tushman, 1990). For more complex products, however, single sets of technologies are rarely optimal. Under conditions of technical ambiguity, dominant designs emerge from sociopolitical processes within and between competing technical communities and their contexts. For more complex products or processes, satisficing replaces optimizing in the closing on industry standards.

De facto standards emerge when users prefer one design over others. David's (1985, 1987) descriptions of the QWERTY typewriter keyboard and the battle between AC and DC power systems indicates that dominant designs sometimes emerge from market demand which is affected by the combination of technological possibilities and economic, organizational and governmental factors. Similarly, the Apple II personal computer or the VHS format in VCR's were not necessarily the best products of the day (measured purely by technical performance), but they contained a package of features that found favor in the market (Freiberger & Swaine, 1984). Though the DC-3 embodied many ideas previously introduced on other aircraft, it offered a unique combination of features that made it the most popular propeller-driven aircraft of all time (Miller & Sawers, 1968).

Dominant designs may also arise in other ways. The market power of a dominant producer may swing enough weight behind a particular design to make it a standard, as in the case of the IBM 370 series mainframe and the IBM personal computer (DeLamarter, 1986), or AT&T's Touchtone standard

(Brock, 1981). A powerful user may mandate a standard, as the U.S. Air Force imposed numerical control on the programmable machine tool industry (Noble, 1984). An industry committee may establish a durable standard, as in the case of computer communications protocols (Farrell & Saloner, 1988) and operating systems (Gabel, 1987), or a group of firms may form an alliance around a standard, as in the case of shared bank card systems (Phillips, 1987). Government regulation often compels the adoption of standards, as in the case of television standards (Pelkmans & Beuter, 1987); some have suggested that governments may employ standards as specific policy instruments capable of erecting barriers to trade (LeCraw, 1987; Teece, 1986).

The crucial point is that with the exception of the most simple products, the emergence of dominant designs is not a function of economic or technological determinism; they do not appear because there is one best way to implement a product or process (e.g., Cohen & Levin, 1989). Rival designs are often technologically superior on one or more key performance dimensions. For example, the IBM PC was not the fastest personal computer, Matsushita's VHS format did not offer the sharpest videocassette reproduction, and Westinghouse's AC power systems were not the most efficient. Indeed, dominant designs may not be particularly innovative; they often incorporate features pioneered elsewhere (Miller & Sawers, 1968).

If dominant designs do not arise from inexorable technical or economic logic, how do they evolve? We argue that because a single technological order rarely dominates alternative technologies across critical dimensions of merit, community level sociopolitical processes adjudicate among feasible technical/ economic options. The closing on critical dimensions of merit is shaped by a process of compromise and accommodation between suppliers, vendors, customers and governments (e.g., Constant, 1989). For example, David (1985) and Frost and Egri (1990) describe the collusion, compromise, accommodation and coalitions between divergent interest groups in the competition between QWERTY and Dvorak typewriter keyboards. Similarly, Noble (1984) and Hughes (1983) describe activities of champions, networks of coalitions and interest groups, and the use of language and negotiation tactics to shape standards in the machine tool and power system industries.

Dominant designs, then, emerge not from technical logic, but from a negotiated logic enlivened by actors with interests in competing technical regimes. Social logic drives technical progress as suppliers, customers or governments react to the uncertainty and inefficiencies associated with eras of ferment. Where technological discontinuities may be driven by random events or strokes of genius (e.g., Fessenden's discovery of the alternator for continuous wave transmission in radio), dominant designs are driven by the visible hand of organizations interacting with other organizations and practitioner communities to shape dimensions of merit and industry standards to maximize local needs (Abernathy, 1978; Aitken, 1985; Noble, 1984).

Dominant designs emerge from these interorganizational dynamics at the product class level. These industry standards cannot be known in advance since they are an outcome of sociopolitical processes within the product class. For a particular organization, betting on a particular industry standard involves substantial risk (witness Sony's bet on beta technology or RCA's bet on videodiscs). During the era of ferment, organizations must develop not only technical competence, but also interorganizational network skills to forge alliances in order to shape critical dimensions of merit and critical industry problems (Astley & Fombrum, 1983; MacKenzie, 1987). The concept of dominant design, then, brings technological evolution squarely into organization and interorganization realms. Actions of individuals, organizations, and networks of organizations shape dominant designs which, in turn, close the era of ferment. These socially driven outcomes directly affect the time path of technical change until the next technological discontinuity.

Era of Incremental Change—Technology-Driven Communities

After a dominant design emerges, product dimensions of merit are settled and critical technical problems are defined (Hughes, 1983). For example, once internal combustion engines dominated battery and steam engines in automobiles, technological progress shifted to safety, distance and reliability of internal combustion driven autos. After dominant designs emerge, technical progress is driven by numerous incremental innovations (Hollander, 1965; Myers & Marquis, 1969). These innovations elaborate and extend the dominant design. As in normal science (Kuhn, 1962), normal technological progress involves puzzle-solving about a given set of technological premises (see also Nelson & Winter's [1982] and Dosi's [1984] work on technological trajectories). After dominant designs emerge, technical uncertainty in a product class decreases and the basis of competition shifts from product to process innovation (Abernathy, 1978; Abernathy & Clark, 1985).

Within technical communities, social structures arise which reinforce this period of incremental, order-creating, technical change. Critical problems are defined, legitimate procedures are established, and community norms and values emerge from interaction between interdependent actors (Van de Ven & Garud, 1989). During periods of incremental change, informal know-how trading occurs between competitors (Von Hipple, 1987). Practice traditions are socially constructed and, unlike scientific progress, cross disciplinary boundaries. For example, Constant (1984) describes the evolution of practice traditions in the turbojet industry as evolving through interactions among combustion, mechanical, aerospace and metallurgical engineers.

Over time, periods of normal technology development build ever more interlinked competencies between technological communities and related suppliers, vendors and customers. As competencies are deepened about given technical premises and as routinized problem solving modes become institutionalized, technological mind-sets and momentum build in a product class (Hughes, 1983; Jenkins, 1975). While technical progress may be substantial, the community of practitioners look more and more inward and problem solving becomes more routinized and rigid as the era of incremental change unfolds (Dutton & Thomas, 1985; Myers & Marquis, 1969). These interlocked and rigid processes are located within the community of practitioners and competing organizations (Cohen & Levinthal, 1990). Where dominant designs are established by the visible hand of a few powerful organizations competing for dominance, in the era of incremental change, technological progress is driven by the invisible hand of a multitude of organizations competing within sharp technical, social and normative constraints (Van de Van & Garud, 1989).

Eras of incremental change persist until they are ended by subsequent technological discontinuities (Anderson & Tushman, 1990; Tushman & Anderson, 1986). Technological discontinuities directly challenge technical premises that underlie the prior period of incremental change. For example, tuning-fork and quartz oscillation both challenged fundamental assumptions about frequency and stability of oscillation in watch manufacture (Landes, 1983). However, these technological threats are met with resistance by technological momentum within the community of practitioners and within competing organizations, especially because any discontinuity is originally associated with substantial uncertainty, ambiguity, and implementation costs.

The response of veteran firms and communities to external threat is often increased commitment to the status quo (Cooper & Schendel, 1976; Foster, 1986). Because technology has social and community effects, threatened technical communities resist technological change by both increased persistence in the prior technical regime and by increased political action (see Frost & Egri [1990] for a thorough discussion of these political processes). For example, in the watch, steel, and power industries, new technologies were resisted by enhanced technical efforts in the soon to be obsolete technology and by increased political efforts (Constant, 1989; Horwitch, 1982; Landes 1983). Given technical momentum generated by normal technological progress, existing technical communities and/or organizations virtually never give birth to radically new, competence-destroying, technologies. The locus of technological discontinuity occurs from outside the existing technical community and from outside veteran organizations (e.g., Cooper & Schendel, 1976; Tushman & Anderson, 1986). During eras of incremental change, then, community and organizational norms and processes drive incremental, normal technical progress, but drive out variance required for breakthrough technical advance.

Normal technical progress builds interdependent competencies within a product class as well as shared norms and values within the practitioner community. Given inertial processes within the era of incremental change, subsequent technological discontinuities are resisted by technological, social, and political processes as veteran organizations and communities defend the existing paradigm. Given the conservative nature of technical communities, technological discontinuities are often initiated from outside the community. This community perspective on technological change puts a premium on social and organizational dynamics in shaping dominant designs and associated incremental change, and in resisting discontinuous technical advance.

TECHNOLOGY AS SYSTEMS IN CONTEXT

Technology is developed to solve problems in a particular context (Alexander, 1964). Except for the most primitive products, technological artifacts are composed of more basic subsystems which must, in turn, be linked together. Technological design involves both subsystem developments and integration across subsystems (Clark, 1985; Constant, 1987). In this section, we build on the idea of technology as systems in context, linking characteristics of systems and contexts to sociopolitical dynamics.

Conceptualizing technology as systems permits detailed understanding of technological evolution at both the subsystem and system levels of analysis. Technological cycles of variation, selection and retention apply both at the subsystem and system levels of analysis (e.g., at the oscillation and watch levels of analysis). Further, the interaction of subsystems leads to emergent system-level concepts of interfaces, linkage requirements, subsystem hierarchies, and critical system problems.

Understanding products as technical systems permits greater understanding of the conditions under which social/political processes affect technical progress. The greater the number of subsystems and the greater the number of interface and interdependence demands, the greater the number of dimensions of merit that must be adjudicated. The more complex the system, the more political, social, and community dynamics operate to resolve trade-offs between alternative technical choices. Similarly, the more central the technical subsystem, the greater its impact on the overall system. Change in central subsystems will involve more sociopolitical dynamics than change in peripheral subsystems (Clark, 1985).

In this section, we develop a typology of products ranging from simple to complex. We distinguish four types of products: (1) nonassembled products; (2) simple assembled products; (3) closed systems; and (4) open systems. We focus on product technology but examine associated process technology for simpler products. With this complexity-based typology, we link technological complexity to the relative importance of sociopolitical factors in shaping technological progress.

Nonassembled Products

Products like aluminum, cement, flat glass, paper, gears, fibers, petroleum, springs, and steel have no separable components. The technological essence of these products stems from the manufacturing process and the raw materials that enter this process. Produced through chemical, thermal or machining processes, nonassembled products are made through a set of sequentially interlinked steps or subprocesses. Linking mechanisms transport the product through the different subprocesses. Raw materials pass through each subsystem in a specific order to produce the finished product. For example, aluminum manufacture is composed of distinct subprocesses of mining, refining, smelting and fabrication. Each of these subprocesses have their own set of processes (Smith 1988; see Figure 2).

For nonassembled products, technological progress occurs either in process or materials. For process technology, either the replacement or elimination of subprocesses increases process speed and/or efficiency. For example, in glass manufacture in the late nineteenth century, artisans blew glass in large cylinders, assistants cut these cylinders and then flattened and polished the pieces of glass. In 1903, the Lubbers machine substituted for artisans blowing glass. These machines could blow glass rapidly and inexpensively and contributed to great increases in the volume and efficiency of glass production (Scoville, 1948; see Figure 2A).

Float glass technology revolutionized glass production by producing polished, smooth flat glass from molten glass passes across a bath of molten alloy. Float glass eliminated three steps from the prior glass production process and resulted in extraordinary production efficiencies (Anderson & Tushman, 1990; Emhart, 1974; see Figure 2B). Similar examples of either subsystem substitution or elimination of subprocesses occur in steel (Tarman, 1972), petroleum (Yin & Dutton, 1986), cement (Lesley, 1924), aluminum (Smith 1988), and textile fibers (Hollander, 1965).

For nonassembled products, dimensions of merit are quality or efficiency related and can be easily measured (e.g., price/unit, price/performance). Substitute subsystems and simpler processes clearly dominate prior production modes on relevant dimensions of merit (e.g., Lubbers machine or float process in glass manufacture). For example, no amount of increase in human glass blowing efficiency could ever compete with machine glass blowing, even as no amount of improving cutting, grinding, and polishing of flat glass could ever compete with the float process.

Substitute processes may trigger design competition between rival designs (Anderson & Tushman, 1990). For example, in glass bottle manufacture, the Owens machine stimulated multiple, rival designs. This design competition converged on the 10-arm Owens machine which became the dominant design in bottle manufacture until gob fed machinery substituted for the Owens

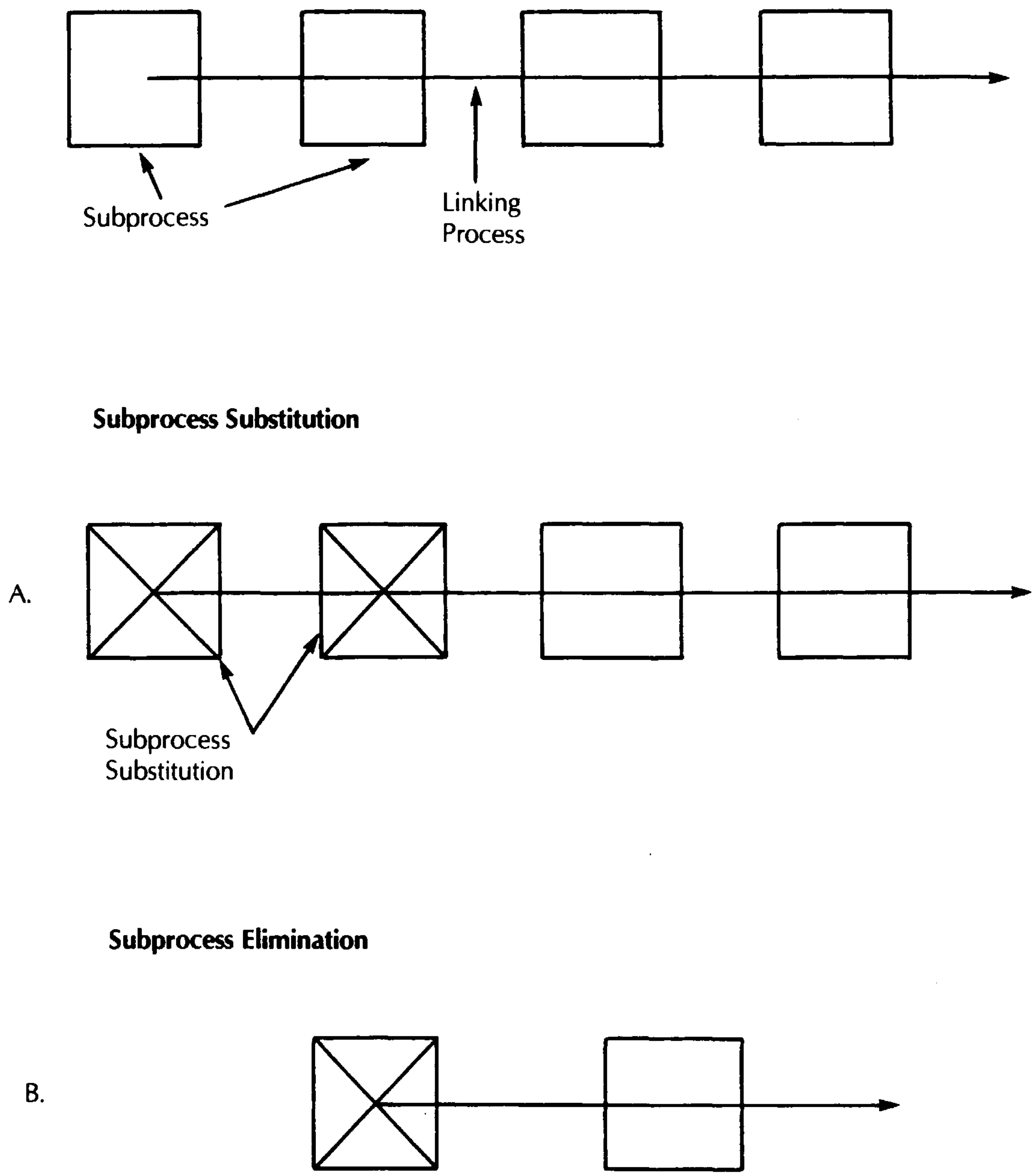


Figure 2. Nonassembled Products

process (Davis, 1949). For nonassembled products, because the dimensions of merit are so unequivocal, the choice between alternative processes is driven by the interaction of professionals in a single professional community (e.g., steel, cement, fiber) with managers in competing organizations. Given the clarity of dimensions of merit and the relative ease in measurement, the amount of sociopolitical dynamics is minimal in shaping technological progress for nonassembled products (e.g., Hollander, 1965; see Table 1).

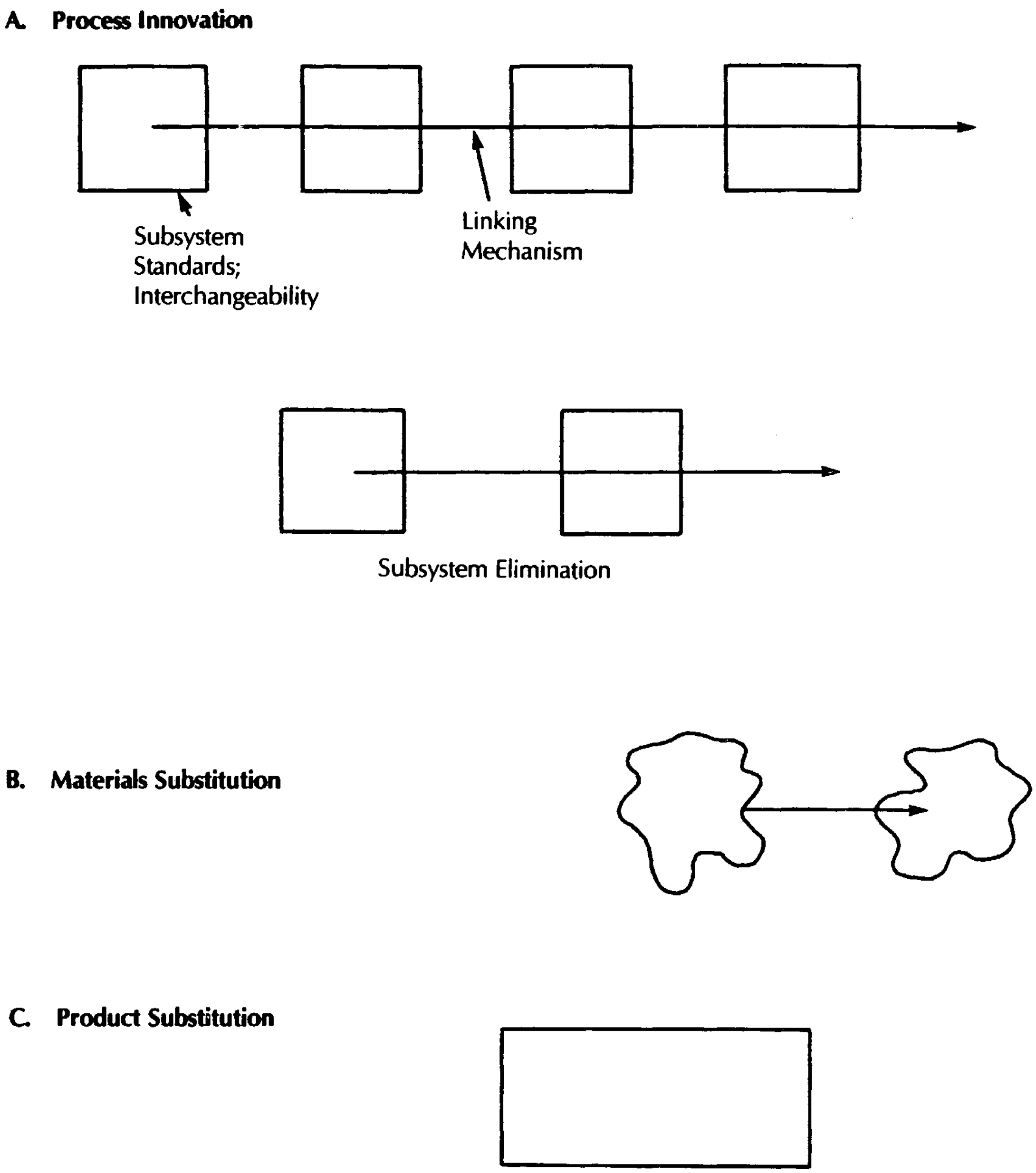


Figure 3. Simple Assembled Product

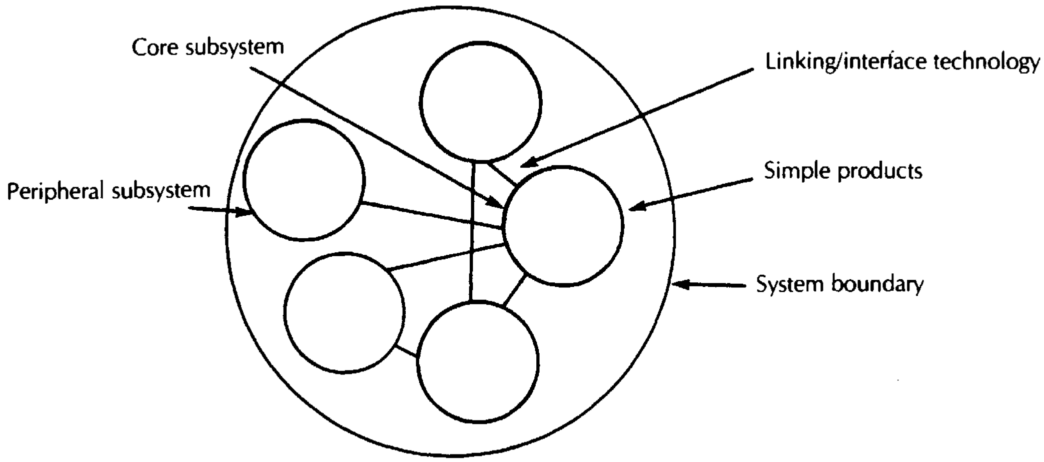
Simple Assembled Products

Classes of products such as stoves, hoses, cans, skis, containers, guns, escapements, and balance wheels are made up of distinct subsystems that are combined or fit together. These subsystems together define the product. Like nonassembled products, simple assembled products are made through a set of interlinked steps that are sequentially ordered. For example, in gun manufacture during the nineteenth century, locks, stocks, and barrels were distinct subsystems which were hand-fitted together to produce the gun (Hounshell, 1984). Similarly, aluminum cans (a replacement for steel cans) were made up of four subsystems (top, bottom, side, opener) which were joined together to produce the finished can (Smith, 1988; see Figure 3).

For simple assembled products, technical progress occurs either through process, material and/or product substitution. The most primitive form of technological progress is process innovation. The use of standardized or interchangeable parts or the combination of subsystems results in a more efficient, higher volume production process. For example, the use of interchangeable parts in gun manufacture permitted more efficient production of the component pieces of the gun (locks, stocks, barrels) and eliminated costly and inefficient hand fitting of the components (Hounshell, 1984). Similarly, as in nonassembled products, process innovations that result in fewer subsystems permit greater speed and volume production. For example, the development of the two-piece aluminum can sharply increased the price-performance ratio of the product (see Figure 3).

Distinct from process innovation, sharp technical progress is also associated with product substitution via either alternate materials or product forms. Substitute materials can drastically alter price/performance characteristics of simple assembled products. For example, alternate materials have transformed many simple assembled product classes including: escapements (jeweled → pin lever), skis (wood → metal → fiberglass), containers (steel → glass → aluminum → plastic). Finally, new product forms may substitute for the simple product itself. For example, disposable diapers, quartz oscillation, and batteries each substituted for the prior product form (cloth diapers, escapements, and springs respectively).

For simple assembled products, as with nonassembled products, dimensions of merit are clear and easily measured (e.g., price/unit or price/performance). Substitute products and/or production processes clearly dominate prior product and process forms. Substitute products and production processes trigger an increase in product and process variation in a product class as old and new product forms compete for dominance (Anderson & Tushman, 1990; Utterback & Kim, 1985). As dimensions of merit are clear for simple assembled products, technical considerations dominate organizational considerations in closing on dominant designs. Industry standards are driven by technical and engineering considerations as articulated by professionals in a given practitioner community in interaction with organizational considerations (see Table 1).



Open Assembled System

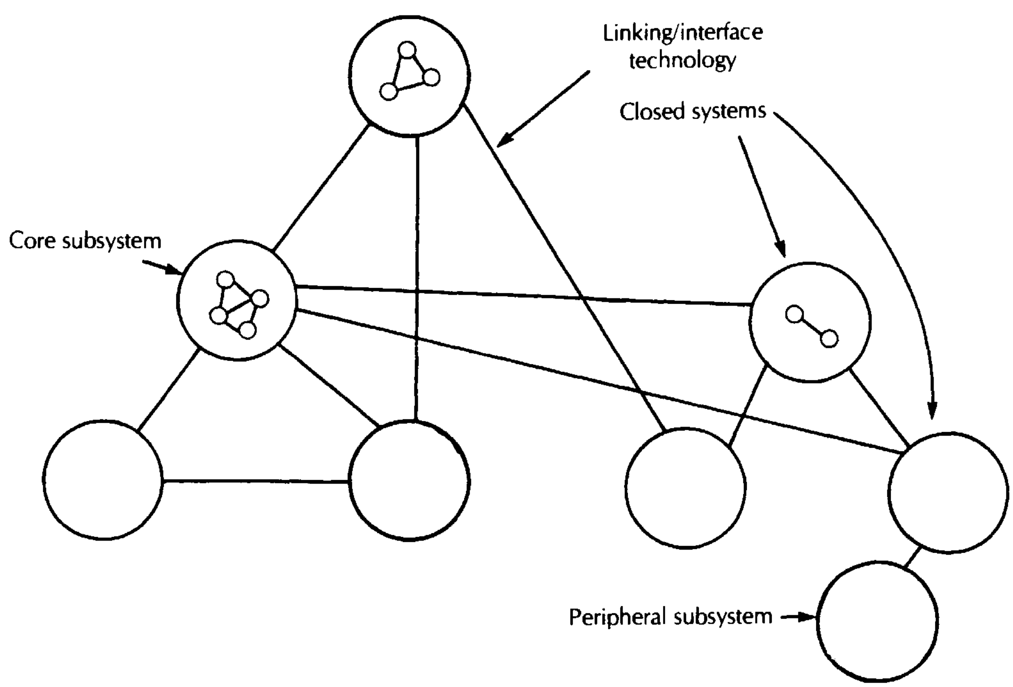


Figure 4. Assembled Systems

Assembled Systems

Classes of products like watches, automobiles, televisions, airplanes, telephone networks, railroad systems, and power systems are made up of distinct subsystems that interact with each other. Assembled systems are, therefore, more complex than nonassembled or simple assembled products since the individual subsystems must be linked together via interface and linkage technologies (Henderson & Clark, 1990). Further, because of complex interdependencies in assembled systems, some subsystems will be more central to the product, while others will be more peripheral.

There are two distinct classes of assembled systems. Closed systems are bounded where open systems are unbounded. In closed systems, the set of subsystems has a clear boundary; the system is enclosed (e.g., watch, bicycle, VCR, automobile, airplane). In open systems, component subsystems (often assembled closed systems) are dispersed and are not enclosed (e.g., telephone, railroad, power systems). Closed assembled systems are produced by single organizations (or units of multidivisional firms), while open systems are produced by networks of organizations (see Figure 4). We discuss the relative importance of sociopolitical and organizational dynamics in the technical progress of both types of assembled systems.

Closed systems are composed of a set of component subsystems or simple products that are linked together through linkage and interface technologies (Henderson & Clark, 1990). Because there are multiple subsystems, closed assembled systems are characterized by multiple dimensions of merit. For example, CT scanners can be described by their speed, resolution, size, scanning mode, and cost (Yoxen, 1987). Technical progress occurs at the subsystem, linkage, and interface levels of analysis. Each subsystem of a closed system has its own unidimensional time path of technical progress which is driven by process or product innovation and by shifts in materials. For example, any watch is composed of five generic subsystems—energy, oscillation, transmission, face, and casing. Each of these simple subsystems has its own history of technical progress (i.e., substitutions and dominant designs, product and process innovation) and can be measured on clearly defined dimensions of merit (e.g., durability, stability, oscillation rate, etc.). The product itself (i.e., the watch) is defined by its subsystems and linking technology. For example, by 1950, watches were composed of springs, escapements, gears, analog faces and precious metal cases and were evaluated by their accuracy, thinness, durability and cost (Landes, 1983).

Closed systems have a set of technological issues that emerge at the system level of analysis—hierarchy, critical problems and system dominant design. Unlike simple or non-assembled products, not all subsystems are of equal importance in closed systems. Some subsystems have more internal linkages and are more central to the system than those less interdependent subsystems. Closed systems can be hierarchically ordered—some subsystems are core while others are peripheral (Clark, 1985; Henderson & Clark, 1990). For example, in automobiles, the engine is a core subsystem in that the body, brakes, steering and ignition are all dependent on the engine's characteristics (see Figure 4). Thus, technological changes in core subsystems are likely to effect complementary changes in interdependent subsystems.

The set of subsystems will together define system-level critical problems—technical problems that emerge from the interaction of the subsystems. For example, in automobiles, after internal combustion engines dominated battery and steam powered engines, critical technical problems shifted from the engine to the brake, steering and body subsystems (Abernathy, 1978). In turbojet development, Constant (1984) defined functional failures and presumptive anomalies as system-level phenomena that arouse out of interactions between subsystem technologies (e.g., compressor and turbine components).

For closed assembled systems, technical progress occurs at the subsystem and linkage levels of analysis. Technical progress at the subsystem level may shift the relative hierarchy of components and the nature of critical technical problems. For example, between 1955 and 1975 each subsystem of a watch was transformed—batteries replaced springs, quartz oscillation replaced escapements and tuning forks, electronic transmission replaced gears, and plastic casing replaced precious metals. By 1975, each watch subsystem evolved through its own technology cycle of substitution and design competition to new dominant design. During this period, the hierarchy of components and critical system problems shifted. For example, the emergence of quartz oscillation shifted critical technological problems away from oscillation (the dominant technical problem for centuries) towards transmission and display (Landes, 1983). Similarly, Henderson and Clark's (1990) description of the photolithography industry demonstrates the shift in critical systems problems from subsystems to their linking technologies.

Just as simple products evolve dominant designs, so too do closed assembled products. For closed systems products, dominant designs are composed of a standard set of component and linking subsystems. Closing on a dominant design ushers in a period of incremental technical change at the component and interface levels of analysis. This incremental progress is shaped by critical system-wide technical problems. For example, by 1920 the dominant design for watches was the mechanical, lever-escapement, spring driven watch. Technical progress through the 1950s focused on incremental improvements to insure even more accurate, durable and thin watches. As discussed earlier, dominant designs are found across diverse closed systems product classes (e.g., bicycles, machine tools, radio, reprographic machines, automobiles, TVs, VCRs, etc.). Because of the centrality of core subsystems, dominant designs of closed systems may shift when the technology of a core component shifts. For example, the shift to quartz as an oscillation standard in watches drove the shift to a new watch standard by 1974 (i.e., battery powered, quartz, electronic watch).

Dominant designs emerge from technical competition between alternative designs. Whereas dimensions of merit are unidimensional for simple assembled products, there are diverse and multiple dimensions of merit for closed assembled systems (e.g., resolution, speed, safety, and cost in CT scanners). These multiple dimensions of merit cannot be adjudicated by technical logic.

Indeed, as closed systems are made up of diverse technologies, heterogeneous technical professionals will themselves disagree on appropriate industry standards (Yoxen, 1987). The closing on a dominant design for closed assembled systems is, then, driven by sociopolitical processes constrained by technical boundaries. The more complex the product, the greater the number of incompatible dimensions of merit, the greater the impact of social dynamics in shaping dominant designs. For example, Noble (1977) provides detail on collusion, bargaining, and coalitional behavior as diverse interest groups worked to shape numerical control as the industry standard in machine tools over record-playback technology (see also Frost & Egri, 1990).

Once a dominant design is selected, however, a diverse community of practitioners develops increasingly interlinked competence and inertia. These emergent community and organizational processes work to resist subsequent competence-destroying technical changes. This resistance to competence-destroying technical change is substantial since roots of the inertia are spread throughout a wide and diverse network of practitioners, suppliers, customers and vendors (e.g., Constant, 1987). This technological momentum (and resultant resistance to fundamental change) emerges out of the internal logic of the product as a hierarchical technical system, and from emergent processes within organizations and in the community of practitioners (e.g., Aitken, 1985; Jenkins, 1975). The resistance to the Dvorak keyboard is an extreme example of community-wide resistance to a superior subsystem technology in the typewriter/word processing product classes (David, 1985; Frost & Egri, 1990).

Open systems, the most complex form of technological systems, are composed of a set of closed systems that are linked together through interface technologies. Unlike closed systems, open systems have no boundaries. In open systems, the product is not self-contained, but is a function of networked components working together over a distance (e.g., television, radio, power, telephone, computer, railroads). Where as closed systems are produced by single organizations, open systems must cope with technological interdependencies and economies of scale via multiple organizations operating at a distance (Astley & Fombrun, 1983; David, 1987).

Open systems have some characteristics that are similar to closed systems. The set of closed subsystems is linked together through linkage and interface technologies. Because there are multiple subsystems, open systems are characterized by multiple dimensions of merit. For example, in the late nineteenth century, AC and DC power systems could be compared on safety, flexibility, distance and efficiency dimensions (Hughes, 1983). Technical progress occurs at the subsystem (i.e., closed system) and interface levels. As with closed systems, an open system is defined by its subsystem and linkage mechanisms at a point in time. Thus by the 1920s, radio systems were composed of vacuum tube transmitters, receivers, and amplifiers (Aitken, 1985). Each closed subsystem and linkage technology evolves through its own technology cycle of discontinuous change, product variation, dominant design and incremental change. Thus in radio, the signal generator itself evolved through three discontinuous technical changes from 1900-1920.

As with closed systems, open systems also have emergent technical issues that arise from the interdependence between subsystems. Not all subsystems are of equal importance. Those subsystems with greater linkages to other subsystems are more central to the system than those subsystems that are peripheral. For example, in both telephone and radio systems, the mode of transmission was the core subsystem in that all other subsystems depended on transmission technology (Aitken, 1985; Wasserman, 1985). Similarly in power systems, the power generation subsystem (e.g., DC, AC, nuclear) affects every other network subsystem (David and Bunn, 1988). Finally, given the distributed nature of open systems, linking and interface technologies assume significant importance over and above subsystems (David, 1987).

The set of subsystems together defines system level critical problems. Uneven growth of subsystems affects the overall network. These network problems define critical technical agendas for practitioner communities (see Barnett, 1990; Barnett & Carroll, 1987). Similarly, interactions between subsystem technologies either produce system failures or potential failures. These real or presumptive failures also focus system-wide problem solving (Hughes, 1983; Smith, 1985). For example, after AC dominated DC in power generation, a range of subsidiary AC technical problems became the focus of power system practitioners (e.g., surge proof transformers, fuses, insulation; see Hughes, 1983). Critical system problems and the technical hierarchy may shift as the network evolves. For example, once local telephone technology stabilized at the turn of the century, long-distance transmission emerged as a central, system-wide problem (Smith, 1985).

Even though open systems are more complex than closed systems, open systems also evolve through periods of system-wide variation leading to a dominant design. Dominant designs are composed of a standard set of subsystems and linking mechanisms. For example, in power systems, the competition between AC and DC systems resulted in the closing on AC as the standard in the United States, but DC in England (Hughes, 1983). Similarly, in radio transmission, competition between spark and continuous wave technology led to the convergence on wave-based radio systems (Aitken, 1985). As with closed systems, convergence on industry standards ushers in a period of incremental, puzzle-solving, technical change at the subsystem, linkage, and interface levels of analysis.

Closing on a dominant design for open systems is an inherently political and social process. Competing systems dominate each other on different dimensions of merit. Given technological uncertainties, the closing on industry standards is driven by sociopolitical dynamics between different sets of organizations that represent competing technological systems (Hughes, 1983).

As open systems often have national consequences, governments (or governmental units) are often involved in closing on standards for network systems (e.g., the Navy in radio systems or the FCC in TV). Because open systems have substantial technological, interorganizational, community, and governmental interfaces, sociopolitical dynamics play a more important role in closing on network standards than they do for closed systems or simple products. For example, Hughes (1983) and Constant (1989) illustrate the actions of system champions, bargaining, sabotage and complex interest group negotiations that led to the emergence of power system and petroleum system standards in the United States.

Once an open system closes on a dominant design, a period of incremental technical change ensues. The network of organizations, the community of practitioners, suppliers, governmental units, and customers develops ever more interlinked relations and enhanced competence. This period of puzzle-solving and normal technical progress builds technical and social momentum. Machines, devices, structures and procedures become so interlinked that the technical system builds technical inertia (Hughes, 1983). Further, the community of practitioners across multiple organizations and disciplines develop a well ordered internally-focused society with its own local problems, norms, values and status hierarchy (Aitken, 1985; Landan, 1984). The technical and social systems required to produce reliable and standard products from a multitude of organizations and professional groups brings with it technical and social inertia which resists all but competence-enhancing technical change (Constant, 1989).

As distributed networks, open systems are composed of multiple closed systems connected by linkage and interface technologies. To achieve scale economies and to effectively utilize the network, standard linking technologies across the entire network are crucial (Farrell & Saloner, 1987). In open systems, linking technologies are always a core technical subsystem. For example, in computer systems, incompatible languages and interface standards hindered the development of fully integrated networks (Brock, 1975). Where linking in closed systems is driven by intrafirm logic, in open systems, linking standards are inherently interorganizational phenomena (Astley & Fombrun, 1983).

In open systems, network interface standards evolve at multiple levels of analysis (David, 1987). System standards evolve to define fundamental units of measure (e.g., time, distance, currency, language, frequencies), minimal system attributes (e.g., safety, quality), and interface standards (e.g., design interfaces, communication protocols or codes). These system interface and linkage standards permit scale economies and orderly system development. Without system standards, confusion stunts the system's ability to develop (e.g., Barnett, 1990). For example, computer networks in the 1960s were paralyzed as there were over 50 different types of tape drives, each with multiple formats and tape width (Brock, 1981). While system linking standards have competitive

Table 1. Technological Complexity and the Relative Influence of Social, Political, Organizational Dynamics

Technological Complexity	*Driver of Technological Progress*	*Basis of Design Dominance*	*Arbiter of Dominant Design*	*Influence of Social, Political, Organization Dynamics*
• Nonassembled Products • Simple Assembled Products	• Subprocess replacement or elimination • Materials substitution • Product substitution	Technical Superiority of easily measured dimensions of merit	Single or focused practitioner community	Minimal
• Closed Assembled System	• Subsystem substitution or dominant design • Core Subsystem evolution • Linking technology	Competition among alternative designs with diverse dimensions of merit	Heterogeneous professional, organizational communities	High
• Open Systems	• Core subsystem substitution/dominant design • Linking and/or interface technologies	Competition among alternative component and interface designs with diverse dimensions of merit	Multiple, diverse organizational, professional, governmental communities	Pervasive

benefits, permit variety in the system through mixing and matching subsystems, and are associated with cost savings, these standards can also get locked in by technical and social inertia (Farrell & Saloner, 1985, 1988).

As illustrated by the Baltimore fire hoses, there are rarely technically optimal linking and interface technologies. Since these technologies are often technically indeterminate, only sociopolitical dynamics between multiple organizations, professional societies and governmental agencies can adjudicate between rival technical options. These standards may emerge from governmental regulation (e.g., radio, TV), international committees (fax, ISDN telephone protocols), mutual agreement between industry leaders (e.g., operating system consortia led by AT&T and IBM), or through market power (AT&T's telephone standards). As with the emergence of dominant designs at the component level, linkage standards also emerge in open systems. These linkage standards emerge from sociopolitical dynamics shaped by technical constraints.

Open systems are the most complex form of product technology. Open systems involve multiple closed systems, multiple practitioner communities, and networks of organizations. With all this social and technical complexity, open systems must evolve dominant designs and standards at the component and linkage levels of analysis. As technology rarely provides optimal choices, the choice from among a feasible set of technical options is driven by sociopolitical processes between organizations, technical practitioners, governmental units and communities. Once open systems close on standards, technical and social momentum drive ever more incremental, competence-enhancing change, and resist competence-destroying technical change. The more complex the system, the more complex the social and technical uncertainty, the greater the intrusion of social and political processes on the nature of technological progress (see Table 1).

TOWARDS A SOCIOLOGY OF TECHNOLOGICAL EVOLUTION

Under what conditions do organization dynamics affect the path of technical progress? Rather than viewing technology as an autonomous force acting on organizations (e.g., Barley, 1990; Blauner, 1964; Ellul, 1964) or as a predictable outcome of an elite set of organizations (e.g., Noble, 1984), we find that technologies evolve through the combination of random and chance events, the direct action of organizations shaping industry standards, and the invisible hand of multiple competing organizations in a technological community. Our purpose has been to illustrate the conditions under which social, political, and organizational dynamics affect technological progress and, in turn, to stimulate theory and research on the organizational determinants of technological progress.

Roots of the nontechnical determinants of technological advance lie in the fundamental nature of technology itself. Unlike science, technology is developed to solve a problem in a particular context (vs. universal understanding of a particular phenomenon). Unlike scientific progress, technological progress involves practitioners from multiple disciplines working to solve problems that are, in turn, shaped by contextual constraints. In technological development, uncertainty resides in the technologies utilized, and in the interaction of these technologies in context. These uncertainties affect the choice of dimensions of merit upon which to evaluate technological options. Except for the most simple technologies, no technological package dominates all dimensions of merit. Tradeoffs must be made between alternative dimensions of merit and, in turn, between alternative technological options.

In science, the locus of decision making is within the disciplinary community. In technology, however, the locus of technical decision making is between multiple disciplines, whose actors reside in competing organizations constrained by community and governmental demands. As networks of interdependence are more complex in technology than science, and because dimensions of merit are more heterogeneous in technology than science, technological progress involves compromise, accommodation and political dynamics between organizations, professional communities, customers and sometimes governmental units. In the context of technologically underdetermined systems, it is only through social, political, and organizational dynamics that technical tradeoffs and decisions can be made (see Constant, 1989; Frost and Egri, 1990; Hughes, 1983; Noble, 1984).

In this section we integrate the community and systems perspectives on technology to investigate the relative influence of sociopolitical dynamics versus straightforward technical logic. The nature of technology and its evolution suggest that the prominence of nontechnical processes will vary with the stage of the technology cycle, the complexity of the technological system, and the centrality of the technological subsystem.

Sociopolitical Dynamics and the Technology Cycle

During periods of technological uncertainty, non-technical dynamics adjudicate between dimensions of merit and technological options. Technological uncertainty is rooted in the nature of technology cycles and in the characteristics of technology as systems. Technology evolves through cycles of variation, selection and retention. Chance and individual genius drive technological breakthrough which ushers in a period of uncertainty as rival technologies compete, and variations of the substitute technology vie for dominance. These rival technologies compete on different dimensions of merit. As a single technology rarely dominates all relevant dimensions of merit, the emergence of a dominant design is driven by sociopolitical dynamics

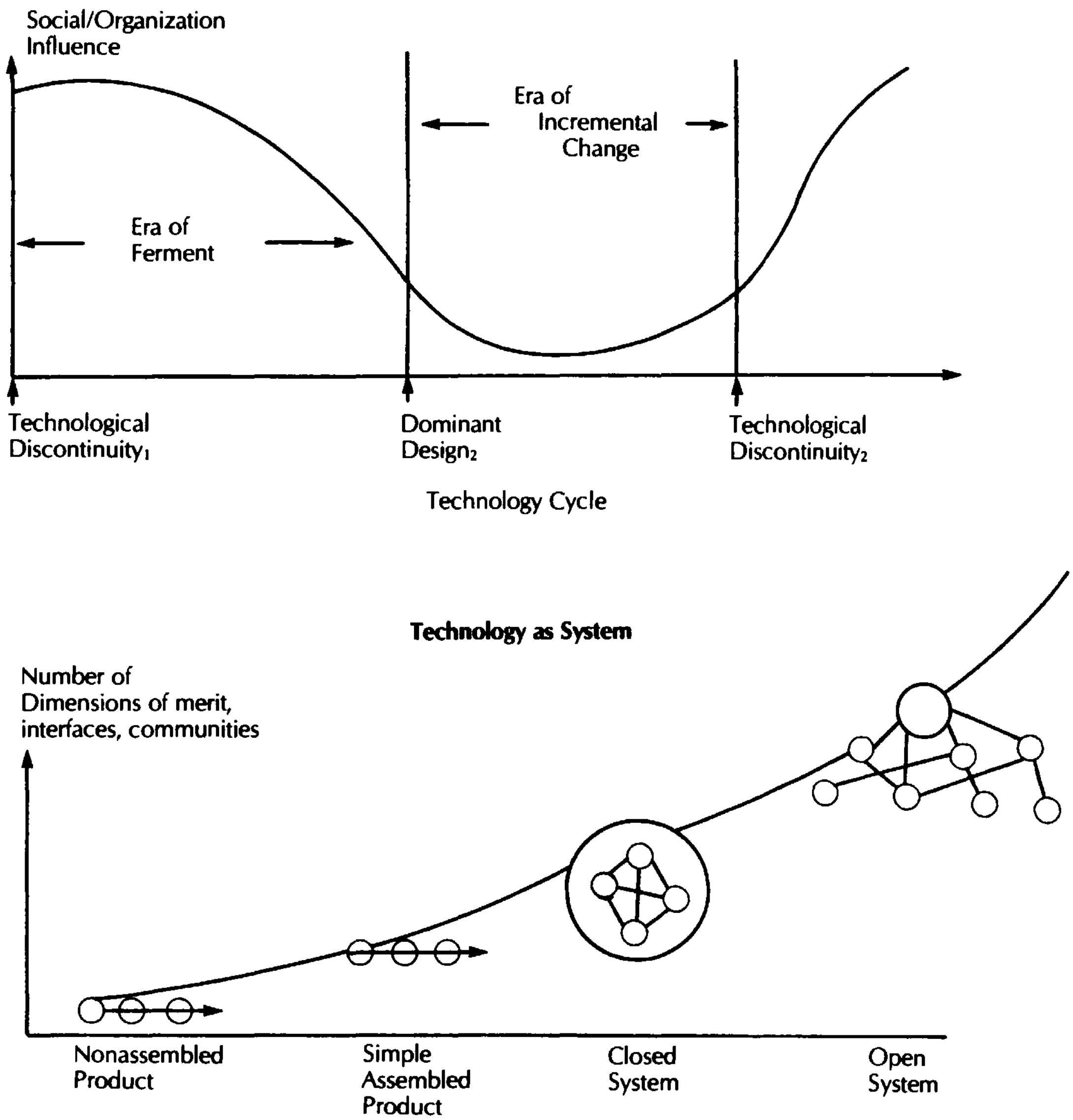


Figure 5. Technology as Community

constrained by technology. These social dynamics are played out between competing organizations, practitioner communities, suppliers, vendors, and customers.

Dominant designs set clear dimensions of merit and technological premises. Dominant designs initiate eras of incremental, puzzle-solving technical progress. Technological uncertainty is reduced as competing organizations, practitioner communities, suppliers and customers develop ever more interlinked and enhanced competencies. During eras of incremental change, technical progress is driven by a logic internal to the technology and by institutional momentum in the community of practitioners. This technical and social momentum admits only competence-enhancing change. Those technological breakthroughs based on alternative premises are actively resisted both technically and politically.

Organizational and interorganizational processes directly shape the selection of product class standards and subsequent incremental technical change and, in turn, perpetuate the selected technology's premises and buffer the core technology from change. Social, political, and organizational dynamics are, then, maximized during periods of uncertainty in a technology cycle—during eras of ferment, in closing on a dominant design and during periods of technological discontinuity (see Figure 5).

Sociopolitical Dynamics and System Complexity

Technology as systems focuses on differences in technical complexity across products. The more complex the product, the more subsystems, the greater the number of internal and external interfaces, the greater the technical and contextual uncertainty. The greater these uncertainties, the greater the intrusion of sociopolitical dynamics in the technology's evolution. Social dynamics are not important for nonassembled or for simple assembled products. For these classes of products, dimensions of merit are unambiguous, subsystems (or processes) are either physically or sequentially linked, and technical progress is carried out by practitioners in a single discipline. For these simple products, differences between alternative technological options can be resolved through technical logic.

Closed assembled systems are composed of multiple simple products that must interact with each other. Closed systems are characterized by multiple dimensions of merit—dimensions of the subsystems and of linking technologies. Moving toward a dominant design for closed systems involves selecting relevant dimensions of merit and choosing between alternative technological packages. As no single technological configuration dominates across dimensions of merit, sociopolitical dynamics adjudicate between technical options. These social dynamics involve interactions between competing organizations, professional communities and influential suppliers and customers. These political processes are also heightened when technological discontinuities threaten core subsystems within closed systems.

Open systems are composed of multiple closed systems and complex linking technologies. Where closed systems are bounded and produced by single organizations, open systems are unbounded, distributed networks whose products are produced by sets of organizations. Open systems are the most complex technological form in terms of subsystems and linking technologies, and in terms of linkages with multiple professional organizations and communities affected by the technology. Open systems, then, have all the technical-context uncertainties associated with closed systems plus those involved with the complex linkage technologies. Given these pervasive technical and contextual uncertainties, sociopolitical dynamics are accentuated in open systems. These dynamics occur at the organizational, interorganizational, disciplinary and community levels of analysis and are maximized during eras of ferment and when technological breakthroughs affect either core subsystems or linking technologies (see Figure 5).

Sociopolitical Dynamics and Subsystem Centrality

Moving from the system to the subsystem level of analysis, there is variation in the extent of sociopolitical dynamics for technological change in core versus peripheral subsystems. Core subsystems are strongly linked to many components of the system. Change in these components requires concurrent or complementary change in peripheral components. Thus, the process of technological change in core subsystems involves the organizations and communities for peripheral subsystems as well as those for the core subsystems. With more constituencies holding a stake in technological outcomes for core subsystems, nontechnical dynamics will be accentuated when core subsystems are threatened.

Integrating Community and Systems Perspectives

Understanding technology cycles and technology as community directs attention to when sociopolitical dynamics have an impact on technological progress. Social logic is least important for nonassembled products. Even during eras of ferment or at technological discontinuities, dimensions of merit are clear and the community of practitioners uses technical logic to resolve differences between alternative technologies. For nonassembled products, technology drives organizations.

On the other hand, sociopolitical dynamics are maximized for open systems either during eras of ferment or when technological discontinuities affect core or linking subsystems (see Figure 6). These sociopolitical dynamics operate across a wide network of competing organizations, suppliers, professional organizations, and communities, all of whom have substantial stakes in the technology's evolution. For open systems, nontechnical dynamics drive technological progress within the feasible set of technological options. The relative importance of sociopolitical forces vs. technical logic increases from simple assembled products, to closed systems to open systems, and as the product evolves through eras of ferment closing on a dominant design and at those subsequent technological discontinuities that affect core subsystems (see Figure 6).

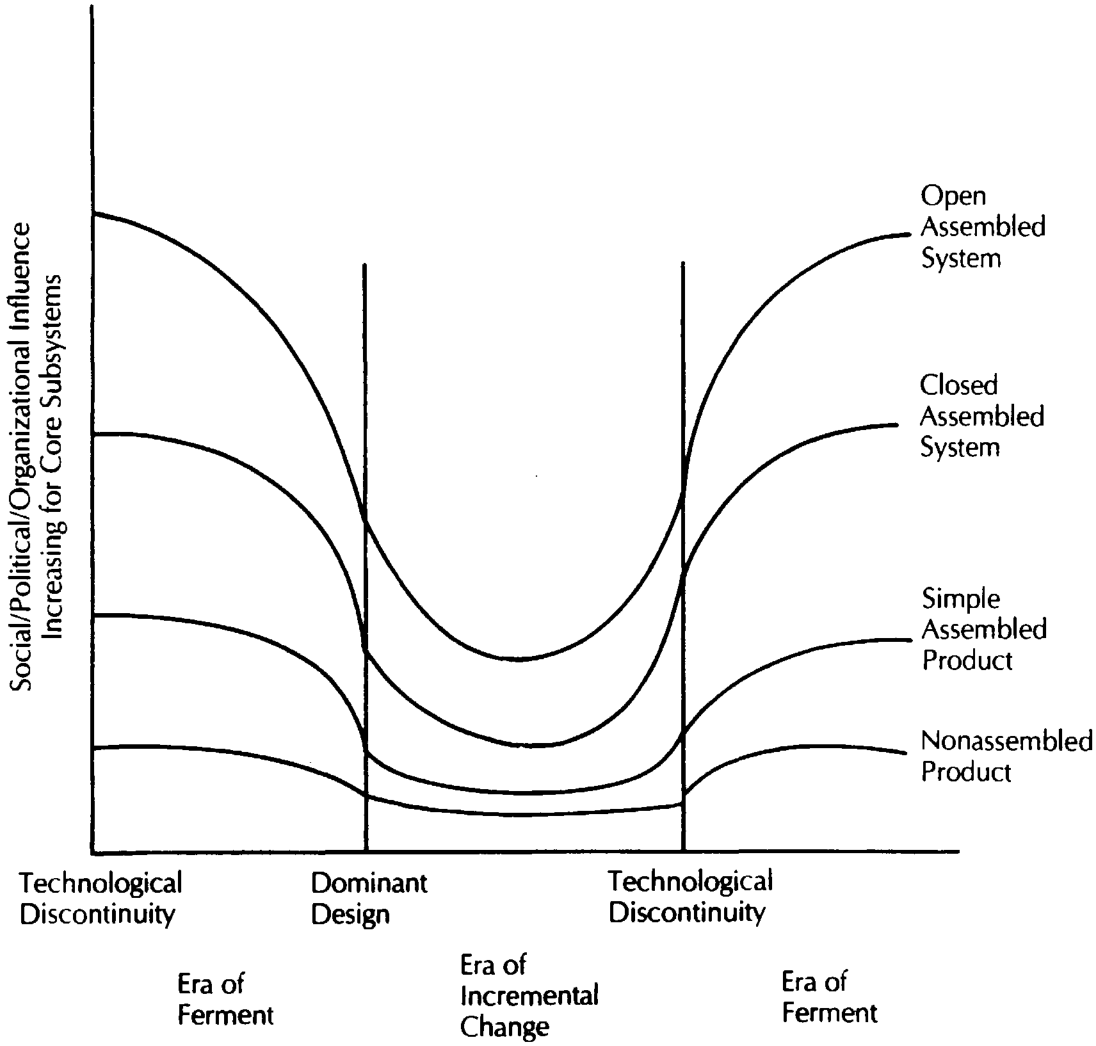


Figure 6. Toward a Sociology of Technology

Sociopolitical dynamics are minimal for peripheral subsystems across all types of products, and are minimal during eras of incremental change. During eras of incremental change, technological dimensions of merit and technical premises are fixed, and competing organizations and practitioner communities evolve well ordered social systems. During these periods, incremental technological change is driven by logic internal to the technology and by well developed norms and values in the practitioner communities. The more complex the technology, the more pervasive this technical and social momentum. Where sociopolitical processes directly shape technology during eras of ferment and at technological discontinuities, during eras of incremental technical change, technological progress is driven by technical logic. Only during periods of incremental technical change does technical logic dominate nontechnical logic in shaping technological progress and, in turn, organization outcomes (see Figure 6).

CONCLUSION

Our objective has been to bring the study of technological evolution more centrally into the realm of organization analysis. Except for the most simple products, at critical junctures in technological evolution choices among technological options cannot be made solely with reference to technology; products are often technologically underdetermined. This paper has explored when and under what conditions social, political, and organizational dynamics affect technological progress. We need to expand upon these ideas and better understand the mechanism by which organizational action affects technical change. We need to know more about how interactions between competing organizations, professional societies, suppliers, customers, and governmental units shape technological evolution. Research on technological progress must be able to span individual, organization and interorganization levels of analysis.

To better understand the nontechnical determinants of technological change, research must focus more attention on those junctures where sociopolitical dynamics are accentuated. Future research could explore the selection of dominant designs and the impact of technological discontinuities in closed or open systems. Any research on organizational impacts on technical progress must move to the interorganization and community levels of analysis. Research could explore roles of individuals and teams in forging coalitions to shape technological progress or the role of practitioner communities and organizations in shaping (or resisting) technical change. Whatever the research question, research on technological evolution must capture the interplay of individuals, organizations, networks of organizations and chance in shaping technological evolution (see also Frost & Egri, 1990).

Because technology is inherently underspecified, sociopolitical processes have an important impact on technological evolution. As technology has pervasive impacts on organizations, it is vital that we better understand when, under what conditions, and the explicit mechanisms by which organizations affect technological progress. This research area calls for research that crosses levels of analysis, and methodologies that can capture organization and interorganization phenomena. The time is ripe to open up the black box of technological change (Rosenberg, 1982), and to use organizational theory and research to understand technology's social, political, and organizational roots.

ACKNOWLEDGMENTS

The authors thank a host of colleagues who have provided careful and critical reviews of this manuscript including: P. Anderson, E. Abrahmson, W. Barnett, W. Boeker, L. Cummings, D. Hambrick, R. Henderson, S. Mezias, C. O'Reilly, E. Romanelli, B. Staw, A Van de Ven, and M. Williams.

NOTE

1. Throughout this paper, we use the term community to refer to the collection of organizations that have a stake in technological development. These organizations include private or public organizations, professional associations, and governmental bodies.

REFERENCES

Abernathy, W. (1978). *The productivity dilemma.* Baltimore, MD: The Johns Hopkins University Press.

Abernathy, W., & Clark, K. (1985). Innovation: Mapping the winds of creative destruction. *Research Policy, 14,* 3-22.

Aitken, H. (1985). *The continuous wave.* Princeton, NJ: Princeton University Press.

Alexander, C. (1964). *Notes on a synthesis of form.* Cambridge, MA: Harvard University Press.

Anderson, P., & Tushman, M. (1990). Technological discontinuities and dominant designs: A cyclical model of technological change. *Administrative Science Quarterly, 35,* 604-633.

Arthur, B. (1988). Self-reinforcing mechanisms in economics. In P. Anderson et al. (Eds.), The economy as an evolving complex system. Reading, MA: Addison-Wesley.

Astley, G. (1985). The two ecologies: Population and community perspectives on organizational evolution. *Administrative Science Quarterly, 30,* 224-241.

Astley, G., & Fombrum, C. (1983). Technological innovation and industrial structure. *Advances in Strategic Management, 1,* 205-229.

Barley, S. (1990). The alignment of technology and structure through roles and networks. *Administrative Science Quarterly, 24,* 286-308.

Barnett, W. (1990). The organizational ecology of a technological system. *Administrative Science Quarterly, 35,* 31-60.

Barnett, W., & Carroll, G. (1987). Competition and mutualism among early telephone companies. *Administrative Science Quarterly, 32,* 400-421.

Basalla, G. (1988). *The evolution of technology.* Cambridge: Cambridge University Press.

Bijker, W., Hughes, T., & Pinch, T. (1987). *The social construction of technological systems.* Cambridge, MA: MIT Press.

Blalock, H. (1979). *Social statistics.* New York: McGraw-Hill.

Blauner, R. (1964). *Alienation and freedom.* Chicago: University of Chicago Press.

Bright, J. (1949). The electric-lamp industry. New York: Macmillan.

Brock, G. (1981). *The telecommunications industry.* Cambridge, MA: Harvard University Press.

Burkhardt, M., & Brass, D. (1990). Changing patterns or patterns of change: The effects of a change in technology on social network structure and power. *Administrative Science Quarterly, 35,* 104-127.

Campbell, D.T. (1969). Variation and selective retention in socio-cultural evolution. *General Systems, 14,* 69-85.

Chandler, A. (1977). *The visible hand.* Cambridge, MA: Harvard University Press.

Clark, K. (1985). The interaction of design hierarchies and market concepts in technological evolution. *Research Policy, 14,* 235-251.

Cohen, W., & Levinthal, D. (1990). Absorptive capacity: A new perspective on learning and innovation. *Administrative Science Quarterly, 35,* 128-152.

Cohen, W., & Levin, R. (1989). Empirical studies of innovation and market structure. In R. Schmalense & D. Willig (Eds.), *Handbook of industrial organization* (Vol. 11, pp. 1060-1107). New York: Elsivier.

Constant, E. (1980). *The origins of the turbojet revolution.* Baltimore, MD: The Johns Hopkins University Press.

Constant, E. (1987). The social locus of technological practice: Community, system or organization. In W. Bijker, T. Hughes & T. Punch (Eds.), *The social construction of technological systems.* Cambridge, MA: MIT Press.

Constant, E. (1989). Cause or consequence: Science, technology and regulatory change in the oil industry. *Journal of Business History,* 426-455.

Cooper, A., & Schendel, D. (1976). Strategic responses to technological threat. *Business Horizons,* 61-69.

Cowan, R. (1987). The consumption junction: Research strategies for the social construction of technology. In W. Bijker, T. Hughes & T. Punch (Eds.), *Social construction of technological systems.* Cambridge, MA: MIT Press.

Crane, D. (1972). *Invisible colleges: Diffusion of scientific knowledge.* Chicago: University of Chicago Press.

David, P. (1985). Clio and the economics of QWERTY. *Economic History, 75,* 227-332.

David, P. (1987). Some new standards for the economics of standardization in the information age. In P. Dasgupta & P. Stoneman (Eds.), *Economic policy and technological performance.* Cambridge: Cambridge University Press.

David, P., & Bunn, J. (1988). The economics of gateway technologies and network evolution. *Information Economics and Policy, 3,* 165-202.

DeLamarter, R. (1986). *Big blue: IBM's use and abuse of power.* New York: Dodd, Mead & Company.

Davis, P. (1949). *The development of the American glass industry.* Cambridge, MA: Harvard University Press.

Dessaur, J. (1975). *My years with xerox.* New York: Manor Books.

Dosi, G. (1984). *Technical change and industrial transformation.* New York: St. Martin's Press.

Dutton, W., & Thomas, A. (1985). Relating technological change and learning by doing. In R. Rosenbloom (Ed.), *Research on technological innovation* (pp. 187-224). Greenwich, CT: JAI Press.

Ellul, J. (1964). *The technological society.* New York: J. Wilkinson.

Emhart Corporation. (1974). *The big picture: Proceedings of executive seminar presented by Hartford Division, Emhart Corporation.* Technical Publication TP-1071B, Emhart Corporation, Farmington, Connecticut.

Farrell, J., & Saloner, G. (1985). Standardization, compatibility, and innovation. *Rand Journal of Economics, 16,*71-83.

Farrell, J., & Saloner, G. (1988). Coordination through committees and markets. *Rand Journal of Economics, 19,* 235-252.

Foster, R. (1986). *Innovation.* New York: Summit Books.

Freiberger, P., & Swaine, M. (1984). *Fire in the valley: The making of the personal computer.* Berkeley, CA: Osborne/McGraw-Hill.

Frost, P., & Egri, C. (1990). The political process on innovation. In L. Cummings and B. Staw (Eds.), *Research in organizational behavior* (Vol. 13). Greenwich, CT: JAI Press.

Gabel, H.L. (1987). Open standards in the European computer industry: The case of X/OPEN. In H.L. Gabel (Ed.), *Product standardization and competitive strategy.* Amsterdam: North Holland.

Hemenway, D. (1975). *Industry wide voluntary product standards.* Cambridge, MA: Ballinger.

Henderson, R., & Clark, K. (1990). Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly, 35,* 9-30.

Hollander, S. (1965). *Sources of efficiency.* Cambridge, MA: MIT Press.

Hounshell, D. (1984). *From the American system to mass production.* Baltimore, MD: The Johns Hopkins University Press.

Horwitch, M. (1982). *Clipped wings.* Cambridge, MA: MIT Press.

Hughes, T. (1987). The evolution of large technological systems. In W. Bijker, T. Hughes & T. Pinch (Eds.), *The social constructions of technological systems.* Cambridge, MA: MIT Press.

Hughes, T. (1983). *Networks of power.* Baltimore, MD: The Johns Hopkins University Press.

Hulin, C., & Roznowski, M. (1985). Organizational technologies: Effects on organizations' characteristics and individuals' responses. In L. Cummings & B. Staw (Eds.), *Research in organizational behavior* (Vol. 7). Greenwich, CT: JAI Press.

Jenkins, R. (1975). *Images and enterprise.* Baltimore, MD: The Johns Hopkins University Press.

Katz, M., & Shapiro, C. (1985). Network externalities, competition, and compatibility. *American Economic Review, 75,* 424-440.

Kuhn, T. (1962). *The structure of scientific revolutions.* Chicago: University of Chicago Press.

Laudan, R. (Ed.). (1984). *The nature of technological knowledge.* Boston: D. Reidel.

Landes, D. (1969). *The unbound prometheus: Technological change and industrial development in western Europe from 1750 to the present.* Cambridge: Cambridge University Press.

Landes, D. (1983). *Revolution in time.* Cambridge, MA: Harvard University Press.

LeCraw, D. (1987). Japanese standards: A barrier to trade? In H.L. Gabel (Ed.), *Product standardization and competitive strategy* (pp. 29-46). Amsterdam: North-Holland.

Leslie, F. (1904). *Automobiles of 1904.* Maynard, MA: Chandler Press.

Lesley, R. (1924). *A history of the United States Portland Cement industry.* Chicago: Portland Cement Association.

MacKenzie, D. (1987). Missile accuracy: A case study in the social processes of technological change. In W. Bijker et al. (Eds.), *Social construction of technological systems.* Cambridge, MA: MIT Press.

Merton, R. (1973). *The sociology of science.* Chicago: University of Chicago Press.

Miller, R.E., & Sawers, D. (1968). *The technical development of modern aviation.* London: Routledge & Kegan Paul.

Mitchell, W. (1989). Whether and why? Probability and timing of incumbents' entry in subfields. *Administrative Science Quarterly, 32,* 208-230.

Myers, S., & Marquis, D.G. (1969). *Successful industrial innovations.* Washington, DC: National Science Foundation.

Nelson, R., & Winter, S. (1982). *An evolutionary theory of economic change.* Cambridge, MA: Belknap Press.

Noble, D.F. (1984). *Forces of production.* New York: Alfred A. Knopf.

Pelkmans, J., & Beuter, R. (1987). Standardization and competitiveness: Private and public strategies in the E.C. color TV industry. In H.L. Gabel (Ed.), *Product standardization and competitive strategy* (pp. 29-46). Amsterdam: North-Holland.

Perrow, C. (1967). A framework for comparative organizational analysis. *American Sociological Review, 32,* 194-208.

Phillips, A. (1987). The role of standardization in shared bank card systems. In H.L. Gabel (Ed.), *Product standardization and competitive strategy* (pp. 263-282). Amsterdam: North-Holland.

Pinch, T., & Bijker, W. (1987). The social construction of facts and artifacts. In W. Bijker et al. (Eds.), *The social construction of technological systems.* Cambridge, MA: MIT Press.

Postrel, S. (1990). Competing networks and proprietary standards. *Journal of Industrial Economics, 29,* 169-185.

Romanelli, E., & Tushman, M. (1988). Executive leadership and organization outcomes. In D. Hambrick (Ed.), *The executive effect* (pp. 129-146). Greenwich, CT: JAI Press.

Rosenberg, N. (1967). *Perspectives on technology.* Cambridge: Cambridge University Press.

Rosenberg, N. (1982). *Inside the black box: Technology and economics.* Cambridge: Cambridge University Press.

Rosenbloom, R., & Cusimano, M. (1987). Technological pioneering and competitive advantage: The VCR industry. *California Management Review, 29.*

Sahal, D. (1981). *Patterns of technological innovation.* Reading, MA: Addison-Wesley.

Scoville, W. (1948). *Revolution in glass-making.* Cambridge, MA: Harvard University Press.

Smith, G. (1985). *The anatomy of a business decision.* Baltimore, MD: The Johns Hopkins Press.

Smith, G. (1988). *From monopoly to competition: Transformation of ALCOA.* Cambridge, MA: Cambridge University Press.

Teece, D. (1986). Profiting from technological innovation: Implications for integration, collaboration, licensing, and public policy. *Research Policy, 15,* 285-305.

Teubal, W. (1979). Market research and product summation. *Business Horizons, 21,* 22-26.

Thompson, J. (1967). *Organizations in action.* New York: McGraw-Hill.

Tushman, M., & Anderson, P. (1986). Technological discontinuities and organizational environments. *Administrative Science Quarterly, 31,* 439-465.

Tushman, M., & Nelson, R. (1990). Introduction: Technology, organizations and innovation. *Administrative Science Quarterly, 35,* 1-8.

Tushman, M., & Romanelli, E. (1985). Organization evolution: A metamorphosis model of convergence and reorientation. In L. Cummings & B. Staw (Eds.), *Research in organizational behavior* (Vol. 7, pp. 171-222). Greenwich, CT: JAI Press.

Utterback, J., & Abernathy, W. (1975). A dynamic model of process and product innovatio. *Omega, 33,* 639-656.

Utterback, J., & Kim, L. (1985). Invasion of a stable business by radical innovation. In P. Kleindorfer (Ed.), *The management of productivity and technology in manufacturing.* New York: Plenum.

Van den Belt, H., & Rip, A. (1987). The Nelson-Winter-Dosi model and synethic dye chemistry. In W. Bijker, T. Hughes & T. Pinch (Eds.), *The social construction of technological systems.* Cambridge, MA: MIT Press.

Von Hipple, E. (1987). Cooperation between rivals: Informal know-how trading. *Research Policy, 16,* 291-302.

Van de Ven, A., & Garud, R. (1989). A framework for understanding the emergence of new industries. In A. Van de Ven & S. Poole (Ed.), *Research and technological innovation, management, and policy* (Vol. 4, pp. 195-225). New York: Harper & Row.

Wasserman, N. (1985). *From invention to innovation: Long distance telephone transmission.* Baltimore, MD: The Johns Hopkins University Press.

Woodward, J. (1965). *Industrial organization.* London: Oxford University Press.

Yin, Z., & Dutton, J. (1986). Systems learning and technological change in 20th century petroleum refining. Working paper, New York University.

Yoxen, E. (1987). Seeing with sound: A study of the development of medical imaging. In W. Bijker, T. Hughes & T. Pinch (Eds.), *Social construction of technological systems.* Cambridge, MA: MIT Press.