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The Cultural Evolution of Technology

Facts and Theories

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Abstract

The gradual cumulative cultural evolution of locally adaptive technologies has played a crucial role in our species' rapid expansion across the globe. Until recently, human artifacts were not obviously more complex than those made by organisms that lack cultural learning and have limited cognitive capacities. However, cultural evolution creates adaptive tools much more rapidly than genetic evolution creates morphological adaptations. Human tools are finely adapted to local conditions, a fact that seems to preclude explanations of cultural adaptation based on innate cognitive attractors. Theoretical work indicates that culture can lead to cumulative adaptation in a number of different ways. There are many important unsolved problems regarding the cultural evolution of technology. We do not know how accurate cultural learning is in the wild, what maintains cultural continuity through time, or whether cultural adaptation typically requires the cultural transmission of causal understandings.

Introduction

Humans have a larger geographical and ecological range than any other terrestrial vertebrate. About 60,000 years ago, humans emerged from Africa and rapidly spread across the globe. By about 10,000 years ago, human foragers occupied every terrestrial habitat except Antarctica and a number of remote islands, like Hawaii, Iceland, and Madagascar. To accomplish this unparalleled expansion, humans had to adapt rapidly to a vast range of different environments: hot dry deserts, warm but unproductive forests, and frigid arctic tundra.

Technology played a crucial role in this process. Spears, atlatls, and later bow and arrow are used to acquire game; flaked stone tools are necessary to process kills and to shape wood, bone, and process hides; clothing and shelter

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are crucial for thermoregulation; fire-making paraphernalia are necessary for cooking, heat, and light. Slings, baskets, and pottery facilitate transport and storage; boats expand the ranges of foragers to include lakes and oceans; fishhooks and cordage make coastal habitats rich sources of protein. In most cases, technological adaptation is specific to local environments because the problems that need to be solved vary from place to place—getting food and regulating body temperature are very different problems in the North American Arctic and the African Kalahari desert.

Humans were able to create this diverse set of tools rapidly because cultural evolution allows human populations to solve problems that are much too hard for individuals to solve by themselves, and it does this much more rapidly than natural selection can assemble genetically transmitted adaptations. In this chapter we attempt to summarize what is known and unknown about this process. We begin with "stylized" *facts*, empirical generalizations relevant to the cultural evolution of technology. We then move to *theory*: there has been a lot of work aimed at understanding the workings of cultural evolution over the last several decades. Here, we summarize some results from those models most relevant to understanding the gradual cultural evolution of complex, adaptive technologies.

We think that these facts and theoretical results indicate that technological change is an evolutionary process. The tools essential for life, in even the simplest foraging societies, are typically beyond the inventive capacities of individuals. They evolve, gradually accumulating complexity through the aggregate efforts of populations of individuals, typically over many generations. People do not invent complex tools, populations do. In this way, the cultural evolution of human technology is similar to the genetic evolution of complex adaptive artifacts in other species, like birds' nests and termite mounds. In both cases, individuals benefit from complex, adaptive technologies that they do not understand. Instead the adaptive design evolves gradually—in the genetic case through natural selection and in the cultural case by individual learning and biased cultural transmission, with natural selection perhaps playing a secondary role. The big difference between these processes is speed. Cultural evolution is much faster than genetic evolution and, as a consequence, human populations can evolve a variety of tools and other artifacts that are adapted to local conditions. In contrast, most animal artifacts are species-typical adaptations to problems which face all members of the species.

Stylized Facts about the Cultural Evolution of Technology

People in Even the Simplest Human Societies Depend on Tools That Are Beyond the Inventive Capacity of Individuals

It is easy to underestimate the scope and sophistication of the technology used in even what seem to be the "simplest" foraging societies. Consider, for

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example, the Central Inuit of the Canadian Arctic. These foraging peoples occupied a habitat that is harsh and unproductive, even by Arctic standards. Their groups were small, and their lifeways were simple compared to other Arctic foragers. Nonetheless, they depended utterly on a toolkit crammed with complex, highly refined tools. Winter temperatures average about –25°C so survival required warm clothes (Gilligan 2010). In the winter, the Central Inuit wore beautifully designed clothing, made mainly from caribou skins (Issenman 1997). Making such clothing requires a host of complex skills: hides must be cured, thread and needles made, clothing designed, cut and stitched. Even the best clothing is not enough during winter storms; shelter is mandatory. The Central Inuit made snow houses so well designed that interior temperatures were about 10°C. There is no wood in these environments, so houses were lit and heated, food was cooked, and ice melted for water using carved soapstone lamps fueled with seal fat. During the winter, the Central Inuit hunted seals, mainly by ambushing them at their breathing holes using multipiece toggle harpoons; during the summer, they used the leister (a three-pronged spear with a sharp central spike and two hinged, backward facing points) to harvest Arctic char caught in stone weirs. They also hunted seals and walrus in open water from kayaks. Later in summer and the fall, the Central Inuit shifted to caribou hunting using bows that are described in more detail below. We could go on and on. An Inuit "Instruction Manual for Technology" would run to hundreds of pages. And you'd need to master the "Natural History Handbook," "Social Policies and Procedures," "Grammar and Dictionary," and "Beliefs, Stories, and Songs," volumes of comparable length to be a competent Inuit.

So, here is the question: Do you think that you could acquire all the local knowledge necessary to create these books on your own? This is not a ridiculous question. To a first approximation, this is the way that other animals have to learn about their environments. They must rely mainly on innate information and personal experience to figure out how to find food, make shelter, and in some cases to make tools.

We are pretty sure that you would fail, because this experiment has been repeated many times when European explorers were stranded in an unfamiliar habitat. Despite desperate efforts and ample learning time, these hardy men and women suffered or died because they lacked crucial information about how to adapt to the habitat. The Franklin Expedition of 1846 illustrates this point (Lambert 2011). Sir John Franklin, a Fellow of the Royal Society and an experienced Arctic traveler, set out to find the Northwest Passage and spent two icebound winters in the Arctic, the second on King William Island. Everyone eventually perished from starvation and scurvy. The Central Inuit have, however, lived around King William Island for at least 700 years. This area is rich in animal resources. Nonetheless, the British explorers starved because they did not have the necessary local knowledge, and despite being endowed with the same cognitive abilities as the Inuit, and having two years to use these abilities, they failed to learn the skills necessary to subsist in this habitat.

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Results from this "lost European explorer experiment" and many others suggest that the technologies of foragers and other relatively simple societies are beyond the inventive capacity of individuals. The reason is not difficult to understand. Kayaks (Dyson 1991), bows (Henrich 2008), and dog sleds (Malaurie 1985) are very complicated artifacts, with multiple interacting parts made of many different materials. The function of these artifacts depends on physical principles known only to engineers during the last two or three centuries. Determining the best design is, in effect, a high-dimensional optimization problem that is usually beyond individual cognitive capacities, sometimes even those of modern engineers (e.g., Dyson 1991). Inevitably, design requires much experimentation, and in most times and most places this is beyond the capacity of individuals (Henrich 2009b).

Tools Usually Evolve Gradually by Small Marginal Changes

Isaac Newton remarked that if he saw farther, it was because he stood on the shoulders of giants. For most innovations in most places at most times in human history, innovators are really midgets standing on the shoulders of a vast pyramid of other midgets. Historians of technology believe that even in the modern world the evolution of artifacts is typically gradual, with many small changes, often in the wrong direction. Nonetheless, highly complex adaptations arise by cultural evolution even though no single innovator contributes more than a small portion of the total (Basalla 1988; Petroski 1994, 1985, 2006).

Two examples (one simple, the other more complex) will illustrate this contention. The simple example is the evolution of the eighteenth-century North American axe. The sharp end of an axe head is called the blade; the other end on the opposite side, with a hole for the handle, is called the poll. The typical "trade axe" introduced from Europe to North America in the seventeenth century had a small rounded poll. This design probably arose from the practice of manufacturing axe heads by bending an iron bar in a U-shape, inserting a piece of steel into the end of the U, welding the two arms and the steel to form the head, and finally sharpening the steel to form the blade (Figure 7.1). The rounded design makes it hard to use the axe as a hammer (e.g., to drive wedges), and the fact that the center of mass of the head is well forward of the handle makes accurate swings difficult (Widule et al. 1978). Over the course of the eighteenth century, a new design, the "American felling axe," was gradually created by North American blacksmiths (Kauffman 2007). This axe had a substantial poll that moved the center of mass backward with a flattened surface, which made it easier to use as a hammer, and is now the standard form of axe heads in Europe and North America. Still, even such a small change took at least a century to emerge and spread.

The evolution of rudders for ships in Europe provides a more complex example of gradual cumulative cultural evolution (Mott 1997). In very small boats, paddles can serve as "rudders." A paddler at the back of the boat tilts

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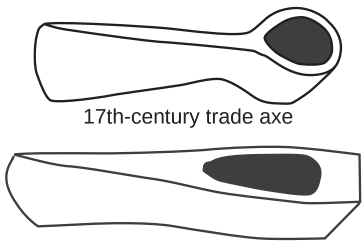

Figure 7.1 (a) Illustration of a European "trade axe" typical of seventeenth-century European axes. This axe has a lightweight, rounded poll. (b) An American "felling axe" of the type which evolved in the eighteenth century in North America and is now used worldwide. The heavier poll makes the axe easier to swing accurately and gives the axe more cutting weight, both tending to increase the "bite" of each swing. The flattened poll allows the axe to be used as a sledge for driving wedges.

the paddle so that it is at an angle to the long axis of the boat creating a torque which causes the boat to turn. However, as boats became larger, the force necessary to accomplish this rapidly became too great. So, paddles became "quarter rudders": a large paddle-like rudder mounted (usually) on both sides of the ship, near the stern, with a long handle at the top end so that the rudder could be rotated around its long axis. Unlike paddles, quarter rudders turn the ship by creating a turning force the same way that a wing creates lift. In classical Greece and Rome, quarter rudders were constructed by fastening a flat piece of wood to a round pole, and were relatively broad compared to their length. Later in the Middle Ages, Mediterranean shipwrights adopted much longer, thinner quarter rudders with a wing-like cross section, a design that greatly reduced drag without reducing turning power. To be efficient, quarter rudders must be about a third as long as the overall length of the ship and mounted so that the long axis of the rudder is at an angle of about 45 degrees to the vertical. As ships became larger, this led to an increasing number of elaborate mounting tackle to handle the very large torques created by the long, heavy rudder. One rudder on a late thirteenth-century Mediterranean trading ship was 18 m long and weighed 11,000 kg. Eventually this led to the invention of the "sternpost rudder," a rudder mounted vertically on the stern using "pintle and gudgeon" hinges (Figure 7.2). This innovation occurred in the Baltic, and it seems likely that sternpost rudders evolved by combining the unusual fixed, quarter rudders used on Norse trading ships and newly developed iron hinges from large castle and cathedral doors. This innovation diffused into the Mediterranean and was applied to the much larger ships common to that region. The first ships that used sternpost rudders in the fourteenth century were otherwise very similar to contemporary ships; they had quarter rudders with a single mast, curved sternposts, and steeply rounded ("bluff") sterns. Because they were mounted in the turbulent wake of the ship rather than the laminar flow along the ship's side,

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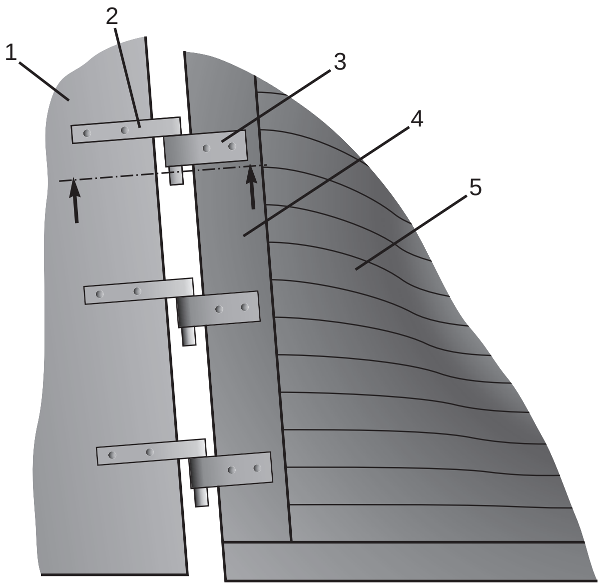

Figure 7.2 A pintle and gudgeon sternpost rudder. The "pintles" are the vertical pins attached to the rudder and the "gudgeons" are the iron loops attached to the sternpost of the hull. The labeled parts are: (1) the rudder, (2) a pintle, (3) a gudgeon, (4) the sternpost, and (5) the hull of the ship. Image created by Eric Gaba for Wikimedia Commons, used with permission.

ships with sternpost rudders were difficult to handle because these rudders created much less turning force than quarter rudders. Gradually over the next several centuries, ship builders added (a) multiple masts which allowed sails to be used to aid steering, (b) a straight, vertical sternpost that allowed more than two pintle and gudeon connectors, and gradually (c) a streamlined stern with more "dead wood" which causes laminar flow around the rudder (Figure 7.3). In this way the modern ship's rudder, and associated design changes, evolved gradually in Europe over a period of more than half a millennium. Interestingly, as Mott (1997) recounts, rudder evolution in China and the Indian Ocean seem to have taken completely independent courses.

Genetic Evolution Leads to Complex, Adaptive Artifacts Often Constructed by Animals with Simple (or No) Nervous Systems

Discussions of animal tool use typically focus on things that animals can carry: stones used by chimpanzees to crush hard-shelled nuts, and leaf tools used by New Caledonian crows to extract insect larvae from holes in branches. The relative rarity of these tools as well as the fact that they are made by animals

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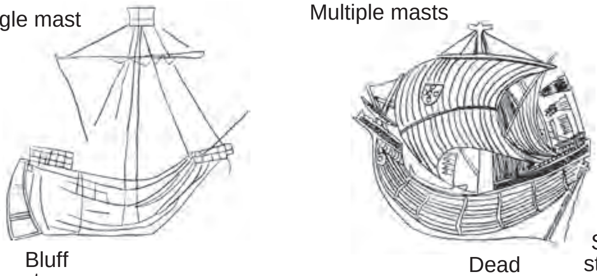

Figure 7.3 Illustration of the development of ship design after the introduction of the sternpost rudder in the Mediterranean region. The left panel shows a tracing of a drawing of a medieval ship from the bell tower of the Cathedral of Palma de Mallorca, which probably dates to the early thirteenth century. The curved sternpost, bluff stern, and single mast were characteristic of contemporary ships with quarter rudders. Note that a very broad rudder was necessary when used with a bluff stern. The right panel shows an early fifteenth-century drawing of a ship with innovations made in response to the introduction of the sternpost rudder, three masts, a straight sternpost carrying a slender rudder and a run of dead wood up to the rudder. Reprinted with permission from Lawrence Mott (1997:131, 139).

like apes and corvids gives the impression that animal artifacts are rare, simple, and limited to clever large-brained creatures, something like ourselves.

Nothing could be further from the truth. Think a bit—you already are aware of many complex animal artifacts. Birds' nests, spider webs, termite mounds, and beaver dams are just a few of the familiar constructions made by nonhuman animals, and a dip into the zoological literature reveals a long list of less familiar artifacts. Many of these artifacts appear highly designed and require very elaborate construction techniques. Take the nests made by the village weaver, one of a number of African weaver birds (Collias and Collias 1964). These hanging nests provide shelter for the brooding young and rival the houses made by many human populations in their complexity. The construction process is highly stereotyped. The bird first weaves a ring, followed by the egg chamber, and finally the entrance. The weaving itself involves elaborate knotting and weaving (Figure 7.4). While practice increases the quality of the construction, social learning plays no role. Birds seem to have some representation of form of the nest, but for the most part it seems that the construction process results from an algorithm which links simple, stereotypical behaviors into a sequence that generates a nest.

The construction of complex artifacts does not require superior cognitive ability. Invertebrates such as termites, funnel wasps, and spiders make complex, highly functional artifacts without any representation of the final form of the artifact (Gould and Gould 2007; Hansell 2005) despite having much

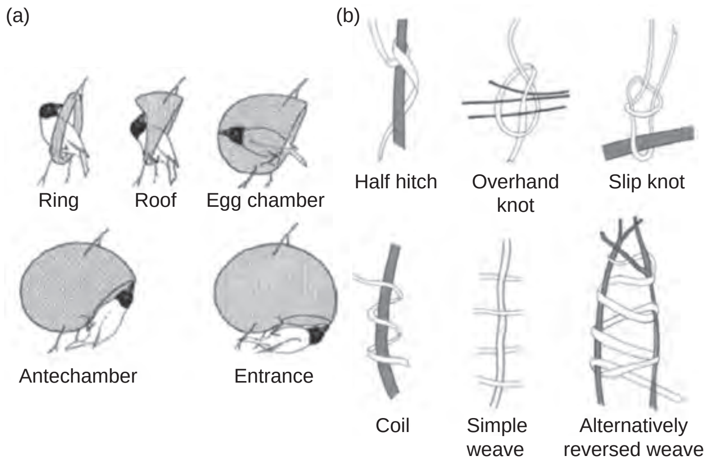

Figure 7.4 (a) Depiction of the construction sequence used by village weavers to construct their nests. The bird first builds a hanging ring by knotting green grass stems onto the fork of a branch and then weaving more stems to make a ring. The ring is extended outward by weaving more stems into the existing structure. (b) A sampling of the knots and weaves found in typical village weaver nests. Reprinted with permission from AOU (Collias and Collias 1964).

simpler cognitive systems than most vertebrates. In fact, complex artifacts can be constructed without a nervous system at all, as demonstrated by Figure 7.5.

The Cultural Evolution of Artifacts Is Usually Faster Than the Genetic Evolution of Morphology

Modern technology evolves with blinding speed. The number of transistors that can be usefully incorporated on an integrated circuit has doubled every eighteen months for almost half a century. The twentieth century saw massive transformations within a few generations. The first author's father grew up in a small town in Upstate New York without telephones, automobiles, or electric lights and now this very same person's grandchildren carry powerful computers in their pockets. These stupendous rates are the end result of an exponentially increasing rate of change that has characterized the technological evolution over most of the last millennium (Enquist et al. 2008).

It is clear that rates of cultural change over the last millennium are much faster than rates of genetic adaptation in a long-lived species like humans. Of course, bacteria can adapt genetically extremely quickly because their generations are measured in minutes. Human genetic adaptation seems to take place on millennial timescales at the fastest. Thus far, the strongest selection

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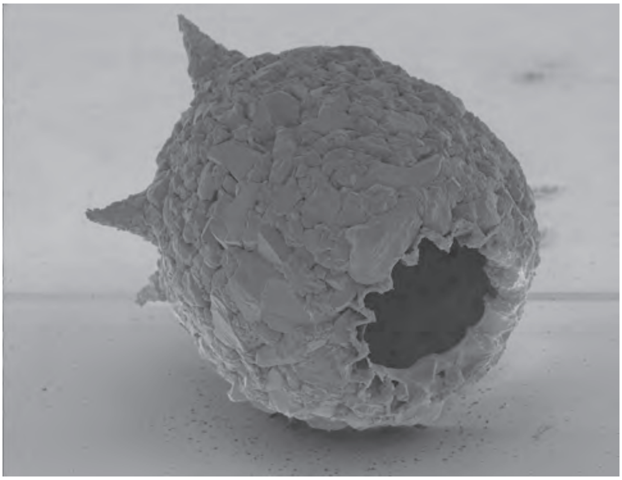

Figure 7.5 The "house" built by the single-celled amoeba *Diffulgia corona*. It is about 0.15 mm in diameter and is made of very small grains of sand. Reprinted with permission from The Natural History Museum, London (Hansell 2005).

signal detected in the human genome by looking for long haplotypes is the gene that allows northern Europeans to digest lactose (Ingram et al. 2009), an allele which has increased to moderately high frequencies in Northern Europe over the last 5,000 years or so.

Until recently it was not so clear that rates of cultural change in less complex human societies were faster than rates of human genetic change, but a recent paper by Perreault (2012) settles the issue: cultural rates are much faster than genetic evolutionary rates. In a famous paper, Gingrich (1983) assembled data from paleontological records which allowed measurement of the rate of change as the percent change in a quantitative morphological character per million years. Gingrich also found that measured rates of change were negatively related to the time period over which the measurement was made. Perreault assembled a sample of 573 cases from the archaeological record (mainly for Holocene North America) and compared the measured rates of change to those in Gingrich's sample of paleontologically measured rates. The effect of the type of transmission on the per generation rate of change estimated in a multivariate analysis is approximately a factor of 50. All other things being equal, the rate of cultural change of the dimensions of pots, points, and houses is fifty times greater than the rate of change in the dimensions of mandibles, molars, and femurs (Figure 7.6).

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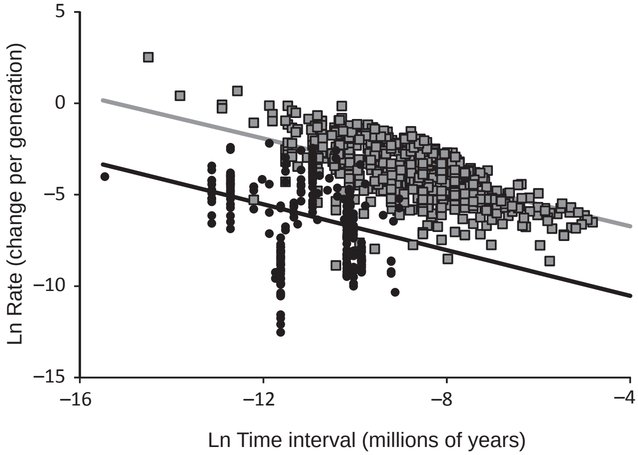

Figure 7.6 The logarithm (Ln) of percent change per generation for genetically heritable morphological traits (black circles) from the fossil record and culturally transmitted traits from the archaeological record (gray squares) plotted against the logarithm of length of time over which the change occurred. The lines represent the best fit in a multivariate analysis of covariance. In both cases, rates decline as the time interval increases, and, interestingly, the per-generation slopes are approximately equal. The distance between the lines gives the difference in cultural and biological traits controlling for other variables. Cultural evolution is a factor $e^{3.91}$ = 49.8 times faster than genetic evolution. Reprinted with permission from Charles Perreault (2012).

An Evolutionary Theory of Technology Requires Independent Theories of Function

Understanding the causal relationship between phenotypic variation and reproductive success is a key component of Darwinian theory. Sometimes it is argued that natural selection is a tautology: genes with higher fitness spread (e.g., Bethell 1976):

> Question: How do we know they are higher fitness?
> Answer: Because they spread.

If biologists worked this way, natural selection would indeed be a useless concept. To understand why, consider the following example: A recessive gene causing a severe vision disorder called achromatopsia has spread to roughly 30% of the population on the Micronesian island of Pingelap. Sufferers of achromatopsia cannot see well under any circumstances, but are especially disadvantaged in the bright sunlight of a tropical island (Sacks 1998). Nonetheless, there is no doubt that this gene spread on Pingelap because people who carried it had more descendants than those who did not carry the gene. However, we know that achromatopsia was not favored by natural selection because it did not *cause* their increased reproductive success. Rather the gene was carried by

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members of a chiefly lineage whose social position allowed them to survive the aftermath of a severe typhoon which struck the island during the 1700s; the spread of the achromatopsia gene was a side effect of other processes, not the result of natural selection.

This kind of functional reasoning is crucial for the inference that complex adaptations were caused by natural selection. For relatively simple characters, it is possible to measure phenotypic variation in nature and connect it to variation in fitness—the study of the evolution of beak morphology in Darwin's finches by the Grants (1986) provides a classic example. However, this tactic is hard to apply to complex characters like the vertebrate eye. Instead, biologists rely on detailed functional analyses which show that many details of the complex adaptation fit with the proposed function of the adaptation. Thus, the lens has to be just the right shape and have just the right index of refraction to form an image on the retina, an exquisitely photosensitive tissue. The iris adjusts the aperture so that the eye works over a wide range of light intensities; three sets of muscles adjust the eye's orientation, up down, right left, and correct for movements of the head. The list of features is long. Moreover, the eyes of different organisms vary in ways that make sense, given the problems they have to solve. Our eyes have "lens-shaped" lenses with an approximately uniform index of refraction, whereas fish have spherical lenses with an index of refraction that gradually increases toward the center of the lens. This difference makes sense, given the optics of living in air and water.

We think that functional analysis should play a similar role in the study of culturally evolved technology. There are good reasons to believe that both payoff-biased transmission and guided variation (Richerson and Boyd 2005) should cause the gradual adaptive cultural evolution of functional artifacts. Thus the careful study of the function of complex culturally evolved artifacts provides evidence that these processes gave rise to the artifacts. The design of bows and arrows provides a good example. Many modern bowyers (bow-and-arrow makers) are interested in recreating designs collected by previous generations of anthropologists. These bowyers include sophisticated engineers, and through their testing and experiments, we have come to know a lot about the design principles of traditional bows and arrows. (For details, see the many papers in the four volumes of *The Traditional Bowyer's Bible*; the paper by Baker [1992] in the first volume provides a good introduction.) Bows used to hunt large game needed to be powerful enough to throw a heavy arrow at high velocity. When a bow is bent, the back (the side away from the archer) is under tension, while the belly (the side closer to the archer) is in compression. This leads to strain within the bow and can result in failure. The simplest way to solve this problem is to make a long bow using some dense elastic wood, like yew or osage orange, a design widely used in South America, Eastern North America, Africa, and Europe. Because a long bow need not be bent very far, this design minimizes the strain on the limbs. In some environments, however, a long bow is not practical. People like the Plains Indians and Central Asian pastoralists, who hunt and fight on horseback, need a short bow. In other environments, like the high Arctic, the right kind of wood is not available. In such environments people make short bows and employ the full range of bowyers' tricks to increase their power. A bow can be made more powerful by removing less wood in shaping the limbs. However, making the bow thicker (front to back) increases the stress within the bow, leading to failure. This problem is exacerbated in short bows because the radius of curvature is greater. To solve this problem, the short bows made by Plains Indians, Inuit, and Central Asian pastoralists are thin front to back, wide near the center, and taper toward the tips. They are also usually recurved, meaning that the bow is constructed so that when it is not braced, it forms a backward "C" shape. Bracing the recurved bow leads to a compound curve (the middle part of the bow curves toward the archer but the tip of each limb curves back away from the archer), a geometry that allows for greater energy storage. Finally, these peoples typically make composite bows. Wood is stronger in compression than tension, so the ability of a bow to sustain strong bending forces can be increased by adding a material that is strong in tension to the back of the bow. Both in Central Asia and Western North America, sinew was glued to the backs of bows to strengthen short bows for use on horseback. The Inuit, however, lashed a woven web of sinew to the back of their bows, probably because available animal glues would not work in the moist, cold conditions of the Arctic. Other components of the bow show similar levels of functional design. Bowstrings need to be strong and should not stretch. In most environments the solution is to make cord by twisting long sinews, often drawn from along the backs of ungulates, and then combining cords into multi-ply bow strings in which the plies twist in opposite directions. In addition, arrows present complicated design problems which have been solved by different peoples in different ways.

The Cultural Evolution of Technology Cannot Be Explained Solely in Terms of Specialized Innate Attractors or Cognitive Biases

A number of authors have argued that the outcomes in cultural evolution are strongly shaped by "inductive biases" created by human cognition (Claidière and Sperber 2007; Boyer 1998; Griffiths and Reali 2011). We agree that such biases probably have important effects, at least in some domains, and have referred to these as "content" or "direct" biases (Boyd and Richerson 1985; Henrich and Henrich 2010). The way that this works is beautifully illustrated by the transmission chain experiments conducted by Tom Griffiths and his collaborators (Griffiths and Reali 2011). For example, in one experiment, subjects are first shown 50 pairs of numbers. Sometimes these are the *x*, *y* coordinates of a straight line, sometimes a curve, and other times they are drawn at random (Figure 7.7). Then the subject is given 50 *x* values and asked to produce the associated *y* value. These fifty pairs are then used to train a second subject, who is given 50 *x* values and asked to produce the *y* values learned during training.

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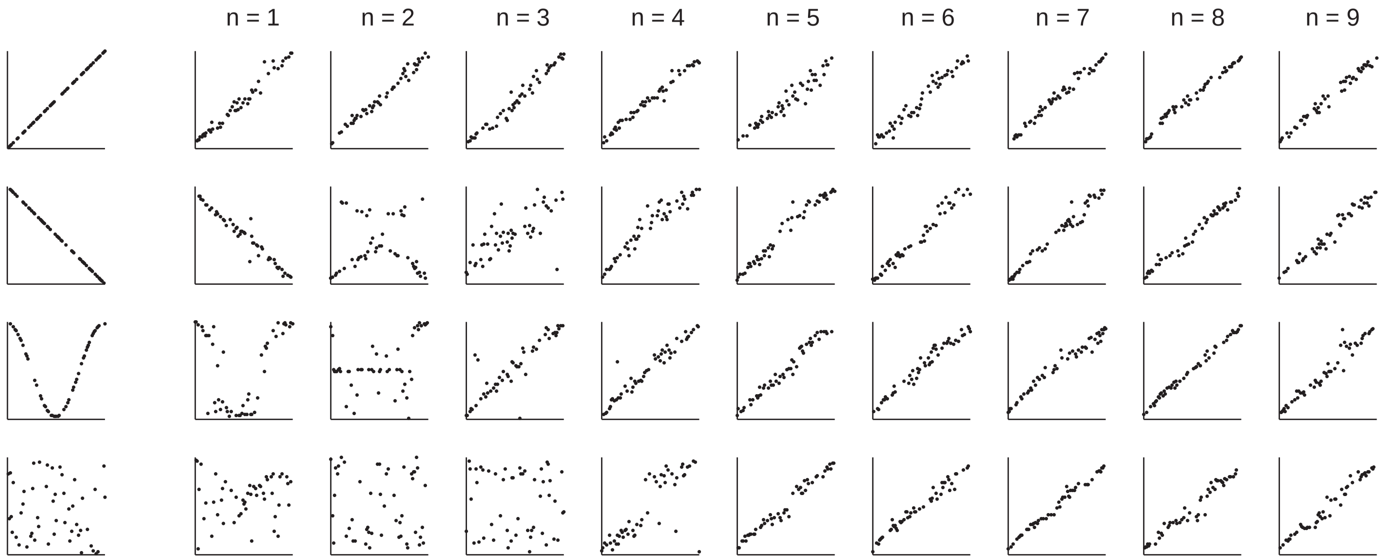

Figure 7.7 Results of four transmission chain experiments which show that an inductive bias in favor of straight line, not the environmental data, determines the final result. The left column shows the data used to train the first subject. The subsequent panel gives that subject's estimates of the *y* value given an *x* value. This data was then used to train the next subject in the chain, and the process was repeated for nine subjects. By the fifth subject, each chain had generated a straight line which was stable thereafter. Reprinted with permission from Griffiths and Reali (2011).

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This procedure is repeated for eight more subjects. As illustrated in Figure 7.7, transmission is strongly shaped by a bias in favor of straight line relationships with a positive slope. The initial data has no effect on the ultimate outcome. Human learning has an inductive bias that causes people to infer straight lines from data, and when combined with error prone learning, this bias gradually causes people to see straight lines where none existed.

Dan Sperber has argued that such inductive biases, which he calls "attractors," are the main source of cultural stability and thus determine the outcomes of cultural evolution (Claidière and Sperber 2007). Sperber believes that the "frame problem" makes cultural learning extremely difficult. It is difficult, he believes, to copy the behavior of others accurately, where behavior includes things like artifacts. Any real artifact is complex, and both the artifact and the process by which it is made contain many irrelevant details. The learner who is trying to learn how to make an artifact by observation must know what to ignore and what to learn. Inductive biases serve this function. Because these biases shape what is learned and what is ignored, they have a strong effect on cultural outcomes.

Functional thinking suggests that Sperber overemphasizes the importance of such attractors. Perhaps innate attractors would work if humans made only one sort of complex technology, but bows, boats, clothing, and all the other components of technology include a stunning diversity of nonintuitive forms that are often exquisitely designed for a particular environment. The short, flat, recurved composite Plains Indian bow is designed for horse-mounted hunting and warfare. Such complex functional design does not arise by chance. The details matter: its shape, the kind of wood used, the glue used to bind sinew to the back of the bow, the kind of sinew, and the number of plies used in the bowstring, and so on. Moreover, as we have seen, complex cultural design does not usually arise from inventive activities of single individuals. Instead, complex functional human artifacts like bows, dogsleds, and kayaks evolve through a gradual process of cultural accumulation. The cultural evolution of the Plains Indian bow, and its stability through time, however, cannot solely be due to an attractor or inductive bias that causes individuals to make Plains Indian bows. Many inductive biases may, of course, be important. The mind is a complex device with many specialized mechanisms, allowing people to solve problems which they face (Barrett 2013). We have mechanisms that allow us to engage in causal reasoning (Gopnik and Schulz 2004), recognize and categorize objects in the world (Carey 2009; Perfors and Tenenbaum 2009), and learn from observing the behavior of others (Tomasello et al. 2005). We may also have evolved intuitions about the function of artifacts (German and Barrett 2005) and the laws of mechanics (Carey 2009). It seems likely that these mechanisms make it easier to learn how to make some kinds of tools and harder to make others, and this will create cognitive biases that affect the cultural evolution of technology. However, such mechanisms cannot account for the details that are crucial for the function of the Plains Indian bow, because these are specific to

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the particular adaptive problems faced by mounted bison hunters. There is no "Plains Indian bow attractor" hidden in the recesses of the human mind. The design of these bows must be transmitted sufficiently accurately from person to person so that it remains stable through time, and so improvements can gradually accumulate.

Theory Relevant to the Cultural Evolution of Technology

Gradual Cumulative Adaptation Can Arise from Rare Individual Learning plus Unbiased Transmission

Quite a bit of work has been done on mathematical models that describe how the gradual cultural accumulation of complex cultural adaptations might occur. These models are usefully divided into three types: (a) models in which cumulative adaptation arises from rare individual learning combined with unbiased cultural transmission, (b) models in which adaptations arise from payoff-biased transmission, and (c) models in which cumulative adaptation arises from rare innovations and accurate communication of causal information. We will review in turn work from each category.

Rogers (1988) created an early, and especially simple, model that showed how learning and imitation could be combined to give rise to gradual cultural evolution. In this model, a population lives in an environment that switches between two states with a constant probability. There is a best behavior in each state, and the adaptive problem facing individuals is to determine within which environment they are living. There are two methods for doing this: individuals can, at a cost, learn the best behavior in the environment, or they can copy another individual for free. As long as the net benefit of acquiring the best behavior is greater than the cost of learning, the optimal strategy is a mixture of costly learning and cheap imitation. Gradual cultural evolution occurs when learning is costly and environmental changes are infrequent. Then, at the optimal mixture of learning and imitation, only a few individuals learn and most imitate; thus after an environmental shift, the fraction of the population with the best behavior gradually increases (Figure 7.8).

Barrett et al. (2007a) and Pinker (2010) argue that the main benefit of social learning is that it allows the costs of learning to be spread over a large number of individuals. Information is, in the jargon of economics, a "nonrival" good, meaning that one person's "consumption" does not reduce the value for others. Once produced, valuable information can spread throughout a population at low, or even zero cost, a fact that is at the core of endogenous growth models discussed below (e.g., Romer 1993). However, Rogers's model shows that this argument is wrong when applied to the evolution of social learning. The equilibrium mixture of learning and imitation leads to the same average payoff as a population in which there are no imitators, only learners.

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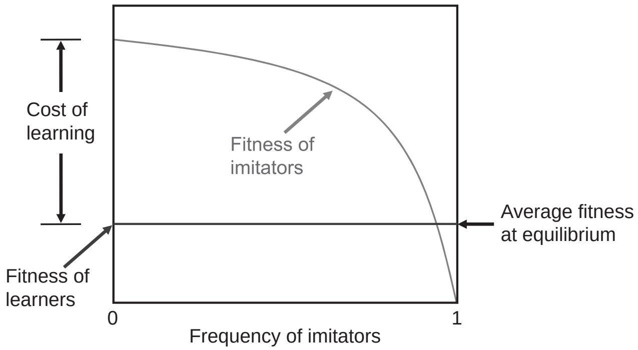

Figure 7.8 A diagrammatic exposition of the model by Rogers (1988). The graph gives the fitness of imitators and learners as a function of the frequency of imitators. Learners monitor the environment and acquire the best behavior at a cost. Imitators copy a random individual for free. When imitators are rare, they have higher fitness than learners because they have the same probability of acquiring the best behavior but do not pay the cost of learning. As imitators become more common, their fitness declines because they increasingly acquire the wrong behavior due to environmental changes. The frequency of imitation increases until both types have the same fitness.

The reason is that imitators do not contribute anything to the population; they just scrounge adaptive information that has been produced by the costly learning efforts of others. This property, often referred to as "Rogers's Paradox," has been the focus of much research (Boyd and Richerson 1995; Kobayashi and Wakano 2012; Lehmann et al. 2010; Rendell et al. 2010; Aoki 2010). So far investigators have discovered three mechanisms that allow culture to increase average fitness.

First, population structure can generate relatedness among interacting individuals, and this in turn alters the evolutionarily stable mix of individual and social learning so that average fitness increases (Rendell et al. 2010; Lehmann et al. 2010). In these models, individual learners are altruists who create benefits for others at a cost to themselves. Thus, simple kin selection arguments predict that when population structure leads to increased relatedness, the evolutionary equilibrium should contain more individual learners than when individuals interact at random. This means that average fitness increases. The work of Lehmann et al. (2010) illustrates how this works in an island model in which local populations exchange genes, but not cultural traits, with the global population. Rendell et al. (2010) simulate gene–culture coevolution on a lattice, and although their results are complex, it seems likely that the increased average fitness which they observe for some parameter combinations is also due to population structure.

Second, cultural learning can allow individuals to learn selectively. The ability to learn selectively is advantageous because opportunities to learn

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from experience or by observation of the world vary. Sometimes experience provides accurate information at low cost. Think of Goodyear accidentally spilling rubber onto a hot stove, or Fleming observing his mold-contaminated petri dishes. Such rare cues allow accurate low-cost inferences about the environment. However, most individuals will not observe these cues, and thus making the same inference will be much more difficult for them. Organisms which cannot learn from others are stuck with whatever information nature offers. In contrast, an organism capable of cultural learning can afford to be choosy, learning individually when it is cheap and accurate, and relying on cultural learning when environmental information is costly or inaccurate. We have shown (Boyd and Richerson 1987b; Perreault et al. 2012) that selection can lead to a psychology that causes most individuals to rely on cultural learning most of the time, and also simultaneously increase the average fitness of the population over the fitness of a population that does not rely on cultural information. In these models the psychology that controls individual learning has a genetically heritable "information quality threshold" that governs whether an individual relies on inferences from environmental cues or learns from others. Individuals with a low information quality threshold rely on even poor cues, whereas individuals with a high threshold usually imitate. As the mean information quality threshold in the population increases, the fitness of learners increases because they are more likely to make accurate or low-cost inferences. At the same time, the frequency of imitators also increases. As a consequence, the population does not keep up with environmental changes as well as a population of individual learners. Eventually, an equilibrium emerges in which individuals deploy individual and cultural learning in an optimal mix. At this equilibrium, the average fitness of the population is higher than in an ancestral population without cultural learning. When most individuals in the population observe accurate environmental cues, the equilibrium threshold is low, individual learning predominates, and culture plays little role. However, when it is usually difficult for individuals to learn on their own, the equilibrium threshold is high, and most people imitate, even when the environmental cues that they do observe indicate a different behavior than the one they acquire by cultural learning. This analysis assumes selection is weak enough so that only learning affects the frequency of alternative cultural variants. If selection is strong enough to lead to the spread of adaptive cultural variants then, of course, mean fitness will increase for the same reason that it does in genetic models, a fact confirmed by the simulation study of Franz and Nunn (2009b).

Third, the ability to learn culturally can also raise the average fitness of a population by allowing acquired improvements to accumulate from one generation to the next. Many kinds of traits admit successive improvements toward some optimum. Bows vary in many dimensions that affect performance, such as length, width, cross section, taper, and degree of recurve. It is typically more difficult to make large improvements by trial and error than small ones for the

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same reasons that Fisher (1930) identified in his "geometric model" of genetic adaptation. In a small neighborhood in design space, the performance surface is approximately flat, so that even if small changes are made at random, half of them will increase the payoff (unless the design is already at the optimum). Large changes will improve things only if they are in the small cone that includes the distant optimum. Thus, we expect it to be much harder to design a useful bow from scratch than to tinker with the dimensions of a reasonably good bow. Now, imagine that the environment varies, so that different bows are optimal in different environments, perhaps because the kind of wood available varies. Sometimes a long bow with a round cross section is best, other times a short, flat, wide bow is best. Organisms which cannot imitate would have to start with whatever initial bow design might be provided by their genotype. Over their lifetimes, they can learn and improve their bow. However, when they die, these improvements disappear with them, and their offspring must begin again at the genetically inherited initial design. In contrast, cultural species can learn how to make bows from others after these have been improved by experience. Therefore, cultural learners start their search closer to the best design than pure individual learners and can invest in further improvements. Thereafter, they can transmit *those* improvements to their offspring, and so on down through the generations until quite sophisticated artifacts evolve. Modeling work (Boyd and Richerson 1985; Borenstein et al. 2008; Aoki 2010) shows that this process can increase average fitness.

In an alternative approach, Enquist et al. (2007) argue that "adaptive filtering" can lead to increased average fitness. They, however, incorporate a number of novel features in their model, and this makes it difficult to compare it with other work in this tradition. Most notably, they assume a large number of traits that have two states: present or absent. The present state of some traits increases fitness compared to the absent state, whereas the present state of other traits reduces fitness. Environmental change is modeled by assuming that traits which are currently adaptive when present change to maladaptive at a constant rate. The fitness effects of all traits are independent, so there is no possibility of cumulative evolution in which each step is contingent on the last. Adaptive filtering increases the rate at which individuals switch from the present to the absent state when the trait reduces fitness. Enquist et al. (2007) show that adding adaptive filtering can lead to increased average fitness. They do not provide any model of how it works at the individual level. We think that adaptive filtering is best thought of as a costless, error-free form of individual learning. To determine whether a present trait is maladaptive in the current environment, individuals need to monitor environmental cues and infer whether the present or absent state of the trait has higher fitness. Adaptive filtering must thus entail some kind of inference process. It is error free because it does not lead to any switch from the absent to present state for maladaptive traits. There is no fitness penalty associated with increased adaptive filtering.

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Gradual Cumulative Adaptation Can Arise from Payoff-Biased Transmission

If cultural learners can compare the success of individuals modeling different behaviors, then a propensity to imitate the successful can lead to the spread of traits that are correlated with success, even though imitators have no causal understanding of the connection. This is obvious when the scope of traits being compared is narrow. For example, you see that your uncle's bow shoots farther than yours, and notice that it is thicker, but less tapered, and uses a different plait for attaching the sinew. You copy all three traits, even though in reality it was just the plaiting that made the difference. As long as there is a reliable statistical correlation between plaiting and power, the plaiting form trait will change so as to increase power. Causal understanding is useful because it helps exclude irrelevant traits, like the color the bow is painted. However, causal understanding need not be very precise as long as the correlation is reliable. Copying irrelevant traits like thickness or color will only add noise to the process. By recombining different components of technology from different but still successful individuals, copiers can produce both novel and increasingly adaptive tools and techniques over generations without any improvisational insights. An Inuit might copy the bow design from the best bowyer in his community but adopt the sinew plaiting used by the best hunter in a neighboring community. The result could be a better bow than anyone made in the previous generation without anyone inventing anything new.

Consistent with this, laboratory and field evidence suggests that both children and adults are predisposed to copy a wide range of traits from successful or prestigious people (Henrich and Gil-White 2001; McElreath et al. 2008; Mesoudi 2011b; Chudek et al. 2012). Advertisers clearly know this. After all, what does Michael Jordan really know about T-shirts? Recent work in developmental psychology shows that young children readily attend to cues of reliability, success, confidence, and attention to figure out from whom they should learn (Birch et al. 2008, 2010). Even infants selectively attend to knowledgeable adults rather than their own mothers in novel situations (Stenberg 2009). This feature of our cultural learning psychology fits a priori evolutionary predictions, emerges spontaneously in experiments, develops early without instruction, and operates largely outside conscious awareness. Humans have an efficient social learning module, if you like.

Gradual Cumulative Adaptations Can Arise from Rare Innovations Which Spread Rapidly Because Their Benefits Are Understood

Economists have developed quite different models of the gradual evolution of technology in which some rational economic actors innovate at a cost while other actors adopt the innovations because they understand how they work and why they are beneficial. The central problem in these models is to explain

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why individuals make costly investments in innovation when others will be able to copy these innovations for free: the rational choice version of Rogers's Paradox. There are two families of models that solve this problem in different ways: in "learning by doing models," innovation is a side effect of other economic activities (Arrow 1962). For example, when firms invest in new factories, the design process may yield a better factory as a side effect. This innovation can then be copied by other actors. Endogenous growth models (Romer 1993) assume that actors choose to innovate because they have market power (modeled as monopolistic competition) and because patents prevent others from copying their innovation directly. However, the knowledge that underlies the innovation is not protected and serves as the basis of further innovations. Social learning is usually not modeled explicitly in either tradition; it is simply assumed that new knowledge is available to all decision makers. Moreover, environments are assumed to be constant so that every innovation increases economic welfare. Thus, cumulative economic progress is built into the models by assumption.

The extent to which these models are relevant to the cultural evolution of technology over the long sweep of human history depends on the answers to two questions: First, are most innovations adopted because their effects are understood, or because they are statistically associated with observable, preferred outcomes? Second, are there mechanisms analogous to patent protection and market power that allow innovators to recoup the costs of attempting to innovate? There is evidence that the adoption of new technologies is not always accompanied by the transmission of causal explanation of how they work or why they are beneficial. Fijian food taboos provide an example. Many marine species in the Fijian diet contain toxins, which are particularly dangerous for pregnant women, and perhaps nursing infants. Food taboos targeting these species during pregnancy and lactation prohibit women from eating toxic foods and reduce the incidence of fish poisoning during this period. Although women in these communities all share the same food taboos, they offer quite different causal explanations for them, and little information is exchanged among women save for the taboos themselves (Henrich and Henrich 2010). The taboos are learned and are not related to pregnancy sickness aversions. The transmission pathways for these taboos suggest the adaptive pattern is sustained by selective learning from prestigious women. If this example is typical, rational actor models do not provide a complete account of adaptive cultural traits like the evolution of technology. From classic literature on the diffusion of innovations (Rogers and Shoemaker 1971) we do know that people do use both the properties of practices and the attributes of the people using or promoting practices in adoption decisions, but precise quantitative estimation of the mechanics of these decisions in the field is still in its infancy.

Obviously there were no patents or similar protections during most of human history, but there may be other ways to recoup the costs of innovation. First, innovations may diffuse slowly throughout a population. Thus genes that

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lead to innovation will have an adaptive advantage during the time period it takes for the innovation to spread widely. It is interesting that something like this seems to have happened in the evolution of blast furnaces in nineteenth-century Pittsburgh (Allen 1983). Innovative firms were copied by other steel firms within the Pittsburgh region, but because the technology did not diffuse rapidly to other cities, Pittsburgh firms as a whole held an advantage, and the share flowing to innovators may have been sufficient to compensate them for their innovative efforts. Second, Henrich and Gil-White (2001) have argued that skillful or prestigious individuals are often compensated by would-be imitators for access. In such cases, the need for access to imitate successfully is analogous to a trade secret and the payments analogous to licensing payments to patent holders (for a detailed discussion and consideration of "innovation-enhancing institutions," see Henrich 2009b).

Rate of Adaptive Accumulation Depends on Population Size and Connectedness

Two models of cumulative cultural adaptation predict that, all other things being equal, large populations will have more diverse and more complex toolkits than small, isolated populations. First, cultural transmission is subject to a process analogous to genetic drift (Neiman 1995; Shennan 2001). This means that cultural variants are lost by chance when their practitioners are not imitated. For instance, the best bowyer may not be copied because he is a poor shot, unsociable, or dies unexpectedly. The rate of loss due to cultural drift will be higher in small populations than in larger ones, where the absolute number of experts is greater. Lost traits can be reintroduced by the flow of people or ideas from other populations, so the equilibrium amount of variation depends on the rate of contact between groups. Second, social learning is subject to errors, and since errors will usually degrade complex adaptive traits, most "pupils" will not attain the level of expertise of their "teachers." In this way, inaccurate learning creates a "treadmill" of cultural loss, against which learners must constantly work to maintain the current level of expertise. This process is counteracted by the ability of individuals to learn selectively from expert practitioners, so that cumulative cultural adaptation happens when rare pupils surpass their teachers (Henrich 2004b; Aoki and Kobayashi 2012; Henrich 2006). Learners in larger populations have access to a larger pool of experts, making such improvements more likely; this means that the equilibrium levels of cultural complexity should increase as population size increases (Mesoudi 2011c). As in the cultural drift models, contact between populations replenishes adaptive variants lost by chance, leading to higher levels of standing variation, and thus more adaptive traits (Powell et al. 2009).

Empirical data provide some support for these models. A number of small, isolated island populations have lost seemingly valuable technology. For instance, the Tasmanian toolkit gradually became simpler after isolation from

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mainland Australia (Diamond 1978; Henrich 2004b, 2006; but see Read 2006), and other Pacific groups have apparently abandoned useful technologies such as canoes, pottery, and the bow and arrow (Rivers 1926). Elsewhere in the world, the isolated Polar Inuit lost kayaks and the bow and arrow when all knowledgeable people died during a plague, only to have these skills reintroduced by long-distance migrants from Baffin Island (Mary-Rousselière 1996). There have been two systematic tests of this hypothesis: Collard et al. (2005) found no relationship between population size and toolkit diversity or complexity; and neither did a reanalysis of those data by Read (2006). However, neither analysis included any measure of contact between populations, and the sample was drawn mostly from northern continental regions of the Western Hemisphere, where intergroup contact was probably common (Kroeber 1939; Balikci 1989; Jordan 2009), making it impossible to estimate effective population size without much better demographic data than we possess. Kline and Boyd (2010) analyzed data on marine foraging tools from ten societies in Oceania and found a strong relationship of both number of tool types and average tool complexity and population size (Figure 7.9) controlling for a number of other variables. It may have been easier to detect the effect of population size in this analysis because islands were bounded and isolated, thus making population size estimates more reliable, and because it focused on ecologically similar islands with a common cultural history. Higher rates of contact

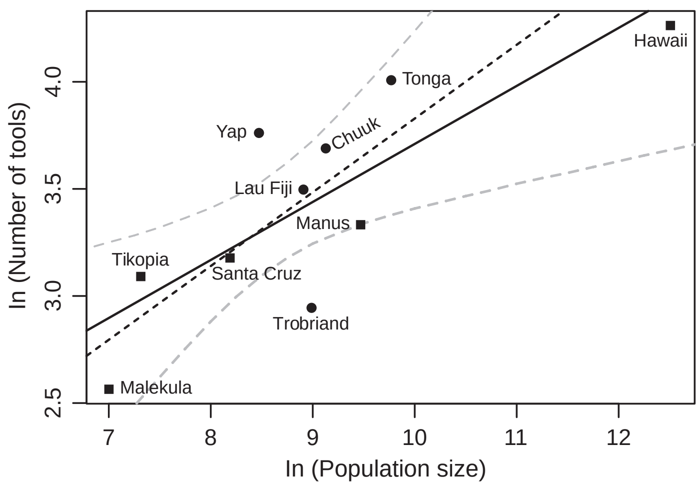

Figure 7.9 Number of tools as a function of population size. Larger populations have significantly more tool types than smaller populations. The trend line is based on a linear regression of the logarithm of the number of tools against the logarithm of population size (ß = 0.805, p = 0.005, n = 10). Four of five low-contact groups (squares) have fewer tools than expected, while four out of five high-contact groups (circles) exceed the expected number of tools. The gray dashed line gives interval estimates. The black dashed line gives the best linear fit when a potential outlier, Hawaii, is removed. Figure courtesy of Richard McElreath.

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between groups also increase tool complexity, but the result was only marginally significant.

Conclusion: What We Don't Know

We think that the evidence reviewed makes a convincing case that in most times and places individuals do not invent tools; tools evolve gradually. People everywhere depend on complex tools, many of which are difficult to understand even with the benefit of modern physics, chemistry, and engineering. Consistent with this picture, the history of technology makes it clear that most technological change is gradual, and models of cultural change suggest that gradual accumulation is to be expected when individual innovation is costly or difficult. This leaves two crucial questions unanswered. First, we know that there is heritability of cultural variation at the population level. Technologies and other forms of cultural variation persist in time and in ways that are not related to differences in the external environment (Richerson and Boyd 2005). Without heritability there can be no cumulative cultural evolution. However, we do not know the causes of heritability at the population level. In genetic evolution, heritability at the population level results from heritability at the individual level and restricted gene flow between populations. Genetic transmission is incredibly accurate, and selection is usually weak. This means that in the absence of high levels of gene flow, gene frequencies in populations change slowly. Most models of cultural transmission assume cultural variation is maintained in the same way. However, this need not be the case. Cultural transmission is an inferential process. How demonstrators behave gives evidence about what is going on in their brains, and learners make inferences based on this evidence. However, many inferences are consistent with the same evidence and, as a result, cultural learning may be inherently noisy. To this must be added individual attempts to learn based on environmental cues. It could easily be that cultural transmission is not sufficiently accurate to generate much heritability at the population level (see, however, the developmental evidence reviewed by Haun and Over, this volume). If this is the case, then observed heritability must be due to some kind of frequency-dependent process, like conformist transmission which preserves between-group variation (for a model of how conformist transmission creates group-level heritability, see Henrich and Boyd 2002a), and, as a result, the process of cultural accumulation of adaptive technology might be quite different than that explored in existing models.

In addition, we do not know the extent to which people have causal understandings of the technologies on which they depend. Once again there are two extreme models. On one hand, innovation is the rate-limiting step, but when innovations do occur they are accompanied by causal understandings of how the innovation works, and why it is better than previously used alternatives.

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The innovation spreads rapidly because causal understanding spreads with it. Innovation driven by modern science in some domains may approximate this hypothesis. At the other extreme, behavior varies randomly and learners adopt behavior that is associated with prestige or other observable markers of success; as a result, better technologies spread due to a process of selective retention. A variety of intermediate hypotheses are also possible. It may be, as in the models described above, that learning is relatively rare and noisy, and so acts like a high rate of mutation in adaptive directions. In this view, individuals have limited causal understanding which increases the rate of adaptive innovation; thereafter, most spread is due to the correlation of observable behavior with markers of success. There are a rich variety of possible hypotheses that should be explored, both theoretically and empirically.

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