8

Long-Term Trajectories of Technological Change

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Abstract

The study of technology is a field in which generalized evolutionary ideas have been current for many years. However, when we start trying to implement a cultural evolutionary approach more rigorously, it turns out to be more complex than usually supposed. One of the important benefits of taking a cultural evolutionary approach is that it goes beyond relatively simple ideas of competition and technological improvement, and introduces a range of other forces whose impact is not often considered. In the case of technology, the entities that are the subject of variation, inheritance, and selection processes are technological lineages, recipes for techniques, routines, and practices linked by ancestor–descendant relationships. To understand them, we must first address histories of the technologies themselves before we can examine the histories of the human populations through which they are transmitted, which may depend at least partly on the histories of technologies. A number of examples of technological innovation and transmission are examined to illustrate the variety of factors affecting them.

Introduction

The study of technology is a field in which evolutionary ideas have been current for many years. The idea of a kind of Darwinian competition between different means of achieving the same practical ends is one that seems obvious, and indeed has been very fruitful. However, when we start trying to implement a cultural evolutionary approach more rigorously, it turns out to be more complex than expected. It can be argued that one of the important benefits of taking a cultural evolutionary approach is that it goes beyond relatively simple ideas of competition and technological improvement, and introduces a range of other forces whose impact is not often considered. A variety of difficulties also become apparent, not least in terms of the availability of quantitative data to test evolutionary hypotheses when we attempt to go beyond the last 150 years or so—the point in time when information about patents and businesses

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becomes available. In this chapter, I outline the framework adopted here for viewing technological change as a variation, inheritance, and selection process and discuss several case studies. These are mainly archaeological, not just because I am an archaeologist, but because prior to the last 150 or so years, only archaeology provides even the possibility of obtaining the quantitative diachronic data necessary to test evolutionary models.

What Evolves?

Arthur (2009) defines a technology as "a phenomenon captured and put to use," and distinguishes between "standard technologies" based on physical effects and "nontechnology-like technologies" that impact human behavior or organization. In the case of "standard technologies," which are the focus of this chapter, the entities that are the subject of variation, inheritance, and selection processes are technological lineages, recipes for techniques, routines, and practices linked by ancestor–descendant relationships, which capture and put to use specific phenomena in particular ways. Thus, ceramic vessels, for example, utilize one set of principles to make containers, whereas barrels or plastic bowls make use of very different sets of principles. The replacement of ceramic vessels by plastic ones does not represent a continuous lineage, but a replacement of one lineage by another (though, of course, plastics have their own lineage). Lineages may be regarded as replicators in Dawkins's terms (1976). However, distinctions here are blurred (Lake 1998; see also the extended discussion in Wimsatt and Griesemer 2007, not least their discussion of Sears kit houses). Artifacts are clearly interactors in some respects rather than replicators, but they can also provide a model for people to copy. On the other hand, as Mokyr (2000) points out, techniques themselves can also be interactors, whose effectiveness determines whether they will be reproduced, and the knowledge behind them can be seen as a replicator. But in the past, as Mokyr also points out, using a successful technique did not generally involve knowledge of the principles behind it, and insofar as people formulated such principles, they were often completely mistaken.

The key point is that the object of the evolutionary analysis of technology is technological lineages, not human populations, and because they are reproduced in different ways, there is no reason that they should run in parallel even though they are obviously linked. The variation, selection, and retention processes that underlie cultural evolution were laid out in detail more than 25 years ago (Cavalli-Sforza and Feldman 1981; Boyd and Richerson 1985) and have been extensively explored and elaborated since (e.g., papers in Boyd and Richerson 2005). However, this has mostly been done from an agent-centered perspective, rather than from that of the cultural lineages themselves—the "meme's eye view"—and the two are not the same. This does not mean that we need to subscribe to memetics in the strict sense of assuming a particulate unit

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of transmission (cf. Henrich and Boyd 2002b; O'Brien et al. 2010; Mesoudi et al. this volume) or to assume that memes are cultural viruses that simply parasitize human brains. It does, however, require us to acknowledge that cultural lineages, including technological lineages, exist and that the transmission of a cultural lineage is by definition vertical with respect to itself, whatever its relation to the human populations through which it is transmitted—a relationship that is very likely to vary over time.

Moreover, the processes that modify what is transmitted also look different, depending on whether one takes the agent- or meme-centered perspective. Thus, in their paper on the evolution of Polynesian canoes, Rogers and Ehrlich (2008) refer to the process which acts on those canoe traits that have a functional significance—technological traits—as natural selection; so it is from the perspective of the traits themselves that traits survive and are copied preferentially as a result of their greater functional effectiveness—something which could, in principle, be tested experimentally. What the authors do not do is to distinguish between *natural selection operating on human agents via cultural traits*, and thus on the *future frequency of those traits*, and *results bias*. In other words, the process could have operated as a result of the makers and users of ineffective canoes drowning more frequently, thus leading to the demise of those designs, whereas groups with better-designed canoes, perhaps different communities, survived and colonized new islands. Alternatively, it could have worked through people observing the performance of different canoe designs and preferentially copying those they perceived as more effective. Making this sort of distinction is actually at the root of some of the most long-standing debates in archaeology; for example, whether the spread of farming into Europe was a process of indigenous adoption (involving results bias) or demographic expansion and extinction (natural selection acting on the bearers of cultural traditions). Despite the numerous attacks on the idea of memes as replicators encouraging their own reproduction, it is emphatically the case in both of the above scenarios that whether or not people reproduce particular traits depends on the specific characteristics of the traits themselves.

In general then, to understand trajectories of technological change we need to do two things:

1. Address histories of technologies.
2. Examine the histories of the human populations through which they are transmitted, which may depend at least partly on the histories of technologies.

With regard to the first, it is necessary to identify histories of technological transmission to show that an ancestor–descendant relationship exists, if indeed it does. Continuities or discontinuities through time may simply reflect contingently optimal responses to stable or unstable local ecological conditions. Moreover, some traits (e.g., the sharpness of a lithic cutting edge) may be so strongly determined by their function that they will contain no signal of their

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transmission history, even though it is likely that they had one (as opposed to being discovered anew by every novice flint knapper through trial-and-error learning). In any case, assuming that a real technological lineage has been identified, we must then attempt to understand the forces shaping it. With regard to the second, we need to understand independently the histories of the *relevant* populations. The possible linkages or feedback loops between technologies and populations are many and varied. A technology may or may not have an effect on the survival and reproductive success of a human population while replicating successfully itself. Even if it does, its effects may be overwhelmed by other factors, such as the extinction of the population for other reasons. If a technology is vertically transmitted with respect to its human population, it may then be particularly vulnerable in this respect. It perhaps goes without saying that few, if any, studies have taken all of these different elements of the evolutionary analysis of technology into account.

Invention and Connectedness

Some inventions are relatively easy to make and have therefore been made again and again. For example, it seems that wherever people came to depend to a significant extent on collected seeds for food, they invented and used grinding stones, since these are very effective tools for processing seeds into food and the cost of producing them is far outweighed by the subsequent benefits gained. It is also worth using this example to raise another issue: It is now increasingly clear, as I will discuss below, that the probability of invention and innovations occurring is a function of the relevant effective population size. However, finding a correlation between technological complexity and population size should not necessarily lead us toward this particular explanation. In the case of the innovation of grinding stones, there is almost certainly a correlation with increasing population density but this is because in many foraging contexts increasing population density leads to increased exploitation of plant resources, which in turn leads to the use of grinding stones for cost–benefit reasons.

In this connection, it is worth referring to Perkins's (2000) contrast in the space of technological search between "Homing spaces," where there is a clear gradient pointing toward a viable outcome, and "Klondike spaces," where high-yield nuggets are sparsely distributed and there are few signs to indicate when you are near one of them. When technologies involve complex and difficult production processes, they are far less likely to be reinvented if lost, simply because of that difficulty. Moreover, Roux (2010) makes the point that training in any production process that involves the acquisition of high levels of expertise which take a long time to acquire is likely to restrict innovation, because the whole process of learning is designed to fix particular sets of skills and knowledge (cf. Martin 2000); this may be particularly the case

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with physical expertise and motor skills. Only the most expert, those who have complete control of all aspects of a process and its associated knowledge, are likely to transcend the limits of what they have learned and invent something new. Roux cites (2010:224) the example of inventions in the field of pyrotechnology by traditional craftsmen in India, which were only made by the most skillful individuals who were "exceptional as much for their skills as for their rarity."

Roux's (2010) account of the apparently strange history of the production in the prehistoric Southern Levant of wheel-fashioned pottery (i.e., coil-built, not wheel-thrown, pottery produced on a slowly rotating wheel at around 80 revolutions per minute), using the principle of rotational kinetic energy (RKE), illustrates the issues raised by what she refers to as "discontinuous innovation" that uses novel principles. Using the technique has the obvious advantage that it leads to a halving of manufacturing time, and one might expect this to give it a clear selective advantage over traditional hand-coiling methods. However, in the Southern Levant, the production of wheel-fashioned pottery comes and goes twice before finally becoming permanently established some 3,000 years later. It seems to have been invented in the late fifth millennium BCE and to have been used for over ca. 300 years solely to make a specific type of bowl, which had a ceremonial function, at a time and in a region of significant politico-religious change, involving the emergence of centralized chiefdoms. In the fourth millennium these societies collapsed; 75% of the settlements that had previously been occupied disappeared and wheel-coiling as a technique disappeared, though the RKE principle continued to be used for finishing vessel surfaces in some cases. The technique reappeared in the early third millennium BCE, a time when large fortified towns were built. However, only ca. 3% of vessels were made by this method, indicating that the technique was probably used only by a small number of craftsmen, a situation that lasted for ca. 500 years. When local cities collapsed at the end of the third millennium BCE, wheel-coiling was lost again, only to reappear in the mid-second millennium BCE, after which it came into much more general use.

Roux (2010:228) locates the explanation in the context of the practice and transmission of the craft. For the later fifth millennium, study of the petrology of the pottery and the techniques used to make it, as well as the contexts in which it was found, indicates that only a few individuals made the bowls, that those individuals moved around and were linked to elites. This restricted group of potters within which wheel-coiling was transmitted was distinct from the generality of potters who made the everyday pottery. The same is true of the earlier third millennium, in that wheel-coiling was restricted to a small number of specialists, whose potter's turntables have been found in palace contexts. When the use of RKE took off in the mid-second millennium it was at a time when cities were expanding, probably in the context of a more market-oriented economy, when specialist workshops used the technique to make a wide range of vessels and domestic pottery production declined as a result.

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Roux characterizes the wheel-coiling technical system prior to the mid-second millennium as fragile and closed. Fragility relates to the size of the network concerned in terms of the number of interconnected elements. In a precise analogy with genetic drift, any practice that is restricted to a small number of individuals is vulnerable to loss as a result of external circumstances, regardless of its benefits (cf. Rivers 1926). The fact that in the earlier periods few potters were using wheel-coiling meant that the practice disappeared in the face of the socioeconomic collapses which ended the fifth millennium Chalcolithic and third millennium Early Bronze Age periods, because the small number of transmission links that sustained it were broken. In contrast, as the number and spatial extent of transmission links increases, the less vulnerable the technical system becomes to the effects of external historical events, because even if part of the network is destroyed in one place it will survive elsewhere, and this is what happened in the Middle Bronze Age with the expansion of the wheel-coiling transmission network.

The size of the network in itself, however, is only one element in the fragility or robustness of a given technical transmission system. One way in which it can expand is by the transfer of the technique to other areas of production than that in which it originally emerged. Again this did not happen in the Chalcolithic or Early Bronze Age. Wheel-coiling remained restricted to a small circle of specialist potters who only used it to produce specific elite items. This changed in the Middle Bronze Age of the Southern Levant with the application of this innovative practice to a wide range of different items in widespread use.

As noted above, the importance of the effective population size involved in cultural transmission in accounting for the emergence and maintenance or loss of innovations that can build on one another, thus leading to cumulative cultural evolution, is now widely recognized (Shennan 2001; Henrich 2004b; Powell et al. 2009). However, Roux makes a further and more specific point relevant to the evolutionary trajectories of the more complex technologies, not least copper and iron production, that have emerged in the last 7,000–8,000 years. If the transmission of technologies based on novel principles involves a long apprenticeship that excludes the possibility of becoming correspondingly adept at other skills, then it will almost inevitably result in a closed and more or less fragile system, at least initially. First, it will only be possible for relatively small numbers of individuals to undertake the apprenticeship. Second, not all societies will be able to sustain the required division of labor. Third, for various reasons, including people's desire to protect their livelihood, they are likely to keep their knowledge and expertise secret and either transmit it vertically to offspring or charge a significant entry fee.

How such processes work in the case of iron production has recently been examined by Charlton et al. (2010), who have taken an evolutionary approach to understanding preindustrial bloomery iron-smelting technology in a case study from northwest Wales. Despite the technical complications of addressing this subject, it has the advantage that the problem can be clearly framed.

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There is no doubt about the goal (at least in general terms), and the conditions required to smelt iron successfully are well understood, arising as they do from universal properties of the materials involved. The bloomery method involves "the solid state reduction of iron oxides into a spongy mass of iron, called a bloom, and the production of a ferrosilicate slag" (Charlton et al. 2010:353), based on the combination of iron ore and charcoal in a furnace supplied with air, where temperatures can reach up to 1400°C, which is still below the melting point of iron. Earlier studies of bloomery iron production in different parts of the world have shown that it is technically extremely diverse.

Once again, as with any study of a technological lineage, the first issue is to identify patterns of cultural descent in the methods used and to distinguish variation arising from transmission from that relating, for example, to the local ore or fuel type; thereafter the forces which affect that variation must be characterized in a situation where, by the very nature of the process, there are only a limited number of successful solutions. The most informative source of information on the processes involved in past episodes of early iron production is chemical variation in the slags produced as a waste product. In this case, the data are quantitative variations in the chemistry of chronologically ordered slag deposits, and the problem is: Can we establish whether or not there is a signal of cultural descent in the chemical variation? If so, what can we infer about the factors that affect the transmission processes which produced it?

Charlton (2009) showed convincingly that a transmission signal could be identified in the slag chemistry, distinct from the effects of ore and fuel composition. In terms of the forces acting on the technical knowledge and practices passed on from one iron producer to another, it is easy to imagine that there might be some more or less random variation in exactly what was done each time. It is also likely that there would be strong selection for those practices that were successful although, given the complexity of the process and its many stages, it would not necessarily be easy to identify precisely what produced a successful smelt on any given occasion. From the point of view of the agents, it is thus likely that transmission would be affected by results bias, albeit in a very noisy form, based on characteristics that the smelters could observe as well as on the connections they were able to make between variation in those characteristics and their techniques of ore preparation, furnace operation, etc. From the point of view of the smelting recipes, this would be a process of natural selection, since recipes would be differentially reproduced depending on their ability to smelt iron successfully. The results of Charlton et al. (2010) suggest that initially all changes related to furnace operation could be accounted for by a drift process, but that at a certain point a second effective procedure was more or less accidentally discovered and a decision was taken to make use of the two distinct procedures, visible in consistently different slag signatures: one of lower yield than the other but producing a higher-quality product in the form of steel. At the same time, there were clear trends in the use of manganese-rich ores with better fluxing capabilities and evidence

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of decreased variability in reducing conditions related to results bias; that is, iron makers consistently reproduced the airflow conditions that gave the best results for a given recipe.

This, however, was a very small operation, using only a single furnace. At present we do not know if the discovery of these Welsh iron smelters was also independently made by others, or if it was passed on outside this group. Roux's points regarding the closed and fragile nature of transmission networks in the context of preindustrial craft specialization would lead us to hypothesize that innovations made by this group of smelters could easily have been lost.

Juleff (2009) provides another example of reconstructing and explaining a technological lineage in the context of iron production, based on the archaeological discovery of wind-powered furnaces in Sri Lanka. She argues that the recognition by early metal producers of the idea of the "combustion zone" or "effective unit area" within the furnace effectively created a technological meme, an indivisible entity that represented the basic building block of a specific iron-production lineage which, in contrast to the predominant Western tradition (which was based on round furnaces), created linear furnaces in which combustion zones were lined up side-by-side through the regular placement of tuyeres in the front wall to create a draft. This had the advantage of eliminating ineffective zones, such as could potentially arise with getting air to the center of an increasingly large circular furnace. It was further adapted in some favorable hilltop locations in Sri Lanka to the use of monsoon winds, which provided the draft.

Juleff suggests that there is a single evolutionary tree of south, southeast, and east Asian linear furnaces deriving from a single Sri Lankan root (though much more work would need to be done to establish this) and notes that some of them produced high-quality carbon steel for weapons. However, in Sri Lanka itself the lineage seems to have died out in the eleventh century CE. In this case, two potentially opposing forces may have had a bearing on the life of this tradition: (a) its likely vertical transmission in a small population of hereditary iron-smelting groups; (b) its visibility to any nonlocal iron smelters who did happen to visit the areas concerned.

The subtle ways in which selection operated in the context of early complex technologies, leading to optimal solutions, is also illustrated by Jackson and Smedley's work on medieval glass production in northern Europe (Jackson and Smedley 2008). Here bracken was used as a main source of plant ash for glass production. Jackson's analysis of the chemical composition of bracken ashes showed that it changes over the course of the growing season, with the concentration of SiO_2, CaO, Fe_2O_3, and MnO increasing throughout the season and K_2O and P_2O_5 peaking in mid-June and then declining. This makes mid-June the best time to harvest bracken since the alkali concentrations necessary to produce glass are high, and other components that produce less satisfactory outcomes (e.g., coloring) are still low. The knowledge that this was the case was encapsulated in the recommendation to be found in contemporary

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documents about glass making, which reported that for the best results, bracken should be harvested by the feast of St. John the Baptist (June 24).

Finally, it is worth noting that the distinction between imitation and invention is not necessarily as great as is generally assumed. As Berg (2002) shows, in eighteenth-century Europe the imitation of such materials as Chinese porcelain by local manufacturers was a major source of novel production processes, as evidenced by secured patents (see also Rogers and Ehrlich 2008:175–184).

Innovation Rates

In the case of genetic variation, mutations are basically random, though of course different genes have different mutation rates. In the case of cultural inventions, it seems clear that rates have varied. One tendency has been to take the view that "necessity is the mother of invention": when people are in a situation which they know is not sustainable, they are more likely to take risks and carry out trial-and-error experimentation (Fitzhugh 2001). As Henrich (2009b) points out, however, experimental evidence tends to be against this, and the risks involved are certainly very considerable, from devising alternatives to embarking on them without prior knowledge of the costs and benefits. As we have already seen, the contrasting view—not that they are mutually exclusive—is that they are more likely to arise simply as a result of the existence of larger effective populations, in terms of absolute size, degree of networking or both, since these are likely to increase the innovation rate per unit time as well as the potential for the new combinations of existing elements (what Roux calls "continuous inventions"). As noted earlier, the collapse of populations and social systems leads to the loss of complex technological lineages that have few bearers.[1]

It is also possible that invention rates vary less than innovation rates, in that even if the invention is made, the chances of it becoming a successful innovation will vary. Once again, population size and connectedness are relevant but another relevant factor is the potential, at any given time, for the technological equivalent of an "adaptive radiation," a situation where the diversity of life increases because speciation rates are greater than extinction rates (Lake and Venti 2009). This generally involves the colonization of an empty or newly created ecological space. Of course, the most famous examples are the

[1] An alternative theoretical possibility following from the previous discussion of "the meme's eye view" is that the relevant population here is the number of instances of the cultural variant itself; here, the number of wheel-fashioned vessels. This may well be the relevant population in cases where a variant is easy to copy simply as a result of seeing it. However, in the case considered here, it seems unlikely given the difficulty of reverse engineering the process from the product and the amount of time that would have been necessary to acquire the necessary skills.

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so-called "Cambrian explosion" and, at a lower taxonomic level, the radiation of Galapagos finches.

O'Brien and Bentley (2011) cite the example of spark arrestors on the smokestacks of U.S. locomotives in the nineteenth century, for which more than 1,000 patents were taken out to solve the problem of trains causing fires while keeping the draft as unobstructed as possible, which they view in terms of fitness landscapes (Kauffman 1993; Kauffman et al. 2000). In this case there was no entirely successful solution, and this new adaptive space remained a rugged fitness landscape with a number of more or less equally fit local optima. Previously empty or newly created niches offer new possibilities for innovation, either because there is no previous history from which to learn or because existing solutions may not work in the new niche. In Kaufmann's adaptive radiation model, whether biological or technological, there is an initial stage in which there are long jumps to new places in the fitness landscape; a second stage when the broad landscape has been explored and local "hill-climbing" occurs, because earlier choices constrain subsequent options in a process of so-called "generative entrenchment" (Wimsatt 1986); and a third stage of relatively little change where adaptations to local peaks cannot be improved but selection between different peaks begins to occur. Lake and Venti (2009) followed through the work of Van Nierop et al. (1997) in exploring Kaufmann's suggestion that the evolution of the bicycle could be seen in precisely these terms. On the basis of a classification of bicycles that takes into account the different levels at which diversity occurs, and thus the process of generative entrenchment, they show through the creation and analysis of a novel kind of taxonomic diversity diagram that the evolution of the bicycle does indeed follow the model of breadth-first search. Lyman et al.'s (2009) analysis of the distribution through time of prehistoric dart and arrow tip diversity in the United States points to a similar conclusion.

Evolutionary Success and Cumulative Culture

As argued at the beginning of this chapter, following the work of Boyd and Richerson as well as many others, the processes at work in the cultural evolution of technology are complex and operate on two main levels: one related to the cultural success of the technologies or technological elements themselves, the other related to the human populations that coevolve with them to varying degrees. Just how "cultural success" is defined is open to discussion; wide-scale prevalence is not necessarily as tautologous an indicator as critics of evolutionary approaches to culture tend to assume. Cultural traits can go to fixation as a result of drift as well as selection, especially in small groups, and small groups have probably characterized most of the past of modern humans and their ancestors. Better evidence comes from cost–benefit comparisons of the type carried out by human behavioral ecologists, based on present-day

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ethnographic study or experimentation, where the demonstration of favorable cost–benefit balances can make it reasonable to suppose that one technology would have had a selective advantage over another. The assumption is usually made that a selective advantage, from the point of view of the meme lineage, corresponds to a survival/reproductive success advantage, from the point of view of the human population, whatever the mechanism involved in any particular case, in terms of the various biases and forces outlined by Boyd and Richerson and others. However, it is important to insist again that this assumption cannot be taken for granted. In the first place, as they pointed out, there is no reason to expect strong correlation in any particular case given the asymmetry in their lines of transmission. In addition, it is very difficult to actually demonstrate that practicing one version of a behavior rather than another leads to greater reproductive success. If we take the milking of domestic animals as a technology, then the selective advantage of the lactase persistence gene in combination with milking is one of the very few examples where we have direct evidence of a technology contributing to reproductive success (Bersaglieri et al. 2004). Using the development of farming more generally, then recent work demonstrates how complex the processes can be. Bowles (2011) has provided strong evidence that cereal-based agriculture is very unlikely to have been more productive initially than foraging in terms of calorific return per unit labor time; thus, its adoption cannot be explained by a superior cost–benefit relationship on a day-to-day basis. Despite this, it is very clear that it provided greater reproductive success, given archaeological evidence for the dispersal of farming populations at the expense of foragers and evidence from genetics and the age distributions of individuals in prehistoric cemeteries that these farming populations were growing whereas forager ones were relatively static (e.g., Bocquet-Appel 2002; Gignoux et al. 2011).

In this context it is worth raising the issue of the so-called "cultural ratchet" (Tomasello 1994). The evidence that social learning is far more important in humans than in closely related primate species, and that human children show a very strong propensity for high-fidelity imitation (e.g., Dean et al. 2012; see also Haun and Over, this volume), is understandably featured in explanations of the fact that human culture more or less uniquely accumulates modifications over time. However, it is important to be clear that the capacity for high-fidelity transmission was a necessary precondition for this to occur, not that the accumulation of cultural modifications was the selective force behind it. Indeed, there is little evidence for this in terms of technology at least, given its very slow rate of change over most of the 2.5 million years since the first stone tools are recognizable in the archaeological record.

In fact, though the general propensity for high-fidelity social learning is a species property, specific instances of cumulative culture itself are actually a property of specific populations or meta-populations linked by transmission processes. Selection will be operating on them through the cost–benefit dimension but, even in cases where the cost–benefit ratio is favorable, transmission

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failures that arise from a variety of factors affecting the fidelity of transmission (Lewis and Laland 2012), including the fact that early networks were often fragile, can overwhelm selection and lead to cultural loss. In this sense the "ratchet" metaphor, with its implications of irreversible accumulation, is misleading (cf. Lombard 2012).

The well-known Howieson's Poort archaeological assemblage from southern Africa ca. 65–60 KYA illustrates these issues clearly. It includes a variety of what can be considered complex cultural (including technological) phenomena. Among them is evidence for the heat treatment of tool stone to improve its workability, of multicomponent stone tools, and probably of the bow and arrow (Lombard and Phillipson 2010; Lombard and Haidle 2012), features which seem to disappear from the record with the end of the Howieson's Poort.

The bow and arrow involved the use of arrows with stone tips hafted in a variety of ways and attached using complex adhesives made from plant gums and ochre, which would probably have required heat treatment to dry. It also required a practical understanding of the use of stored energy and the best wood types for making use of it. In this connection, it has been argued that the range, size, age, and behavior of the animals represented in the bone assemblage from the site of Sibudu Cave may point to the use of snares for trapping (Wadley 2010). The use of strong cord or hide strips, with appropriate knots, would also have been required. Lombard and Haidle's (2012) detailed analysis shows that compared with the production of a simple wooden spear, or even a composite stone-tipped spear, the bow-and-arrow combination represented a major increase in the number of material items and different operations that had to be brought together, supporting Lewis and Laland's suggestion, based on their simulation results, that trait combination may be the most important creative process producing cultural accumulation (Lewis and Laland 2012).

Of course, this does not mean that the bow and arrow was bound to continue. Explanations for its subsequent disappearance, and that of the Howieson's Poort generally, vary between those that relate it to loss as a result of decreased population densities or interaction rates and thus a smaller effective population size (e.g., Powell et al. 2009), and those which see it as simply no longer successful in cost–benefit terms in a changed environment. Mackay and Marwick (2011) emphasize the importance of evaluating the costs and benefits of more and less complex technologies in different environments, arguing that we should see the innovations of the Howieson's Poort as adaptations to local circumstances, not as systems that for intrinsic reasons "should have" continued, the perspective, as we have seen, that the "cultural ratchet" idea tends to encourage (again, cf. Lombard 2012). These debates will only be resolved by further data collection. In this context, a recent synthesis of demography and climate in later Pleistocene Africa (Blome et al. 2012) has not found evidence for population decline in southern Africa at the relevant time period, though the temporal resolution remains poor.

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Conclusion

A cultural evolutionary approach to technology has a number of important attractions, perhaps the main one being the "population thinking" that it brings. This has had, and will continue to have, a number of important consequences. First, it suggests that population size and connectedness are key factors in affecting rates of cultural innovation and evolution, and that social institutions have an effect on those rates to the extent that they impact transmission fidelity and encourage or discourage connectedness between individuals and groups: who you know is far more important than what you know (cf. Henrich 2010). Early complex or specialist technologies had a number of intrinsic features that would have encouraged small effective population sizes, in terms of both absolute numbers of practitioners and the likelihood of them sharing information. Second, it makes us aware of the importance of characterizing technological lineages and distinguishing them from populations of human agents, thus forcing us to think about the relations between them. More generally, the theoretical work of the last thirty years has demonstrated the wide range of transmission forces potentially operating in any given case, not least the role that can be played by unbiased transmission in finite populations. Far from encouraging the tautologous view (i.e., what is prevalent is by definition that which has been competitively successful), work in cultural evolution has demonstrated the complexity of making inferences about the forces at work while providing the tools to deal with it, including cost–benefit analyses of the type central to human behavioral ecology and mathematical modeling. It also points to the contingency of the supposed "cultural ratchet," despite the undeniable human propensity for high-fidelity social learning.

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