Chapter 5
The Devil is in the Details

Since the early 1990s, archaeologists have shown a heightened interest in explaining technological change. Indeed, this general research goal is now supported by archaeologists of every theoretical persuasion (e.g., Bleed 2001b; Dobres 2000; Dobres and Hoffman 1999; Fitzhugh 2001; Gordon and Killick 1993; Gould 2001; Hayden 1998; Hughes 1998; Kelly 2000; Killick 2004; Kuhn and Sarther 2000; Lemonnier 2000b; Mithen 1998; Neff 1992; O'Brien et al. 1994; Rice 1999; Roux 2003; Sassaman 1993; Schiffer 1992, 2001a; Schiffer et al. 2001; Shott 1997; Sillar and Tite 2000; Skibo 1994; Stark 2003). Moreover, most archaeologists agree that technologies are context dependent, their form and prevalence contingent upon local, historically constituted conditions. Thus, specific explanations are tied to a given group in time and space and are richly supplied with relevant particulars of the societal context. On the basis of these contingencies, the archaeologist fashions an empirically grounded narrative that accounts for a given technological change.

The provision of historical narratives is not the exclusive aim of technological studies because archaeologists also craft crosscutting theories and models. This strategy is pursued when researchers ask, and seek answers to, *general* questions – those lacking time–space parameters. Although archaeologists have offered generalizations about processes of technological change, such as adoption or consumption (e.g., Spencer-Wood 1987; see also references in Schiffer 2001b; Schiffer et al. 2001; van der Leeuw and Torrence 1989), invention processes have been woefully undertheorized (Fitzhugh 2001).

If we aim to achieve a comprehensive understanding of technological change, then our corpus of principles must come to include generalizations about the sources of material novelty. After all, invention is a commonplace human behavior, and so its study offers an opportunity to fashion principles of great generality. Fortunately, recent efforts suggest that at least some invention processes are patterned and can be described by models and theories (e.g., Fitzhugh 2001; Hayden 1998; Schiffer 1993, 1996, 2002).

Given that myriad activities can generate material novelty, the first task is to identify behaviorally based kinds of invention processes. Each kind of process is operative in a specific "behavioral context" (LaMotta and Schiffer 2001; Walker et al. 1995), an analytic unit defined by shared "characteristics among seemingly dissimilar – often culturally diverse – empirical phenomena" (Schiffer 1996:651). The second task is to devise the theory or model that best accounts *in general terms* for the operation of each kind of process. Our expectation is that by defining and studying varied behavioral contexts, we can create a family of generalizations that encompass diverse invention processes. Given these intellectual resources, the archaeologist could not only furnish a contextualized narrative of a given invention, but could also invoke the appropriate model or theory, which would implicate the relevant nonunique factors that tie the case to many others.

This chapter focuses on the kind of invention processes that arise in the behavioral context of "complex technological systems" (CTS). I define CTS as any technology that consists of a set of interacting artifacts; interactions among these artifacts – and people and sometimes environmental phenomena – enable that system to function. Because the archaeologist has wide latitude in interpreting the terms of this definition and because technological complexity is ostensibly a continuum (e.g., Oswalt 1976), the determination of whether a specific technology constitutes a CTS is necessarily driven by the archaeologist's research problem. Given the flexibility of this definition, one can expect to discern CTSs in diverse – even small-scale – societies (see "Operationalizing the Cascade Model on Archaeological Cases").

For handling CTS-related invention processes, a "cascade" model is presented, which is a behavioral adaptation, elaboration, and generalization of Thomas P. Hughes' (1983) model of "reverse salients." According to Hughes, during the development of a complex sociotechnical system, like an electric power network, certain components lag and present critical problems, such as generators of insufficient capacity to meet demand and power poles vulnerable to lighting strikes. If the system is to become functional, then such problems must be solved – usually through invention. Hughes' model, especially the notion of lag and the construct of reverse salient, derives from a military metaphor that implies grand, if not grandiose, development campaigns. On the other hand, the cascade model is expressed in terms that appear to fit a wider range of CTSs, including those that might be present in small-scale societies. Also, the cascade model seems well suited to explain the serial spurts of inventive activities that accompany a developing CTS (see also Gould 2001).

In a nutshell, the cascade model posits that, during a CTS's development, emergent performance problems – recognized by people as shortcomings in that technology's constituent interactions – stimulate sequential spurts of invention. As adopted inventions solve one problem, people encounter new and often unanticipated performance problems, which stimulate more inventive spurts, and so on. The result is a series of "invention cascades." A distinctive feature of the model, which promotes its generality, is the premise that processes in a CTS's life history are the immediate contexts in which performance problems emerge and stimulate invention cascades. Thus, life-history processes are suitable analytical units for investigating invention processes in CTSs.

It is important to emphasize that the cascade model does not explain how or why the development of a CTS is initiated; rather, it accounts for the spurts of inventive activities that transpire during the course of development.

This chapter has five major sections: (1) general considerations concerning CTS-related invention processes, (2) elaboration of the cascade model, (3) illustration of the model with the development of the nineteenth-century electromagnetic telegraph, (4) discussion of the model's applicability to small-scale societies, and (5) enumeration of the model's broadest implications for studying technological change.

General Considerations

We begin by presenting definitions tailored to the cascade model. "Invention" is the activity that creates a novel *technological object* or artifact – that is, a new kind of part, assembly, component, or subsystem. To qualify as "new," a technological object is expected to differ, *in one or more performance characteristics*, from other artifacts in the same society. Clearly, archaeologists can consider only inventions that have been materialized in some form (e.g., drawings, models, full-scale hardware). The term "inventor" designates not an occupational specialization but the person, task group, corporate group, or collective that created the new technological object.

An important premise of the cascade model is that, in a CTS's development, people respond to each performance problem by engaging in inventive activities until one or more of the resultant technological objects contributes to an acceptable solution. Thus, a performance problem usually causes inventors to generate a set of technological variants, from which individuals (and social units at various scales) select for incorporation into other activities. For example, artisans – as manufacturers – elect to replicate only some inventions, which are further winnowed by consumers (on the "replicative success" of artifacts, see Leonard and Jones 1987). Needless to say, when they are subjects of explanation, replication (or manufacture) and consumption (or adoption) require their own models (see Schiffer et al. 2001). Although a source of variation subject to selection, invention processes are far from random, and so are not equivalent to genetic mutation (cf. Fitzhugh 2001; see Schiffer 1996 on "stimulated variation").

Generalizing from historical examples, it is suggested that most inventions – even those that become hardware – are unsuccessful owing to shortcomings in performance characteristics; they are neither replicated by artisans nor adopted by consumers. Successful inventions are evidently a small, and almost certainly unrepresentative, sample of the products of human creativity. If we aspire to construct *general* theories and models, then it behooves us to consider all (knowable) technological objects, successful or not, that result from an invention process. Otherwise, our narratives are apt to consist of presentistic chronicles of only replicated and adopted technological objects.

The relentless variety-generating feature of invention processes has straightforward implications for understanding archaeological variability. Variants that became hardware but were judged unsuitable usually end up being reused or discarded.

In either case, barring deterioration, the remains may be included in archaeological deposits. Thus, the cascade model can help the archaeologist to seek, identify, and explain certain patterns of formal variability that might otherwise elude scrutiny.

In building and illustrating the cascade model, a well-documented case from the historical record is used. As Dethlefsen and Deetz (1966) demonstrated long ago in their studies of New England gravestones, the historical record is fertile ground for cultivating new archaeological method and theory (see also South 1977). Inventions that arose in the course of creating the electromagnetic telegraph are lavishly recorded in a huge technical literature. These writings furnish information about the proximate contexts of invention cascades and on the countless technological objects, successful and unsuccessful, that they begat. On the criterion of sufficient surviving evidence, the electromagnetic telegraph is an ideal case. In drawing inspiration from a CTS in a capitalist-industrial society, I have strived to fashion a model that by virtue of its generality and flexibility is also applicable to small-scale societies (see "Operationalizing the Cascade Model on Archaeological Cases" and "Discussion").

CTSs of great complexity, like the electromagnetic telegraph, have three common concomitants. First, some require a complex social organization, with many people performing specialized, hierarchically related roles, as in automobile factories, churches, and ships. Second, a number of CTSs, such as an electric power grid, road network, and canal irrigation system, exhibit considerable spatial extension. And third, CTSs having complex social organizations and great spatial extent tend to endure for many decades, sometimes centuries. These concomitants are most likely to co-occur in the technologies of complex societies. Indeed, the terms "socio-technical system" (Hughes 1983) and "large technical system" (Joerges 1988), which were formulated by historians to handle certain Western industrial technologies, imply both organizational complexity and spatial extension. However, these are *not* essential features of a CTS, as defined here. CTSs and cascade invention processes can also occur in small-scale societies (see "Operationalizing the Cascade Model on Archaeological Cases").

Another scale issue that enters into the designation of CTSs is that of bounding the unit of study. For example, in investigating the telegraph, we may choose any of the following: (1) one telegraph, (2) one telegraph network, (3) all telegraphs in one nation, or (4) all telegraphs in the world. Because the telegraph developed as a result of inventions made in several nations, by members of an international community of inventors competing for patents, financial support, employment, prestige, and social power, it is justifiable to choose the largest scale – that is, all telegraphs. Nonetheless, the American Morse telegraph, which was eventually adopted throughout the world, serves overwhelmingly in the examples below and effectively illustrates the model.

In the past few decades, students of technology in many disciplines have properly called for greater efforts to show how technologies develop in response to a variety of contextual factors – for example, religious, economic, political, social, and ecological (Adams 1999; Arnold 1993; Bijker 1995; Dobres 2000; Dobres and Hoffman 1999; Galison 2003; Hughes 1983; Killick 2004; McGuire and Schiffer

1983; Mom 2004; Mills and Crown 1995; Nelson 1991; Schiffer and Skibo 1987; Schiffer et al. 1994a; Shackel 1996; Skibo and Schiffer 2001; Staudenmaier 1985, 2002). It is widely appreciated that people in virtually any realm of society, from religious leaders to subsistence farmers, can foment the development of new technologies. Moreover, the actual course of development depends greatly on the kinds of social roles and social units available to underwrite the process, such as branches of government, political leaders, stock-issuing corporations, communities, religious congregations, elites, kin groups, aggrandizers (Hayden 1998), sodalities, households, and task groups. Such organizational variation can affect, for example, the resources available to support and reward inventive activities, acceptable values of core performance characteristics, decisions to pursue development, strategies for developing CTSs, and ultimate outcomes (e.g., Galison 2003; Hughes 1983). Although the cascade model itself draws attention mainly to the *proximate* contexts of invention processes, both proximate and distant contextual factors are essential for crafting well-rounded, anthropologically sound narratives of technological change (Fitzhugh 2001). Needless to say, identifying the more distant contextual factors and linking them *rigorously* to specific technological changes is the creative challenge we all face.

It is also important to note that performance problems in a developing CTS are sometimes solved by organizational inventions (Chandler 1977), including new ways to recruit, train, and discipline workers. Such solutions, however, are not within the cascade model's compass. Perhaps archaeologists whose inspiration comes from other theoretical programs, such as social construction (Killick 2004) or agency theory (Dobres 2000; Dobres and Hoffman 1999), can build models for handling all responses to performance problems.

The Cascade Model

A CTS has a life history consisting of a minimal set of processes: creating the prototype, replication or manufacture, use, and maintenance. These processes, however, do *not* comprise a unilinear sequence; some may occur in parallel and others can recur. Depending on the CTS and one's research interests, many more processes can be specified. Thus, to accommodate the telegraph's diverse invention cascades, a large set of processes is delineated (some of which may apply only to CTSs in capitalist-industrial societies). Although the model can be elaborated ad infinitum, a key premise remains invariant: life-history processes, however subdivided, are the proximate contexts of invention cascades. By employing life-history processes as analytic units, one can operationalize the model systematically (see below).

A life-history process consists of interrelated activities, which in turn incorporate one or more technological objects. If the CTS's life history is to have a forward motion – that is, proceeding from activity to activity and from one process to the next – people must judge that the technological objects have reached acceptable values of "core" or "critical" performance characteristics (see Schiffer and Skibo

1997). As behavioral capabilities, performance characteristics can enable any kind of interaction – for example, mechanical, electrical, thermal, or chemical. In addition, many performance characteristics pertain to human senses, such as olfactory, gustatory, tactile, and visual, and facilitate symbolic behavior (Schiffer and Miller 1999a). The effort to achieve acceptable values of critical performance characteristics – whether utilitarian or symbolic – usually provokes a spurt of inventions, which can in turn foster further spurts. Each life history process, consisting of activities and their constituent interactions, is a potential incubator of invention cascades.

The minimal unit of an invention cascade is a flurry of inventions that tend to cluster somewhat in time but not necessarily in space. As variants of a particular kind of technological object, defined on the basis of utilitarian and/or symbolic functions, the inventions usually differ in how well they achieve the critical performance characteristics. These performance differences affect selection processes: many inventions are judged unsuitable and are not replicated; some, though promising, are replicated but only sporadically adopted; and others, regarded as successful, are replicated and adopted widely. In some cases, no suitable variants are invented, which truncates or radically redirects the CTS's development.

Cascades can occur at any scale of technological object, from part to subsystem; in very complex CTSs, one often finds a hierarchy of invention cascades. For example, in the 1890s, when marked interest arose in building automobiles, there was a cascade of prototype vehicles with different motive powers: steam, electricity, gasoline, compressed air, and even springs (Hiscox 1900). Manufacturers quickly selected in favor of gas, steam, and electric. Inventors in turn created countless alternative designs for specific parts, assemblies, and so on for each vehicle type. Among the cascades that arose were inventions for ignition and cooling systems in gasoline automobiles, for batteries and controllers in electrics, and for boilers and condensers in steamers. During the next two decades, the symbolic functions of gasoline and electric cars also stimulated invention cascades in body styles and interior furnishings (Mom 2004; Schiffer et al. 1994a). As in the automobile case, inventors may initially adopt different approaches to achieving the CTS's core performance characteristics, leading to diverse technological objects at many scales. Gould (2001:201) has compared the proliferation of early steamship designs to "adaptive radiations" in biology.

In capitalist-industrial societies especially, CTSs sometimes undergo a succession of invention cascades lasting many decades or even centuries (cf. Mokyr 1990). Indeed, the gasoline automobile in the twentieth century experienced virtually continuous cascades. Major cascades arose, for example, in response to changes in contextual factors, such as fuel costs, road design, and governmental regulations, which affected the criticality of performance characteristics relating to fuel economy, puncture and wear resistance of tires, and permissible quantities of exhaust chemicals. In addition, the adoption of a technological object can alter the performance requirements of other objects with which it interacts, leading to further cascades (on such "disjunctions," see Schiffer 1992, Chap. 4). CTSs in small-scale societies, such as canal irrigation systems, also would have experienced, one would think, more or less continuous invention cascades.

Illustrating the Model: The Electromagnetic Telegraph

This section, which treats the electromagnetic telegraph, serves several purposes beyond illustrating the cascade model. First, it defines along the way the four basic processes (i.e., creating a prototype, replication or manufacture, use, and maintenance) in more detail. Second, it demonstrates how easily the cascade model can be elaborated beyond the four basic processes. Third, this section calls attention to the host of unsuccessful technological objects that an inventive spurt can leave in its wake, which can potentially reach the archaeological record. Fourth, it emphasizes that many kinds of performance characteristics, utilitarian and symbolic, become critical in specific life-history processes. And fifth, it instantiates the behavioral tenet that archaeologists can study people–artifact interactions in any society, without regard to time or space (Reid et al. 1975).

Creating the Prototype

A CTS often begins its life as an idea or vision for a technology that is expected to have certain use-related performance characteristics. In capitalist-industrial societies, these visions have many sources, including existing technologies; previous but unsuccessful attempts to construct a similar CTS; literatures of science, engineering, and popular culture – including science fiction; playfulness of creative people; and "cultural imperatives" (*sensu* Schiffer 1993). Often, the vision arises independently among many individuals. Indeed, in a community of practice, such as electrical experimenters, astronomers, or shipbuilders, ideas for a new CTS may be obvious to its more knowledgeable members. As the telegraph case makes clear, however, the hard work of inventing is in the details, in working out the CTS's numerous "little" inventions that comprise cascades.

Captivated by the vision, inventors strive to make prototypes that exhibit minimal functioning. "Minimal functioning" means the achievement of the CTS's core performance characteristics at a level merely adequate to demonstrate to the inventor (and perhaps kin, friends, or associates) that such a system is technically possible. Constructing a prototype often leads to many invention cascades.

"Telegraph" was already a familiar term in the early nineteenth century, for by then various mechanical–optical telegraphs, such as semaphores, had been operating in France, Germany, and England (Shaffner 1859). Indeed, all of France had been knit into a single, government-controlled network centered on Paris (Beauchamp 2001). Limited to line-of-sight transmission, these telegraphs required many relay stations and personnel; moreover, they worked slowly compared with the speed of electricity; and most shut down at night. These were the performance shortcomings identified by the many proponents of *electrical* telegraphs.

Visions for an *electrical* telegraph originated in the middle of the eighteenth century (Fahie 1884; Schiffer et al. 2003). Surprisingly, a handful of inventors actually built prototypes employing electrostatic generators and Leyden jars (the latter were the first capacitors, which store an electric charge); none was replicated. Such prototypes continued to be built into the early nineteenth century, but these designs eventually were selected against in favor of telegraphs employing electromagnetism and batteries.

After Oersted's surprising discovery in 1820 that an electric current, flowing through a wire, created magnetism that could, for example, deflect a compass needle (Dibner 1961), researchers appreciated the possibility that electromagnetic apparatus could produce action at a distance, capable of carrying information. Thus, in several nations, electrical researchers conjured up visions of *electromagnetic* telegraphs; this was, after all, an invention that appeared "obvious" (Barlow 1825:105) – at least in principle.

The development of prototype electromagnetic telegraphs received added impetus after Joseph Henry's redesign of Sturgeon's electromagnet in 1831 (Henry 1831), and the invention, beginning in 1836, of various "constant batteries" by J.F. Daniell, W.R. Grove, and others. Though hardly constant in output, the new batteries needed maintenance less often than earlier designs, and so could power a telegraph for longer periods (Meyer 1972).

Prototype telegraphs included, at a minimum, technological objects that met the following use-related performance requirements: (1) a transmitter for encoding information into electrical signals, (2) a receiver, using an electromagnet, for decoding the electrical signals and displaying the resultant information visually or acoustically, (3) a battery for supplying electricity to activate the electromagnets, (4) one or more wires for connecting the transmitter and receiver, and (5) a codebook for enabling translations at both the sending and the receiving stations.

In attempting to realize these performance requirements, inventors generated many prototype telegraphs in the 1830s and 1840s whose technological objects varied greatly (the best book-length sources on these inventions are Preece and Sivewright 1891; Prescott 1888; Sabine 1869; Schellen 1850; Shaffner 1859). For example, some systems used one wire, while others used two or five, and a few many more; some employed a needle indicator on the receiver, while others employed a printer or sounder; some used codes representing letters and numbers, while others were keyed to sentences in a telegraphic dictionary. And transmitter designs were equally diverse. Some systems worked reliably, others did not, but many achieved the ability to send and receive information over many miles.

During the telegraph's early years, patents were already being treated in many nations as a form of intellectual property that could be sold, leased, or otherwise managed (Cooper 1991; Post 1976). Ambitious inventors throughout the West patented their systems, along with thousands of technological objects, which furnish a stunning record – partial, to be sure – of the invention cascades occurring during the telegraph's first decades (e.g., United States Commissioner of Patents 1883; Great Britain Patent Office 1859, 1874, 1882).

With functioning prototypes and patents, inventors can sometimes acquire modest funding and entrepreneurial expertise to continue development. And so it was with some early telegraphs. In the United States, for example, Samuel Morse teamed up with Alfred Vail whose father was a successful manufacturer (on the early history of the Morse telegraph, see Morse 1973; Taylor 1879; A. Vail 1845, J. Vail 1914). Other inventors, including Wheatstone and Cooke in England and Siemens in Germany, also obtained support, generated new technological objects, and brought their telegraph systems to market.

Technological Display

Inventors easily come to believe that their prototypes, usually assembled of jury-rigged components in a laboratory or workshop and often operating erratically, are technically feasible. Promising prototypes occasionally attract the first backers, but deep-pocket capitalists, potential manufacturers, governments, and a curious public (perhaps tempted by stock offerings) require a convincing demonstration. In the technological display process the CTS is exhibited, usually in an elaborate show-and-tell, to an outside and sometimes skeptical audience.

Because technological display must impress mostly nontechnical people, visual performance characteristics of the technological objects become critical. Indeed, the appearance of the system contributes, symbolically, to demonstrating the inventor's technical competence.

The Morse telegraph provides a dramatic example of technological display. In the telegraph's first major show-and-tell for a nontechnical audience, which took place in February 1838 in Washington DC, Vail and Morse – exploiting a connection in Congress – were able to garner an august group of onlookers that included President Martin van Buren, members of the House Commerce Committee, and heads of executive-branch departments (Vail 1845:78). These men witnessed the transmission of information through two spools of wire, each five miles long, between committee rooms in the Capitol. In preparation for this display, Vail had given the electrical parts a finished appearance. Moreover, this was the first Morse telegraph that transmitted all information – numbers and letters of the alphabet – as dots and dashes, which were recorded by a fountain pen bobbing up and down on a spring-driven, paper-covered drum. Needless to say, it was a most impressive electrical and visual performance.

Demonstrating "Practicality"

The CTSs constructed for technological display are often essentially complete systems but built on a very small scale. What is more, they are usually presented in an environment more benign than would be encountered in real-world operation. Thus, even after a successful show-and-tell, many questions remain about the system's performance characteristics. That is why a large-scale demonstration is sometimes needed to convince others that the system is "practical" (the usual nineteenth-century term was "practicable").

Practicality is taken here as the judgment that outsiders render after witnessing, or learning about, a full-scale demonstration. In capitalist-industrial societies, such judgments are based on critical performance characteristics, such as cost estimates for building and operating the CTS, the likely reliability of the system and its components, and how well it performs symbolically in specific activities and in relation to particular groups. These assessments often lead to forecasts about the size and socio-economic composition of anticipated markets. A judgment of practicality may liberate resources for replicating the system; a negative judgment may presage the CTS's demise.

The successful demonstration of practicality does not, however, ensure that the CTS will be brought to market, for replication depends on contextual factors far beyond the inventor's control, such as political enablers and inhibitors, and the availability of capital. On the other hand, inventors with considerable resources of their own may ignore negative judgments based on market forecasts and manufacture the invention anyway.

With the technical feasibility of Morse's system apparently not in doubt, Congress furnished Morse in 1843 with $30,000 to build a telegraph line connecting the Capitol, in Washington DC, with the railroad depot on Pratt St. in Baltimore, Maryland – a distance of about 40 miles (Vail 1845). As Morse and other inventors began constructing demonstration telegraphs, they encountered countless problems, which occasioned many invention cascades. For example, Morse began installing his line underground, believing that it would be more secure from vandals and sabotage than an overhead arrangement. However, after laying just 10 miles of line, Morse had already spent half the government grant; more troubling still, he found that the cable was defective. He abandoned the original plan and resorted to suspending the wires from wooden poles. In England and Germany inventors devised different – and somewhat more successful – designs for underground cables along with their diverse designs for aboveground lines.

Aboveground lines were cheaper, but they too required new inventions, such as appropriate poles (wood or metal), for suspending the wires, insulators to electrically separate the wire from the pole, rain and snow shields, methods of treating wooden poles to retard decay, treatments of the (usually iron) wire to deter corrosion, techniques for splicing wires, and new kinds of electrical connectors. For each of these performance requirements, inventors devised numerous technological objects. And, to furnish electricity for their telegraph lines, Morse and other system builders could choose among many dozens of battery designs, some invented for telegraph use.

Once a demonstration telegraph line was up and running, performance characteristics relevant for judging practicality could be assessed, including rates of transmission and operating costs. Observers judged Morse's line a rousing success. For example, the Secretary of the Treasury wrote to the Speaker of the House that "the perfect practicability of the system has been fully and satisfactorily established" (quoted in Vail 1845:98). Comparable large-scale demonstration projects in Europe of quite different telegraphs led to similar judgments.

Replication

On both sides of the Atlantic, substantial resources were poured into building telegraph systems. In European countries, some of whose governments underwrote telegraph replication, this new communication system became, like the semaphore telegraphs, a political technology (Nickles 2004). For example, the far-flung British empire was governed telegraphically from London as soon as submarine cables united the continents in the early 1870s (Headrick 1981). In the United States, however, the telegraph was proliferated by private companies, and some even competed against Morse with alternative technologies (Reid 1879). Despite differences in political and economic contexts, comparable invention cascades arose on both sides of the Atlantic during replication and in subsequent life-history processes.

In the replication process, new activities arise for manufacturing multiple instances of the technological objects. In turn, these manufacturing activities have critical performance requirements that lead to new tools, sometimes even to specialized workshops or factories. The result is usually a plethora of inventions. Moreover, as new tools are winnowed in manufacturing activities, the CTS's technological objects themselves sometimes undergo design changes to enhance ease of manufacture.

As telegraph companies were formed in the United States and in other nations, demand surged for telegraph components. Not only were new companies formed to manufacture transmitters and receivers, but established makers of wire, electrical instruments, and so on scaled up their operations (for an overview, see Israel 1989). In companies old and new, manufacturers tried out countless inventions that might promote rapid and efficient production. For example, to make wire to demanding specifications and in unheard-of quantities required new production machinery. Diverse machines were also invented for applying insulation to wires and for winding wire on electromagnets.

Marketing and Sales

To facilitate marketing activities, wholesale and retail, inventors devised lavish brochures, fancy demonstration devices, tokens, and so on. For decades, telegraph companies and manufacturers of components used these kinds of symbolically loaded objects to hawk their wares at electrical exhibitions and world fairs. Likewise, offices where people could send messages had to be furnished not only with telegraph equipment and new writing technologies (such as forms), but also with characteristic trappings, such as signs and furniture, that could help people to symbolically distinguish a telegraph office from other places of business.

Installation

As people begin to gain experience in installing the system, still more invention cascades arise. Installation-related inventions are generated to solve recurrent problems and also to routinize work, reduce labor requirements, and conserve materials.

To assist in installing aboveground lines, machines were invented that could stretch the wire to an appropriate tautness between the poles. Achieving good insulation of the wires where they attached to the poles led to dozens of insulator designs, in which inventors strived, for example, to increase electrical resistance, durability, and ease of installation.

Additional invention cascades arise when the CTS is installed in a different environment because new critical performance characteristics can come into play. Attempts to lay telegraph lines under rivers, across the British Channel, and eventually across oceans created seemingly endless invention cascades. Submarine lines required a waterproof, heavily insulated, good conducting, and strong cable that could be laid reliably. A great many people invented cables aimed at achieving acceptable values of these performance characteristics.

Accompanying the efforts to lay ocean cables, which began around 1850, were many inventions for storing the cable aboard ships and paying it out. This machinery was complex, requiring constant monitoring of the tension on the cable as well as brakes that could be applied firmly but gradually so as not to cause a break (Dibner 1959). Eventually, ships equipped with special-purpose equipment were built for cable work (Finn 1973).

Entirely new kinds of electrical instruments, such as Thomson's mirror galvanometer, enabled faint signals to be detected and allowed installers to pinpoint the location of breaks in the cable or weak places in the insulation as it was being laid.

Use/Operation

As users begin to acquire familiarity with a CTS, new use-related performance characteristics, even some unanticipated by manufacturers, may become critical. Indeed, inventions made by users are sometimes incorporated through feedback into the CTS's design (Oudshoorn and Pinch 2003). For example, people discovered quickly that lightning could wreak havoc with the telegraph, and so they invented protection devices; some lightning conductors were attached to insulators, while others were emplaced on the poles or telegraph stations.

The process of use may involve varied activities and social groups, each with different performance preferences. In the case of the telegraph, at least two user groups contributed to invention cascades: (1) telegraph operators and (2) customers (people who sent and received messages). Throughout the telegraph's first decade, operators crafted endless varieties of transmitters, receivers, batteries, and so forth in order to improve ease of use and reliability; Thomas Edison was the most famous member of this group (Israel 1998). Consumers, actual and potential, can contribute to invention cascades by calling attention to new applications (see "Functional Differentiation").

Perhaps, the most important source of invention cascades during use is growth of the system. As a CTS is forced to accommodate more users or a greater intensity of use, scalar effects can degrade core performance characteristics. Solving these problems necessitates expansion of the system, either by building more systems identical to the original or by changing the CTS's technological objects to increase its capacity. Both solutions were adopted as demand for telegraph service rose sharply during the middle of the century. In addition to building more lines, or adding new wires to old lines, inventors such as Edison came up with countless technologies for sending two or even four messages on the same wire.

Maintenance

As installed systems begin their uselives, varied maintenance activities are necessitated. Some are easily predicted or become apparent quickly because they occur often; others may not be evident until the system has been in use for some time. Both high- and low-frequency maintenance requirements can occasion invention cascades.

Refurbishing telegraph batteries was a predictable and high-frequency maintenance activity, one that was distasteful to telegraph operators because batteries contained acid. Replacing electrodes and renewing the acid was a messy and dangerous job. Not surprisingly, efforts to invent more easily maintained batteries created a constant flow of inventions, some offered by telegraphers themselves.

Infrequent maintenance activities, such as repairing damage to poles and lines after an ice storm, also stimulated invention cascades. In particular, the need to locate breaks in the line and to troubleshoot malfunctioning equipment led to new instruments and standard units for measuring voltage, current, and resistance.

The repair of submarine cables, damaged by animals, anchors, contact with rocks, and other causes, gave rise to rich invention cascades. To recover the ends of a severed cable, for example, required new kinds of grappling hooks. Once the cable was captured, of course, the free ends had to be joined by special splicing technologies – the source of another invention spurt.

Functional Differentiation

After replication, a CTS often enters a visible public realm where people in diverse communities of practice consider using it for their own activities. The process of adapting the technology for new activities sets off more invention cascades (on the process of technological differentiation, see Schiffer 2002). The new systems that result could, for purposes of analysis, be treated as entirely new CTSs and studied in their own right.

In the case of the telegraph, many new invention-stimulating functions materialized early on. Among the first were railroad telegraphs for signaling the locations and conditions of trains to the dispatcher (Langdon 1877). Inventors came up with varied transmitters for use on trains and others that could tap into the line anywhere along the tracks. Eventually, there were alternative designs for trackside, electrically controlled signaling systems that responded to the movement of trains and to orders from dispatchers.

Another new application was the municipal "fire-alarm telegraph," developed simultaneously, and probably independently, in the United States and Germany around 1850 (Anonymous 1862; Channing 1855). A fire-alarm telegraph furnished fire stations with timely information on the location of fires. Throughout cities, fire-alarm boxes containing telegraph transmitters were placed along streets. When a signal announcing the outbreak of fire in a particular district arrived at the central station, a dispatcher would alert the closest fire brigade, also by telegraph. These systems stimulated a flurry of inventions that, among other performance characteristics, (1) enabled anyone to set off a fire alarm, (2) provided the dispatcher with a display indicating which alarm had been activated, and (3) permitted fire brigades to receive alerts.

Visions of other specialized telegraph systems also provoked invention cascades, including hotel "annunciators," through which guests could signal their needs to staff; burglar and fire alarms in homes and businesses; stock tickers for connecting offices and homes to stock exchanges; and portable military telegraphs that could be moved along with troops.

Operationalizing the Cascade Model on Archaeological Cases

This section suggests that the cascade model can become a useful archaeological tool for investigating CTS-related invention processes in diverse societies.

Applicability of the CTS Construct

Inquiring minds doubtless wonder whether CTSs are even present in the societies that most prehistorians study. Employing the flexible definition of CTS presented above, many technologies in small-scale societies appear to conform. For example, the bow and arrow is a CTS, composed of several separately functioning technological objects that help to achieve the system's core use-related performance characteristic: the ability to aim an arrow and launch it at a sufficient velocity to wound or kill an animal (see Hughes 1998). Domestic cooking technology might be a near-universal CTS, consisting of technological objects, such as containers, utensils, ingredients, and a heat source, which functions to transform edible substances into culturally appropriate meals. Some ritual technologies, recreational technologies, enculturative technologies, political technologies, soil- and water-control technologies, plant-cultivation and animal-husbandry technologies, and the like could also be regarded as CTSs. In view of the construct's definitional flexibility, I submit that CTSs should be identifiable in virtually all societies.

The next issue is whether the cascade model's life-history processes are applicable to CTSs in small-scale societies. It would appear that the basic set of processes – that is, creation of a prototype, replication (or manufacture), use, and maintenance – is general enough to be nearly universal. As in the telegraph case, the archaeologist can add other processes to the basic set.

Another issue is whether the development of CTSs in small-scale societies gives rise to invention cascades. In principle, performance problems should emerge during life-history processes in the development of any CTS – regardless of societal context. Consider once more, in a thought experiment, the bow and arrow. Inventors could acquire the vision for this CTS from many sources: thinking about new ways to hunt, watching hunters in another society, or even handling a bow and arrow made elsewhere. Regardless of the vision's origin, attempts to realize it might have stimulated trials with new materials that had to be worked and assembled in new ways. Moreover, the creation of bow-and-arrow prototypes likely entailed the invention of new tools and processing techniques. And the bow and arrow's use on different game animals might have disclosed additional performance problems. It is doubtful that ancient hunters would have arrived at completely workable designs on the first try. Probably there were flurries of inventions, which yielded along the way unsuccessful technological objects. Moreover, if bows and arrows acquired important symbolic functions, then relevant visual performance requirements would have stimulated still more invention cascades. If this thought experiment is indicative, then one would expect that creating even the simplest CTSs in prehistory resulted in some invention cascades. The alternative position, it would appear, is that prehistoric inventors were omniscient, able to predict unerringly which technological objects would allow a CTS to carry out its utilitarian and symbolic functions.

Seemingly, the cascade model is sufficiently general and flexible to be operationalized on the archaeological record of small-scale societies. Yet, there remains a pressing question: in applying and evaluating the model, how might the archaeologist proceed? The answer consists of a thumbnail sketch of possible research activities. The list that follows is not a recipe, however, for it is likely that provisional findings will give investigators a basis for repeating the research activities in varied sequences.

One begins by identifying a CTS. Let us take, for purposes of discussion, "canal irrigation among the Hohokam," an archaeological culture that occupied a large part of southern Arizona between about AD 500 and 1450 (inspiration for this CTS comes from Ackerly et al. 1987; Dart 1989; Gumerman 1991; Haury 1976; Huckleberry 1999).

The investigator next defines the CTS in behavioral terms by specifying a small set of core performance requirements that would have permitted a prototype system to function. Thus, a riverine canal irrigation system has to convey water from a river to cultigens and enable farmers to control the amount of water reaching individual fields.

Using life-history processes as analytic units, the archaeologist specifies the kinds of performance problems that would have emerged during development. In attempting to solve these problems, farmers qua inventors would have generated invention spurts to yield technological objects having suitable performance characteristics. Replication, for example, probably required durable digging implements, major and minor canals capable of handling the usual flows, devices for easily and reliably controlling the flows to each field, and fields whose design promoted ease of irrigation. Farmers also might have come up with inventions that enabled the laying out of suitable canal routes. To handle maintenance problems, farmers likely would have devised artifacts that could remove accumulated sediments, patch weak or eroded places in canals, repair or replace control devices, and rehabilitate washed-out fields. In extreme cases, such as the aftermath of a huge flood, large parts of the system might have been rebuilt with new canals that had differing lengths, grades, and cross sections. To deal with salinization of fields, farmers could have tried out new crops to find salt-resistant varieties. Expansion of the system might have necessitated additional inventions, such as new kinds of canals as well as technologies for lengthening and raising the capacity of old ones. If the canal system acquired new functions, such as furnishing water for domestic consumption and clay for making pottery, new performance requirements could have stimulated further invention cascades.

In inferring the performance problems that emerged in a developing CTS, the archaeologist must understand in detail how the system would have worked. To acquire such knowledge – that is, “techno-science” (Schiffer and Skibo 1987) – one can exploit modern engineering literature and expertise, conduct experiments, and draw upon ethnographic, ethnoarchaeological, and historical information. This high level of understanding (*not* displayed in the canal irrigation example) lays a foundation for inferring – from archaeological evidence – the technological objects that seemingly had the requisite performance characteristics for taking part in specific life-history activities.

After inferring which artifacts were likely to have been part of the CTS, the archaeologist partitions them into sets according to life-history processes. Next, the time–space distributions of the members of each set are delineated as precisely as possible. The archaeologist can then scrutinize these distributions for any patterning that might be interpretable as invention cascades, paying special attention to variants that apparently were unsuccessful. For example, suggestions of invention spurts may come from diversity in canals, especially those that went nowhere, were damaged without repair, or were abandoned and replaced almost immediately after construction. Repair episodes and other modifications that appear to have been used for only the briefest period might also help to pinpoint invention spurts. In attending to unsuccessful variants as products of invention cascades, the archaeologist might be able to make sense of variability that was previously obscure or ignored.

Although it would be desirable to make predictions about the temporal patterning of technological objects (aggregated by life-history processes) in the development of CTSs, such an effort would be premature in light of current knowledge. After all, it can be expected that different CTSs will have different developmental trajectories. Moreover, predictions are rendered difficult for CTSs that underwent relatively continuous invention cascades in response to changing contextual factors (e.g., automobiles, the electromagnetic telegraph, and perhaps canal irrigation systems). After all, new technological objects could be invented early, late, or throughout the CTS's life history, precluding *general* predictions about the order of specific invention spurts. Clearly, the development of each CTS must be examined empirically. In the future, however, archaeologists might be able to formulate some generalizations after conducting comparative studies of invention cascades in diverse CTSs. Such studies might also lay a foundation for subdividing the general behavioral context – CTS – into varieties that are characterized by distinctive developmental trajectories and thus temporally patterned invention cascades.

Discussion

As noted elsewhere (Schiffer 2002), by employing behavioral models the investigator can establish a foundation for constructing historical narratives of technological change. Thus, after doing an analysis guided by the cascade model, the archaeologist could fashion a reader-friendly narrative about the CTS's development. The structure and content of that narrative, however, would be underdetermined by the cascade model. This leaves ample room for archaeologists who prefer, for example, agency, social construction, or evolutionary explanations to craft their own narratives on the behavioral foundation. Indeed, because behavioral models direct attention mainly to proximate contexts, one can create narratives that invoke more distant, but still causally relevant, contextual factors.

It should be apparent that the cascade model's demanding inferential requirements could preclude its literal application in many cases. For example, the technological objects of canal irrigation systems, especially the canals themselves, are difficult to date (but see Eighmy and Howard 1991). Nonetheless, even in such difficult cases the cascade model can serve a useful purpose by calling attention to hitherto neglected and unexplained kinds of archaeological variability, such as the unique variants – from canals to firepits to decorated sherds – that do not conform to established types. These variants are often treated as inexplicable idiosyncratic variation, dropped into "other" categories and promptly forgotten. *Some* of these artifacts and features could have been failed variants generated by invention cascades. Merely asking questions about the sources of such variability might provide an inductive entrée into the invention cascades of a CTS.

Implications of the Cascade Model

The cascade model provides potentially fruitful ways to conceptualize some processes of technological change.

CTSs and Material Technologies

A CTS can, and often does, include technological objects made by artisans working in different material technologies. As examples, the telegraph incorporated objects of metal, wood, and glass, and the CTS of domestic meal preparation can include ceramic, chipped stone, and wooden objects – not to mention plants and animals. Thus, a CTS's invention cascades can lead to new variants in different material technologies. Once a CTS has been delineated, the investigator attempts to pinpoint the performance problems that provoked invention cascades in diverse materials.

By the same token, temporal change in the objects of a particular material technology might have resulted from invention cascades in different CTSs (cf. Sillar and Tite 2000:14). For example, let us consider the continuous changes in Anasazi ceramics of the American Southwest that took place from about AD 600 to around 1400 (e.g., Cordell 1997; Chap. 3). Such changes doubtless resulted from altered performance requirements in several CTSs, such as ritual technology, domestic meal-preparation technology, and feasting technology. Potters responded by inventing vessels having an amazing variety of pastes, forms and sizes, and surface treatments, some of which were replicated in large numbers. It might be productive to consider the possibility that practitioners of a given material technology were inventing objects that were supposed to interact in different CTSs.

If a CTS can foment invention cascades in several material technologies and if a material technology can create new variants for several CTSs, then we need to rethink analytical strategies that treat material technologies as autonomous behavioral phenomena. This discussion also implies that any given material technology could have been invented, in various places, in response to the development of different CTSs (Rice 1999 has made this argument for pottery origins).

Necessity as the Mother of Invention

The cascade model also invites reconsideration of the old question: Is necessity the mother of invention? (For a discussion of this question from the standpoint of evolutionary ecology, see Fitzhugh 2001.) Setting aside the issue of whether the telegraph was a response to needs, once efforts were underway to develop a functioning system, inventors had to devise new technological objects necessitated by the system's core performance requirements. Although these requirements could be met in many ways, all functioning telegraph systems employed some constellation of new objects. Likewise, developing a functioning Hohokam canal system required the invention of new technological objects, including water-control devices, canals of several kinds, and irrigable fields.

We suggest that any CTS has core or critical performance requirements, emergent during life-history processes, that determine its functional "needs" (utilitarian and symbolic). Meeting these needs, through invention cascades, entails the creation of new technological objects. Thus, *in functional terms*, the inventions spawned by a given CTS result from necessity: if the CTS is to operate as a system, then these inventions must be made. Given the apparent prevalence of CTSs, one could argue that necessity is the mother of a great many inventions (for a contrary view, see Basalla 1988).

Developmental Distance

Although the vision of a new CTS is sometimes obvious to knowledgeable members of a society or community of practice, far from obvious are the forms, specific functions, performance characteristics, and manufacturing processes of the new technological objects needed for the system's replication, operation, and maintenance. Indeed, the vastness of the development enterprise often becomes apparent only as inventors encounter the innumerable performance problems that emerge during life-history processes.

This idea is shown in the writings of countless visionaries, from Leonardo da Vinci onward, which indicate that machine-powered human flight was an idea that cropped up often. In the nineteenth century, especially after the advent of the railroad and steamship, the vision of self-propelled road vehicles also occurred to many people throughout the Western world. Both visions stimulated invention cascades that resulted in prototypes, but only the automobile achieved acceptable values of core performance characteristics before 1900. Neither CTS was widely replicated and adopted until after many invention cascades led to new technological objects that solved myriad "little" performance problems, such as the ability to control an inherently unstable aircraft or to cool an internal combustion engine.

In order for a CTS to move from a vision – obvious or not – to a replicated technology, its inventors must traverse a certain "developmental distance." That is, they must generate cascades sufficient to produce variants that can help solve the entirety of emergent performance problems. Some developmental distances are short, perhaps because a functional CTS can be cobbled together from technological objects already invented and replicated in other contexts. Sometimes only a few performance problems arise, and so generate only a few spurts of invention. In other cases, developmental distances are lengthy, such as those attending the emergence of telegraph, automobile, and riverine canal systems. A large developmental distance usually compels an enormous investment of human and material resources in inventive activities. As already noted, the societal context looms large in determining whether and in what manner the necessary resources can be devoted to the project.

In small-scale societies, there might have been a lack of sufficient resources for bridging huge developmental distances quickly or at all. At the very least, scheduling conflicts can preclude the diversion of human labor into inventive activities which, as Fitzhugh (2001) reminds us, usually have an uncertain outcome. Consider the case of domestic structures used for storage and habitation, a CTS among the Anasazi of the American Southwest (Cordell 1997). During a period lasting many decades, the Anasazi transformed their structures from pit houses and sundry storage facilities to mostly aboveground, masonry pueblos encompassing both habitation and storage functions. Evidently, changing contextual factors in Anasazi society, such as community reorganization, lengthier stays by households in one settlement, and longer settlement occupations (perhaps set in motion by larger village populations and increasing dependence on agriculture), gradually established new core performance requirements for dwellings and storage facilities (Cordell 1997; Gilman 1987; McGuire and Schiffer 1983; Whalen 1981). Regardless of the causes, inventing the new technological objects (and their manufacturing processes) appears to have entailed a considerable developmental distance.

Remarkably, the invention cascades that contributed to the development of pueblo structures left obtrusive traces in the archaeological record. "Transitional" Anasazi structures were characterized by diverse building techniques and designs, which testify to invention cascades that we know – thanks to tree-ring dating – played out over many decades. This lengthy period of experimentation, which relied on efforts spread over a large region, furnished the Anasazi with reliable information on the performance characteristics of various structure designs, from which they eventually selected the pueblo, which combined both storage and dwelling. One could argue that, had the selective pressures exerted by contextual changes been more insistent, the Anasazi might have been unable to marshal resources needed to traverse the developmental distance *quickly*.

Indeed, one can imagine that the failure to span a large developmental distance rapidly – for example, creating a new agricultural technology in the face of pressing demand for more food or a rapidly deteriorating environment – might have led to other behavioral changes, such as emigration, new kinds of regional organization, modified exchange networks, or violence. It would be unwise to assume that all societies had the resources to reach across large developmental distances in a timely manner. Perhaps many of the gradual technological changes so prevalent in prehistory merely reflect those occasions when there was a good match between the severity of selective pressures and the capacity of traditional societies to generate invention cascades and thereby respond with a functioning CTS.

In one surprising respect, Anasazi structures and electromagnetic telegraphs seem remarkably similar. As CTSs involving great developmental distances, both were built by the pooling of numerous small inventions, generated by cascades, that had been made over several decades by many inventors working in many places. Perhaps this pattern is common.

Conclusion

Drawing upon the richly documented history of the electromagnetic telegraph, a model of invention cascades was presented that applies to complex technological systems (CTSs). The model's key premise is that performance problems emerging during a CTS's development stimulate sequential invention spurts – cascades – that can be conveniently studied in relation to life-history processes. The minimal set of life-history processes, which should apply to most CTSs, is making a prototype, replication or manufacture, use, and maintenance. Depending on the CTS under investigation, the archaeologist may subdivide these processes and proliferate others. In principle, this model should be applicable even to the smallest-scale human societies studied by archaeologists. The cascade model, however, is just one of many models that we require for understanding the variety of invention processes prevalent in human societies.

It should be emphasized that the building of general models does not conflict with the creation of deeply contextualized historical narratives. Beginning with their earliest writings, behavioralists have acknowledged the importance in archaeology of both generalizing and historical research strategies (e.g., Reid et al. 1975), and have also crafted lengthy narratives of technological change (e.g., Schiffer 1991; Schiffer et al. 1994a, Schiffer et al. 2003). However, archaeologists have seldom exercised the generalizing research option when studying invention. This leaves the door open for devising new models and theories that can complement narratives by implicating widespread invention processes operative in specific behavioral contexts, such as CTSs. By constructing and evaluating general models of invention processes, archaeologists can make significant contributions to the study of technological change.