

The Cultural Evolution of Technology and Science

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Abstract

This chapter explores how the principles and methods of cultural evolution can inform our understanding of technology and science. Both technology and science are prime examples of cumulative cultural evolution, with each generation preserving and building upon the achievements of prior generations. A key benefit of an evolutionary approach to technological or scientific change is “population thinking,” where broad trends and patterns are explained in terms of individual-level mechanisms of variation, selection, and transmission. This chapter outlines some of these mechanisms and their implications for technological change, including sources of innovation, types of social learning, facilitatory developmental factors, and cultural transmission mechanisms. The role of external representations and human-constructed environments in technological evolution are explored, and factors are examined which determine the varying rates of technological change over time: from intrinsic characteristics of single technological traits, such as efficacy or manufacturing cost, to larger social and population-level factors, such as population size or social institutions. Science can be viewed as both a product of cultural evolution as well as a form of cultural evolution in its own right. Science and technology constitute separate yet interacting evolutionary processes. Outstanding issues and promising avenues for future investigation are highlighted and potential applications of this work are noted.

Introduction

Aims and Overview

Our aim in this chapter is to explore how the methods and concepts developed in the field of cultural evolution can be applied to the domains of technology

and science. Both technology and science are prime examples of cumulative cultural evolution. Technological and scientific knowledge is accumulated over successive generations, with each generation building upon achievements of prior generations. Both have had an inestimable impact on our species' way of life. As Boyd et al. (this volume) argue, the cumulative cultural evolution of locally adaptive technology has allowed humans to colonize and inhabit virtually every terrestrial environment on the planet. Yet there are also numerous examples of the negative consequences of technology, such as the overexploitation of resources, facilitation of large-scale warfare, and increase in wealth inequality. Technology can significantly transform the way we think and act at a quite fundamental level (Stout, this volume); it can also generate novel coevolutionary dynamics between human lineages and the technology that they use (Shennan, this volume). Science, a more recent cultural innovation, has dramatically accelerated technological evolution and represents a unique system of knowledge not seen in any other species (McCauley, this volume). Advances in our understanding of these two phenomena have been achieved across the social sciences and humanities. Here we explore how the burgeoning interdisciplinary science of cultural evolution (Boyd and Richerson 2005; Mesoudi 2011a) might further this understanding.

In the following sections we outline the individual-level mechanisms that are thought to generate population-level patterns of technological change. We then explore the role of external representations and human-constructed environments in technological evolution and examine the factors which determine the varying rates of technological change over time. Discussion follows on how science and technology interrelate and how scientific and technological evolution differ as processes. We conclude by highlighting outstanding issues and promising avenues for future investigation and note some potential applications of this work.

Definitions and Scope

Both technology and science are challenging concepts to characterize, and numerous definitions of each exist. It is, nonetheless, helpful to delineate the scope of the domains of interest here to focus our chapter and distinguish our topic from the other three topics that formed this Strüngmann Forum: the cultural evolution of sociality (Jordan et al., this volume), language (Dediu et al., this volume), and religion (Bulbulia et al., this volume).

Science and technology are both forms of *knowledge*. Knowledge is the potential of an individual (individual knowledge) or a group (shared knowledge) to solve problems by individual or collective action. Knowledge is typically stored in individual brains (internal representation), as well as in social structures, material artifacts, external representations, and environmental structures (external means). Knowledge is socially transmitted from individual to individual via various processes, typically involving many of these external means.

We can therefore distinguish between knowledge itself (the product) and the means by which that knowledge is acquired and transmitted (the process).

Technology refers to goal-oriented shared knowledge together with its external means. It is thus knowledge geared to, and organized around, solving specific problems faced by a group or society (see also Shennan, this volume). For example, the bow and arrow solves the problem of killing animals from a distance; sextants and GPS solve the problem of navigation; and telephones and smoke signals solve the problem of remote communication. These are all examples of external, physical manifestations of technological knowledge. External *representations* are a special class of intentional external manifestations of technological knowledge which contain information that is interpretable by human minds, and which can become important for the transmission of that technology. These are discussed in the section, External Representations and Human-Constructed Environments.

Our focus in this chapter is on technological *evolution*; that is, technological change as an evolutionary process. As Darwin noted, evolutionary processes require “descent with modification,” by which he meant the gradual accumulation of modifications over time. This aspect of our account, we argue, restricts technological evolution to humans, among extant species, as well as some extinct hominin species. Many nonhuman species use tools, but only humans appear to possess cumulative technological evolution (Boyd and Richerson 1996; Tomasello et al. 1993). Chimpanzees, for example, exhibit regional traditions of tool use behaviors, such as nutcracking or termite fishing, that have potentially spread via cultural transmission (Whiten et al. 1999). Yet none of these behaviors show clear evidence of having been gradually accumulated and improved upon over time. One test for the presence of such “descent with modification” in tool use is the presence of behaviors that are outside the individual learning ability of an organism, or what Tennie et al. (2009) refer to as the “zone of latent solutions.” No such behaviors have been unambiguously reported in chimpanzees, and it seems vanishingly unlikely that any widely used human technology—from the bow and arrow to the iPad—could have been invented by a single person alone. This unique aspect of human technology likely arises from the unusually high-fidelity social learning exhibited by humans compared to other species, as we discuss in the section, How Do Individual-Level Mechanisms Generate Population-Level Patterns of Technological Change?

We restrict our attention here to technologies that have clear external, physical means. These range from artifacts and texts to structured environments and collective practices. Whether individual behavior that does not involve objects (e.g., bodily techniques) qualifies as “technology” is controversial. Some researchers within both cognitive science and cultural anthropology have distinguished at least some human behavior as involving “enactive representations” (Bruner 1964), which may seem to constitute sufficient grounds for inclusion. It has also been argued that language can be viewed as the “technology of the

intellect” (Goody 1973; see also Everett 2012). We acknowledge these alternative perspectives but restrict our focus here to technology that involves clear external means, leaving language to be discussed elsewhere in this volume (Dediu et al., this volume), and consider non-object-based behavior to be too broad (see Stout, this volume).

Science is defined as means-oriented shared knowledge together with the process responsible for its generation. Unlike technology, scientific knowledge is primarily pursued with no instrumental goals in mind. Science is facilitated by technology, most obviously in the form of scientific instruments (e.g., telescopes or microscopes), as well as by symbolic representation systems such as writing. In addition, science, in turn, facilitates and accelerates technological evolution in a coevolutionary feedback process. As McCauley (this volume) points out, we must be careful to make a clear distinction between knowledge that appears to be scientific, such as folk knowledge possessed by nonliterate societies, and knowledge that results from scientific institutions and practices. Nonliterate societies may have extremely sophisticated folk understanding of the world, such as the astronomical knowledge used by Polynesian sailors to navigate the Pacific islands. However, such knowledge is typically characterized by location-specific features (e.g., valid only for observers close to the equator), is not subject to procedures characteristic of science (e.g., open criticism afforded by publications and their discussion in a scientific community), and is prone to loss without the institutional elements of science that only emerged over the last couple of centuries in literate, large-scale societies. The interrelation between science and technology, and how scientific change can be understood as an evolutionary process, is discussed in the section, Science.

How Do Individual-Level Mechanisms Generate Population-Level Patterns of Technological Change?

One of the key benefits of adopting an evolutionary approach to culture is Darwinian “population thinking” (Richerson and Boyd 2005), in which patterns and trends at the population level are explained in terms of the underlying, individual-level mechanisms of variation, selection, and transmission. For biological (genetic) evolution, these individual-level processes are natural selection, mutation, recombination, etc. Cultural evolution may be determined by similar individual-level processes, but several processes unique to cultural change have also been modeled and explored, thus necessitating a departure from strictly neo-Darwinian assumptions. For example, where genetic mutation is blind with respect to selection, cultural innovation may, to some extent, be directed by purposeful agents (Mesoudi 2008). In this section we attempt to catalog these processes and, where possible, apply them to technological change. Table 11.1 provides an overview of these individual-level processes, along with their population-level effects and presence in nonhuman species.

Table 11.1 Individual-level mechanisms responsible for population-level patterns of cultural evolution.

Individual-Level Processes	Population-Level Effects	Presence in Non-human Species
<p>1. Sources of innovation</p> <ul style="list-style-type: none"> • Chance factors (accidents, copy error) • Novel invention (trial and error, insight, or exploration, through personal or group endeavor) • Refinement (modification or improvement of existing variant, through personal or group endeavor) • Recombination (combining existing elements to form a new variant, through personal or group endeavor) • Exaptation (applying existing technology to new function) 	<p>All sources generate cultural variation</p>	<p>All sources are observed in humans but little evidence exists for refinement and recombination in nonhuman species</p>
<p>2. Type of social learning</p> <ul style="list-style-type: none"> • Imitation (including “overimitation”) • Teaching (including scaffolding, pedagogical cueing supported by language) • Emulation • Enhancement effects (local, stimulus) • Facilitatory effects (social, response) • Observational conditioning 	<p>Capable of supporting technological evolution through facilitating high-fidelity transmission</p> <p>Thought incapable of supporting technological evolution because fidelity is typically too low</p>	<p>Rare or absent in nonhuman species</p> <p>Common in humans and other species</p>
<p>3. Facilitatory developmental factors</p> <ul style="list-style-type: none"> • Zone of proximal development • Structuring the learning environment • Apprenticeship, collaboration, and cooperation 	<p>Further enhances the fidelity of information transmission by directing and motivating learning</p>	<p>Little compelling evidence for these mechanisms outside of humans</p>
<p>4. Cultural transmission processes</p> <ul style="list-style-type: none"> • Evolved biases <ul style="list-style-type: none"> ◦ Content bias ◦ Direct/results bias ◦ Context biases (model-based, frequency-dependent, state-based) • Unbiased transmission/random copying 	<p>Capable of biasing the direction and rate of cultural evolution; differentially affects the distribution of cultural variants and pattern of diffusion</p> <p>Incapable of biasing the direction and rate of cultural evolution; differentially affects the distribution of cultural variants and pattern of diffusion</p>	<p>Observed in humans and nonhumans</p> <p>Observed in humans and nonhumans</p>
<ul style="list-style-type: none"> • Guided variation 	<p>Causes cultural evolution to shift toward inferential prior knowledge</p>	<p>Observed in humans but presence in nonhumans is contentious</p>

Sources of Innovation

Innovation is a tricky term to delineate. In different disciplines, it has been variously deployed (see O'Brien and Shennan 2010) to refer to (a) a successful novel variant (i.e., inventions that succeed, as used in sociology), a novel variant (characterized independently of whether they propagate, as used in biology), or any kind of variant; (b) as the ideas underlying an invention or its first implementation; and (c) both the process by which variants are generated as well as the product. Within the field of cultural evolution, innovation has generally been thought of as the functional equivalent to mutation in biological evolution (Cavalli-Sforza and Feldman 1981); that is, innovation introduces new cultural variation into the population through copying error, novel invention, refinement, recombination, and exaptation. Hence, innovation is not a synonym of variation, the latter being a broader category that encompasses diverse forms only some of which are novel.

The technological record contains numerous examples of innovation (Basalla 1988; O'Brien and Shennan 2010; Ziman 2000; Petroski 1994). One example of innovation through recombination is given in Boyd et al. (this volume), where door hinges were likely co-opted for use on rudders in medieval ships (this can also be seen as an example of exaptation, given that the function of the hinge has changed). A fruitful area of study in archaeology has been the modeling of copying error due to limitations of the human perceptual system, loosely analogous to random mutation in genetic evolution. For example, Hamilton and Buchanan (2009), building on previous work by Eerkens and Lipo (2005), modeled the population-level effects of small, imperceptible errors in the repeated cultural transmission of artifact shapes or sizes. Imagine an artifact manufacturer intends to make an exact replica of an existing artifact. If the manufacturer's artifact differs from the original artifact by less than a certain amount (e.g., by less than 3%, which is a typical threshold for shapes), then even though the artifacts may appear identical to the manufacturer, the new artifact may in fact be imperceptibly larger or imperceptibly smaller than the original. If these tiny, random errors are compounded over successive generations of artifact makers, then different artifact lineages can diverge randomly within known limits (ultimately set by the magnitude of the copying error). Hamilton and Buchanan (2009) showed that Clovis projectile point size across late Pleistocene North America fit the predictions of this process of accumulated copying error, suggesting that this technology changed solely due to this random, unbiased process. However, other cases do not fit the predictions of this accumulated copying error (Eerkens and Lipo 2005; Kempe et al. 2012), thus showing how unbiased copying error can provide a useful null model for detecting nonrandom, biased cultural transmission (see section below on Cultural Transmission Processes).

Types of Social Learning

Social learning refers to the transfer of knowledge or behavior from one individual to another. Social learning is a necessary prerequisite for technological evolution, and much recent research has focused on the fidelity of different social learning processes. This is because social learning must be of sufficient high fidelity such that technological knowledge, which is often cognitively opaque and difficult to acquire, is preserved and accumulated over successive generations (Lewis and Laland 2012). If fidelity is too low, then technological knowledge is easily lost due to the copying error discussed in the previous section.

Comparative, social, and developmental psychologists have explored in detail various types of social learning and their potential to support the high-fidelity transmission of knowledge, including stimulus/local enhancement, emulation, imitation, and teaching (Whiten and Ham 1992; Hoppitt and Laland 2008). Forms of social facilitation, such as stimulus or local enhancement, do little more than draw attention to aspects of the environment. Emulation provides information about how the environment can be manipulated or about the affordances of different objects. Social facilitation and emulation are typically considered to be unlikely to provide the necessary high fidelity required for successful cultural accumulation (although for experimental evidence that emulation can result in cumulative improvement in lineages of simple artifacts, such as paper airplanes; see Caldwell and Millen 2009).

Imitation (including “overimitation”) and teaching (often through verbal instruction) appear to be better candidates for facilitating high-fidelity transmission of knowledge; indeed, experimental evidence links these processes to cumulative cultural learning (Dean et al. 2012). Imitation refers to the copying of motor actions performed by other individuals (as opposed to emulation, in which the result of behavior is copied, but not the behavior itself; for further discussion, see Stout, this volume). With respect to technology, it is likely that complex artifactual knowledge (e.g., how to make a projectile point) can only be transmitted faithfully through imitating the precise actions required to make the artifact or through verbal instruction and other forms of teaching. It is rarely the case that complex artifacts can be reverse engineered from the finished product (i.e., through emulation), at least not without introducing substantial variation into the technique (Dean et al. 2012; Flynn and Whiten 2008a; Tennie et al. 2009).

Overimitation (Lyons et al. 2007; McGuigan et al. 2007) describes the tendency of human infants (and also adults, Flynn and Smith 2012) to copy the actions of others with such high fidelity that they reproduce aspects of what they have seen which are not necessarily causally relevant to the goal of the task. For example, children who observe an adult tapping a tool into a hole on the top of a transparent box before using the tool to unlock the box and retrieve a reward will copy both the causally relevant (unlocking) and irrelevant

(tapping) actions. Interestingly, chimpanzees do not appear to overimitate; they only copy causally relevant modeled actions (Horner and Whiten 2005). This may indicate a general lack of high-fidelity social learning in chimpanzees and may, in turn, be related to their lack of cumulative culture (Tennie et al. 2009).

One may wonder, however, how overimitation can result in the adaptive accumulation of effective technological knowledge (see Boyd et al., this volume) when it allows the preservation of irrelevant actions. We think that this is probably an artifact of the experimental tasks typically used to test for overimitation, in which relevant and irrelevant actions are clearly defined. Such a contrast would be difficult to discern for much of the technological knowledge acquired by humans (both children and adults) in nonexperimental settings. This excessive imitation of others' actions may therefore be a manifestation of a hypertrophied human tendency for imitation that is highly adaptive in natural settings where the functional aspects of a task may be ambiguous. Alternatively, overimitation may serve a social function, such as indicating and enhancing affiliation with in-group members (Haun and Over, this volume) or the adoption of normative behavior (Kenward 2012). Teaching, or the “pedagogical stance” (Csibra and Gergely 2009), may further enhance the fidelity of imitation, with experts tailoring their behavior to maximize the likelihood of successful acquisition by the learner and using cues like eye contact to indicate the pedagogic importance of a particular expert act. Language, too, allows the high-fidelity transmission of knowledge necessary for much technological learning, in the form of verbal and written instructions.

Facilitatory Developmental Factors

Various developmental factors may further enhance the fidelity of information transmission. The *zone of proximal development* (Vygotsky 1978) is defined as the difference between what an individual can achieve alone and what that individual can achieve with the support of an expert other. Thus, the acquisition of specific cultural behaviors will be achieved at different times during childhood, depending on the complexity of the behavior and the available social support. Equally, different social learning processes will be more appropriate at different ages. Negotiation or collaboration, for example, may not be an appropriate form of transmission during early childhood (Flynn and Whiten 2012). With age comes cognitive development, and changes in abilities such as theory of mind or inhibitory control may facilitate learning and the ability to use different social learning mechanisms.

Thus, as children get older they acquire more experience with the world—buttons can be pressed, levers pushed and handles pulled or turned. When faced with novel technologies, children can draw on their previous experience and the internal representations associated with that experience (Wood et al. 2013). Experience can help tremendously in dealing with a world that contains numerous artifacts. On the other hand, previous experience can also hinder

solutions via “functional fixedness,” where the intended use of an object overrides alternative, potentially superior uses (Adamson 1952; see also Barrett et al. 2007b).

Through active (e.g., imitation) as well as passive (e.g., teaching) social learning, the zone of proximal development will also improve cognitive capacities of children over time, leading to what has been called cultural intelligence (Herrmann et al. 2007; Tomasello 1999). This ontogenetic cultural intelligence complements phylogenetic cultural intelligence, such as the species-specific social learning abilities discussed above, which evolve biologically over much larger time frames via natural selection and lead to a species’ zone of latent solutions (Tennie and Over 2012). Because of this, we likely share with our great ape relatives some degree of basic phylogenetic cultural intelligence, which could have acted as an important initial impetus for innovativeness in our species, and thus as a potential—and necessary—starting point for cumulative culture (Enquist et al. 2008).

Cultural Transmission Processes

Where sufficiently high-fidelity social learning is present, a further set of cultural transmission biases potentially come into play that describe who, when, and what people copy. Formal models of cultural evolution have identified several such biases that are supported by empirical evidence from psychology, sociology, and other disciplines (Boyd and Richerson 1985; Mesoudi 2009). Content biases relate to the content of the information being transmitted, with some forms of knowledge intrinsically more cognitively attractive or more easily copied (e.g., less complex and/or skill intensive technologies) than others. Direct or results bias occurs when traits are copied based on their observed effects on the world. Context biases refer to factors external to the content or consequence of knowledge, such as the preferential copying of prestigious or powerful individuals (model-based bias, Reyes-García et al. 2008), the copying of traits that are common or rare (frequency-dependent bias), or the preferential copying of traits under certain circumstances, such as copying when uncertain or when the environment has changed (state-based bias; for an overview, see Rendell et al. 2011). Studies of the diffusion of technological innovations suggest that conformist (positive frequency-dependent) bias may be responsible for much technological cultural transmission (Henrich 2001).

Unbiased transmission, or random copying, occurs when learners select models to copy entirely at random (although where different individuals within a population deploy inconsistent transmission biases, the summed effect may resemble unbiased transmission). Archaeologists have borrowed drift models from population genetics to model random copying, showing that certain artifacts change as if they were being copied at random (Neiman 1995), with a lack of fit to such models indicating nonrandom, biased transmission

such as anti-conformist frequency dependence (Shennan and Wilkinson 2001; Mesoudi and Lycett 2009).

Finally, guided variation occurs when individuals modify their behavior as a result of individual learning and this modified behavior is then copied by others. If individuals in the population tend to modify their behavior in the same way, this leads to directional change, a process that Boyd and Richerson (1985) labeled guided variation. Guided variation, unlike the various transmission biases, does not depend on the amount of variation in the population and, as a result, it works quite differently to what we normally think of as “selection.” To see why this is important, imagine a population in which all individuals are identical, and an environmental change favors a different behavior. Selection will not lead to the spread of the new behavior, because there is no variation to select. In contrast, guided variation can lead to change because it is the result of individual learning, not the culling of existing variation.

Modeling Technological Change

This distinction between selection and guided variation is captured by one of the canonical mathematical representations of evolutionary change, the Price equation (Price 1970), and provides one potential formal framework for modeling cultural, including technological, change (although other modeling frameworks are both possible and useful, see Cavalli-Sforza and Feldman 1981; Boyd and Richerson 1985; Gintis 2000). As we illustrate here, the Price equation allows the formal delineation of these different kinds of processes that drive cultural change, as well as incorporating evolution at multiple levels, and the coevolution of multiple traits, all of which are particularly relevant for technological evolution. It also suggests that a more nuanced definition of “fitness” is required with respect to technological change, compared to biological definitions of fitness (see also Shennan, this volume).

Suppose there is a population of variable cultural entities, for example, different design variants of a tool or weapon or other technological trait, such as two variant bow designs, simple and recurved. Labeling the frequency of one of the variants q , the change in this frequency, Δq , is proportional to:

$$\Delta q \propto \beta \text{var}(q) + E(w_i \Delta q). \quad (11.1)$$

The first term, $\beta \text{var}(q)$, gives the change due to what biologists typically call selection. The β parameter measures how much changing the cultural variant affects the fitness of that variant (i.e., the regression of fitness on trait frequency). For example, if people tended to copy more powerful bow designs, then β would be the effect on power of switching from simple to recurved variants. This is multiplied by $\text{var}(q)$, the variance of the trait in the population. If most people use the same design, then the variance will be small and selective processes will have little effect, whereas if both designs are in regular use,

comparison by learners can lead to rapid change. Just as the strength of natural selection depends on the amount of genetic variation in a population, the strength of cultural selection depends here on the amount of cultural variation.

The second term, $E(w_i \Delta q)$, is the expected amount of change due to individual-level processes. For example, it could be that individuals experiment with their own bows and sometimes switch from one design to the other as a result of their individual experimentation. This term would give the net effect of this individual experimentation. This individually driven change operates differently to selection because it does not depend on the amount of variation in the population. Thus, if we define cultural fitness in exactly the same way as biological fitness, it will determine the rate and direction of cultural change due to selective processes but it will not capture this latter nonselective change. It seems likely that nonselective change due to individual learning as well as shifts induced by the inferential nature of cultural transmission are more significant in cultural evolution than are nonselective processes in genetic evolution (such as meiotic drive). If so, knowing the cultural fitness of alternative variants alone will not allow prediction of the overall direction of cultural change.

Alternatively, it might be possible to define cultural fitness in terms of the “goals” of the learning processes that govern both individual learning and various forms of biased transmission. This would have to be averaged with the direct effects of selection on cultural variants, for example, due to the fact that these variants affect fecundity of a trait with significant vertical transmission to create a metric that predicts overall cultural change.

This framework can be extended to address evolution at multiple levels. Cultural variation affects the success, prestige, and survival of different levels of social organization. For example, some new fishing technique or invention such as fine nets might allow an individual to obtain more fish relative to other individuals within their group, but groups in which this technique/invention is common may do worse in competition with other groups with less effective fishing techniques due to the former’s overexploitation of fishing stocks. The change in this cultural variant can then be partitioned into the average effect of individual variation on the rate of cultural transmission within groups, and the effect of the variation among groups on the rate of, say, group survival. This can be expressed using the Price equation as follows:

$$\Delta q \propto \beta_g \text{var}(\bar{q}) + E(\beta_w \text{var}(q_i)) + E(w_i \Delta q), \quad (11.2)$$

where β_g gives the effect of differences in frequency of the trait on group survival and $\text{var}(\bar{q})$ is the variance in trait frequency across groups, such that the first term gives the change in frequency due to group-level processes. Analogously, the second term is the average of the changes within groups and the third term is, as before, the effect of individual transformations. Notice that within this framework there are two fitnesses: the average effect on group replication and the effect on individual replication within groups.

It is also possible to accommodate multiple cultural traits. For example, suppose that the usefulness of projectile points depends on both the length and the width of the point. This leads to two new dynamic processes. First, the fitness value of one trait may depend on the value of the other trait. For example, it might be that as points get longer, they must also get wider. This will mean that changes in the frequency of one trait will depend on the other trait, and thus evolution will lead to coherent change linking functional suites of cultural traits. Second, cultural “hitchhiking” may result from accidental correlations between traits. For example, there is evidence that languages have often spread because they are spoken by groups that possess advantageous agricultural technologies (Diamond and Bellwood 2003). For more detailed analysis of cultural change using the Price equation, see Beheim and Baldini (2012).

External Representations and Human-Constructed Environments

External Representations

All technological knowledge has some external manifestation in the form of material artifacts, according to our characterization above. More interesting, perhaps, is the way in which artifacts can both constrain human behavior patterns and embody information about their own production and reproduction (see Stout, this volume). The functional properties of existing artifacts can clearly channel behavior. In this sense, artifacts may be said to embody information about their use that both afford and constrain possibilities for innovation. As the saying goes, “if all you have is a hammer, everything looks like a nail.” Note, however, that the respects in which information is “embodied” in features of the external world or in which it is “contained” in artifacts, which is to say the respects in which these items *represent* information, is always relative to an apprehending mind. All such information is inherently relational and dependent on the goal-oriented interpretations of agents. Taking this a step further, it is also possible for human agents to interpret the physical form of artifacts as evidence of the processes by which they were produced. Examples include many prehistoric technologies, like Acheulean handaxes, that became “extinct” but have been reverse engineered by archaeologists from material remains. Unlike the functional properties of tools, which (at least arguably) were intended by the manufacturers, reverse engineering is a process of interpretation purely on the part of the observer. Finally, in considering the cumulative cultural evolution of technologies, we should also remember that it is not just ideas that have accumulated but actual physical artifacts. Many modern technologies (e.g., automobiles) require a vast industrial apparatus that has built up over generations; as a thought experiment, it seems implausible that this apparatus could be reassembled “from scratch” in a single generation, even if all relevant knowledge was somehow preserved.

Thus, artifacts themselves are a medium of cultural transmission. Once this is recognized, it then becomes apparent that researchers may sometimes need to incorporate this factor into their models, as the frequency, longevity, or rate of change of artifacts may not resemble that of their users (see section below on Human-Constructed Environments and Niche Construction). Can we simply treat artifact lineages as if they were equivalent to biological lineages? Some cultural evolution researchers have successfully taken this approach (e.g., O'Brien and Lyman 2003b; Tehrani and Collard 2002), and in the interests of methodological tractability, researchers can in practice often ignore many of the cognitive, behavioral, and social processes through which humans reproduce artifact types. The same approach is taken by evolutionary biologists, who have achieved great success with phylogenetic analyses of phenotypic variation without necessarily understanding the developmental processes that produce the phenotypes. Nevertheless, in other instances it is unlikely that researchers can get away with ignoring the human vehicles (see Stout, this volume); more recent phylogenetic analyses of cultural diversity are indeed more mechanistically and demographically explicit (e.g., Bouckaert et al. 2012).

External *representations* are special cases of material culture: artifacts or design elements whose primary intended function is to convey information. This is accomplished by making use of shared mappings between particular physical signs and specific concepts or items. Classic archaeological examples include art such as cave paintings or figurines, personal adornments like beads, containers with decorative or “symbolic” markings, tally sticks, tokens and so forth. The information conveyed by external representations may be (a) symbolic, in the sense that the shared mappings are more or less arbitrary and involve complex associations between signs (cf. Deacon 1997), (b) indexical (i.e., based on reliable correlations such as that between shell beads and the many hours of labor required to produce them), and/or (c) iconic (i.e., based on physical resemblance as in much artistic expression). Of these, indexical reference is often thought to be important for social signaling whereas symbolic representation may also be relevant for the creation, manipulation, and transmission of technological and scientific knowledge. For example, symbolic systems make it possible to just focus on a particular aspect of the material world, such as the countability of objects, thus giving rise to new mental constructions, such as numbers and arithmetic.

The Evolution of Writing Systems

Perhaps the most prominent system of external representation is writing. As well as greatly facilitating the transmission of technological and scientific knowledge, writing itself is the result of a lengthy process of cultural evolution (Hyman and Renn 2012). The first writing systems emerged around 3300 BCE in Mesopotamia, initially in the form of clay tablets with numerical notations and seals which were likely used in the state administration of taxes

and expenditure. From this, a system known as archaic cuneiform or proto-cuneiform evolved as a technology for the administration of centralized city-states. This proto-writing system did not represent the meaning of words or sentences, nor did it reflect grammatical structures of language, but rather disclosed meanings related to specific societal practices such as accounting. Since it was not used as a universal means of communication, it could only represent specific meanings in limited contexts. Nevertheless, it was on this basis that a long-term and stable Babylonian administrative economy developed, which in turn served as a precondition for the second stage in the evolution of writing: a universal means of codifying language. This second stage would have been impossible without the spread and manifold use of the earlier proto-writing.

Early Egyptian writing was more closely associated with representational and aesthetic functions (e.g., in monumental inscriptions legitimizing the authority of priests and rulers). Here, as well, writing gradually assumed an ever greater range of functions, such as for correspondence, historiography, and literature. Writing thus filled an increasing number of niches in the growing knowledge economy of a complex society as well as in new societies with varying socioeconomic structures. Accordingly, it underwent, as in Babylonia, an evolution characterized by an adaptation to these new niches and functions. Thus, writing took on new forms: it transformed from hieroglyphic into hieratic and demotic forms, evolved from a predominantly logographic Sumerian cuneiform into a predominantly syllabic Akkadian cuneiform, and developed into the West Semitic writing systems.

Further development of writing systems is characterized by processes of spread, variation, and selective adaptation to local needs and speciation. Speciation occurs when the adaptation of a writing system to a new niche (e.g., a new domain of knowledge, a new language or a previously illiterate society) leads to changes in the writing system that fundamentally affect the way in which the system functions as an external representation of knowledge. Thus, Minoan writing probably emerged as a result of diffusion from Mesopotamia in the context of the palace economy on Crete around the turn of the third to the second millennium BCE in the form of two different systems: Cretan hieroglyphs and the syllabic Linear A script. The latter was apparently the source of the Cypro-Minoan script, employed on the island of Cyprus in the second half of the second millennium, which in turn was the source of the Cypriot syllabary, which came into use toward the end of the first millennium. Given the significant Phoenician presence in Cyprus and the extensive contact between Phoenicians and Greeks, this syllabary may have influenced the emergence of alphabetic writing in the ninth century. Whereas Phoenician alphabetic writing possessed characters only for consonants, the Greek script adapted certain Phoenician semivowel characters as vowels. A West Greek alphabet became the source for the creation of the Latin and Cyrillic alphabets, two of the most frequently used scripts in the world.

Earlier writing systems suffered from ambiguities, with the same written symbols mapping onto many different spoken forms, but they led to a more concise representation of language and thus became a universal means for representing knowledge. An interesting feature of the evolution of writing systems is that the use of a particular system may expose genetic differences among speakers not seen when using an alternative system (see Dediu et al., this volume). For example, dyslexia, which has a strong genetic basis, is expressed less frequently and less strongly in speakers of languages with a simple mapping between orthography and phonology, such as Italian, compared to languages with more complex orthography–phonology mapping, such as English or French (Paulesu et al. 2001) This may point to gene–culture coevolutionary interactions triggered by the cultural innovation of writing technology.

Human-Constructed Environments and Niche Construction

An important ramification of external representation is that artifacts and features of the environment constructed or modified by human activities can feed back to shape other aspects of technology. This can be regarded as a form of niche construction, the process of environmental modification through which organisms modify patterns of selection acting on themselves and other organisms (Odling-Smee et al. 2003). Insights from niche construction theory (NCT) suggest that where organisms manufacture or modify features of the external environment experienced by their descendants (including artifacts), they can affect the evolutionary process in a number of ways, affecting the rates and direction of change, the equilibria reached, the amount of variation maintained, the carrying capacity of populations, the evolutionary dynamics (e.g., momentum, inertia, autocatalytic effects), and the likelihood that costly traits evolve (Odling-Smee et al. 2003; Laland et al. 1996, 1999; Silver and Paolo 2006; Lehmann 2007, 2008; Kylafis and Loreau 2008). Nonhuman examples of niche construction include beavers creating and inheriting lakes through their dam-building activity and earthworms changing the structure and nutrient content of soil by mixing decomposing organic material with inorganic material, thus making it easier for the worms to absorb water and allowing them to retain their ancestral freshwater kidneys, rather than evolve novel adaptations to a terrestrial environment. It is likely that human-manufactured external representations will generate similar kinds of feedback effects on cultural evolution, at which point explicit models will be required to track environmentally based resources.

Archaeologists have recently begun to use the framework of NCT to investigate the long-term effects of niche construction on technological evolution (Riede 2011; Riel-Salvatore 2010; Rowley-Conwy and Layton 2011; Wollstonecroft 2011; Smith 2007). For example Riel-Salvatore (2010) has used NCT to examine the technological changes in stone tool assemblages from the

Middle Paleolithic to the Upper Paleolithic in Italy. In this study Riel-Salvatore argues that the transition occurred sporadically in time and space over the Italian peninsula depending on the specific traits of the ecological and cultural inheritance system in each region. NCT also has been used in more recent time periods to examine technological changes associated with the domestication of plants and animals. In particular, Smith's (2007) work has emphasized the potency with which sedentary hunter-gatherers and agriculturalists engage in niche construction and the subsequent impact this niche construction has had on technology. Smith (2007) describes a number of technologies associated with the manipulation of plants and animals including the controlled use of fire, the construction of fish weirs, and the use of rainfall collection features and irrigation ditches (see also Wollstonecroft 2011). Smith suggests that the independent centers of plant domestication around the world had the common feature of being located in resource-rich zones. It also follows from NCT that it is within these resource-rich zones that we should expect to find evidence for high rates of technological evolution. Interestingly, this prediction runs counter to evolutionary ecological models of risk which suggest that invention should occur in more marginal environments (Fitzhugh 2001).

Rates of Technological Evolution

Determining Factors

Rates of technological evolution vary widely across time periods and regions. Several factors have been identified that explain different rates of change (summarized in Table 11.2). These range from the intrinsic characteristics of single technological traits to larger social and population-level properties. Rather than seeking a single factor that determines the rate of all technological change, we see these as a list of factors that may apply, singly or jointly, to specific case studies.

Units of Technological Evolution

The range of phenomena listed in Table 11.2 raises the issue of what the appropriate scale is when measuring rates of technological change. This is another way of framing the question—What are the units of cultural evolution?—which has been a source of confusion and contention within the field (e.g., Aunger 2000). We suggest that it is not inherently problematic, with the understanding that the pragmatics of quantification may be problematic in particular cases, and truly universal measures that can be applied across different technologies remain elusive.

Cultural evolution researchers can focus on, count, or model (a) knowledge, (b) behavior, and/or (c) artifacts, which are loosely equivalent to gene,

Table 11.2 List of factors that differentially affect rates of technological change.

Factor	Example
Intrinsic characteristics of the technology	Functional features of Polynesian canoes change less rapidly than stylistic nonfunctional traits (Rogers and Ehrlich 2008)
Manufacturing cost	Japanese Katana swords remained unchanged for centuries because any slight modification disrupted the manufacturing process (Martin 2000)
Fit with prior knowledge	Boiling of water fails to spread as a health practice due to incompatibility with preexisting beliefs of “heat illness” (Rogers 1995)
Generative entrenchment (lock-in of technology due to frequency-dependent adaptive landscapes)	QWERTY keyboard, originally designed to slow down typing in early typewriters to avoid jamming, but still used in computer keyboards where jamming is not a problem (Rogers 1995)
Key innovations (which transform adaptive landscapes and open up new innovation opportunities)	The vacuum-tube radio, which led to a cascade of innovations related to radio design and technology (O’Brien and Bentley 2011)
External representation of knowledge	Written records of medicinal plant use in medieval Italy reduce variation and change compared to regions without written records (Leonti 2011)
Social network structure	Centralized expert hubs facilitate transmission of adaptive food taboos on Fiji (Henrich and Henrich 2010)
Population size	Loss of technology on Tasmania due to reduction in population size (Henrich 2004b); increase in complexity in Upper Paleolithic Europe due to increased population densities (Powell et al. 2009)
Social institutions (e.g., trade networks, guilds, market economies, elite classes, universities)	Market integration in contemporary hunter-gatherer and horticultural populations results in the loss of ethnobotanical knowledge (Reyes-García et al. 2005)
Intergroup conflict	Technology conferring an advantage in intergroup conflict spreads rapidly, e.g., horses in ancient China (Di Cosmo 2002)
Intergroup boundaries and ethnic identity	Weaving techniques in Iranian tribal populations fail to spread due to norms against sharing knowledge with women from other tribes (Tehrani and Collard 2009)
External environmental change	The origin and spread of agriculture in the Holocene due to warmer, wetter, and less variable climate (Richerson et al. 2001)

phenotype, or extended phenotype frequencies within biological evolution. The appropriate level of analysis depends on the nature of the research. Historical reconstruction may benefit from a systemic approach that encompasses all three levels. Empirical researchers tend to focus on the level that is most practical and measurable (e.g., archaeologists are typically constrained

to artifacts, whereas anthropologists are able to measure knowledge and/or behavior), which also allows them to consider the factors that affect the dynamics of each of the system's component parts. Mathematical modelers tend to track the smallest indivisible unit in the system. Thus, while debates over units have often received attention in the more philosophical literatures, it has not greatly hindered research in any of these more empirically focused domains.

As discussed above, several modeling frameworks now exist within which to address rates of cultural evolutionary change and levels of selection. As well as the Price equation, there are also other population genetic and game theoretical models of cultural evolution and gene–culture coevolution (e.g., Boyd and Richerson 1985, 2005; Cavalli-Sforza and Feldman 1981). Such methods include models of macroevolutionary change and cumulative cultural evolution (Mesoudi 2011c; Enquist et al. 2011; Strimling et al. 2009; Pradhan et al. 2012; Aoki et al. 2011; Ehn and Laland 2012; Perreault 2012), many of which have addressed issues of rates of cumulative technological change. Phylogenetic methods have also been increasingly applied to technological evolution (O'Brien and Lyman 2003a; Lipo et al. 2006), which has allowed the reconstruction of macroevolutionary patterns and, as a consequence, the rate of change (frequency of branching) over time.

Fitness Landscapes and Technological Evolution

Several of the factors listed in Table 11.2 draw on concepts of fitness landscapes from evolutionary biology (Wright 1932), with the shape of the fitness landscape either speeding up technological evolution (e.g., where a key innovation changes the shape of the landscape resulting in a burst of diversification) or slowing it down (e.g., when a technology becomes locked in due to the frequency-dependent nature of the fitness landscape, preventing further change). Shennan (this volume) provides several examples of how the concept of fitness landscapes has illuminated specific case studies, such as the evolution of the bicycle (Lake and Venti 2009). Although the shape (e.g., ruggedness) of the underlying fitness landscape is likely to be a major determinant of technological evolution (Boyd and Richerson 1992; Arthur 2009; Kauffman 1993), it has tended to be overlooked in formal models and experimental simulations of cultural evolution, which typically make simplifying assumptions about trait fitness (although see Mesoudi and O'Brien 2008a, b). This is likely because modeling cultural evolution on changing (e.g., frequency-dependent) fitness landscapes reduces the tractability of such models. Nevertheless, we see fitness landscapes as a fruitful line of investigation for the study of technological evolution. The important point here is that the fitness landscapes associated with technological innovations should be regarded as dynamic and frequency dependent, rather than fixed, such that the spread of an innovation can both channel the direction of new innovations and open up a suite of new possibilities.

Science

Conceptual and Cultural Foundations

Science is a recent cultural innovation that emerged primarily in large-scale literate human societies (see McCauley, this volume). Theoretically important characteristics of science are as follows (Renn 2012):

1. It is primarily noninstrumental in character and is not just concerned with technology but with explanation for its own sake.
2. It has a sustained tradition of criticism and public scrutiny.
3. It is dependent on literacy as well as, in particular, lasting external linguistic representations that precisely preserve scientific knowledge and allow abstraction of thought.
4. It is, at least partly, intellectually independent from political and religious authority.

Historically, the introduction of science had a major impact on the level of discourse and standards of truth within societies, through the formalization of argument and use of evidence. With the invention of printed publications (scientific pamphlets, journals, and books), a new level of public scrutiny was reached. Increasing costs of acquiring scientific knowledge and the mastering of scientific methods also led to the invention and spread of universities and other scientific institutions.

Historical Evolution

Like writing, science as a process is a product of cultural evolution, and we can again examine the historical precedents and selective pressures that gave rise to it (Renn 2012). Science, in the sense of a pursuit of knowledge for its own sake, emerged in large-scale literate societies when administrative elites required schooling and resulted in a division of physical and intellectual labor. This happened in Babylonia and Egypt by the second millennium BCE, somewhat later in China, and much later in Mayan culture, resulting in the emergence of mathematics, astronomy, and medicine. Throughout this period, science was merely a contingent by-product of other social activities (e.g., administration) and was not a necessary or valued function in these societies. Indeed, most societies prior to the early modern period did not systematically support science. Instead, science was pursued because of individual interests or prestige.

This situation changed fundamentally after the early modern period due to the increasing and sustained economic and ideological significance of science in European societies. Early modern science was characterized by the take-up of technological challenges such as ballistics, ship building, large-scale construction (e.g., of cathedrals), urban infrastructure (e.g., hydraulics), and

machines (e.g., mills and other labor-saving technology). The printing press enabled the dissemination of technical knowledge that was previously transmitted orally and by participation. For the first time in history, an extensive technical literature emerged. The rapid development and scaling-up of science led to new forms of institutionalization of good scientific practice which the new academies (e.g., Accademia del Cimento, the Royal Society) articulated and imposed, thus creating a scientific community with its own norms. Early modern science was practiced by a broad network of participants that extended throughout Europe and then, with colonization, globally. Science as practiced within this network and its institutional support by political and ecclesiastical authorities was accompanied by a broadly shared conviction about its practical utility. Its actual technological benefit was initially limited but that hardly affected this societal perception.

In this historical situation, a self-reinforcing mechanism emerged that connected the production of scientific knowledge with socioeconomic growth. The mechanization of labor processes in the late seventeenth and eighteenth centuries provoked new scientific questions and opportunities for science to improve technology. The combination of this mechanization of labor with new ways of exploiting energy, in particular the use of coal for the steam engine, led in the nineteenth century to the Industrial Revolution in England. Together with the driving forces of market economies, this created further challenges and opportunities for science to improve technology. In this way, science and technology became inextricably intertwined with each other and with economic development. From that point on, science ceased to be a contingent by-product of cultural evolution and became one of its driving forces.

Evolutionary Character

The evolution of scientific knowledge itself exhibits all the dynamics characteristic of an evolutionary process, here referred to as “epistemic evolution” (following Renn 2012; see also Hull 1988; Thagard 1992; Renn 1995; Damerow et al. 2004). The exploration of the inherent potential of the means for gaining knowledge in a society gives rise to a variety of conceptual alternatives within a knowledge system, corresponding to mutation in biological evolution. As these alternatives are elaborated and pursued, they lead to internal tensions and contradictions, resulting in the transformation or the branching of a new knowledge system; this can be seen as analogous to speciation. For example, in the early modern period a broad variety of proposals for a new theory of motion was advanced by Galileo, Descartes, Harriot, and others which eventually led to convergence on a new understanding of motion (Damerow et al. 2004; Schemmel 2008). Various selective pressures may act on scientific knowledge systems and theories, such as compatibility with existing knowledge, internal coherence, compliance with methodological and institutional constraints, as well as societal expectations, prestige, fashions, and ideologies. Existing

proposals for epistemic evolution are verbal rather than mathematical, and it remains a challenge for the future to construct formal models that successfully incorporate these processes.

The Future

We can also ask about the future state of science from an evolutionary perspective. Despite much talk about the importance of interdisciplinarity, the course of science seems to be one of increasing disciplinary specialization, as fields of study become so complex and knowledge intensive that a single scientist struggles to specialize in more than one domain. In a sense, this is an inevitable by-product of the inherently cumulative nature of science. As more and more scientific knowledge is accumulated in a particular field, it becomes more and more costly for a single scientist to acquire that accumulated knowledge. There is evidence of this from the quantitative analysis of science, scientometrics. First, analysis of scientific accumulation (measured using number of publications or number of patents) shows an exponential increase since records began (e.g., May 1966; Price 1963), thus supporting the assumption that science is cumulative. Second, the length of time it takes for a scientist to become expert in their field has increased; for example, the average age at which Nobel prize winners made their prize-winning discovery has increased from 32 to 38 in the hundred years since Nobel prizes were first awarded (Jones 2010). This is not due to increased life expectancy, but due to increasing training periods in fields such as mathematics and physics (Jones 2010). Mesoudi (2011c) modeled this process, showing that the increasing costs of acquiring ever-increasing knowledge can eventually constrain further innovation, at a point where individuals spend so much time learning what has gone before that they have no time left to discover anything new.

One potential solution to this increasing burden of acquiring prior knowledge is disciplinary specialization, with scientists becoming more specialized as their fields become more complex. However, specialization comes with its own potential costs. As science gets bigger and more specialized, inevitably divisions arise between scientific disciplines, which leads scientists to grasp at conceptual tools to render their activities more manageable. This includes screening off and dismissing domains as the business of other disciplines, treating complex phenomena as black boxes, and regarding certain processes, or sources of variation, as relatively unimportant. As a result, scientific disciplines can effectively become “clubs” in which like-minded researchers share consensus over what is, and what is not, reasonably treated as “cause” and “context.”

Although this black boxing or screening off is often initially useful, it becomes a problem when core assumptions become dogma or entrenched. A good example is Ernst Mayr’s distinction between proximate and ultimate causation, where an initially useful heuristic has sometimes become an unthinkingly

applied convention in which developmental processes are seen as irrelevant to evolution, leading to divisions between academic fields of enquiry, and prompting several major debates within biology (Laland et al. 2011). The danger here is that discipline-based scientific fields emerge which through their core assumptions exclude, or hinder, certain phenomena from being considered as causes, leading to the neglect of relevant processes that contribute to evolutionary change or stasis, and hindering interdisciplinary exchange. One solution proposed by Levins (1966) is to encourage pluralism with regard to model building, with different classes of models screening off different processes, but collectively covering all processes. Levins's (1966) idea focused on formal models but the same point holds for conceptual frameworks. Pluralism is vital to scientific progress (McCauley 2001).

Conclusions

Progress So Far

In the course of our discussions, we were encouraged by the progress being made in the study of technological and scientific change within a number of different disciplines, which use a number of different methods, all inspired by a cultural evolutionary framework. We discussed research from archaeology, anthropology, psychology, the history and philosophy of science and technology, neuroscience, and economics. The methods used to pursue this research have included mathematical models, agent-based simulations, laboratory experiments, ethnographic surveys and experiments, archaeological/historical analysis, phylogenetic methods, comparative studies of nonhuman species, and brain-imaging techniques. We see this interdisciplinary, multi-method approach as one of the key benefits of a cultural evolutionary approach (thus combating the disciplinary fragmentation noted earlier), as empirical findings inform the assumptions of models, which in turn guide empirical work by highlighting key variables upon which to focus (Mesoudi 2011a). The methodological toolkit and theoretical framework are now in place, and thus the hard work of applying these methods to specific empirical case studies can now begin.

Outstanding Questions

Despite our optimism, outstanding questions remain and thus we wish to highlight promising avenues for further study. First, we see potential for greater links to the economic models of the evolution of institutions, which may prove useful for modeling such phenomena as trade networks, guilds, and universities—institutions that affect the course of technological and scientific evolution. Economists conceptualize institutions as self-sustaining normative

systems that structure individual behavior within groups. For example, Greif (1993) has studied the evolution of institutions governing international trade in the Renaissance Mediterranean. Merchants from the Maghreb organized their enterprises based on kinship, while Genovese merchants based them on contractual arrangements. Both institutions regulated behavior and thus solved the principle-agent problem inherent in long-distance trade and, as a consequence, competed with each other on an equal basis during the early Renaissance. However, as the volume of trade increased, the Genovese system scaled up more easily and ultimately replaced the kinship-based system. In economics modeling, there is a growing literature on institutional change using this kind of framework.

Second, an empirical question raised by Boyd et al. (this volume) remains unanswered concerning the extent to which technological change depends on a rational causal understanding of problems, which is then transmitted to others along with technological artifacts. This is a typical assumption of rational actor economic models, and is also assumed by some evolutionary psychologists (e.g., Pinker 2010). However, ethnographic and archaeological evidence suggest that people are rarely fully aware of the causal reasons behind why a particular technology works (Henrich and Henrich 2010; Shennan, this volume). If this is the case, then relatively content-free transmission biases (e.g., prestige or results bias) will play a more important causal role in technological evolution than sophisticated and explicit cognitive representations. An additional question concerns how science affects this issue: science provides explicit tools for determining causal explanations for phenomena in the world, at least in theory, enhancing people's ability to adopt efficacious technology.

Third, a repeated theme in our discussion of both technology and science was the notion of "fragility." It is apparent that science, as a cultural system, is highly fragile (McCauley, this volume), originating and persisting only in the presence of a precarious set of social, political, and economic conditions. Technology, too, is often surprisingly fragile, easily susceptible to loss in the face of population reduction or disruption to social networks (see Table 11.2). Certain factors, such as particular forms of long-lasting external storage like writing, can reduce the fragility of technological and scientific knowledge. However, the stability of scientific and technological knowledge in our own industrialized societies should not be taken for granted, as a historical perspective demonstrates the ease with which knowledge can be lost. One potentially fruitful line of study might be to more explicitly conceptualize and model the notion of fragility, incorporating factors that may increase or decrease the fragility of a technological system.

Practical Applications

A final line of discussion centered around the practical applications of the research outlined above. One potential application relates to the predictability

of technological evolution: Can we predict, using the mechanisms listed in Table 11.1 and the factors in Table 11.2, whether a particular technology will spread through a population or not, and how rapidly? Although technological evolution, like genetic evolution, is likely to be inherently stochastic and future evolutionary trends may never be predicted with absolute certainty, the criteria listed above may provide some guides to likely general trends. If so, this raises the possibility of intentionally designing technology or creating social conditions to favor the spread of technologies deemed to be beneficial to society and, alternatively, to prevent the spread of technologies deemed to be harmful. This is being attempted in some fields such as marketing (Heath and Heath 2007) and the diffusion of innovations within sociology (Rogers 1995), both of which share substantial overlap with the cultural evolution literature discussed here. For example, Heath and Heath (2007) discuss content biases such as the emotional salience of a particular cultural variant (Heath et al. 2001), whereas Rogers (1995) discusses factors such as the prestige or centrality of actors within social networks equivalent to model-based prestige biases. Ethnographic studies may prove particularly useful here, presenting opportunities to track the spread (or loss) of knowledge within small-scale societies (Reyes-García et al. 2008, 2009). Network-based diffusion analysis (Franz and Nunn 2009a; Hoppitt et al. 2010), originally developed to detect social transmission in nonhuman species, may also prove useful.

However, the study of science and technology itself gives reason to be cautious about imposing practical objectives onto science, given the risk that this may in fact *inhibit* scientific innovation. The history of science amply illustrates that major innovations have rarely been the result of imposing specific societal expectations onto science but rather of serendipity and accident, such as the discovery of X-rays or antibiotics. The very autonomy of science is in potential conflict with its functional role in society as a promoter of technological innovations and economic growth. This intrinsic tension between science and society is becoming more acute because science has become relevant not only to societal welfare, but also to the very survival of the human species. Thus, challenges such as climate change, global energy, food and water provision, global health, and living with nuclear technology require persistent scientific innovation at a global scale, yet remain unbiased by immediate economic and political constraints. Such global basic science has yet to find the societal niche and support that it requires. The concepts and tools of cultural evolution may prove helpful in defining this niche.