The Vienna Series in Theoretical Biology

Innovation in Cultural Systems

Contributions from Evolutionary Anthropology

edited by
Michael J. O'Brien and
Stephen J. Shennan

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Contents

Series Foreword

Biology is becoming the leading science in this century. As in all other sciences, progress in biology depends on interactions between empirical research, theory building, and modeling. However, whereas the techniques and methods of descriptive and experimental biology have evolved dramatically in recent years, generating a flood of highly detailed empirical data, the integration of these results into useful theoretical frameworks has lagged behind. Driven largely by pragmatic and technical considerations, research in biology continues to be less guided by theory than seems indicated. By promoting the formulation and discussion of new theoretical concepts in the biosciences, this series is intended to help fill the gaps in our understanding of some of the major open questions of biology, such as the origin and organization of organismal form, the relationship between development and evolution, and the biological bases of cognition and mind.

Theoretical biology has important roots in the experimental biology movement of early-twentieth-century Vienna. Paul Weiss and Ludwig von Bertalanffy were among the first to use the term *theoretical biology* in a modern scientific context. In their understanding the subject was not limited to mathematical formalization, as is often the case today, but extended to the conceptual problems and foundations of biology. It is this commitment to a comprehensive, cross-disciplinary integration of theoretical concepts that the present series intends to emphasize. Today, theoretical biology has genetic, developmental, and evolutionary components, the central connective themes in modern biology, but also includes relevant aspects of computational biology, semiotics, and cognition research and extends to the naturalistic philosophy of sciences.

The “Vienna Series” grew out of theory-oriented workshops, organized by the Konrad Lorenz Institute for Evolution and Cognition Research (KLI), an international center for advanced study closely associated with the University of Vienna. The KLI fosters research projects, workshops, archives, book projects, and the journal *Biological Theory*, all devoted to aspects of theoretical biology, with an emphasis on integrating the developmental, evolutionary, and cognitive sciences. The series editors welcome suggestions for book projects in these fields.

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Günter P. Wagner, Yale University and KLI
Werner Callebaut, Hasselt University and KLI

Preface and Acknowledgments

Innovation has long played a significant role in the social sciences in structuring arguments about how and why human behavior changes. Certainly innovation was implicit in the nineteenth-century writings of ethnologists such as Edward B. Tylor and Lewis Henry Morgan, as it was in the mid-twentieth-century work of Julian Steward and Leslie White. For these cultural evolutionists, the appearance of cultural innovations was almost a preprogrammed process, which kicked in whenever a cultural group “needed” to overcome social- or physical-environmental problems. Archaeological explanations of cultural change, too, have long centered around the introduction and spread of novelties. American culture historians of the twentieth century routinely looked to diffusion and trade as a source of innovations, in the process adopting, often without comment, the models of their ethnological colleagues as to how and why the innovations arose in the first place.

With the renewed interest in evolution that became noticeable in the social sciences, particularly ethnology and archaeology, in the 1980s, researchers began to reconsider the role of innovation in the evolution of cultural systems. Importantly, modern evolutionary research in the social and behavioral sciences is being geared toward identifying innovation not only as a product but also as a process. In that vein, a recent workshop at the Santa Fe Institute, New Mexico, centered on the issue of innovation, building on the work of Austrian economist Joseph Schumpeter, who made the distinction between invention—the creation and establishment of something new—and innovation—an invention that becomes economically successful and earns a profit. This distinction had been made previously in biology—introduction of a novelty versus long-term success of a species—but not in the social sciences. There, the long-held belief that humans were somehow exempt from Darwinian processes such as natural selection ensured that the only brand of evolutionism discussed was of the unilinear Tylor–Morgan–White brand.

To build on the growing body of work on cultural innovation, we organized a workshop at the Konrad Lorenz Institute for Evolution and Cognition Research (KLI) in Altenberg, Austria, in September 2007. We adopted something of a similar topical approach to the Santa Fe workshop, but our emphasis was decidedly on innovation and its role in the evolution of cultural systems. All 17 participants had extensive experience with researching innovation and had made significant contributions to the literature on the subject. We assembled what we believe to be an impressive list of participants from a number of different disciplines—anthropology, archaeology, evolutionary biology, philosophy, and psychology. We asked the participants to prepare and circulate papers before arriving in Altenberg, which allowed us to move ahead with meaningful discussion once everyone was assembled. Additionally, we asked various individuals to concentrate on select aspects of innovation so that we achieved wider coverage than we might otherwise have gotten.

By all measures, the KLI workshop was a success—a point hopefully underscored by the content of the chapters included here. The book consists of a general introduction and three sections. The introduction documents the role that innovation has played in the explanation of cultural phenomena from roughly the late nineteenth century to the present. Ethnologists working early in the twentieth century paid particular attention to what typically were termed "culture traits," using them as a means of linking related cultures together. Archaeologists did the same. Rarely, however, was there consensus on what a culture trait entailed and at what scale it should be examined. Beginning in the 1980s there occurred an emerging interest in applying evolutionary principles to the study of culture, and one area in which considerable advance was made was the study of cultural inheritance. As interesting and valuable as these studies are, there remain areas that need in-depth research, especially with respect to the production of cultural innovation and the scale and tempo at which it is produced.

Part II, "The Biological Substrate," offers detailed discussions of innovation from several standpoints—epistemology (André Ariew), animal studies (Kevin Laland and Simon Reader), systematics and phylogeny (Jeffrey Schwartz), phenotypic plasticity and evolvability (Daniel Larson), and EvoDevo (Werner Callebaut). One thing becomes clear after reading the papers in this section: It no longer is sufficient to think of selection as "tinkering" with subtle variations, slowly effecting change over long periods of time. Rather, there are times when innovation appears as larger packages, the product of emergent human behaviors at fairly large scales.

Part III, "Cultural Inheritance," documents the relevance of modern insights into innovation, including the simulation of cultural innovation in the laboratory (Joseph Henrich; Alex Mesoudi), the characterization of innovation using the random-copying (neutral) model (Alexander Bentley), the demographic analysis of culturally inherited skills (Adam Powell, Stephen Shennan, and Mark Thomas), evolutionary advantages of noninnovation (Craig Palmer), and variation in diffusion and rates of cultural change (Anne Kandler and James Steele).

Part IV, "Patterns in the Anthropological Record," presents case studies that have examined cultural innovation in the archaeological and ethnographic records. Topics include technological innovation, developmental trajectories, and modes of social organization (Valentine Roux); the study of cultural variation from a behavioral perspective

(Michael Schiffer); and innovation as a social institution (Todd VanPool and Chet Savage).

We are extremely grateful to the KLI for funding the workshop. Our hosts—Gerd Müller, Werner Callebaut, Astrid Juette, and Eva Karner—went out of their way to make the event memorable. We also thank the fellows of the KLI, who added substantially to the discussions during and between sessions. Professor Müller, who along with Professor Callebaut is an editor for MIT Press's *Vienna Series in Theoretical Biology*, guided us through the proposal process with the press. Finally, we thank Bob Prior, executive editor of MIT Press, for his unflagging support of the project, Susan Buckley, and Katherine Almeida, our editor. Melody Galen redrafted the figures into a common format, and Carla Schlink helped edit early versions of the chapters for consistency. Regina Gregory edited the final version.

I INTRODUCTION

1 Issues in Anthropological Studies of Innovation

Michael J. O'Brien and Stephen J. Shennan

It would be difficult to find a topic in anthropology that has played as central a role as innovation in attempts to explain why and how human behavior changes. Likewise, it would be difficult to find a topic that has caused more debate and resulted in such a lack of consensus. At first glance, this might seem a little odd, given that the term *innovation* is used so widely and has what appears to be a straightforward definition: something new and different. Although there is nothing wrong with that definition, it barely scratches the surface of what in anthropology has turned out to be a complicated concept. For example, the definition doesn't tell us how we would recognize an innovation, nor does it tell us anything about its origin.

Of course, a simple definition shouldn't be held to such a high standard, but it might be helpful if those using the term for more than casual purposes were specific about such matters. Such has rarely been the case in anthropology, although it hasn't been for lack of trying. Anthropologists for over a century have recognized the complexity of the conceptual and methodological issues surrounding innovation, especially with respect to units and scale. In short, how do we identify not only innovations but the units involved in the transmission of those innovations? Are they the same units that we can use to measure transmission? Are there different scales of units, with units at one scale subsuming those below them?

Here we briefly examine those issues, bypassing extended discussion of any single topic and focusing instead on the development of some of our current notions of innovation. Definitions of this term and its relation to "invention" have varied considerably. Fagerberg (2005), for example, regards invention as the first appearance of an idea for a new product or process, whereas innovation represents the first attempt to put it into practice, which may occur considerably later. Moreover, innovation may be seen not as a "one-off" but as a continuing accumulation of changes (see chapter 9, this volume). Barnett (1953: 7–8), on the other hand, claims to be following popular usage in regarding inventions as physical things, whereas an innovation is defined as "any thought, behavior or thing that is new because it is qualitatively different from existing forms," which sets the bar quite high with its emphasis on the qualitatively novel. The distinction made by Elster (1986) in his study of technical change corresponds closely to that advocated by Fagerberg, in that innovation is viewed as "new technical knowledge" (p. 93) and invention as the generation of a new idea. Elster also points out that diffusion often involves innovation, as modifications to a product or process are made in response to a new context, whereas substitution, making a change in some process using existing technical knowledge, also easily shades into innovation.

Schumpeter (1934) placed his main emphasis on the qualitative disjunction side—"[Innovation] is that kind of change arising within the system which so displaces its equilibrium point that the new one cannot be reached from the old one by infinitesimal steps. Add successively as many mail coaches as you please, you will never get a railway thereby" (Schumpeter 1934: 64). Schumpeter also gave a role to adaptive technical change and the importance of the accumulation of small changes over time (Elster 1986). Whether such innovations, small and incremental or large and discontinuous, will be successful is another matter again and depends on the various selection and bias processes discussed below.

Most discussions of innovation have focused on the technical dimension, including the organizational aspects of technical processes, as the discussion above suggests. However, there is no reason why fashions should not be included, and here success, in terms of increasing frequency, may be simply the result of the vagaries of random copying (see chapter 8, this volume). Indeed, as contributors to this volume make clear, the issue of innovations in cultural systems is almost unlimited in terms of scope, and we leave it to our colleagues to explore the myriad directions that lie beyond our focus.

Although it is sometimes forgotten, much of what we take for "modern" perspectives is actually built to varying degrees on decades of thoughtful research by our forebears. We were reminded of this recently while perusing the abundant social science literature on memes, which some social scientists argue underlie the spread of innovations. It would be worthwhile for those interested in memetics to spend an afternoon or two looking at how ethnologists and archaeologists of the first half of the twentieth century wrestled with what culture traits are. The parallels in thought processes, analytical approaches, and even research dead ends are enlightening.

Anthropological Views on Innovation

Innovation was explicit in the nineteenth-century writings of ethnologists such as Tylor (1871) and Morgan (1877), both of whom viewed the production of novelties—new ideas, new ways of doing things, and the like—as the underlying evolutionary force that propels cultures up the ladder of cultural complexity. Innovation was equally important in the work of later cultural evolutionists such as Steward (1955) and White (1959). For them, the evolutionary process was less orthogenetic than it was for the earlier evolutionists, with the source of innovation wrapped up in the kind of mechanisms a group needs to meet the challenges of its physical and social environment.

Innovation has also played an essential role in American archaeology (Lyman 2008; Lyman and O'Brien 2003; Lyman et al. 1997; O'Brien et al. 2005). Culture historians of the twentieth century routinely looked to diffusion and trade as sources of innovations, and hence of culture change, adopting without comment the models of their ethnological colleagues. Sometimes innovations were viewed as having been borrowed, often from incredible distances (e.g., Ford 1969; Meggers et al. 1965). Other times they were viewed as products of what Adolf Bastian referred to in the mid-nineteenth century as the "psychic unity of mankind" (Lowie 1937: 35). These two contrasting processes—diffusion versus independent invention—were at the heart of discussions of cultural relatedness. Thus, Steward (1955) argued that if the ethnologist (or archaeologist) could determine which traits were at the core of a culture and which ones were secondary, then the traits could be used to assess the degree of cultural relatedness between that culture and others. The more core traits that two cultures possess, the more historically related they are. If two cultures hold few or no traits in common, then either the cultures are unrelated or they were once related but at such a distant point in the past that the phylogenetic signal has all but disappeared.

Units of Culture in Twentieth-Century Anthropology

Despite the widespread use of culture traits as measures of relatedness or of functional convergence, there was much less emphasis on trying to figure out exactly what a culture trait *is*. This raises particular difficulties if our focus is innovation because if we cannot even define the cultural features we are dealing with, deciding what represents an innovation is problematical in the extreme. Researchers universally assume that such traits are mental phenomena that one acquires through teaching and learning, but through much of the twentieth century there were few explicit theoretical definitions of a culture trait (Osgood 1951). This was highly problematic and meant that the units varied greatly in scale, generality, and inclusiveness (Lyman and O'Brien 2003). There were numerous efforts to resolve the difficulties of classification and scale (e.g., McKern 1939; Willey and Phillips 1958), but they did little to resolve the issue.

Biologists might well point out that there are also procedural problems in their discipline, where there is no standard set of characters used in the creation of taxa, but the situation is murkier in anthropology (see chapters 3 and 4, this volume). The one place where anthropologists *have* made insightful comments is with respect to what early in the twentieth century became known as *trait complexes*—minimally defined as "groups of culture elements that are empirically found in association with each other" (Golbeck 1980).

Although trait complexes have traditionally been used as another means of comparing cultures, the concept has a role to play in modern cultural evolutionary analysis, if for no other reason than it reminds us that cultural phenomena may evolve as complex wholes, not as tiny parts (Boyd et al. 1997; Guglielmino et al. 1995; Henrich and McElreath 2003; Pocklington 2006; Shennan and Steele 1999; chapter 14, this volume). Selection can, and often does, act as a tinkerer—and "one who does not know exactly what he is going to produce but uses whatever he finds around him" (Jacob 1977: 1163)—but it is the potential "cascading" effects (Schiffer 2005; chapters 13 and 14, this volume) of that selection that may be important. A key goal of evolutionary analysis is to identify which applies in any given case, rather than making blanket assumptions about the holistic or atomistic nature of innovation and change.

Our point is that novelties are often more than simple character-state changes (Basalla 1988; Reid 2007). This is more or less what Trigger (1998: 364) apparently had in mind when he said that evolutionary archaeology should abandon a "reductionist biological terminology in favor of one that explicitly takes account of the unique, emergent aspects of human behavior." Of course, the insistence on human uniqueness is overdone; biological evolution has plenty of examples of the emergence of entirely new phenomena (see, e.g., Maynard Smith and Szathmary 1995). Nevertheless, "emergent aspects"—aspects that have irreducible novel properties—are important considerations in any discussion of cultural innovation (O'Brien 2007; Sawyer 2005; Shennan 2002a). Recent evolutionary approaches to culture have had to address the "units of culture" issue head-on, and their contribution is outlined below.

Cultural Transmission—The Spread of Innovation

From the beginning, regardless of how ethnologists and archaeologists viewed culture traits, and irrespective of their arguing over whether a particular trait was transmitted vertically (cultural ancestor to cultural descendant) or horizontally (cultural group to unrelated cultural group),[1] there was agreement that traits are learned, not genetically inherited (see chapter 3, this volume). Transmission, particularly between parents and offspring of the same sex (Shennan and Steele 1999), creates what archaeologists have long referred to as *traditions*—patterned ways of doing things that exist in identifiable form over extended periods of time (chapters 9, 10, 13, and 15, this volume).

It seems naive, given what we know of the archaeological record, not to believe that forms are modeled on preexisting forms. Further, cultural phenomena are parts of human phenotypes in the same way that skin and bones are, and as such they are capable of yielding data relevant to understanding both the process of evolution and the specific evolutionary histories of their possessors.

With the growing interest in evolution that became noticeable in anthropology in the 1960s and accelerated through the 1970s and 1980s (e.g., Campbell 1965, 1970, 1975; Dunnell 1980; Durham 1976, 1978, 1979, 1982; Rindos 1980), researchers began to reconsider the relationship between biology and culture (see chapters 2 and 5, this volume), and nowhere was this more evident than in attempts to understand the role of innovation in the evolution of cultural systems. One area of sustained focus not only in anthropology but in the social sciences in general was *cultural transmission* (e.g., Boyd and Richerson 1985; Cavalli-Sforza and Feldman 1973, 1981; Cloak 1975; Durham 1991; Lumsden and Wilson 1981; Pulliam and Dunford 1980; Richerson and Boyd 1978, 1992; chapters 7–9, 11, and 12, this volume).

A key question that arose within this evolutionary context was, What, exactly, *is* the unit of cultural transmission? Further, how would we know if we found one (Pocklington 2006)? Various names were proposed for units—*menemotype* (Blum 1963), *sociogene* (Swanson 1973), *instruction* (Cloak 1975), *meme* (Aunger 1999, 2002; Blackmore 1999, 2000; Dawkins 1976), and *culturgen* (Lumsden and Wilson 1981)—but there is still considerable debate over what the units embody (Atran 2001; Sperber 1996, 2000). Although perhaps a bit more sophisticated, these debates, with one major exception, are similar to those seen decades earlier with respect to culture traits (Lyman and O’Brien 2003; O’Brien 2007).

The exception concerns the nature of the units of cultural inheritance: Do they have a physical nature similar to genes? No ethnologist or archaeologist of the twentieth century ever assumed that the ideas behind the physical manifestation of culture traits had a physical presence, but some modern researchers in memetics have made that proposal (e.g., Aunger 2002). However, Henrich et al. (2008; see also Boyd and Richerson 1985; Henrich and Boyd 2002) have shown that it is possible to build a valid theory of cultural evolution on Darwinian foundations without assuming particulate inheritance. This is good news for those of us interested in cultural evolution because we can focus on understanding where the units that get culturally transmitted come from in the first place.

Simply because the units of cultural inheritance are not particulate in the same way genes are (assuming this to be the case, at least at the phenomenological level) does not mean that biology is incapable of offering helpful analogues when it comes to understanding the production and transmission of novelties (Eerkens and Lipo 2007; Mesoudi and O’Brien 2009; Shennan 2002b; chapters 3–5, this volume). The key point is that the “calculated heritabilities for human behavioral traits are as high as or higher than measurements for behavioral and other phenotypic characters in natural populations of non-cultural organisms. . . . Thus it may be that [social learning] is as accurate and stable a mechanism of inheritance as genes” (Boyd and Richerson 1985: 55). Even where there is considerable noise in transmission at the individual level, there are powerful evolutionary mechanisms that can lead to stability at the population level (Henrich and Boyd 2002; Henrich et al. 2008).

Innovation, then, becomes a key area of analytical focus in any evolutionary study, especially with respect to the form of the innovation, its composition, and the process that created and maintained it. It is one thing to know how and under what conditions an innovation is transmitted, but it is a different matter to understand where it came from. Even more important is understanding that, especially with respect to cultural transmission, which is exponentially faster and has less fidelity than biological transmission, the transmission process itself can be a continuous creator of innovation. Much more so than is typically the case in biology, tempo and mode can interact in cultural situations to create a new source of innovation and to create it at scales that may be both large and complex. This undoubtedly is what Trigger (1998: 364) had in mind when he referred to the "unique, emergent aspects of human behavior."

Recipes

In the social sciences there is a tendency to think of innovations as monolithic entities—the television set, ceramic cooking vessels, and the like. It might be useful, however, to remember that innovations are amalgams of units of varying scale that are linked functionally (and sometimes not [Shennan 2001; chapters 8 and 9, this volume]). One way of viewing innovations is in terms of "recipes" (Lyman and O'Brien 2003; Mesoudi and O'Brien 2008c; Neff 1992)—the materials ("ingredients") required to construct a tool, for example, and the behavioral rules ("instructions") required to construct and use the tool. Cognitive psychologists (e.g., Weber et al. 1993) have proposed that people represent tools as interlinked, hierarchical knowledge structures, incorporating behavioral scripts governing their construction and use, much like the recipe concept (Stout et al. 2008). Biologists, too, use the "recipe" metaphor to describe the development of organisms from genetic information (Dalton 2000; Ridley 2003).

Krause (1985: 30–31) was one of the first to employ the concept of "recipe" in a cultural context, defining it as a "list of ingredients and amounts" and a "part that tells you what to do, how to do it, when to do it, and for how long." Schiffer and Skibo (1987: 597) developed the notion, defining a "recipe for action" as "(1) a list of raw materials, (2) a list of tools and facilities employed, (3) a description of the sequence of specific actions undertaken in the technological process, and (4) the contingent rules used to solve problems that may arise." They note that recipes are often culturally transmitted, which requires a teaching framework that includes imitation, verbal instruction, hands-on demonstration, and self-teaching by trial and error (see Guglielmino et al. 1995; Shennan and Steele 1999; chapters 10, 13, and 15, this volume).

The concept of recipe is useful for three reasons (Lyman and O'Brien 2003). First, the commonsense meaning of the term captures what anthropologists mean when they use the term "cultural trait"—how, when, where, and why to produce something, whether a behavior or an artifact (a behavioral by-product). Second, the recipe concept contains multiple parts of two general kinds—ingredients and rules—that can be reconfigured to form a different recipe. Any change in ingredient acquisition, preparation, type, or amount; change of rules or the order of their implementation; or some combination of each results in a different product. Third, the recipe concept highlights the flexibility built into virtually all ways of doing something and still producing a usable product (see chapter 14, this volume).

This again emphasizes the point that units of cultural transmission and replication can be of different scales. In biology, we know the scale of the unit of transmission and replication—the gene—but we also know that there often is no one-to-one correspondence between a gene and a somatic character. One phenotypic character of an organism can be polygenic (influenced by multiple genes), whereas others can be pleiotropic (a single gene influences those several characters). The same applies to cultural transmission, where conceivably every human behavior is underpinned by a recipe of unique composition, scale, and complexity (Lyman and O'Brien 2003).

Dual-Inheritance Theory

Boyd and Richerson's collective work (e.g., Bettinger et al. 1996; Boyd and Richerson 1985, 1989; Henrich and Boyd 1998; Richerson and Boyd 1992; see also Cavalli-Sforza and Feldman 1973, 1981), often referred to as "dual-inheritance theory" (Richerson and Boyd 1978; Shennan 2002a), is particularly useful here (chapters 5, 7, and 12, this volume). It posits that genes and culture provide separate, though linked, systems of inheritance, variation, and evolutionary change. The spread of cultural information is viewed as being affected by numerous processes, including selection, decision making, and the strength of the transmitters and receivers. However, there is much more to Boyd and Richerson's work than how and why traits spread. Their models also demonstrate that some innovation is produced through the intricacies of the transmission process itself. This calls into question the primacy of selection as the single most important evolutionary process.

We in no way want to remove selection from its prominent place at the evolutionary table. Rather, we point out that an overemphasis on selection as *the* key component of evolution (e.g., O'Brien and Holland 1990) has shifted attention away from adequate consideration of how variation is produced and transmitted and the effects that production and transmission, irrespective of selection, have on evolution (Lipo et al. 1997; O'Brien 2007; Shennan 2001; chapter 8, this volume).

Numerous anthropological studies have made use of models derived at least in part from the work of Boyd and Richerson and their colleagues to examine patterns of cultural transmission in archaeological contexts (e.g., Bentley and Shennan 2003; MacDonald 1998; Shennan and Wilkinson 2001; chapters 7, 9, 11, and 12, this volume), and the variety and complexity of the processes involved is increasingly clear (Shennan 2008a, 2008b). One interesting study of the spread of innovation is Bettinger and Eerkens's (1997, 1999) analysis of stone projectile points from the Great Basin of the western United States. There, the bow and arrow replaced the atlatl (spear thrower) around A.D. 300–600—a replacement documented by a reduction in size of projectile points. The weight and length of points manufactured after A.D. 600, however, was not uniform across the region. Rosegate points from central Nevada vary little in weight and basal width, whereas specimens from eastern California exhibit significant variation in those two characters. Why are there differences, and what, if anything, do they tell us about the production and spread of innovations?

Bettinger and Eerkens propose that the variation is attributable to differences in how the inhabitants of the two regions obtained and subsequently modified bow-related technology. Bow-and-arrow technology in eastern California was both maintained and perhaps spread initially through what Boyd and Richerson (1985) refer to as *guided variation*, wherein individuals acquire new behaviors by copying existing behaviors and then modifying them through individual and independent trial and error to suit their own needs. Conversely, bow-and-arrow technology in central Nevada was maintained and spread initially through *indirect bias*, in which individuals acquire complex behaviors by opting for a single model on the basis of a particular trait identified as an index of the worth of the behavior (see chapters 7, 11, and 12, this volume).

Bettinger and Eerkens propose that in cases where cultural transmission is modified by guided variation, human behavior will tend to optimize fitness in accordance with the predictions of a cost–benefit model in which individual fitness is the index of success, with little opportunity for the evolution of behaviors that benefit the group as a whole. In instances where transmission is through indirect bias, which tends to produce behaviorally homogeneous local populations, conditions may be ripe for the evolution and persistence of group-beneficial behaviors and cultural group selection (Henrich 2004b). On the other hand, as a result of the disconnection from current local conditions that indirect bias implies, the practice or product may be suboptimal.

From the standpoint of innovation, the models present widely differing scenarios. In both, individuals copy existing behaviors wholesale—innovations can suddenly "appear" in a new region as large, complex packages (e.g., projectile points), perhaps by diffusion—but in guided variation individuals begin tinkering with certain aspects, whereas in indirect bias they do not. Under perhaps extreme conditions, individuals may not even be aware of the underlying principles of how and why something works. All they know is that it *does* work, at least reasonably well, and they attempt to reproduce it in toto. Of course, the copying process itself is rarely faithful, thus presenting plenty of chance for copying errors, which themselves are novelties (Eerkens and Lipo 2005). Whether or not the errors are reproduced, and at what rates, are separate matters entirely.

Theoretical models are powerful tools, and applications of the models to actual data are why we do science, but controlled "middle-range" experiments provide the necessary bridge between the two (Mesoudi 2008a; chapter 11, this volume). In that vein, Mesoudi and O'Brien (2008a, 2008b) designed an experiment to examine the cultural transmission of projectile-point technology, simulating the two transmission modes—indirect bias and guided variation—that Bettinger and Eerkens suggested were responsible for differences in Nevada and California point-attribute correlations.

In brief, groups of participants designed "virtual projectile points" and tested them in "virtual hunting environments" with different phases of learning simulating indirectly biased cultural transmission and independent individual learning. As predicted, periods of cultural transmission were associated with significantly stronger attribute correlations than were periods of individual learning. This obviously has ramifications for how one looks at innovation. In simplified terms, more "loners," more innovation; more conformist individuals who want packages off the shelf, less innovation. The experiment and subsequent agent-based computer simulations showed that participants who engaged in indirectly biased horizontal cultural transmission outperformed individual-learning controls (individual experimentation), especially in larger groups, when individual learning is costly and the selective environment is multimodal (Mesoudi 2008b; Mesoudi and O'Brien 2008a, 2008b).

Cultural transmission in a multimodal adaptive landscape, where point-design attributes are governed by bimodal fitness functions, yields multiple locally optimal designs of varying fitness (Mesoudi 2008b; chapter 11, this volume). Mesoudi and O'Brien hypothesized that innovations, represented by divergence in point designs resulting from individual experimentation (guided variation), were driven in part by this multimodal adaptive landscape, with different individuals converging by chance on different locally optimal peaks. They then argued that indirectly biased horizontal cultural transmission, where individuals copy the design of the most successful person in their environment, allows individuals to escape from these local optima and jump to the globally optimal peak (or at least the highest peak found by people in that group). Experimental results supported this argument, with participants in groups outperforming individual controls when the group participants were permitted to copy each other's point designs. This finding is potentially important to the production of innovation, as it demonstrates that the nature of the selective environment will significantly affect aspects of cultural transmission.

How realistic is it to assume the presence of a multimodal adaptive landscape? Boyd and Richerson (1992) argue that multimodal adaptive landscapes are likely to be common in cultural evolution and may significantly affect the historical trajectories of artifact lineages, just as population-genetic models suggest that multimodal adaptive landscapes have been important in biological evolution by guiding historical trajectories of biological lineages (Arnold et al. 2001; Lande 1986; Simpson 1944). Many problems and tasks faced by modern and prehistoric people would have had more than one solution, some better than others, but all better than nothing, and solutions are likely to represent compromises among multiple functions and requirements.

Tempo and Mode

What about the tempo of the jumps across the adaptive landscape? The ethnological and archaeological records are replete with evidence that the tempo of cultural change is rarely constant, but there are few cases in which it has been measured directly (but see Shennan and Bentley [2008] for changing innovation rates in pottery decoration and Henrich [2004a] for a broader analysis and discussion). Again, how are scale and tempo correlated? Is the apparent rapid emergence of a new form actually sudden, or is it an illusion, meaning that the scale at which we are examining something makes it appear as if the object is new when in actuality it is the product of myriad small-scale cumulative modifications that took place over a relatively long period of time? (See the discussion at the beginning of this chapter and chapter 13, this volume.)

This same question was asked in paleontology for decades. Darwin's notion of the evolution of species was based on gradualism—the slow buildup of small-scale change over geological time—although his theory did not require that tempo. Simpson (1944) opened the door on the notion of accelerated tempo, and Eldredge and Gould (1972; Gould and Eldredge 1977) opened it wider with their concept of *punctuated equilibrium*. They argued that *cladogenesis*—the division of a taxon into itself and at least one sister taxon—is the general mode under which evolution operates (as opposed to *anagenesis*, or the evolution of one taxon into another) and that rapid cladogenesis is orders of magnitude more important than gradualism as a tempo of speciation.

Paleobiologists have erroneously used punctuated equilibrium to model evolution's temporal component, despite warnings from Gould and Eldredge that the model is "a specific claim about speciation and its deployment in geological time; it should not be used as a synonym for any theory of rapid evolutionary change at any scale" (Gould 1982: 84). They issued such warnings to emphasize the cladogenetic aspect of the punctuated-equilibrium model, thus trying to ensure that it was not confused with saltationism—the belief that evolution depends on the appearance of macromutations that exhibit significant disjunctions with their parents (see chapter 4, this volume).

Discussion

Tempo and mode are only two of the myriad issues that have as yet been inadequately addressed with respect to the origin and spread of cultural innovation, yet they offer exciting entry points into the discussion (Eerkens and Lipo 2007; O'Brien 2005, 2007; O'Brien and Lyman 2000). Whether one views punctuated equilibrium as a particularly useful model in understanding the origin and spread of innovation, there should be no denying that it calls attention to the linkage between tempo and mode. Clearly, by definition, any innovation in a cultural lineage is cladogenetic, creating a new branch in an evolutionary tree. However, these may be on a relatively trivial scale, those characterized by small innovations in pottery decoration, for example, or highly significant, such as subsistence innovations that have a major impact on many aspects of the subsequent trajectory of those who adopt them, differentiating them along many dimensions from the continuing non-innovating branch. Moreover, the second case is likely to be associated with an increased tempo of change, while the first will probably not be.

Conclusion

Given the exponential growth in the evolutionary literature on both the units of transmission and the processes through which information is transmitted and received, the next decade should witness substantial progress in our understanding of cultural innovation in all its various guises. On a broader plain, evolutionary anthropology has made great strides in developing a body of theory that complements biological evolutionary theory as opposed to borrowing it wholesale and hoping that it contains something of value (Shennan 2000, 2008b; chapter 2, this volume). There is every reason to suspect that this trend will continue, and the chapters in this volume strongly support that claim.

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Note

1. Of course, the trait in question is indeed the descendant of its specific ancestor; it's just that it now finds itself in a milieu where most of the other traits have different histories of descent.

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II THE BIOLOGICAL SUBSTRATE

2 Innovation and Invention from a Logical Point of View

André Ariew

In *Natural Theology*, a book that Darwin read numerous times throughout his life, William Paley argues that the existence of God can be inferred from the existence of exquisitely functioning natural designs. Paley's conclusion is based on the inference between artifact and natural features: "When we come to inspect [a] watch, we perceive . . . that its several parts are framed and put together for a purpose" (Paley 1802: 1).

Paley's argument is an instance of what philosophers call a "teleological argument." The central inference can be summed up with Aristotle's dictum "as in art, so in nature." Whereas Paley, and numerous philosophers before and after him, used Aristotle's dictum to found an argument for the existence of God, it need not have theological implications. Take, for example, the debate over the legitimacy of Darwinism in archaeology. Bamforth (2002) argues that Darwinism has nothing to offer archaeology beyond metaphorical language. In response, O'Brien et al. (2003: 574) invoke a rather strong version of Aristotle's dictum when considering the distinction between humanity and the natural world: "Like it or not, culture and its material consequences are the result of biological phenomena." More than "as in art, so in nature," O'Brien et al. appear to be arguing "art *is* nature."

More generally, Erwin and Krakauer (2004) wonder whether the conditions for natural selection can be legitimately applied to explain the dynamics and creation of human inventions and innovations. They take their cue from the economist Joseph Schumpeter's (1942) distinction between "inventions" as new creations and "innovations" as inventions that become economically successful (hence spread) and earn profits. Schumpeter's distinction reminds Erwin and Krakauer of natural selection's explanation of both the process that gives rise to biological novelties and the process that allows some novelties to spread to fixation in a population. Aristotle's dictum is once again summoned, but this time in reverse: "as in nature, so in art."

How should we assess the legitimacy and explanatory usefulness of evolutionary theory to explain cultural artifacts? What should we infer about the parallel between technological inventions/innovations and biological novelty/fixed traits? For their part, Erwin and Krakauer (2004: 1117) resolve to meet with biologists, paleontologists, technologists, and economists to "consider the nature of evolutionary novelty and the similarities and differences between biological and technological invention and innovation." As for the similarity and differences, as one might expect, their answer is "some" for both similarities and differences. This is an unsatisfying result and does little to resolve the debate.

The problem is Erwin and Krakauer's approach. A mere list of similarities and differences settles nothing. I doubt any such list would result in "absolutely no similarities" or "absolutely no differences." Proponents and critics alike agree that the answer will be "some." Taking our cue from classical teleological arguments, we have to put the list in the form of an inference to a conclusion. What is the form of the inference, and how do we evaluate it? This is a philosopher's job, and I am delighted to present some of my thoughts. Once we settle on the proper form of inferences and establish some ground rules for evaluating them, we need to consider the scope and limits of natural selection explanations. It would do no good if we invoke a theory to explain a sort of phenomenon that the theory is not designed to explain.

The first section of this chapter presents two inductive-argument forms—argument by analogy and inference to the best explanation. I suggest that the debate over the legitimacy and explanatory usefulness of evolutionary approaches to cultural change, including the analysis of technological innovations and inventions, should be conducted as various hypotheses under an inference to the best explanation.

Yet, when we consider how to construct the terms of the inference to the best explanation—when we consider what natural selection explains and how it explains it—we will find further logical constraints that impact whether natural selection sufficiently explains both innovations and inventions (technological and biological). This is the subject of the second part of the chapter. I argue that innovations are appropriately explained by natural selection but that inventions are not. Natural selection does not make anything—it requires preexisting variants for its evolutionary effect.

Argument by Analogy

An argument by analogy is a species of inductive inference. By definition, inductive inferences are defeasible, which means they are open to further information that can undercut the support that the premises give to the conclusion. Hence, we never say that the conclusions of an inductive inference, analogy or otherwise, logically follow from the premises. No inductive inference is ever valid. Rather, we evaluate inductive inferences in terms of strength.

In an argument by analogy, inductive strength depends on the degree to which the analogues resemble each other. This comports to what I said earlier about the contents of a list of similarities and differences between biological and cultural traits. No one would say "none"; all would say "some." The disagreement is over the *degree* to which the analogue resembles the target. Winnie the Pooh somewhat resembles a real-world honey-loving bear but not enough to warrant the conclusion that the latter enjoys the friendship of a piglet just because the former does. An archaeologist concluding that an excavated knife was used in ritualistic sacrifice because it resembles other sacrificial knives in its size, shape, materials, and carvings is on much stronger grounds (Fogelin and Sinnott-Armstrong 2006). Regardless of their different strengths, the three analogies—honey-loving bears, ritualistic knives, and evolution—all have the same common form:

1. Object A has properties P, Q, R, and so on.
2. Objects B, C, D, and so on also have properties P, Q, R, and so on.
3. Objects B, C, D, and so on have property X.
4. Therefore, object A probably also has property X.

Object A is the excavated knife, objects B, C, and D are previously found knives that are known to have been used in sacrifices. Properties P, Q, R, and so on are the size, shape, materials, and carvings that make A analogous to B, C, D, and so on. X is the property of something being used for sacrifice. If knives B, C, and D have this property, then this constitutes some (I would say high) degree of support for the conclusion that object A is probably (to a high degree) a ritualistic knife. Here's a first run at a principle for evaluating an argument by analogy (which will be revised later): The more the analogue and the target resemble each other, the stronger the inference to the conclusion.

In *Dialogues Concerning Natural Religion* (1779), Hume offers both a negative lesson of what cannot constitute a resemblance criterion and a positive proposal about what can. The negative lesson is that it is not enough to pick and choose the properties P, Q, and R willy-nilly without rendering the argument susceptible to a charge of bias. There are some notable similarities between artifacts and biological items, but there are many relevant dissimilarities that are ignored: Watches are made of metal; mammals are not. Some mammals hop; watches don't. Once you remove the bias, the analogy between artifacts and natural items is weak.

In its place, Hume advocates overall similarity as a criterion to evaluate the strength or weakness of an argument by analogy. Looking at the overall similarities between particular artifacts and natural items such as kangaroos and watches, you will conclude after all that watches and kangaroos are not very similar; hence, an argument from analogy based on their overall similarity is rather weak (Sober 2001).

Bamforth could be arguing along Humean lines in his critique of applications of evolutionary theory to archaeology. There are significant overall dissimilarities between cultural and biological evolution that would undercut the motivation to use a biological model to understand technological or cultural innovations and inventions. For instance, biological evolution involves genetic inheritance, and cultural inheritance is not genetic. However, something is amiss. The critique that there is little overall similarity between token artifacts and token biological items doesn't seem to get at the heart of the motivation for evolutionary archaeology or the heart of Erwin and Krakauer's proposal to apply evolutionary theory to understand how inventions become innovations. No modern scientist would claim that a particular arrowhead is the product of random genetic variation acted upon by natural selection!

Evolutionary archaeologists wonder whether natural selection theory aids in the explanations of general trends like the success of VHS over Betamax, the creation of life-history graphs for projectile points (Lyman et al. 2008; O'Brien and Lyman 2002), or the evaluation of new engineering designs and optimization strategies. In these instances, the relevant issue is not the overall similarity between biological and cultural artifacts nor between the process of biological evolution and that of cultural evolution. Rather, the appropriate issue is methodological; for example, what do the conditions for evolution by natural selection offer by way of explaining novelty (invention) and conditions for successful spread (innovation)?

Hume's argument that overall similarities determine an analogy's strength has to be modified in the context of the current debate about the virtues of evolutionary archaeology. The question is how one determines the appropriate relevant similarities. Remember, in the face of Hume's objection, one must avoid appearing biased. Perhaps there is an objective or principled way of distinguishing relevant from accidental or ad hoc similarities. Or maybe there is an easier way—one that involves abandoning arguments by analogy in favor of a distinct sort of inference logic.

Inference to the Best Explanation

To sharpen the distinction between analogies and inference to the best explanation and to highlight other features that will be useful to evolutionary archaeologists and anthropologists, I'll briefly expound on Paley's argument. I'm asking that we take lessons from a creationist argument (see Ariew [2007] for details). How ironic!

Paley's argument starts with an analogy between living organisms and human artifacts. If you come across a watch while walking along a dirt path and inquire as to its existence, you would not take seriously the conclusion that watches are the product of natural forces. It is highly improbable that natural forces would randomly coalesce matter into a watch. The possible existence of a designer who can manipulate the parts for his own purpose makes the existence of watches much more likely. An "inference to the best explanation"—the existence of a designer—best explains watches and living organisms.

To schematize the argument: Take H_1 to be the hypothesis that the object in question was produced by random natural forces (earthquakes, tectonic pressures, wind, rain, etc.). Take H_2 to be the hypothesis that the object was produced by an intelligent designer. Take O to be the observation of some object, for instance, a watch. The issue is, given O, which hypothesis—and there can be any number—is most likely? This is an example of what Sober (1993) calls the "Likelihood Principle." In this case, the Likelihood Principle ranges over O, H_1, and H_2 and can informally be expressed as follows: O strongly favors H_1 over H_2 if and only if H_1 assigns to O a probability that is much larger than the probability that H_2 assigns to O. In the language of probability theory, we rewrite this to read as follows: O strongly favors H_1 over H_2 if and only if $P(O/H_1) > P(O/H_2)$.

Paley did not explicitly formulate his argument this way, but the Likelihood Principle does clarify what he seems to have had in mind. Indeed, given the intricacy of the watch, its observation O strongly favors the likelihood ($P[O/H_2]$) that a watch designer exists over the possibility ($P[O/H_1]$) that random forces coalesce to produce the watch.

One of the features of the likelihood construal of inference to the best explanation is that it allows us to postulate unobservables. It is unnecessary to have any sensory experience of a designer or random forces actually creating a watch. This feature distinguishes inferences to the best explanations from straightforward inductive arguments, which involve observing characteristics of a sample and extending those characters to a larger subset (Fogelin and Sinnott-Armstrong 2006). The truth of the expression $P(O/H_1) > P(O/H_2)$ is evaluated by comparing two probability conditionals: the probability that the observation comes about if H_1 is true versus the probability that the observation comes about if H_2 is true. It says nothing about the prior probability of the existence of the thing referred to in either H_1 or H_2.

This feature—postulating unobservables—makes inferences to the best explanation useful for science. Sober (2001) provides an apt example of how Mendel confirmed the existence of genes by means of an inference to the best explanation and without ever actually observing genes. Paley, too, noticed that his inference is not weakened without direct evidence: "Nor would it, I apprehend, weaken the conclusion, that we had never seen a watch made; that we had never known an artist capable of making one; that we were altogether incapable of executing such a piece of workmanship ourselves, or of understanding in what manner it was performed" (Paley 1802: 4).

Bamforth (2002: 440) criticizes the usefulness of Darwinism on the grounds that "archaeologists cannot directly observe the actual processes of evolution that operated in the past; instead, we are forced to infer the operation of these processes from patterns in material culture." Yet, not being able to directly observe actual processes cannot be a criticism of Darwinism or any other scientific hypothesis that relies on inference to the best explanation. Rather, it is an accurate statement of how scientific practice sometimes works. Not even the creationist Paley makes this mistake. O'Brien et al. (2003) make a similar point.

Next, Paley (1802: 554) considered what would happen if we found a self-replicating watch:

> Suppose, in the next place, that the person who found the watch should after some time discover that, in addition to all the properties which he had hitherto observed in it, it possessed the unexpected

> property of producing in the course of its movement another watch like itself—the thing is conceivable; that it contained within it a mechanism, a system of parts—a mold, for instance, or a complex adjustment of lathes, baffles, and other tools—evidently and separately calculated for this purpose; let us inquire what effect ought such a discovery to have upon his former conclusion.

In addition to serving the function of telling time, this watch has a further extraordinary feature: It produces well-functioning offspring. The "discovery" of a self-replicating watch affects the former conclusion—the existence of watchmakers—in two important ways. First, it strengthens the inference to the existence of a designer at the same time that it weakens the inference to the hypothesis that the item is the product of natural forces alone. As Paley (1802: 9) put it, "If that construction without this property, or, which is the same thing, before this property had been noticed, proved intention and art to have been employed about it, still more strong would the proof appear when he came to the knowledge of this further property, the crown and perfection of all the rest." The probability of natural forces randomly producing a watch is very, very small, but the probability of natural forces randomly producing something as extraordinary and exquisite as a self-replicating watch is even smaller.

In our schema, substitute in O a self-replicating watch rather than a garden-variety one. Now, compare the probability that a living organism appears given H_1 (random forces) with the probability that a living organism appears given H_2 (a designer). The point of the second step is (in our more formal schema) to show how unequal are the two quantities of the following expression:

$$\text{O strongly favors } H_1 \text{ over } H_2 \text{ if and only } P(O/H_1) \gg P(O/H_2)$$

If we thought that the inequality was strongly in favor of $P(O/H_1)$ when O is a watch, then we will believe that the inequality is much stronger in the case where O is a self-replicating watch. The general lesson is, the more complex the parts, the stronger the evidence of a designer.

However complex watches are, most of us with average intelligence and skills could imagine learning, after extensive training, how to create them. But to have the skill of a self-replicating watchmaker would be extraordinary or even supernatural. The general lesson here is the more complex the design, the more intelligent (or skillful) the designer. All that is left for Paley to do is to convince us that because living tissues, organs, organisms, and ecosystems are so much more complex than self-replicating watches, their parts are much more attuned to the functions they serve.

One might not share the intuition that Paley's argument from inference to the best explanation is distinct from an argument by analogy. After all, the analogy between watches and living organisms plays a central role in the inference to the best explanation. However, the analogy doesn't drive the argument; rather, it serves as a means to strengthen the inference from complex adaptation to the explanation invoking a designer. In other words, the relevant feature in common between watches and living organisms is their complexity and suitability for the functions they serve. If designers are the best explanation for highly functioning artifacts, they will be even better explanations for the more complex and highly functioning forms found in nature. In this way, Paley avoids Hume's argument from overall similarity. Paley's claim is that an organism's intricacy ought to be explained in the same way that a watch's intricacy is explained. It doesn't matter if one is made of metal and the other hops. Overall similarity is irrelevant (Sober 1993).

Readers, especially evolutionary biologists, might have noticed an obvious limitation to inferences to the best explanation: The success of inference-to-the-best-explanation arguments depends on the relative success of the given hypotheses, and, as Darwin would show, there are other hypotheses to consider besides the random action of matter and cause and an intelligent designer. Therein lies a formal limitation of inference-to-the-best-explanation inferences: The strength of an inference to the best explanation is only as good as the proffered hypotheses. For any given set of hypotheses, the interlocutor always has the option of remaining agnostic as to the cause of the phenomenon in question. To suggest otherwise—for instance, to argue that because God is a better explanation than matter and cause, God must exist—is to commit "the only-game-in-town" fallacy (Sober 1993: 34). If a rival account better explains the observation, it does not follow that the account itself is even plausible.

What Natural Selection Explains

Suppose we are convinced that evolutionary biology offers the best overall explanatory scheme for technological invention and innovation. The next issues are (1) what exactly *does* evolutionary biology—and natural selection in particular—explain? and (2) how does it explain it? The questions are relevant for both evolutionists such as Darwin—motivated to refute Paley—and evaluators of evolutionary anthropology. After all, in a debate over an inference to the best explanation, we need to know what is being explained (the "Os") and how the rival hypotheses (the "Hs") explain it. The problem is that there is little agreement among biologists about what natural selection explains and how it explains it. As O'Brien and Lyman (2002) point out, biologists are in disagreement over what constitutes an evolutionary event! Even Darwin's answer is not as obvious as it might first appear on a casual reading of the *Origin.*

In April 1982, one hundred years after Darwin's death, the *New Scientist* published an issue featuring several prominent evolutionists offering their assessment of what natural selection means today. Strikingly, each had a distinct view about what Darwin's theory is meant to explain. To biologist Richard Dawkins, natural selection is the only viable explanation for the existence of adaptations. To paleobiologist Stephen Jay Gould, natural selection is one of several explanations of the patterns of extinction and speciation. And to population geneticist Brian Charlesworth, natural selection is one of several explanations for changes in trait frequency over generational time. Not a single author suggested that Darwin's theory best explains all three phenomena. Yet, Darwin's own vision of evolution by natural selection was just that—a grand, unifying theory.

If we take a close look at the characteristics of each explanation—generational trait spread, speciation and extinction, and adaptation—it is difficult to imagine how Darwin thought natural selection could explain all of them in one sweeping, unified theory. Each explanation features a distinct category of phenomena. Perhaps this best explains why modern biologists offer distinct answers to the question "What does natural selection explain?" Let's briefly examine each explanation.

Generational Trait Spread

A change in trait frequency over generational time is a population-level phenomenon. It concerns a pattern that is true in the large scale and detected in the use of averages but untrue for any particular individual life history or particular lineage. Individuals experience life, death, and reproduction, but only populations evolve. The explanatory scheme is akin to that of a theory of gases. Pressure is a property of the aggregate of molecular motion, not of any particular molecule of gas. To explain pressure, we need not know the movement of any particular gas molecule. However, through the application of probability, we can predict how in the long run the various molecular motions and collisions would, in their aggregate, produce the population-level effect, pressure.

Speciation and Extinction

Patterns of extinction and speciation are at a level removed from the patterns of trait evolution. First, whereas evolutionary patterns concerning changes in trait frequency emerge from a particular population that varies in individual life histories, the patterns of speciation and extinction emerge over a variety of populations over a much grander timescale. Second, trait evolution is determined by a catalog of birth and death rates and reproductive schedules, as well as by initial population size and population dynamics. But a unified theory of extinction and speciation patterns is not necessarily so sensitive to these factors, given that it must account for the patterns across a variety of contingent events and conditions, including variations in birth rates, death rates, reproductive schedules, and population dynamics.

The difference between the two sorts of questions is often characterized in terms of "microevolution" and "macroevolution" (Lyman and O'Brien 2001). Both are population-level phenomena that differ in their level of abstraction. The debate among paleontologists is whether macroevolution can be explained merely in terms of microevolution on a grander scale or whether the fossil record, especially the existence of large gaps in the otherwise gradual transitions, suggests that factors outside of microevolutionary processes have to be accounted for. Darwin was a unifier; the role of natural selection (and the principle of divergence) in explaining microevolutionary patterns is sufficient to explain macroevolutionary patterns as well—a point made by O'Brien and Lyman (2002).

Adaptation

The issue of the origin of adaptation is distinct from the other issues in a more fundamental way. Rather than explaining population patterns, it involves an existential question, how to account for the first appearance of a biological item. In this context, natural selection is Darwin's answer to the argument from design. Contrast the question "How did the mammalian eye come to exist?" with a question about trait spread: "How did the mammalian eye, once it came to be, become so prevalent in the present-day population?"

The difference in questions about origins of adaptation and changes in trait frequency reminds us of Schumpeter's (1942) distinction between invention, the first appearance of something new, and innovation, the spread of a successful invention. Both questions are asked about adaptations—how do they first appear and how do they spread in a population—but they are distinct. For something to spread, it must exist in the first place. Darwin recognized the distinction between populational and existential explanations.

Populational Explanations

Evolution by means of natural selection occurs when the following conditions are in place. First, there is a struggle for existence as a result of the inherent tendency of organisms to produce more offspring than could possibly survive in the environment in which they are born. This is called the "Malthusian condition," which Darwin thought was universal for all organisms but which plays little or no role in modern evolutionary thought (Gayon 2003). Second, individuals vary from one another in any way that matters to their struggle of life. Third, offspring tend to resemble their parents. Fourth, following the three conditions (in a near syllogism), evolution by natural selection occurs. Those variants that provide their bearer any advantage whatsoever in the struggle for existence will be passed on to its offspring.

Putting it all together, Darwin (1859: 80–81) wrote as follows:

> Can it, then, be thought improbable . . . that other variations useful in some way to each being in the great and complex battle of life, should sometimes occur in the course of thousands of generations? If such do occur, can we doubt (remembering that many more individuals are born than can possibly survive) that individuals having any advantage, however slight, over others, would have the best chance of surviving and of procreating their kind? On the other hand, we may feel sure that any variation in the least degree injurious would be rigidly destroyed. This preservation of favourable variations and the rejection of injurious variations, I call Natural Selection.

What about the populational question concerning speciation and extinction? Here, Darwin makes a leap—that the mechanism of preservation of favorable variations, natural selection, also explains how life's diversity forms out of single ancestry: "Several classes of fact . . . seem to me to proclaim so plainly, that the innumerable species, genera, and families of organic beings, with which this world is peopled, have all descended, each within its own class or group, from common parents, and have all been modified in the course of descent" (pp. 457–458). "Modification" here refers to the process of natural selection.

The explanation of speciation and extinction requires two ingredients: the set of Darwin's conditions for evolution by natural selection and a condition of isolation of subpopulations into distinct selective regimes. Suppose the soot from nearby factories blankets only parts of the English countryside. Some trees retain their light-colored bark whereas others become dark from soot. In this case, diversity in a moth population subject to the vagaries of tree color is preserved by the variation in the ecological conditions of the English countryside. Now, suppose variants within each moth subpopulation experience different ecological conditions such that certain variants in the dark population prevail in their isolated ecosystem and distinct variants in the light population prevail in theirs. Eventually, differences between the dark and light moths will widen to other characteristics. In this case, diversity increases.

It is not difficult to imagine cases in which the diversity blossoms—just keep subdividing the populations into distinct selective regimes and let distinct variants prevail within each subpopulation. It is this sort of story that Darwin thought eventually led to speciation. Whether it does or not does not concern us. What matters is that some degree of trait diversity between populations is explained by natural selection plus a condition of isolation.

Applying these lessons to the debate between Bamforth and O'Brien and colleagues, let us focus on a statement made by the latter: "The replicative success of these units is what evolutionary archaeologists seek to explain. Those units that are functional will be sorted by natural selection; those that are stylistic will be sorted by the vagaries of transmission. Whether the former units, as manifest in artifacts, influence the biological reproductive success of their human bearers is an empirical matter" (O'Brien et al. 2003: 576).

By "replicative success of these units" we are reminded of Schumpeter's (1942) notion of an innovation, a novel trait that successfully spreads to fixation in a population. If so, then the question O'Brien et al. pose as empirical is whether or not a particular fixed cultural trait (e.g., a habit particular to some culture or other population) is an "innovation" or not. Putting their point in the form of an inference to the best explanation, the phenomenon to be explained (the "O") is a "culturally transmitted" trait. "H_1" is natural selection. "H_2" is a non-natural-selection mechanism, one that is not unified by the bearers having any sort of reproductive success. The form of the inference to the best explanation follows, the question being $P(H_1/O) > P(H_2/O)$? O'Brien et al. are correct in saying that determining whether the expression is true or not—whether natural selection or some other transmission scheme (unified or not) better explains an instance of a culturally transmitted trait—

should be decided on empirical grounds. Bamforth's attempt to dismiss the question a priori is contrary to normal science, where inference to the best explanation is one of several inference forms.

Filtering Explanation

What about the existential question concerning the origins of adaptive traits? This question is important in order to make sense of Erwin and Krakauer's (2004) claim that evolutionary biology suitably explains "inventions" as well as innovations. Here matters get complicated. To answer the populational questions without relying on supernatural powers of creation, Darwin made a conceptual distinction between the internal processes that determine how an organism is formed and the external processes, involving the environment, that determine whether a trait is to be selected (Lewontin 2000). The process that determines how individuals vary is causally independent from the conditions of selection. Darwin knew little about the causes of variation, except to say that they are external effects on the "reproductive functions" (Schweber 1977).

By hypothesizing that the mechanism that produces variations is independent from the conditions for their adaptive evolution, Darwin's theory serves as an alternative to Lamarckian "use and disuse" theories, whereby adaptive variants appear for the sake of their usefulness. Further, by requiring that variants preexist their spread in the population, natural selection serves as an alternative to Paley's view that novel traits appear all at once.

Natural selection is not, strictly speaking, a primary cause of anything. The mechanisms of variation ultimately produce novel traits. Natural selection operates over premade variants. Further, natural selection explains not an existential event (such as the cause of an organic form) but a populational event, the "spread" of a "favorable" trait. Individuals struggle to live and reproduce, and, on the theory, their existence is a condition for natural selection, not the object to be explained.

Notice a paradox emerging. On the one hand, Darwin is known primarily for his non-supernatural answer to the existential question about how exquisite adaptations arise. However, on the other hand, Darwin's distinction between how individual variants arise and how traits evolve by selection suggests that the existential question is not part of natural selection because, for Darwin, the spread of traits requires the prior existence of traits. Darwin had nothing (useful) to say about how new variations come about.

If so, this has ramifications for Erwin and Krakauer's call for an explanation of innovations and inventions in terms of natural selection. It seems the enterprise of modeling explanations of innovations and inventions on Darwin's theory is flawed—Darwin's theory is tailor-made to explain only innovations, given that inventions (novel variants) preexist selection.

In the quote above where Darwin defines natural selection, his conception of "preserving" advantageous traits suggests that natural selection is a type of "filtering explanation." Abstractly, natural selection explains why "all Qs are P" by referring to a filter whose role is to sort out all non-Ps in the population (preserving some, eliminating others). For example, all descendants of earlier wolf populations are (to some standard metric) swift because all nonswift wolves were eliminated by selection—the filter. Now, one would think that if natural selection explains why all Qs are Ps, then by an explanatory version of the mathematical principle of transitivity the filter would also explain why a particular Q is a P in virtue of the fact that all Qs are Ps. Yet, surprisingly, transitivity does not hold in filtering explanations. This is the source of the paradox, and it harkens back to the distinction between an explanation of how variations arise and the conditions for which traits are selected. There may be a reason why a particular Q is P—why Harry the wolf is swift as opposed to slow—but natural selection does *not* explain it because natural selection merely eliminates non-Ps and preserves Ps. It does not create Ps.

Explaining Invention

The upshot of the discussion of "Darwin's paradox" is that we should draw a line between the explanation of innovation and that of invention. Natural selection is a filtering process and hence is well suited to explain innovations—the spread of variants—but not to explain inventions, the existence of new traits. This preliminary conclusion gives lie to claims made by popular evolutionary writers, such as Carroll (2006), who claim that natural selection is the primary cause of adaptation. Carroll prefers the metaphor of "forging" as in "natural selection for incremental variation forged the great diversity of life" (Carroll 2006: 30).

Darwin (1859: 459) himself recognized the paradox: "Nothing at first can appear more difficult to believe than that the more complex organs and instincts should have been perfected, not by means superior to, though analogous with, human reason, but by the accumulation of innumerable slight variations, each good for the individual possessor." The key to Darwin's brilliant way out of the paradox is to attend to the difference between the *process* of natural selection and one of its many *products* or consequences. The process of natural selection is a filtering of profitable from unprofitable variants. When reiterated over many generations, the product of natural selection is the prevalence in the population of a single profitable variant. Reiterate natural selection over many more generations and over many more variations, and the product is the gradual accumulation of forms, each better adapted than the ones before it. At an even larger timescale, the product of natural selection and the mechanism of variations is the first appearance of an organ of "extreme perfection," such as the mammalian eye.

Arrival of the Fittest

Still, reiterated natural selection does not *make* anything. The mechanisms of variation do the making; they are the primary cause of the existence of exquisite traits. The role of natural selection in the explanation of the first appearance of a trait is derivative of its filtering function. To illustrate, suppose after a year of reading lessons there is a selection for entering the fifth-grade reading class (my example is modified from Sober 1993). Suppose Tom and Allison make it and Joel does not. True, in the case of reiterated selection the selection of Tom and Allison to the fourth-grade reading class in part explains why they are in the fifth-grade reading class. Further, if the question is why Tom and Allison are in the fifth-grade class, then both selection events—the one for the fourth grade and the one for the fifth grade—fully explain that. However, if the question is existential, for instance, why Tom and Allison read at the fifth-grade level, or why there are fifth-grade readers to be selected in the first place, then the selection events are insufficient. The answers to the latter question might vary—Tom got a tutor, Allison bribed the committee.

Let me summarize by placing the point in the form of an inference to the best explanation. Let the phenomenon to be explained, "O," be a novel trait formed from a new variant and derived from an adaptive trait more or less fixed in the population. Let H_1 be natural selection as the purported cause of the trait "O." Let H_2 be developmental mechanisms, including the mechanism for variation (e.g., recombination). The question is whether in this instance $P(O/H_1) > P(O/H_2)$. My conclusion is that natural selection alone does not explain novel traits, but a history (etiology) of developmental mechanisms stretching back through the lineages does. Thus, the answer to the question will be "no."

And so it remains true, despite Darwin's answer, that the language of "forging," "forming," and "creating" inherent in the popular discussion of natural selection explanations of adaptations is misleading. Selection is a filter, and as a side consequence of its filtering, it provides some explanatory role in the first appearance of traits. Strictly speaking, a distinct line remains between innovation and invention—natural selection is tailor-made to explain innovations and how they spread, but it explains inventions only derivatively. Perhaps that is why advocates of evolutionary developmental biology—"EvoDevo"—state that while Darwin's natural selection explained "the survival of the fittest," EvoDevo explains "the arrival of the fittest." As Müller (2002) explains, the study of invention (he calls it "novelty") addresses causal factors in organismal evolution, whereas the study of the spread of innovation addresses the macroevolutionary processes of trait spread.

Nevertheless, there is still a way to apportion explanatory responsibility between the processes of development and the conditions for selection in the explanation for the origins of a trait, though it is not straightforward, given that each plays a distinct role. This is akin to apportioning causal responsibility for the creation of a brick wall between two workers, one of whom spreads the mortar and the other of whom lays the bricks. Take an extreme case where a mortarless wall is one brick high. The bricklayer is fully responsible (unless the mortar spreader retains a supervisory role). Label a trait in question as "V." The mechanism of variation fully explains the first appearance of V. The role of selection as making probable compound variations is nil. Darwin envisioned the other extreme, whereby the mechanism of variation produces only minute differences. In this case, the buildup from the prevalence of V to the prevalence of, say, 10,000V would require 10,000 reiterations of the two-step schema, just as a wall 100 feet high made from standard-size bricks would require the equal cooperation of the two workers. Yet, imagine a middle case whereby some bricks are extraordinarily tall. The taller the brick, the less there is a need for the mortar spreader to exert herself. Likewise, the emergence of a "sport," or discontinuously large variant, reduces the number of reiterations required from the two-step schema.

Conclusion

The definition of novelty I have offered—a new variant—that gives rise to my argument against natural selection as the best explanation for novelty is open to the charge that the sort of novelty I am considering is not the sort of thing that interests biologists or cultural evolutionists. Erwin and Krakauer (2004) recognize that "evolutionary novelty" has several meanings in evolutionary biology and offer three definitions polled from a workshop they conducted at the Santa Fe Institute.

First, evolutionary novelties are "rare morphological transitions that result from breaching genetic or morphological constraints, exemplified by a developmental mutation in the Yucca moth that gave rise to a new antennal limb" (Erwin and Krakauer 2004: 1117). This is a paradigm example of the notion of novelty that faces the charge that natural selection derivatively explains novelties because natural selection operates over new variants but does not cause them. Second, evolutionary novelties are changes that have important consequences for the environment, the classic example being the origin of oxygen-dependent photosynthesis that led to an oxygenated atmosphere. Third, evolutionary novelties are changes resulting in the generation of abundant taxonomic diversity, such as the cichlid fishes of East African lakes or the diversification of flowering plants. For the purposes of understanding the consequences of my distinction between explaining innovations and inventions, the third definition offers nothing that is not inherent in the first.

The lesson learned is, contrary to my simplistic definition of novelty as a new variant, no one is particularly interested in the first appearance of just any garden-variant, given that many new variants are disadvantageous and most cause death. Rather, we are interested in the first appearance of "successful" traits. Success is indicated either by spread as a result of selection or by design analysis—the remarkable adaptiveness of the trait to its local environmental condition. Thus, it is a bit misleading to say (so goes the objection to my claim) that we are particularly interested in the first appearance of traits because what we are really interested in is first appearance of "successful" traits.

Yet, this is not to dismiss the importance of the distinction between an explanation of a trait's prevalence and an explanation of a trait's first appearance. Once again, Darwin's distinction between the source of variation and conditions of natural selection is important here. Complex traits are built by the reiteration of two distinct steps. One is the primary cause of novel traits, and the other describes the conditions for which a trait spreads. Together (reiterated), they answer the existential question of how traits come to exist, but natural selection alone answers the question about the prevalence of preexisting traits. Consequently, if one favors a natural selection explanation for the spread of a particular trait, it does not necessarily follow that natural selection is the sole explanation for the diversity of or first appearance of a trait or that filtering explanations do the causal work required to explain the existence of a novel trait.

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3 Comparative Perspectives on Human Innovation

Kevin N. Laland and Simon M. Reader

In 1921 in Swaythling, a village in the south of England, a blue tit began opening milk bottles left outside homes, drinking the high-energy cream (Fisher and Hinde 1949; Hinde and Fisher 1951; Martinez del Rio 1993). Ornithologists noted the repeated appearance of the behavior, and over the next 30 years milk-bottle opening was observed at tens of sites and in thousands of birds across the United Kingdom and mainland Europe (Hinde and Fisher 1972), producing the best characterized and perhaps best known example of the spread of a novel behavior pattern (innovation) in nonhuman animals. Experimental tests on captive birds (Kothbauer-Hellman 1990; Sherry and Galef 1984, 1990), combined with wave-of-advance models borrowed from archaeology (Lefebvre 1995), demonstrated that the innovation rate can be quite high and that the likeliest explanation for the spread of bottle-opening behavior was local innovation, where milk bottles were introduced, followed by social learning from bird to bird within that locality (Ingram 1998).

Milk-bottle opening is just one example of hundreds of innovations reported in nonhuman animals, with examples ranging from the incorporation of new items or techniques into avian foraging repertoires and novel elements in the songs of birds to novel courtship displays, deceptive acts, social behavior, and tool use in primates (Byrne 2003; Casanova et al. 2008; Lefebvre et al. 2004; Reader and Laland 2003a). Many innovations are in response to changed circumstances such as human impacts, but innovations are also produced in stable environments, where an animal discovers a new method of exploiting the environment (Reader and Laland 2001). Thus, many animals invent new behavior patterns, modify existing behavior to a novel context, or respond to social and ecological stresses in an appropriate and novel manner (Biro et al. 2003; Kummer and Goodall 1985; Lefebvre et al. 1997; Reader and Laland 2001, 2002, 2003b). We have long argued that such behavior can sensibly be termed "innovation," and although the consanguinity of animal and human innovation is a matter of debate (Reader and Laland 2003a), we believe that experimental, comparative, and observational research on animal innovation can also inform studies of human innovation.

Research into animal innovation is at a formative stage with many unanswered questions. For example, it is conceivable that a variety of alternative psychological processes underlie innovation and that innovation is not a unitary phenomenon. There still are open questions as to what roles innovation plays in facilitating the flexibility of individual development, survival, reproductive success, and evolution of animal species. Is the ability to innovate an adaptation, and if so, what factors have selected for a propensity to innovate? Under what circumstances is innovation adaptive? Is innovation a driver of brain evolution, or is it simply a covariate of more fundamental characteristics (e.g., sociality or foraging mode) or an indicator of more general abilities (such as behavioral flexibility)? Many of these issues would be problematic to address using human studies alone but can be addressed using animal models or through comparative work.

We argue here that a strong case can be made for the assertions that many animals, not just humans, innovate; that innovation can be regarded as qualitatively distinct from related processes such as exploration and learning; and that innovation has played an important role in primate and avian brain evolution. The goal of this chapter is to provide an overview of some recent research on animal innovation, illustrating comparative and experimental approaches to the issue.

The Ecological and Evolutionary Significance of Animal Innovation

Innovation is phylogenetically widespread, but behavioral scientists have long noted that species differ in their tendency to innovate (Cambefort 1981; Cousteau 1958; Lefebvre et al. 2004; Thorpe 1956). For instance, Morgan (1912) speculated that behavior may be composed of a repetitive component that has occurred before and a smaller proportion of novel behavior—found particularly in so-called “higher” organisms—that can be regarded as a creative departure from routine. Although there are long traditions of research into related topics such as neophilia, exploration, and insight learning in animals, and whereas innovation in humans has been subject to considerable investigation, animal innovation has only recently begun to receive attention. A critical paper drawing attention to the topic was Kummer and Goodall’s (1985) review of primate innovation, which suggested that some innovations derive from the ability of the individual to profit from an accidental happening, others result from the ability to use existing behavior patterns for new purposes, and still others are completely new behavior patterns. Innovation may be prompted by two factors: need (such as a period of drought or a social challenge) or an excess of resources, which will allow animals to bear the costs of exploration (Kummer and Goodall 1985; Laland and Reader 1999a). Necessity is likely the dominant factor prompting animal innovation (Gajdon et al. 2006; Laland 2004; Laland and Reader 1999a, 1999b; Sol, Lefebvre, and Rodríguez-Teijeiro 2005).

Two major surveys of innovation have documented over 2,200 examples of foraging innovations in birds (Lefebvre et al. 1997, 2004)—the most complete survey of animal innovation—and over 500 examples of innovations in primates (Reader and Laland 2001, 2002). These surveys collated reports from published literature, using keywords such as "novel" or "never seen before" to classify behavior patterns as innovations. Although these kinds of studies are vulnerable to reporting biases, Lefebvre and colleagues have devised statistical methods for evaluating and counteracting these biases, and there are reasonable grounds to be confident that these innovation data represent a valuable, robust measure of an aspect of behavioral flexibility (Lefebvre et al. 2004).

Furthermore, innovation rate correlates with laboratory measures of learning, supporting the idea that innovation is a cognitive measure (Lefebvre et al. 2004). In both birds and primates, innovation rate (per avian parvorder or primate species) has been shown to correlate positively with measures of forebrain size. This parallel finding in two independent taxa, and at different taxonomic levels, supports the idea that brain volume is an indicator of behavioral flexibility and raises the possibility that increased innovativeness may have yielded a selective advantage, thus driving brain enlargement over evolutionary time.

Innovative individuals and species tend to show low neophobia and superior performance on a variety of cognitive measures (Bouchard et al. 2007; Reader 2003). The phylogenetic distribution of innovation suggests that selection may have favored innovativeness as part of a cognitive suite of traits in particular lineages (Lefebvre et al. 2004; Reader and Laland 2002), with innovation perhaps part of a survival strategy based on flexibility to cope with unpredictable, changing socioecological environments and to alter behavior to outcompete others.

The pioneering work of Lefebvre et al. (1997) has inspired further analyses in birds and in primates that explore the relations among innovation, ecology, and cognition. There are multiple descriptions of specific innovations apparently facilitating survival in changed circumstances (Sol 2003). Innovation might also be of critical importance to those endangered or threatened species forced to adjust to impoverished environments (Greenberg and Mettke-Hofman 2001). To test the idea that innovations may facilitate survival in novel circumstances, Sol and colleagues (Sol 2003; Sol and Lefebvre 2000; Sol, Duncan, et al. 2005; Sol et al. 2002) took advantage of a series of natural experiments where humans have introduced species into new habitats, first in New Zealand and then in a global analysis. Innovative species were found more likely to survive and establish themselves when introduced to new locations. If innovativeness is the causal variable in this relationship, it suggests that innovation can aid survival in changed environments. Similarly, nonmigratory birds innovate most in the harsher winter months (Sol, Lefebvre, and Rodríguez-Teijeiro 2005), whereas migratory species are less innovative than nonmigrants, suggesting that migratory birds may be forced to migrate because of an inability to adjust behaviorally to the changed winter months.

Innovation has been proposed to have a key influence on the tempo and course of evolution. For instance, Wilson's (1985) "behavioral-drive" hypothesis argues that innovation combined with cultural transmission led animals to exploit the environment in new ways, exposing them to novel selection pressures and increasing the rate of genetic evolution (see also Wyles et al. 1983). Studies of birds and primates support a key assumption of behavioral drive—that brain size, innovation rate, and social-learning rate are linked (Lefebvre et al. 1997; Reader and Laland 2002). Innovation rate and brain size have recently been shown to correlate with avian species and subspecies richness, suggesting that, as the behavioral-drive hypothesis predicts, evolutionary rates are accelerated in large-brained, innovative taxa (Nicolakakis et al. 2003; Sol 2003; Sol, Stirling, and Lefebvre 2005).

When a novel learned behavior spreads through an animal population and as individuals learn from one another, typically a single individual will have initiated the process. Such diffusion requires two processes: the initial inception of the behavioral variant, *innovation*, must occur, and the novel trait must spread between individuals, which is *social learning*. Many books, conferences, and papers have been dedicated to animal social learning (e.g., Box and Gibson 1999; Fragaszy and Perry 2003; Galef and Giraldeau 2001; Heyes and Galef 1996; Shettleworth 2001; Zentall and Galef 1988). In comparison, the first step of the spread of a novel behavior (innovation) received little attention until recently. Innovation is now increasingly recognized as an important component of animal social-learning research, particularly in relation to population differences in behavior that are proposed to reflect cultural diversity (e.g., Huffman 1996; Laland and Janik 2006; Leca et al. 2007; Ramsey et al. 2007; van Schaik, van Noordwijk, and Wich 2003; van Schaik, Ancrenaz et al. 2003; Whiten et al. 1999). Counterintuitively, relatively few innovations appear to spread through animal groups (Gajdon et al. 2006; Kummer and Goodall 1985; Laland and Hoppitt 2003)—a phenomenon also noted in humans (Rogers 1995).

Innovation is also key to cumulative cultural evolution, where a careful balance must be struck between faithful social transmission (to minimize loss of previous innovations) and innovation (to minimize stagnation and allow adaptive change). Although clear evidence of cumulative cultural evolution is lacking in animals, tool manufacture in New Caledonian crows has been suggested to be a possible case (Hunt and Gray 2003).

Evidence is mounting that innovation plays an important role in ecology (e.g., range expansion), in evolution (e.g., subspecies diversification), in cognition (as the first step of social learning), and in cultural diversification. Innovation not only is widespread in nonhumans but is conceptually and functionally important.

Defining Animal Innovation

It was only in 2003 that a detailed definition of animal innovation was first proposed, appearing in the first book on the topic. Reader and Laland (2003b) proposed two *operational* definitions. *Innovation sensu product* is a new or modified learned behavior not previously found in the population. *Innovation sensu process* is a process that introduces novel behavioral variants into a population's repertoire and results in new or modified learned behavior. Thus, innovations are learned, and their novelty is defined at the population level. Innovations can spread by social learning; however, the introduction of a novel behavior into a population by social learning is not considered innovation. This contrasts with some definitions of human innovation, which refer to acquisition of a novel act by any route as innovation and the initial inception as "invention" (Rogers 1995).

Ramsey et al. (2007: 397) proposed an individual-level definition of innovation as "the process that generates in an individual a novel learned behavior that is not simply a consequence of social learning or environmental induction," the latter being behavior that "emerges reliably in all or most individuals exposed to the environmental stimulus." However, defining innovation at the individual level and determining environmental induction pose problems of operationalization (Giraldeau et al. 2007; Kendal et al. 2007; Reader 2007)—concerns that lead us to prefer the 2003 definition.

Reader and Laland (2003b) proposed deliberately broad definitions and made no distinction between totally novel behavior and modifications of existing behavior, as has been the practice among researchers studying birdsong learning (Slater and Lachlan 2003). Although some objectors might prefer to reserve the term "innovation" for qualitatively new or cognitively demanding tasks or processes, a broad definition is justified given the primitive state of knowledge of animal innovation. The key characteristic of innovation is the introduction of a novel behavior pattern into a population's repertoire, and it would be foolhardy to insist that an innovator must express a previously unobserved motor pattern or unusual cognitive ability. For example, the milk-bottle-opening birds likely used motor actions already in their repertoire (Hinde and Fisher 1951); thus, the innovation involved the application of a familiar behavior to a novel food source. Moreover, subjective judgments of cognitive ability are vulnerable to anthropocentric prejudice, and the ecological and evolutionary consequences of innovations need not depend on the cognitive sophistication of the innovative process. Making premature distinctions potentially jeopardizes the ability to see genuine relationships between different kinds of novel behavior.

Experimental Studies of Animal Innovation

How can innovation be studied experimentally? Kummer and Goodall (1985: 213) offered a suggestion: "Systematic experimentation (such as the introduction of a variety of carefully designed ecological and technical 'problems') both in free-living and captive groups would provide a new way of studying the phenomena of innovative behaviors and their transmission through and between social groups." In the last decade, this approach has started to be implemented in animal studies. Innovation can be studied experimentally in captive animals by presenting them with novel challenges such as foraging-puzzle boxes and exploring the factors influencing innovation (e.g., sex, age, and social rank). Described below are four experimental studies we have been involved in that illustrate some of the methods and findings of experimental studies of animal innovation.

Case Study 1: Innovation in Captive Populations of Callitrichid Monkeys

The prevailing assumption in the primate literature is that young or juvenile primates are more innovative than adult individuals. This innovative tendency among the young is frequently thought to be a consequence or side effect of their increased rates of exploration and play. Conversely, Reader and Laland's (2001) review of the primate-innovation literature noted a greater reported incidence of innovation in adults than in nonadults, which they interpreted (in part) as a reflection of the greater experience and competence of older individuals. Within callitrichids (marmosets, tamarins, and lion tamarins) different studies document different effects of age on responses to novel objects, foods, and foraging tasks. However, these differences across studies may reflect the small samples used (Kendal et al. 2005).

Kendal (née Day) and colleagues presented novel extractive foraging tasks to a large number of family groups of callitrichid monkeys in zoos in order to examine whether there are positive or negative relationships of age with neophilia, exploration, and innovation and whether youth or experience most facilitates innovation. Novel "puzzle-box" foraging tasks were given to 108 callitrichids in 26 zoo populations ranging in size from two to eight individuals. Kendal recorded the first individual to approach, contact, and solve each task in each population as well as a variety of other dependent variables relevant to the subsequent spread of the solution through social learning (Day 2003; Kendal et al. 2005). Her study revealed systematic age differences in callitrichid innovation, with older monkeys significantly more likely than younger monkeys to be the first to solve the tasks. Whereas younger monkeys (particularly subadults and young adults) were disproportionately represented among those first to contact the task, adults (older than four years of age) were disproportionately first to solve the tasks. Older individuals were significantly more likely than younger individuals to turn manipulations into successful manipulations. This finding is consistent with Reader and Laland's (2001) meta-analysis. Statistical analyses provided evidence that at least some of the innovations subsequently spread throughout the group by social learning (Day 2003).

When the overall performance of individuals who interacted with the tasks is considered, the results of Kendal et al.'s experiment suggest that experience and competence allow older individuals to solve novel problems more effectively than do younger individuals. The positive relationship between age and task success suggests that the greater life experience of individuals over four years old may enable them to outperform younger individuals. However, other developmental factors, such as improvements in manipulative skills, increased strength, and maturity with age, cannot be ruled out.

Individuals over age four produced more successful than unsuccessful task manipulations than individuals in the younger age categories. This suggests that there may be a developmental watershed (at about four years for callitrichid monkeys) when prior manipulative experience generates sufficient competence in extractive foraging for individual callitrichids to efficiently translate unsuccessful manipulations into successful manipulations. In accordance with such a competence hypothesis, Menzel and Menzel (1979) suggested that *Saguinus fuscicollis* (brown-mantled tamarin) adults acquire information more efficiently and can recognize and classify objects more quickly than nonadults.

Age was not the only source of variation in innovative performance. The results revealed consistently shorter response latencies, higher levels of successful and unsuccessful manipulation, and greater attentiveness to the task and to conspecifics in *Leontopithecus* (lion tamarins) than in both *Saguinus* (tamarins) and *Callithrix* (marmosets; Day et al. 2003). This is consistent with the hypothesis that species dependent on manipulative and explorative foraging tend to be less neophobic and more innovative than other species (Gibson 1986). *Callithrix* is classified as a "specialized extractive forager," and the *Saguinus* species studied have been described as "nonextractive foragers" (Dunbar 1995). Hence, the experimental results of increasing innovation from *Saguinus* to *Callithrix* to *Leontopithecus* fit the hypothesis that extractive foraging may have promoted the evolution of intelligence in the form of an ability to respond to environmental change (Gibson 1986). The findings also support Lefebvre's (2000) hypothesis that there is a positive association between neophilia and innovation.

Case Study 2: Predictors of Foraging Innovation in Starlings

There are numerous reports of novel learned-behavior patterns in animal populations, yet the factors influencing the invention and spread of these innovations remain poorly understood. Boogert et al. (2008) investigated to what extent the pattern of spread of innovations in captive groups of starlings (*Sturnus vulgaris*) could be predicted by knowledge of individual and social-group variables, including association patterns, social-rank orders, measures of neophobia, and asocial-learning performance. Small groups of starlings were presented with a series of novel extractive foraging tasks, and the latency for each bird to contact and solve each task as well as the orders of contacting and solving were recorded.

Which variables best predicted the observed diffusion patterns? Object neophobia and social-rank measures characterized which animal was the first of the group to contact the novel foraging tasks, and the subsequent spread of contacting tasks was associated with latency to feed in a novel environment (a possible indicator of vigilance). However, asocial-learning performance, measured in isolation, predicted the first solvers of the novel foraging tasks in the group. In other words, one can predict how innovative a starling will be on the basis of its previously measured learning performance. If social learning underlies the diffusion of innovations, we would expect individuals acquiring the behavior later in the diffusion to exhibit shorter learning times, given that they will have more administrators than individuals that acquire the behavior early. This proved to be the case. Contact latency and solving duration were negatively correlated, consistent with social learning underlying the spread of solving.

However, perhaps surprisingly, association patterns did not predict the spread of solving: Birds were no more likely to learn from close associates than from birds with which they spent little time. This may reflect the relatively small size of the groups and enclosures; innovations may be more likely to spread along networks of association in larger groups living in more naturalistic environments.

Case Study 3: Experimental Studies of Innovation and Diffusion in Fishes

Laland and Reader (1999a, 1999b) explored individual differences in the propensity to innovate in fishes. Small populations of guppies (*Poecilia reticulata*) were presented with a novel maze task containing food; the first individual to solve the task was characterized as an innovator. Mazes were composed of one or more partitions with small holes or compartments through which the fish had to swim to find the food. The mazes were designed so that fish were required to swim away from the smell of the food in order to get to it so that the task could not be solved merely by swimming up an odor gradient.

Laland and Reader (1999a) exposed small groups of guppies, composed of individuals varying in sex, hunger level, and body size, to the novel mazes and recorded the category of the first fish to reach the novel food source. A subsequent study has found a significant correlation in guppies between time taken to complete a maze for the first time and number of trials to learn the maze according to a trials-to-criterion measure (Reader and Laland 2000), legitimizing the use of the first individual in a population to swim the maze as a proxy measure of innovation. Laland and Reader found that females were more likely to innovate than were males, food-deprived fish were more likely to innovate than were non-food-deprived fish, and smaller fish were more likely to innovate than were larger fish.

It appears that differences in innovatory tendencies in guppies are best accounted for by differences in motivational state. Innovators were neither the most active fish (males) nor those with the fastest swimming speed (large fish). Moreover, the observed patterns disappear when the experiments are repeated with no food in the mazes. Here, the most parsimonious explanation for the observed individual differences in problem solving is that innovators do not need to be particularly intelligent or creative but are driven to find novel solutions to foraging problems by hunger or by the metabolic costs of growth or pregnancy.

These findings did not rule out the possibility that over and above these state-dependent factors there are "personality" differences that affect an individual's propensity to innovate. To investigate this, Laland and Reader exposed populations of fish to three novel foraging tasks, recording whether fish that completed the first two tasks fastest performed faster in the third task than fish that had not innovated in the first two tasks. Past innovators were found to be more likely to innovate than past noninnovators. The design took steps to rule out a number of potentially confounding variables, constituting evidence that there are genuine personality differences in innovative tendency in guppies. It is interesting that there is evidence for innovative individuals in a species not particularly renowned for its intelligence or problem-solving capabilities.

To further investigate how motivational state affects innovation, Laland and Reader (1999b) explored the relationship between past foraging success and foraging innovation. Weight changes of individuals in two mixed-sex populations of guppies were monitored over two weeks, and the competitive foraging ability of each individual was measured by recording the number of food items eaten. These populations were then exposed to three novel maze tasks, and the time for each fish to complete the task was recorded. The prediction was that poor competitors—fish that had gained the least weight and obtained the least food items during scramble competition—would be more likely to innovate when presented with the novel foraging tasks. In male guppies, the latency to complete the foraging tasks was indeed found to correlate with both weight gain and the number of food items consumed during scramble competition. There was no such correlation in female guppies, however. Females appeared more motivated to solve the foraging tasks than males, regardless of how they had fared during the scramble competition.

What could explain the finding that female guppies are more likely to show foraging innovations than are male guppies, irrespective of past foraging success? Laland and Reader (1999b) reasoned that parental-investment patterns could account for these sex differences. In many vertebrate species, female parental investment exceeds that of males, leading to the suggestion that male reproductive success is most effectively maximized by prioritizing mating, whereas female reproductive success is limited by access to food resources (Trivers 1972). This rings true in guppies, where females can store sperm, are viviparous (thus female parental investment is much greater than that of males), and, unlike males, have indeterminate growth, with a direct correlation between energy intake and female fecundity (Reznick and Yang 1993; Sargent and Gross 1993). Consequently, finding high-quality food has greater marginal fitness value for females than for males, which may explain why females should be more investigative than males and are constantly searching for new food sources.

Having established that individual guppies vary in their propensity to innovate, Reader and Laland (2000) turned to the ways in which innovations spread through animal populations. Mixed-sex populations of guppies were presented with three novel foraging tasks, and time to complete the task was recorded for each individual over 15 trials. In a first experiment the populations were made up of equal numbers of food-deprived and non-food-deprived individuals, whereas in a second experiment small, young fish were compared with large, older fish. Food-deprived fish were faster than non-food-deprived fish at completing the tasks over repeated trials. Although there was no overall effect of size, there was a significant interaction between sex and size. Adult females completed the tasks much faster than adult males, but no sex difference was found in younger adults.

In both experiments there was a significant sex difference, with novel foraging information spreading faster through female subgroups than through male subgroups. Females also were found to learn at a faster rate than males. These findings are most likely a result of motivational differences between the sexes, corroborating the earlier findings of Laland and Reader (1999a, 1999b). The absence of a sex difference in younger fish is also consistent with the above-mentioned parental-investment explanation, given that younger fish are not expected to show investment asymmetries.

These observations are consistent with the findings of Reader and Laland's (2001) meta-analysis of primate innovation (see also van Bergen 2004). They observed more reported incidences of innovation in low-status individuals than expected and fewer reports of innovation in high-status individuals than expected, given their representations in the population. Van Bergen (2004) reports greater innovation in male primates than expected and fewer reports of female innovation than expected, given their representation. This sex difference was particularly strong in relation to sexual and courtship behavior and aggression. The latter finding can be explained in a similar manner to the sex difference in guppy innovation, except that in the case of the primates it is the males for whom the marginal benefits of innovation are greater, given that the innovations allow them to access mates.

Case Study 4: Social Transmission of Foraging Information in Rats

Rats have been reported digging for buried foods or foraging in loose litter for food items (Barnett 1975). Laland and Plotkin (1990, 1992) carried out a series of experiments in which they explored the social learning and transmission of foraging information concerning buried food and, in the process, shed light on behavioral innovation. Demonstrator rats were trained to dig for pieces of carrot buried beneath lightly compressed soil in a small enclosure. Each experimental subject or observer was then placed in a similar enclosure containing buried food, in the presence of a single demonstrator and separated by a wire mesh partition, for a 10-minute period. A preliminary experiment established that the foraging performance of observer rats was enhanced by social learning from a trained demonstrator conspecific, with control groups confirming that the elevated performance could not be attributed to social facilitation or motivational factors (Laland and Plotkin 1990). This established, Laland and Plotkin embarked on a series of experiments with an "animal A demonstrates to animal B, which demonstrates to animal C . . ." transmission-chain design.

In the first experiment the animals were assigned to one of three groups. Two groups were social-transmission groups in which each animal first observed a demonstrator conspecific that had various degrees of experience in foraging by digging. The observer then became the demonstrator for the next animal in the line of transmission. In the first, or "standard-transmission," group, the first demonstrator had been trained to dig for carrots beneath the soil surface of the enclosure. In the second, or "innovator," group, the initial demonstrator was untrained, but again each observer became the demonstrator for another animal. The third group was a control, in that no social transmission could occur and so there was no transmission chain. Each observer was paired with an untrained demonstrator that had no carrots buried on its side of the enclosure; thus each animal performed on the basis of its own individual learning. After having one such opportunity, the control animals were removed from the experiment.

Animals in the standard-transmission group exhibited elevated foraging performance relative to the control group throughout the transmission chain. Animals in this group were more active, began digging earlier, and dug up more pieces of carrot than did animals in the control group. It was clear that pertinent foraging information had been transmitted from the original demonstrators to other animals in the chain. Although this group showed some decline in performance in the early steps of the chain, this appeared to flatten off at a level that still was significantly above that of the controls. This pattern is consistent with the interpretation of an initial loss of information at each transmission step, resulting in each successive animal being a less effective demonstrator for the next animal in the line of transmission.

The innovator group was so called because, given that the transmission chain began with an untrained demonstrator, whatever information was being transmitted between animals was the result of cumulative innovation. Animals in this group also reached performance levels that were significantly above that of the controls. Thus, for this group there seemed to be an accumulation of information during the first few steps of the chain, with performance "asymptoting" at a level similar to that found in the standard-transmission group. The innovator-group data suggest that although there was loss of information at each transmission step, this can be offset by successive observers' benefiting from the sum of the demonstrator's social and individual learning. Toward the end of the transmission chains, both transmission groups appeared to have reached equal levels of performance, where equivalent amounts of information were gained and lost.

More qualitative data revealed further differences in the digging styles of the rats under different conditions. Control rats dug boisterously by moving their forelegs away from them and kicking with their rear legs, and showed little sign of searching for food. Conversely, rats in the standard-transmission group, like demonstrators, dug more carefully and in a directed manner, moving their forelegs toward them and with little kicking with the rear legs, in what much more obviously resembled foraging behavior. Interestingly, rats in the innovator group at early steps in the transmission chain dug with the "wanton" style of the controls, but as the transmission chain proceeded, they were observed to dig increasingly in the more directed foraging style of the trained demonstrators.

The performance curves of subjects in the two transmission groups illustrate certain distinctive properties of social transmission. First, information can be gained as well as lost throughout transmission. Second, innovation does not necessarily require creative or clever individuals but can accrue through the accumulated activities of many individuals. Third, there may be an equal amount of socially transmitted information that can be stably transmitted throughout a population. Where performance levels are higher than the equilibrium, information is likely to be lost; where performance levels are below the equilibrium, information may accrue.

Summary

Numerous animals acquire novel skills and information from others, and behavioral innovations frequently diffuse through natural and captive populations by social-learning processes. It is instructive to refer to the initial inception of such behavioral variants as *innovation* and to investigate the factors that underlie and predict variation in innovation within and between species. Innovation can be studied experimentally in animals by presenting novel tasks to captive or natural populations and then carefully monitoring the spread of the solution. Experimental studies of animal innovation in various vertebrates including fish, birds, and primates, together with a meta-analysis of primate innovation (Reader and Laland 2001), suggest that the adage "necessity is the mother of invention" explains a lot of data. Hungry, small individuals and individuals of low status disproportionately engage in innovative behavior. Sex differences in innovation can be interpreted, and to some extent predicted, using conventional behavioral-ecology theory such as parental-investment and sexual-selection theory.

Species differences in innovativeness among monkeys suggest that certain life-history characteristics, particularly a diet reliant on extractive foraging, may favor enhanced innovation. Both experimental studies in monkeys and a meta-analysis across primates in general imply that adults perform a disproportionate amount of innovation, despite the observation that younger individuals are often quicker to approach novel objects than are adults (Kummer and Goodall 1985). The greater experience, strength, and maturity of elder individuals may be necessary to translate exploration into successful exploitation. In captive birds, asocial-learning performance measured in isolation predicts which individuals will innovate in a social context. Whereas most innovation is the product of a single animal, sometimes innovation can accrue through the accumulated activities of many individuals. Animal innovation is a topic that has only recently received recognition, but one that is starting to command serious attention from behavioral scientists.

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4 Organismal Innovation

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The theme of this volume—innovation in cultural systems—is certainly in need of serious discussion. The subtitle of the workshop—contributions from evolutionary anthropology—provokes the question, does the word "evolutionary" have the same meaning in cultural and biological contexts? More specifically, can the intellectual construct that underlies the theme of this workshop—namely, economist Joseph Schumpeter's (1942) distinction between "invention" (the creation and establishment of something new) and "innovation" (an invention that becomes economically successful and earns a profit)—be successfully applied to both cultural and biological systems? If so, how? If not, why? In attempting to address these questions, it might be informative first to outline what I think are the relevant elements of biological change and then to see if, and/or how, they map on or relate to the notions of "invention" and "innovation."

A Brief Historical Prelude to the Question

With Darwin's (1859) first edition of the *Origin*, a debate previously pursued largely in the form of private conversation and correspondence became public, namely, the topic of evolution, its reality, and its elements. Indeed, in addition to public and religious outcry, Darwin's venture into evolutionary discourse immediately prompted a long, and not altogether positive, critique by his supposed bulldog, Thomas Huxley (1860). In that review, Huxley took Darwin to task on most aspects of the *Origin*, especially his unjustified claim that organismal change generally occurs smoothly and gradually (and thus "natura non facit saltum" ["nature does not make leaps"]), his unsystematic and disorganized presentation of "data" in support of his claims, and his theoretical and methodological shortcomings in arguing for natural selection.

A second major blow to Darwin's theory of evolutionary change as a process involving long-term adaptation mediated by something called "natural selection" came in 1867 with the publication of Jenkin's review of the *Origin*. Jenkin pointed out that, contrary to Darwin's claims, not only was there no evidence whatsoever of transitional forms in the fossil record—only the picture of the abrupt appearance of organisms with fully developed features—or between living species but also Darwin's conception of natural selection was incapable of producing change. Rather, Jenkin argued, given that the theory of natural selection does not preclude the interbreeding of individuals with less advantageous variants of a trait, the greater number of offspring these presumably less well-adapted individuals produce will overwhelmingly swamp any contribution to future generations that the one or two supposedly better adapted individuals could make.

More so than Huxley's, Jenkin's review had such a profound effect on Darwin that he not only wrote in anguish to the former scholar as well as to other colleagues about this egregious oversight on his part but then, in the fifth and sixth editions of the *Origin* as well as in other monographs (Darwin 1868, 1871), he proceeded to diminish the role of natural selection in producing significant organismal change. Although in the first through fourth editions of the *Origin* Darwin had invoked use–disuse arguments as potential sources of variation, Jenkin's review provoked him to situate them much more centrally in his model of evolution. Indeed, in his theory of heredity—pangenesis—Darwin (1868) went so far as to propose a scenario as to how the effects of use–disuse could be passed on from an impacted parent to offspring and then to generations beyond. Yet, despite reducing the importance of natural selection, both in producing variation and in selecting the most advantageous variations, Darwin remained intellectually mired in the consequences of his assumptions, which included postulating the existence of enormous amounts of variation as a requisite for organismal change.

For the most part, Darwin perceived the tempo of organismal change as slow, even ploddingly so. Consequently, although on rare occasion in the *Origin* as well as in the *Descent* Darwin allowed that change might in some cases occur rapidly, he was committed to the notion that evolutionary change—that is, the origin of new species—was essentially the process of adaptation protracted over an incredibly long period of time. Whether it was gradual or rapid, however, Darwin was so convinced that change was the result of a smoothly continuous process of transformation by means of a string of transitional forms that he rejected all evidence to the contrary. This included a lack of confirmation from the fossil record and the fact that in virtually all recorded cases of the establishment of a new breed of domesticated animal or plant, the progenitor had emerged "per saltum," with its novel feature or features fully formed, and was subsequently bred with "normal" mates to produce more of its kind (Huxley 1860; Mivart 1871).

These observations were not, however, lost on all evolutionists of Darwin's day. Huxley (1860) and Mivart (1871) used some of the same examples of the establishment of new domesticates to which Darwin denied any evolutionary significance to argue for the saltational appearance of novel features and thus of new species. Jenkin (1867) cited both the sudden appearance in the fossil record of organisms with novel yet fully formed features and the absence among living forms of transitional forms as evidence against Darwin's claim that evolutionary change is smoothly transitional and predominantly gradual. Mivart (1871) reiterated Jenkin's refutation and additionally proposed that the emergence of anatomical novelty, and thus of new species, results from a reorganization that occurs very early in an individual's development, when all elements of this reorganization achieve a new state of viable equilibrium.

Although Darwin occasionally remarked that selection could not act on a feature unless it already existed, his perception of evolution as the process of adaptation extended over vast amounts of time meant that he conflated two different processes, namely, the survival of species (or the persistence of novelty) and the origin of species (or the emergence of novelty). Nevertheless, the distinction between the two processes did not escape other evolutionists. Inherent in Mivart's (1871) and subsequently Bateson's (1894) developmentally based formulations about the emergence of evolutionary significant change was the recognition that one should dissociate adaptation or the survival of a species from any process that led to its appearance. Indeed, this distinction between the origin and survival of species was central to the botanist de Vries's (1910a, 1910b) theories of mutation and intracellular pangenesis and subsequently to Morgan's (1903), Goldschmidt's (1940), and Schindewolf's (1950) criticism and rejection of Darwinism.

In light of the various counterarguments to Darwin's conception of evolution, one might reasonably wonder how Darwinism came to be the dominant evolutionary theory of the later twentieth century. This shift can be traced to the very same Morgan who had initially been one of Darwin's harshest critics (Schwartz 1999). It is a curious twist of history that, after rejecting all biological endeavors with the sole exception of genetics as being relevant to the study of evolution (Morgan 1910), Morgan went on to establish the first fruit-fly population-genetics laboratory. Experiments initially configured to demonstrate the validity of the "chromosome theory," and consequently to map "genes" on chromosomes, eventually led Morgan to propose a scenario in which Mendelism—which was seen by Mendelians as supporting the notion that traits, the individuals that bore them, and the species these individuals constituted were distinct and discontinuous entities—could be melded with Darwinism—in which variation was seen as continuous and, although absent from the fossil record and between extant species, the emergence of novel features and of new species was a smoothly continuous process of transformation (see the review in Schwartz 1999).

To his credit, however, in the course of arriving at this presumed epiphany, Morgan (e.g., 1916) introduced into the discussion of evolution some missing yet important elements: Mutation is random; mutations underlie the variations upon which selection acts; the basis of any mutation, large or small, is the same; and observations derived from laboratory experiments on heredity are relevant to understanding these processes in nature (Schwartz 1999). Nevertheless, Morgan succumbed to his predispositions. For example, while rightly asserting that if mutation was random, the probability of subsequent mutations' continuing a course of transformation that was seemingly foreshadowed by the first mutation was like a coin toss—each toss or mutation reset the probability to fifty-fifty—

Morgan contradicted himself by claiming that a mutation in a certain direction actually predisposed subsequent mutations to proceed in that direction.

But Morgan went even further. Like Darwin, he ended up embracing as biologically relevant only a certain kind of observation derived from his fruit-fly breeding colonies. That is, although he and his coworkers recorded numerous instances of the sudden appearance in one generation of individuals with large-scale morphological changes as well as individuals with minor changes, and they successfully bred both "kinds" of these individuals with normal or "wild"-type individuals to produce more of the different individuals, Morgan (e.g., Morgan et al. 1926) declared that the only evolutionary significant mutations were those that produced minor variations.

Morgan's reason for discarding the evidence of large-scale mutation as provoking marked morphological change and yet not interfering with reproductive viability was, however, pure conjecture: Large-scale mutations and their effects would, he declared, be too disruptive to the biology of organisms to be viable in nature. Consequently, despite having argued that large- and small-scale mutation derived from the same mechanism, and that observations in the laboratory reflected natural processes, Morgan consciously chose to disregard a major source of information as having any bearing whatsoever on evolutionary questions (Schwartz 2006a).

Having eliminated large-scale mutation and morphological change from the realm of biological reality, Morgan could then argue that, although Mendelism was based on a model of "discrete hereditary units," the mutational changes and the morphological changes they provoked were so slight that, in effect, genetic and morphological variations were continuous. As such, the decades-long intellectual schism between Mendelians and Darwinians was unnecessary and imaginary, for, in truth, the two "isms" were completely compatible (Schwartz 1999). In turn, this conflation permitted the recentralization of Darwin's earlier presumption that the process that leads to what would be considered evolutionary change is simply the process of adaptation extended over a vast period of time.

The Synthesis and Its Aftermath

Morgan's legacy to what became known as the "modern evolutionary synthesis" (Jepsen et al. 1963) is obvious and in part explains the resistance of its founders to nonselectionist if not also nongradualistic theories of evolutionary change, especially those of Goldschmidt (1940) and Schindewolf (1950; Schwartz 1999). Indeed, although not initially fully committed to gradualism or selectionist arguments (Dobzhansky 1937), Dobzhansky (1941) subsequently championed both in reaction to Goldschmidt's (1940) theory of systemic mutation, which made central the former scholar's work on chromosomal rearrangement in a genetically based theory of developmental reorganization that could lead to large-scale—that is, evolutionary—change. With Mayr's (1942) emphasis on the population, individual variation within populations due to micromutation, and selection pressures and the slowly emerging and ever-changing adaptations they induced as the basis of evolutionary change, a picture of evolution solidified in which it was impossible to define an evolutionary novelty except by reference to the claimed artifice of discontinuity between closely related taxa, both fossil and living.

Indeed, in his contribution to the Synthesis, Simpson (1944) used the presence of discontinuities, or "gaps," in the fossil record not as evidence of the abrupt appearance of novel morphology (and thus of species) but as the basis of his theory of quantum evolution. Given the unlikely event of an individual's remains becoming fossilized and subsequently persisting in the fossil record, these "gaps" represented periods when a small number of individuals were rapidly changing as they adapted under different selection pressures to different ecological niches. Once they made this rapid but smoothly continuous transformation from one ecological zone or plateau to another, however, individuals of this new species would continue to change, but now slowly and gradually, as they adapted to the slowly and gradually changing environment around them.

Although a paleontologist and therefore someone who, from Morgan (1910) on, was essentially defined as being unable to contribute to a discussion on the origin of species, Simpson (1944) nonetheless attempted to embrace Mayr and Dobzhansky's emphasis on populations and the presumed genetics of intrapopulational variation. He even represented his theory of quantum evolution diagrammatically in a manner similar to the mathematical population geneticist Sewall Wright's (e.g., 1931) shifting-balance theory, with organismal change being mediated and expedited by selection as a species traversed from one adaptive peak through a valley to get to new adaptive peak (see chapter 11, this volume). When in a review of Simpson's monograph Wright (1945) took the paleontologist to task for misunderstanding the genetics underlying his model of the adaptive landscape, Simpson (e.g., 1953) became more committed to gradualism as the predominant tempo of evolutionary change.

Is Darwinian Evolution Biological?

Given that the 1940s were not too far removed in time from the clash between the first evolutionists and the creationists, it is not surprising to find in the writings of the founders of the Synthesis passages that sought to address the nonscientific elements of creationism. However, perhaps more interestingly, as Burkhardt (1977) argued, the founders of the Synthesis and their scions sought to clean up Darwin and Darwinism by seemingly expunging use–disuse argumentation from evolutionary discussion. Yet while specific reference to the words "use" and "disuse" may have been excised from the language of twentieth-century Darwinism, the underlying intent remained the same (Schwartz 2005b, 2008). Indeed, phrases that typify Darwinian arguments, such as "a feature was selected and evolved in order to . . . . ," underscore the persistence of use–disuse thinking despite the fact that, in their quest to sanitize and rewrite the history of Darwin, the neo-Darwinians purposefully promoted Lamarck as the sole author of the untenable claim that acquired characteristics can be passed on from one generation to the next (Burkhardt 1977). Witness the recent assertion that standing upright on branches with locked knees predisposed the hominid ancestor to bipedalism, for which specific signal-transduction pathways were subsequently selected in order to complete the evolutionary deed (Thorpe et al. 2007).

Further, it is important to understand that any formulation—Darwin's or the Synthesis's—of Darwinism relies on a force or forces external to the individual in shaping the "born" individual and its "born" descendants (Schwartz 2005a). This focus becomes obvious upon recognizing that in order for use–disuse and selection to play a role in molding an organism and its features, the individual and its traits must already be formed to some extent (Schwartz 2008). Even the concept of "sperm competition" (e.g., Birkhead and Møller 1998), while initially giving the impression of a focus on a preembryonic phase, makes sense only in the context of an adult (or at least reproductively mature) individual producing sperm that, if truly the case, "compete" to fertilize an ovum or ova, themselves the cellular product of a nonembryonic individual.

Equally situated in the "born" or at least somewhat formed individual is the notion of "selfish genes" (Dawkins 1976), which use the organism they create in order to replicate and extend their existence into future generations. Inherent in the conception of "selfish genes," which derives directly from the focus of population genetics, is the supposed existence of "genes for" traits. Thus, if a mutation changes a gene slightly, the trait it underlies will change accordingly. Indeed, beginning with Morgan, because of the emphasis in population genetics on a direct one-to-one relationship between a trait and a gene, evolutionists such as Williams (1966) could resort to the abstract, in which a gene is anything that is heritable and, under the direction of selection, can be molded to allow its bearers to adapt to their surroundings. A gene that confers a slight advantage to its bearer over its counterpart in another individual will be selected by means of selection acting on the trait itself.

But is this really how organisms develop and how novel features may arise? It seems not. True, there are differences, for example, between fruit flies and mice in number of orthologous homeobox genes that affect segmentation and the spatial positioning of appendages (Duboule and Dollé 1989). However, abundant evidence now demonstrates that differences between invertebrates and vertebrates result less from specific gene differences between diverse taxa than from different manners, in time and space, in which the same developmental molecules are recruited and subsequently interact to produce disparately configured organisms (e.g., Duboule and Dollé 1989; Stern et al. 2006). Consequently, it is not appropriate or even biologically real to think in terms of "genes for" any particular trait or structure.

This is not to say that one cannot identify what may be called genes in metazoans by way of recognizing start and stop codons. However, in contrast to bacteria, in which there is a predominant relationship between the linearity of nucleotide sequences and the coding of metabolically active proteins, in metazoans a “gene” can produce myriad proteins depending on how introns are alternatively spliced and whether transcription occurs in “sense,” “nonsense,” or combined “sense–nonsense” directions (Ast 2005).

Of further note regarding multicellular organisms, which subsume plants as well as metazoans, is the importance of epigenetic events (e.g., maternally induced DNA methylation, the role of RNA in “reintroducing” DNA nucleotide sequences not present in the P1 generation but present in earlier generations) in influencing development (Lolle et al. 2005; Rassoulzadegan et al. 2006; Stotz 2006). This clearly muddles any attempt to speak intelligibly about the reality of “genes for” any trait or behavior (Pearson 2006). In fact, accumulating evidence on the effect of molecular signaling from potential predators (vertebrates and invertebrates) on the development of size and shape, as well as on mode of reproduction (asexual or cloning versus reproductive), of the larvae of potential prey (e.g., Gilbert 2003; Vaughn and Strathman 2008) blurs further distinction between the organism, its genotype, and its environment. This realization makes it that much more wonderful, as Darwin, Huxley, and other Victorian evolutionists often remarked, that like tends to beget like. But it also helps focus attention on the real aspects of cells and “genes” and returns the discussion to the necessity of distinguishing between and disentangling notions of “evolution” and “adaptation” before embarking on a discussion of innovation.

Evolution versus Adaptation

Examples of invertebrate, amphibian, and fish larvae or embryos changing size, shape, and even mode of reproduction in response to chemical cues from potential predators in their “environment” would at first glance seem to validate the long-held belief that organismal change is nothing more than a process of adaptation extended across generations of individuals. After all, are these organisms not “adapting” to their environments?

Indeed, in the latter part of the twentieth century, the notion of an organism’s features being so potentially malleable (embodied in the phrase “phenotypic plasticity”) that studying and comparing them for purposes of phylogenetic reconstruction was seen as an exercise in futility (e.g., Gibbs et al. 2000; Sarich 1971) gained such status that it led to the virtual abandonment of morphologically based systematics and its replacement by an endeavor that became known as *molecular systematics* (see review in Schwartz 2005b). Curiously, and despite the fact that any molecular change that would affect, for example, protein folding or the efficacy of DNA repair would have enormous consequences for the integrity and reproducibility of an individual’s development (Schwartz and Maresca 2006), molecular systematics rested on the assumption that molecular change had absolutely no effect on the organism, even though it was viewed as an ongoing phenomenon.

Clearly lost from this conception is the history that preceded it, namely, that initial hypotheses about the relevance of DNA sequences and gene products of metazoans were based on bacteria, in which responses to "environmental conditions" appeared to generate a response in the individual (Jacob and Monod 1959). It is now known, however, that approximately 98 percent of a bacterium's genome is coding (encodes metabolically active proteins; Eisen 2000). In metazoans, it is approximately the reverse. Even in plants such as rice, the vast majority of the genome is noncoding (Goff et al. 2002). Nevertheless, once the realization that bacterial genomic change was correlated with adaptive change (as seen in Jacob and Monod's [1959] lac operan experiments) was naively applied to multicellular organisms, the molecular underpinnings of adaptation and thus also of evolution appeared verified. Consequently, it seemed entirely justified to refer interchangeably to changes in bacterial genomes as adaptive as well as evolutionary (Lenski and Travisano 1994) because the two concepts had been historically so conflated.

However, is molecular—nucleotide sequence—change in bacteria the same as molecular change in multicellular organisms? It is not. When bacterial nucleotide sequences change, and not because of lateral transmission, it is because the bacteria are adapting to their surrounding circumstances. Jacob and Monod's (1959) early experiments with lactose-rich versus depauperate environments were a clear demonstration of bacterial adaptation. But if, as seems true, mutation in nucleotide sequences is random, then in multicellular organisms such change would have a much higher probability of affecting promoter and control regions, or introns, than coding regions (Schwartz and Maresca 2006).

Consequently, given that coordination of the interplay between transcription factors and other regulatory molecules and promoter and control regions is crucial to the development of a viable organism, were it true that unconstrained mutation affecting nucleotide sequence did occur, we would expect to see evidence either of rampant extinction or of unbridled morphological novelty emerging with virtually every generation. Yet, again as Victorian evolutionists well knew, like tends to beget like.

The skeptic, however, might ask why instances in which the larvae or embryos of metazoans alter development, and thus adult size and/or shape, in response to chemical or other stimuli from potential predators are not evidence of evolution. After all, are these not examples of the emergence of morphological novelty resulting from an adaptive response to a cue or stimulus in the organism's environment? At first glance, this might appear to be so. However, these examples are similar to earlier described cases of progenesis in amphibians and Arctic insects. Here, acceleration of sexual maturation in response to changing environmental conditions truncates normal metamorphosis into somatic adulthood to create larval forms that can reproduce (de Beer 1930; Gould 1977). That is, the "ability" to adjust to differing environmental conditions—whether by becoming smaller in size, producing or increasing "armature," or switching from sexual to asexual reproduction in response to stimuli from predators—while certainly presenting phenotypic plasticity and appearing to be adaptive, more accurately reflects genomic plasticity. This can reasonably also include sex determination in various fish and reptiles in response to temperature or crowding (see the review in Streelman et al. 2007).

Yet, similar to the necessity of a feature's being present before selection can "act" on it, the basis of or potential for genomic plasticity (or reactivity, sensu Gilbert 2003) must already be present in a gamete's genome for elements of intra- and intercellular signaling to be affected by external stimuli. That this should be true at least to some extent comes from observing that larvae or embryos of generations that are not subjected to such external cues or stressors develop into the typical adult size and/or form (e.g., as in the axolotl [de Beer 1930; Gould 1977] and Alaskan sticklebacks [Cresko et al. 2004]). Consequently, these examples of morphological difference from one generation to the next, rather than being Darwinian in demonstrating either the gradual appearance of structural change or the synonymy of adaptation and evolution, more reasonably reflect these organisms' sphere of possible adaptation, the molecular basis of which might have itself been the evolutionary novelty.

The Origin of Organismal Novelty

On the presumption that there is sufficient biological information to pursue a research program in which processes underlying adaptation are decoupled from those underlying the origin of novelty, it might seem that cultural "invention" could correspond to biological innovation (the emergence or origination of organismal novelty) and cultural "innovation" to biological adaptation. However, before we can explore this potential correspondence, it is necessary to understand how organismal novelty might arise.

For example, the emergence of multicellular organisms probably resulted from gene duplication and a massive increase in DNA, followed by the functional divergence of new genes (see the discussion in Maresca and Schwartz 2006). New morphologies likely result from the diversification and modification of regulatory signaling pathways (Gerhart and Kirschner 1997) as well as from changes in the expression of developmentally regulated genes via mutations affecting promoter regions and/or transcription factors (Grzeschik 2002). Nevertheless, because individuals of the same species are basically similar and differ from other species because they all possess the feature or features that make their species distinct, a biological hurdle must be overcome, namely, how to disrupt DNA homeostasis and tightly constrained developmental signaling pathways mediated by stress (heat-shock) proteins that act to prevent change from occurring (Maresca and Schwartz 2006). Given that the only constant physical source of (point) mutation is ultraviolet radiation, and spontaneous mutation rates are incredibly low (10^{-8} to 10^{-9}), one must seek a mechanism that could increase the *effective* mutation rate (Maresca and Schwartz 2006).

First, let us use the term "mutation" in the broadest sense, to refer not only to changes in DNA sequence, chromosomal arrangement, or gene duplication, but also to changes in, for example, protein folding, input–output "switches," "plug-ins," intron splicing, diffusion of morphogenetic gradients, and timing and location of expression of developmentally regulated genes. In this context, emphasis shifts from DNA alone to elements that affect the regulation of development. However, with myriad molecular safeguards, primarily heat-shock or stress proteins, in the cell to prevent derailment of a particular signaling pathway and thus of a particular course of development, one way in which the potential for organismal change can be introduced is to overtax the ability of molecular "housekeepers" to maintain homeostasis (Maresca and Schwartz 2006). Because all organisms with a heat-shock response can adjust their response "window" to adapt to changes in the intensity of stressors as long as the stress is not too sudden and intense, a possible provocateur of change would be a stress spike that exceeds the cell's capacity to produce sufficient heat-shock proteins to perform all the housekeeping duties that would prevent or weed out the potential for change (Maresca and Schwartz 2006).

Given that different tissues have different heat-shock responses, the potential effects of a stress spike will be different throughout an individual, as it also will be between individuals, who would thus not respond molecularly in the same way. Further, whatever potential for novel regulatory networks a stressor may introduce, the only cells in which this has potential evolutionary significance are the sex cells (Maresca and Schwartz 2006; Schwartz 1999). Effects on somatic cells die with their bearers. But if each individual can have a slightly different response to overstress, how do many individuals end up with the potential for and, if not lethal, the expression of, organismal novelty?

As Bateson (1913) recognized decades ago, most nonlethal mutations must arise in the recessive (inactive, unexpressed) state because most mutations in the dominant state are lethal. In the inactive state, a "mutation" can spread silently throughout a population (Fisher 1930; Haldane 1932; Wright 1932). If the population is small and/or there is a certain amount of inbreeding, a "mutation" will spread more quickly (Haldane 1932; Wright 1932). At some point, many individuals will have inherited the "mutation" in its inactive state, that is, will be heterozygous for it. Perhaps, during this period, the population is again overstressed and other potentials for change in the regulation of development are introduced. With heterozygote saturation, the likelihood of homozygotes for the "mutation" emerging increases (Schwartz 1999). If the reconfigured signaling pathway does not interfere with the viability of the zygote, embryo, or larva, or a later developmental stage, multiple individuals with the resultant novelty will emerge. In turn, perhaps abetted by some form of species mate recognition, the bearers of the novelty will interbreed and produce more of their kind. Eventually, as we know must occur, the recessive becomes dominant (active, expressed), and heterozygosity emerges.

An interesting consequence of this model of organismal change is that while the "environment," in the form of a stressor, is the provocateur of potential change, the impetus for the novelty and thus the novelty itself are divorced from the circumstances in which its bearers find themselves. In other words, the persistence of a novelty is more a function of its not interfering with the survivability of organisms than it is of the feature's being necessary for the survival of the individuals that possess it (Schwartz 1999).

Once a "significant" (significant being, of course, often mostly in the eye of the beholder) evolutionary novelty such as the arthropod body plan or the vertebrate tooth-bearing jaw has been established, modification of the signaling pathway underlying it is commonplace, giving rise to different versions of that particular Bauplan (Hulsey et al. 2006; Ronshaugen et al. 2002). I do not use the term "variation" to mean intraspecific or individual variation but rather, as Bateson (1894) used the term, to refer to taxically relevant difference. That is, whereas the former reflects differences in *degree* of expression or manifestation of a particular morphology, such as larger or smaller appendages of the same configuration, the latter reflects taxonomically distinctive configurations, or *kinds*, of morphologies such as differently configured or different numbers of appendages (Schwartz 2006b). Developmentally, there is a hierarchy of instructional information that spans from gene-regulatory networks (GRNs) that underlie basic body plans to gene batteries (DGBs) involved in the terminal differentiation of tissues and structures (Davidson and Erwin 2006). In the context of the discussion here, different levels of diversification of GRNs would underlie taxic diversity, from the establishment of major clades to the subclades and species that form them, which would require various alterations of signaling pathways. The final DGBs would provide the between-individual variability that typifies any species and would result from differential expression of extant signaling pathways.

Organismal Innovation and Phylogenetic Reconstruction

In terms of phylogenetic reconstruction, the loss of features is cladistically equivalent to the origination of these features because both phenomena reflect deviation from an ancestral or theoretically more primitive condition. For example, the development of fish with tooth-bearing jaws is derived relative to the jawless agnathan configuration, but the subsequent loss of pharyngeal teeth in some teleosts would be considered another level of derivedness because this would be a relatively rare condition among the diversity of pharyngeally toothed taxa.

However, whereas determination of the phylogenetic valence of derivedness may be based on relative uniqueness, the developmental context of the emergence of morphological innovation is not equivalent to its subsequent alteration, especially in reduction in or loss altogether of structure. For example, the origination of limbs with terminal digits required a tightly constrained *Hox* gene-regulated signaling pathway (Tarchini et al. 2006), whereas synpolydactyly can result from mutations in the *Hox-D13* gene alone (Muragaki et al. 1996). Although in fish the details of the signaling pathways underlying the formation of pelvic fins, eyes, pigmentation, armor, and teeth are still incompletely known, the specific gene or transcription factor whose inactivation or change in expression can cause the loss of each of these structures has been identified (Streelman et al. 2007). Consequently, one might be justified theoretically and for purposes of phylogenetic reconstruction in referring to structural "gain" and "loss" as cladistic equivalents, but developmentally they are not. Indeed, "gain" clearly lies in the domain of GRNs, whereas "loss" is disruption in an element of a GRN.

Conclusion

From the foregoing it is evident that neither a conception of cultural invention nor one of cultural innovation can be synonymized with organismal innovation (see chapter 2, this volume). From a biological perspective, the processes that precede the emergence of organismal novelty, while initially stochastic and affected by physical properties, must be integrated or the organism will not survive. Further, if the model of stress as a provocateur of regulatory and thus developmental change is in any way correct, there is no correlation between the emergent novel feature or structure and the environmental circumstances in which its bearers find themselves. In other words, while cultural inventions often result from necessity, structures do not emerge in order to serve a purpose or function or to solve some evolutionary problem. Simply put, if a novelty does not kill its bearer, it has it.

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5 Innovation, Replicative Behavior, and Evolvability: Contributions from Neuroscience and Human Decision-Making Theory

Daniel O. Larson

When faced with having to explain how and why innovations spread, we could adopt any number of explanatory stances. We could, for example, argue that the choice of adopting an innovation is tied to an individual's perception of how that innovation will become profitable under particular natural and social environmental circumstances. Conversely, we could argue that consideration of cost and profit is irrelevant and that humans are predisposed as psychological conformists to copy, imitate, or mimic the behavior of others. Motivational factors that may influence replicative behavior include direct rewards such as increased mating opportunities and the favor of elites (see chapter 7, this volume). I suggest that cultural rewards coevolved with neurological rewards that stem from the midbrain, which contains reward-related neural circuitry. In other words, there are both cultural incentives and neurobiological propensities for individuals to be creative and to adopt innovations.

I argue that human cognitive processes and brain functions have evolved from a shared common history of natural selection under varying social and natural pressures. The human brain is a unique organ that is a by-product of dual-inheritance processes—the interplay of culture and genes. I suggest that although neuroscience is a relatively new field, its potential to contribute to our understanding of human behavior and evolution is immense. It is a research domain that is inherently interdisciplinary and is grounded in the pursuit of empirical data using cutting-edge technologies. Ultimately, I want to understand the cultural and neurological processes that guide humans to accept or reject innovations. Do we, in fact, have propensities for conformist and replicative behaviors such as copying, mimicry, and imitation?

Invention and Innovation

Research associated with novelty, innovation, and acceptance or rejection of alternatives should involve the study of human decision-making heuristics, but the topic of how humans make cognitive decisions and take particular actions is a matter of debate (Bowles

2004; Gintis 2000). The prevailing belief is that much of human behavior is the product of calculated alternatives that optimize one's economic and biological success. It is presumed that humans are rational in their decision making and that, given a set of alternatives, the one that benefits the individual most will prevail.

Several researchers have challenged this traditional notion from an array of fields including economics, psychology, political science, and philosophy (Gintis et al. 2005). Herbert Simon, a pioneer in the challenge, posed an alternative perspective grounded in a conceptual framework he called *bounded rationality* (Simon 1982, 1990, 1996). He realized that human decision making is always restricted by human cognitive abilities, incomplete access to information, and environmental constraints, and, as such, rational or optimal decision making is a false premise. He argued that decision making and problem solving are not optimal but rather are near-optimal or adequate under the rubric of *satisficing*. Satisficing models dispense

> with the fiction of optimization, which in many real-world situations demands unrealistic assumptions about the knowledge, time, attention, and other resources available to humans. Note that dispensing with optimization (as a model cognitive process) does not imply that the outcome of a nonoptimizing strategy is bad. For instance, optimization is often based upon uncertain assumptions, which are themselves guesswork, and as a consequence, there may be about as many different outcomes of optimizing strategies as there are sets of assumptions. In these real-world cases, it is possible that simple and robust heuristics can match or even outperform a specific optimizing strategy. (Gigerenzer and Selten 2002: 4)

Models of bounded rationality are still in their developmental phase, although a number of researchers have enumerated the principles that guide this contemporary view (Callebaut and Laubichler 2007; Gigerenzer 2000; Gigerenzer and Selten 2002). Perhaps most pertinent to discussions of innovation are alternative heuristics used in decision making related to change in technologies and engineering design. Recently, Goldstein et al. (2001) identified several heuristics that humans employ in their deliberation of choice, including imitation, equal weighting, take the best, take the first, and small-sample inference. Under each heuristic, individuals are replicating the behavioral characteristics observed within the context of their specific social environments.

Clearly, each category is pertinent to the study of human behavior, but for the spread of innovation, I believe that imitation should figure most importantly. Imitation is beneficial because "it is a fast and frugal strategy that saves an organism from having to extract information from the environment anew, or from calculating from scratch" (Goldstein et al. 2001: 174). It also maximizes historic efficiency and success of prosperous individuals or groups (Brass and Heyes 2005; Schlag 1998). However, although imitation is typically a successful strategy, it is not without its limitations. For example, if physical or social conditions are highly variable, the previously beneficial strategy may become a liability, even deadly, under new conditions (Goldstein et al. 2001).

Conformist Behavior

Boyd and Richerson (2005; Richerson and Boyd 2005) suggest that through the coevolution of genes and culture we have evolved a predisposition for conformist behaviors. Thus, evolution preadapted us to living in larger groups and replicative behaviors were reinforced, which led to greater complexity in human relationships and political organization (Richerson and Boyd 2008). Mimicry, imitation, and copying have strong selective advantages (Henrich and Gil-White 2001), and according to Henrich and McElreath (2003: 126), "when information is costly, natural selection will favor cognitive mechanisms that allow individuals to extract adaptive information, strategies, practices, heuristics and beliefs from other members of their social group at a lower cost than through alternative individual mechanisms."

Richerson and Boyd (2005) discuss a list of cultural evolutionary forces that they posit have had a strong influence on the spread of innovations throughout prehistory and history. Random forces include *cultural mutation* and *cultural drift*, and decision-making forces (nonrandom forces) include *guided variation*, *direct-* and *indirect-bias transmission*, and *frequency-dependent transmission*. Guided variation involves individual trial-and-error learning and the selective retention of behaviors found to be successful. Direct-bias transmission is the copying, imitation, or mimicry of preexisting behaviors considered successful. Indirect-bias transmission refers to the selective copying, imitation, and mimicry of behaviors of individuals considered to have prestige or other characteristics that an individual emulates regardless of that behavior's cost and success. Frequency-dependent transmission refers to replicative behaviors that are chosen because of their commonness or rarity without consideration of cost or success.

Boyd and Richerson (1985, 2005) and colleagues (e.g., McElreath and Boyd 2007) have developed mathematical models of how such behavior would become fixed in the human evolutionary trajectory. As they and others (e.g., Henrich et al. 2004, 2006; chapter 7, this volume) have shown, the theory and mathematical modeling of conformist and replicative behaviors have a strong ethnographic empirical referent. My objective below is to present a research framework that incorporates evolutionary theory and techniques grounded in the neurosciences that will hopefully complement previous work on replicative behavior.

Theoretical Framework

Principles derived from bounded rationality and dual-inheritance theory predict that replicative behavior of technologies, labor structures, and communication strategies will explain the spread of many innovations evidenced by the archaeological record in multiple regions throughout the world (O'Brien 2008; various chapters in this volume). Indeed, scholars argue that our evolution as a species involved cognitive mechanisms that enhance our ability to learn and copy conspecifics. Language was the ultimate tool used for copying (Nowak 2006). The ability to mimic parents begins at the earliest developmental stages, and this infantile propensity is evidence for our evolved cognitive structures and associated phenotypic plasticity (Cacioppo et al. 2006; Falck-Ytter et al. 2006; Gergely and Csibra 2005; Gergely et al. 2002).

What rules govern the cognitive selection process under conditions of multiple goals? I presume that human decision-making processes are grounded in the idea that “human rational behavior . . . is shaped by a scissors whose two blades are the structure of task environments and the computational capabilities of the actor” (Simon 1990: 7). Simon, among others, stresses that human decision making can be understood only from an interdisciplinary perspective and that human decision making is linked in multifaceted ways to evolutionary developments in human neural cognition, biochemical process, and evolutionary history. I argue here that decision-making heuristics—including imitation, copying, and mimicry—are all evolved forms of conformist and replicative behaviors that have, on average, outperformed other cognitive and behavioral strategies.

Recent mathematical models of Hauert et al. (2007) support the argument that humans have a propensity for conformist and replicative behaviors as a result of natural selection and complex evolutional processes at the group level. An opportunity now exists to couple bounded rationality, dual-inheritance theory, and human decision-making theory with the theoretical perspectives and advanced methods of neuroscience—a relatively young field that examines brain anatomy, biochemistry, molecular neurology, neurogenetics, and human behavior, including cognitive functions and emotions (Kandel and Squire 2000; Kandel et al. 2000). An important unifying principle of neuroscience is acknowledgment that the human brain is an evolved organ that has been subject to both natural and cultural selective pressures.

Recent advances in the neurosciences are attributable in part to the development of new technologies such as functional magnetic resonance imaging. Real-time neurological processes can be visualized and measured with great accuracy, providing a basis for decoding how the brain functions, formulates memory, and experiences emotion (e.g., Cabeza and Kingstone 2001; Kandel et al. 2000; Lin et al. 2006, 2007). Rather than presupposing how the brain, mind, and cognition work, neuroscience produces observable, measurable evidence. For example, Fedulov and colleagues (e.g., Fedulov et al. 2007; Lin et al. 2007) focused on neurological processes associated with how we learn and store memories. This work has significant implications for evolutionary anthropology in that it sheds light on the neurological manner in which we learn our culture, create novelty, decide to accept or reject innovations, and store information for future recall. It turns out that, neurologically, there are bits of information that are stored by synapses in the brain by neuron-to-neuron connectivity, referred to as long-term *potentiation*. Clear instrumentally derived evidence shows both a synaptic growth and a reshaping associated with learning and memory acquisition (see also Costa-Mattioli et al. 2005).

One question raised by some of this work is whether we have identified memes or meme complexes (Aunger 2000; Dawkins 1999). Molecular studies of the constituents of the growth material will be important for future research. It is too early to confirm or reject the possibility of the presence of meme structure or some other, as-yet-to-be-named, memory property (more likely), but it is evident that mapping coded neurological properties or systems–networks–modules may be on the horizon (Kandel et al. 2000).

Indeed, neurological experiments demonstrate that the potential now exists to allow the generation of binary memory-coded structures of specific kinds of experiences. Experiments by Lin et al. (2007) have yielded 99 percent accuracy in predicting three types of trauma experienced by mice under prior laboratory conditions. The limited scope of this chapter precludes a detailed description of this research, but several important conclusions are pertinent to our consideration of human propensity for innovation, novelty, and probability reasoning:

1. The idea that the mammalian brain forms neural networks or modules seems to have empirical support, including abstract, general information and specific experience structures dubbed *neural cliques*. It would appear that the brain reflects a hierarchical structure that maximizes use of information and possible variability of alternative behaviors.
2. Information "is coded in a manner similar to the way that the four letters or nucleotides that make up DNA molecules can be combined in a virtually unlimited number of patterns to produce the seemingly infinite variety of organisms on earth" (Tsien 2007: 58; see also Gilbert 1996).
3. These structures provide the basis for perception, knowledge, and subsequent behavior.
4. Experiments are supported by laboratory instruments that deliver reliable measurements, produce mathematically described neurological data, and allow directly visualized neurological processes.
5. Perhaps most important to anthropologists, neural cliques, or brain codes, are not inheritable but are acquired only through experiences, unlike genetically inherited codes for breathing, heartbeat, control of thermal physiology, and other reflexes. Lin et al. (2006: 55) put it this way: "genetic codes act as predetermined scaffolds for behavior, providing blueprints for the development and basic functionality of the organism; brain codes are dynamic and self-organizing, arising out of internal structures and connectivity of neural networks upon behavioral experiences." This leads me to conclude that humans are structurally designed by natural selection for culture, including related propensities to replicate behaviors of conspecifics. These inferences, coupled with epigenetic studies (e.g., Müller and Newman 2003), hold promise for explaining human cognitive evolution and function.

Neurological research associated with education and learning has increased dramatically over the last decade and is intellectually rich concerning cognitive factors that generate novelty and control human decision making (Kandel et al. 2000; chapter 11, this volume). I include here studies of patients with damaged brains who experience a fluorescence of creativity and extraordinary memory capabilities; patients who lose all capability for creativity and remembering; people with extremely high scores on intelligence tests who exhibit only limited creative ability; and savants who excel in creative abilities and memory demonstrations (Dowling 2004; Ramachandran 2004).

Neuroscientific Evidence of Conformist and Replicative Behaviors

Combining neurosciences with well-designed psychological experiments has recently generated extraordinary results. In fact, scientists have detected neuroanatomical, neurobiological, and behavioral mechanisms that drive attitudes of conformity and replicative behavioral tendencies. Experiments in neuroeconomics and neuroimaging research have revealed specific mechanisms that control cognitive processes associated with how people construct and transmit cultural information regarding replicative and normative behavior. The lesson learned from this research is that any study of human decision making must take into account both cultural and neurological factors and propensities.

Copying, imitation, mimicry, and related neurological processes of cooperation may well relate to evolutionary events embedded in our primate lineage. Recent work with mirror neurons in monkeys suggests there is a neurological basis for recognizing what actions might be taken by another individual—the concept of mind reading (Dehaene et al. 2005; Johnson-Frey et al. 2005; Stamenov and Gallese 2002; Umiltà et al. 2001). Furthermore, human infants show strong propensities for mimicking behavior of a parent or siblings at a very early age (6 to 10 months). Cognitive–psychological and neurological research demonstrates that children in their very early developmental stages process information and store memory for appropriate and inappropriate behaviors—what anthropologists term "cultural norms." Toddlers are willing to accept rules and guidelines as a part of their growing value structure. In effect, displays of normative and replicative behaviors reflect past actions that were copied, mimicked, or imitated and subsequently rewarded. Interestingly, there is also a strong propensity in children to punish norm violators.

The neurosciences have produced evidence that human propensities for conformist and replicative behaviors are reinforced by both cultural and neurological–biochemical reward systems. Specifically, Fehr and colleagues (Fehr et al. 2005; Kosfeld et al. 2005) demonstrated that neurological structures, biological chemistry, economic decision making, and human behavior are strongly linked. They argue that humans establish social norms and that violators of such norms risk the revenge of a community of reciprocators. This connectivity is evident in situations of experimental games involving prosocial and antisocial behaviors (Singer and Fehr 2005), which provide a basis for understanding replicative behavior and related brain activities and neurochemical processes. Specifically, players who detect replicative fair behaviors from other game participants experience both neurological (activation in the dorsal striatum) and neurochemical rewards (Delgado et al. 2003; Kosfeld et al. 2005). Particularly interesting is the evidence of a positive relationship between the neuropeptide oxytocin and human trusting and trustworthy behavior. I posit that oxytocin is the hormone that induces both cooperative and replicative behaviors (see Zak 2008).

De Quervain et al. (2004) found that under conditions of experimental games, humans have a strong predisposition to seek revenge when a social cheater has victimized them. The emotional dynamic (schadenfreude) expressed by their human subjects was captured using neuroimaging equipment at a point in the game when a player's opponent would elect to not reciprocate and/or to defect. De Quervain and colleagues found that the striatum increased its consumption of oxygen, which evidences the activation of neural networks (see also de Quervain and Papassotiropoulos 2006; Singer et al. 2006). The striatum becomes charged under pleasurable conditions, and thus there is a neurological reward to individuals when they personally punish norm violators (Sanfey et al. 2003). Rules for "fair play," or norms, clearly incorporate expectations that each player will reciprocate or replicate behaviors of other fair players. Natural selection must have favored both cultural and neurobiological mechanisms which reinforced and rewarded individuals who replicated the behaviors of conspecifics. I argue that replicative behaviors, in effect, contributed to the avoidance of norm violations with family and extended family members. Furthermore, I believe this neurological propensity is rooted in our cognitive structures associated with adaptive child and parent relationships.

Importantly, neuroeconomics has successfully demonstrated that preferences in economic decisions are not self-regarding, which supports alternative arguments presented by proponents of bounded rationality and gene-culture coevolution over mainstream economic theory (Fehr et al. 2005; Sanfey et al. 2003). Fehr et al. (2005) provide evidence that humans care about fairness, equity, and reciprocity as well as their own self-interest. This is an evolved component and an important part of our phenotypic plasticity.

Finally, I argue that the above-referenced studies offer indisputable neurological and biochemical evidence to support the arguments of Hauert et al. (2007) regarding the evolutionary benefits of conformist and replicative behaviors. Evolution would favor those societies that cooperated in a manner that benefited the group as a whole. If a group accepted the practice of punishing norm violators, and if individuals voluntarily commit to following group-sanctioned rules, then cooperative behavior emerges and cheaters are eliminated or greatly reduced. Group membership is in part defined by characteristics that are shared by a majority of the members who copy, mimic, and imitate normative behavior. Hauert et al. (2007: 1907) advance the following proposition: "Once established, group selection, conformism, and reputation effects may maintain prosocial norms and promote their spreading. Eventually, institutions for punishing free-riders may arise, or genetic predispositions to punish dissidents."

The theoretical arguments and mathematical modeling discussed in this section support Nowak's (2006) claim that numbers and behavioral experiments can generate clarity and beauty of scientific thought. Neurological evidence for "hardwired" propensities of conformists and replicative behavior is, in my mind, compelling, but I would also opine that an individual's expressed behavior is mediated by both epigenetic and cultural factors that are historical (life experiences and culture histories) and individualistic.

Conclusions

Neuroscience research related to human propensities for replicating behaviors of conspecifics, coupled with theoretical and mathematical arguments, will go a long way toward explaining the spread of innovations in technology, labor organization, language, and a host of other behavioral characteristics evidenced archaeologically and ethnographically. An evolutionary process such as the one I have argued for here and elsewhere (Larson 2005) is compatible with complex evolutionary dynamics (Nowak 2006), cognitive evolutionary theory (Heyes and Huber 2000), and processes associated with phenotypic plasticity and the evolution of human behavior (Müller and Newman 2003).

I would be the first to concede that progress in the scientific explanation of human evolution and cultural change remains rudimentary. I would assert, however, that archaeologists and anthropologists, especially those new to the field, should be skeptical of those who claim evolutionary theory is useful only as a "metaphor" or "just so story" in the social sciences (e.g., Bamforth 2002; see chapter 2, this volume).

Progress in the neurosciences and advances in numerous kinds of biochemical and neuroimaging instrumentation offer unprecedented opportunities to observe human subjects at various levels of investigation (e.g., neurologically, biochemically, behaviorally) when subjected to laboratory and field experiments such as fairness games. If we as anthropologists and archaeologists elect to employ the powers of modern science in the study of human behavior, we need to restructure and reinvent our research approach to incorporate theoretical and methodological advances in evolutionary theory, experimental psychology, and the neurosciences. Using the methods of neuroimaging in archaeological research associated with technology is not new, but the theoretical and methodological approaches that I advocate here may be somewhat novel.

How can we further demonstrate scientifically that humans have a neurological propensity for replicative behavior, including copying, imitating, and mimicry? An appropriate strategy may be similar to that of neuroscientific research conducted to detect normative behavior and propensity for conformism. Under well-designed experimental conditions, we could give individuals and select groups opportunities to accept or reject innovations in technology, new ways of organizing labor, linguistic expression, or a host of other behaviors. This would entail the creation of various experiments, including psychological tests not unlike the work of Mesoudi (2007a, 2007b, 2008; chapter 11, this volume), Mesoudi and O'Brien (2008a, 2008b, 2008c), and Henrich et al. (2006).

During the process of interviews or laboratory experiments associated with acts of copying, mimicry, and imitation, brain scans and other types of neurological imaging (when possible) could be conducted to locate the cerebral regions that are activated under such experimental conditions. I predict that areas associated with both emotions and probability reasoning (the midbrain, striatum, orbitofrontal cortex, and prefrontal cortex) will signal strong neurological activity associated with human decisions to either accept or reject innovations. When individuals are experimentally placed in competing cooperative groups, replicating behavioral experiments should reveal strong evidence for copying conspecifics rather than members in other groups. These behavioral and emotional tendencies and related cognitive processes should be detectable using both experimental neurological imaging and biochemical testing (e.g., for oxytocin levels).

In the future, I believe psychological experiments and advances in the neurosciences will be invaluable to research associated with innovation and human decision-making processes. I expect that future scholars will generate indisputable evidence for both the ultimate and proximate causes behind the spread of technologies and other cultural characteristics. Should this proposal be accused of the *scientification* of human culture, then so be it.

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6 Innovation from EvoDevo to Human Culture

Werner Callebaut

Most chapters in this volume deal with innovation as an empirical or theoretical topic in evolutionary anthropology or in studies of cultural inheritance in general. However, innovation also features prominently in other social sciences, in particular economics and science and technology (policy) studies—so much so that some researchers have recently tried to find out "to what extent [there] now exists a unified community of innovation scholars [who] identify themselves with innovation studies as a field rather than particular sub-fields within other, more traditional disciplines" (Fagerberg and Verspagen 2006: 1). Moreover, the origin of evolutionary innovations, a problem in comparative evolutionary embryology (Love 2003), is a hot area in evolutionary developmental biology (EvoDevo), which contributes to our understanding of evolution by focusing on the contributions of development to the origin of phenotypic novelties (Müller 2007; Müller and Newman 2005).

The three scientific communities loosely referred to here[1]—anthropologists, economists, and biologists with an interest in innovation—have barely interacted hitherto, but awareness that their closer interaction could benefit all parties involved is growing (Erwin and Krakauer 2004). This chapter aims to modestly contribute to the long-term project of a *general theory of innovation* in a rather indirect way, through a comparative analysis of the reasons for the neglect throughout much of the twentieth century of innovation and novelty in diverse fields and through a reflection on the various ways in which this bias is being overcome. I do not consider innovation in anthropology per se, which is covered elsewhere in this volume, but will focus on three cases that, at least prima facie, are completely disparate: the synthetic theory in evolutionary biology, neoclassical economics, and logical-empiricist philosophy of science. My view is that an adequate understanding of cultural evolution, human or animal, requires us to seriously take into account ontogeny and that, more generally, EvoDevo offers some resources that may help us correct the selectionist and adaptationist biases that characterize not only much of evolutionary psychology (Richardson 2007) but also much, if not most, work in animal-behavior studies (Callebaut 2007; see also Griffiths 2007; Wimsatt 2006; Wimsatt and Griesemer 2007).

Toward a General Theory of Innovation?

Reporting on a workshop on Innovation in Natural, Experimental and Applied Evolution held at the Santa Fe Institute in 2004, Erwin and Krakauer (2004: 1119) suggested going beyond occasional reciprocal exchanges of "principles" between researchers working on biological and technological innovation and called for "a general theory of innovation within which to organize existing case studies and models." They went on to suggest that a theory uniting biology with technology would require "some new combination of the dynamics of development (or construction more generally) and selection" and probably also "nontraditional models of computation coupled to a better understanding of the complex feedback present between individuals and their environments" (p. 1119).

Regarding dynamics, evolution can be regarded as the exploration of morphospace by populations (Mitteröcker and Huttegger 2009). State space typically is represented as a configuration space with concepts of neighborhood and distance defined by variable operators such as mutation and/or recombination. However, not all variation-generating processes induce well-defined topological structures. Shpak and Wagner (2000: 41) suspect that "notions of proximity and distance are not defined for a process of unequal crossover," an example of innovation in which the number of elements can change as a result of the action of an operator, thus leading to more or fewer copies of the gene. Unequal crossover "defines a directionality to evolution which is independent of selection." Other innovation processes may likewise lead to unconventional topologies.[2]

Regarding the feedback between individual and environment, two obvious avenues to explore are biological niche construction (Odling-Smee et al. 2003) and its economic and cultural equivalents (e.g., Anderson 1991) and the hierarchical organization of life, which implies the breakdown of the traditional equation of *selection* as a causal process and *sorting*, the differential birth and death among varying organisms within a population. Sorting can arise from selection at the focal level itself and as a consequence either of downward causation from processes acting on individuals at higher levels or upward causation from lower levels (Vrba and Gould 1986).

The call for the Altenberg Workshop on Innovation in Cultural Systems: Contributions from Evolutionary Anthropology (2007), which produced the present volume, echoed Erwin and Krakauer's reference to economist Joseph Schumpeter's (1934) celebrated distinction between *invention*—the creation and establishment of something new—and *innovation*—an invention that becomes economically successful and earns profits. This distinction, in turn, resonates with the one commonly made in evolutionary biology between the sources of genetic and phenotypic variability among organisms and the factors leading to the fixation of a favored variant within a population (e.g., Müller and Newman 2005). Both distinctions highlight "the elusive nature of innovation with its connotation of influence and success" (Erwin and Krakauer 2004: 1117). A *positive bias* (Kimberly 1981) thus pervades the study of human-made innovations, including scientific discoveries. Innovation is typically viewed as a "good thing" because the new idea must be useful—profitable, constructive, solving a problem that is perceived as such. (A new idea that is not perceived as useful is usually called a "mistake.") Likewise, in-depth appraisals of the role of the entrepreneur are rare, and glorification is usual (Evans 1949).

Is a general theory of innovation as called for by Erwin and Krakauer (2004) desirable, and if so, is it in the cards? We will find out only by trying to develop it! My strategy in this chapter is to probe the solidity of various attempts to "evolutionize" the social sciences in the last three decades or so and to compare them with some of the recent developments in developmental and evolutionary biology that culminated in the advent of EvoDevo. I include the philosophy of science in this enterprise because I am convinced that a consistently "naturalized" philosophy (Callebaut 1993; Giere 1988), of which evolutionary epistemology is an integral part (Callebaut and Pinxten 1987; Callebaut and Stotz 1998; Hull 1988), must crucially include economic, psychological, sociological, and other social-scientific considerations in addition to being thoroughly informed by the history of science and other human cognitive enterprises. For our purposes here, "naturalism" can be defined as the view that "theories come to be accepted (or not) through a natural process involving both individual judgment and social interaction," without any appeal to supposed rational principles of theory choice ("rationalism"; Giere 1988: 7). Evolutionary epistemology thus becomes a chapter in the study of cultural evolution (Hull 1988). Innovation as understood in these various fields will be the test case for my probing.

A Comparative Case Study

A comparison of innovation as understood in biology, economics, and philosophy may seem far-fetched, but it seems to me to make perfect sense if we take into account the rather advanced state of the art in evolutionary modeling and theorizing in various fields and the impressive cross-fertilization between fields that is currently taking place (Boschma and Frenken 2005; Carrier 2005; Frey and Stutzer 2007; Martens 2004). Specifically, Mesoudi et al.'s (2006) attempt to create a unified science of cultural evolution by "outlining the methods and approaches employed by the principal subdisciplines of evolutionary biology and assessing whether there is an existing or potential corresponding approach to the study of cultural evolution" (p. 329) can be a methodological anchoring point for my endeavor. As they point out,

> Existing approaches within anthropology and archaeology demonstrate a good match with the macroevolutionary methods of systematics, paleobiology, and biogeography, whereas mathematical models derived from population genetics have been successfully developed to study cultural microevolution. Much potential exists for experimental simulations and field studies of cultural microevolution, where there are opportunities to borrow further methods and hypotheses from biology. Potential also exists for the cultural equivalent of molecular genetics in "social cognitive neuroscience," although many fundamental issues have yet to be resolved. (Mesoudi et al. 2006: 329)

The *organismic systems approach* proposed by Callebaut et al. (2007) as a framework for extending Modern Synthesis evolutionary theory (see also Müller 2007) differs from Mesoudi et al.'s proposal mainly in that it puts more emphasis on epigenetic issues—a need that Mesoudi and O'Brien (2008: 63) recognize when they describe several parallels between the hierarchically structured, "recipe-like organization of behavioral knowledge" and the manner in which biological organisms develop. As a philosophical naturalist, I also want to be more critical when it comes to embracing game-theoretical modeling tools, which may smack of aprioristic rationalism (Callebaut 2007). I am also more impressed than Mesoudi et al. (2006) seem to be by arguments to the effect that there is a profound functional discontinuity between human and nonhuman minds and cultures that results from our unique capability to symbolize (Penn et al. 2007) and from different mechanisms of cultural propagation (Sperber and Claidière 2006). However, these differences need not further concern us here.

Evolutionary Biology

In biology, where, contrary to the social sciences, it has long been accepted that "nothing makes sense except in the light of evolution" (Dobzhansky 1970: 5–6), there is a growing consensus that *origination*, in the sense of the first formation of biological structures (Newman and Müller 2005), and *innovation*, the evolutionary modes and mechanisms underlying novelty generation (Müller 2002, 2003), are underrepresented in the standard theory with its focus on variation and adaptation (Müller and Newman 2005). This neglect is a consequence of the "black-boxing" of development in the Modern Synthesis. Whereas the initiating causes of innovation, acting at the population level, are held to be unspecific, the conditions for the physical realization of specific novelties must be sought in development. EvoDevo points the way to a balanced integration of the "innovation triad" of origination, innovation, and novelty (Müller and Newman 2005), as well as related topics such as homology, phenotypic plasticity, and modularity, into an extended synthesis (Callebaut et al. 2007).

Neoclassical Economics

In economics, Schumpeter's (1934) innovating entrepreneur has long been recognized as "the apex of the hierarchy that determines the behavior of the firm and thereby bears a heavy responsibility for the vitality of the free enterprise society" (Baumol 1968: 64). And yet neoclassical economics, which continues to dominate the field despite increasing discontent, has failed for more than a century to develop an adequate formal analysis of entrepreneurship and innovation and of technical and institutional change (Freeman 1988, 1991). In recent decades, evolutionary economics (e.g., Dopfer 2005; Hodgson 1993a; Nelson and Winter 1982; Witt 2003) and the new institutional economics (e.g., Brette 2006) have set out to correct this bias by viewing economic change (as the classical "political economists" did) as just one aspect of the general question of evolution and understanding economies in evolutionary terms rather than those of traditional equilibrium assumptions.

Philosophy of Science

In line with the older antipsychologism of Frege and Wittgenstein, which remains influential to this day (Kitcher 1992), philosophers of science in the 1930s aligned to exclude the *context of discovery* from philosophical scrutiny. Their "logic of science" now focused exclusively on the so-called rational reconstruction of the *context of justification*—a move that made Popper (1959) deny the very existence of the subject matter that the title of his publication *The Logic of Scientific Discovery* announced (Simon 1977). As a result, with few exceptions, discovery and invention were relegated to investigation by cognitive psychologists, artificial intelligencers, and historians and sociologists of science and technology (e.g., Brannigan 1981; Cozzens 1989; Gorman et al. 2005; Merton 1973; Mulkay 1972)—so much so that when Thomas Nickles, the editor of a double volume on scientific discovery, proudly announced in his introductory essay that his collection "open[ed] up a new period in philosophy of science, one in which discovery, innovation, and problem solving will take their places as a legitimate area of study" (Nickles 1980: 2), he had to admit that "philosophers of science themselves are just now finding their sea legs in the hitherto unnavigable waters of scientific discovery" (p. 1).

The Long-Term Neglect of Innovation: Three Different Etiologies

We can now examine three areas in which long-term neglect of innovation has been the rule rather than the exception. The contextual specifics of the neglect differ, but the intellectual parallels are informative.

Evolutionary Biology and the Hardening of the Modern Synthesis

Complaints about the long-term neglect of the emergence of evolutionary novelties have frequently been voiced in evolutionary biology, beginning with Mayr, whose authority is invoked by EvoDevo proponents (e.g., Love 2003) as well as by behavioral biologists. Reader (2003) and Reader and Laland (2003; see also Ramsey et al. 2007) deal with the sources of new learned variations, the mechanisms underlying their generation, and the evolutionary effects newly generated variations may have on animal behavioral development and evolution. They regret that although as a component of behavioral flexibility animal innovation is important to the survival of many animals, animal innovation has been neglected by behavioral biologists, psychologists, social learning researchers, and conservation-minded biologists. Müller (2002), noting that the issue of innovation gains importance as the incongruences between molecular evolution and higher levels of organismal organization become more evident, suggests that innovation may have been given less attention than variation because the latter is much more frequent. Yet "innovations and novelties are found at all levels of organization and are fundamental for the process of phenotypic evolution" (Müller 2002: 829).

The root of this disregard is, in Gould's (1983) apt expression, the "hardening" of the Modern Synthesis, which did not lead to a literal "expulsion" of development (as well as of anthropology, ecology, and other fields) but rather to their "black-boxing," concomitant with an increasing fascination with population genetics (Smocovitis 1996). Population genetics still rules today. And yet,

> It is not within the problematic of population geneticists to discover the basic biological phenomena that govern evolutionary change, as it was for nuclear physics to discover universal forces between nuclear particles. The basic phenomena are already provided to population genetics by biological discoveries in classical and molecular genetics, cell biology, developmental biology, and ecology. Nor is it within the problematic of observational population genetics to discover the ways in which the operation of these causal phenomena can interact to produce effects. The elucidation of the structure of the network of causal pathways, and of the relation between the magnitudes of these elementary forces and their effects on evolution, is an entirely analytic problem. (Lewontin 2000: 193–194)

Such was the power of the genecentric perspective of the Modern Synthesis that it allowed one to gloss over the innovation problem by tacitly assuming that genes, acting in linear fashion, were the sole variable determinants of structure: "It was sufficient to focus on the dynamics of alleles in populations, assuming the prior existence of the phenotypic entities to which they correspond. No feedback between genes, gene products, the material properties of developmental systems and their environments was taken into account" (Müller 2008: 18). And yet, the capacities for the emergence of evolutionary novelty lie precisely in these interactions (Müller 2007; Müller and Newman 2005).

The late 1970s and early 1980s witnessed an increasing awareness of explanatory deficits in the prevailing paradigm. If neo-Darwinism seemed to work well for the population-genetic phenomena on which it concentrated, concern accumulated about its difficulty in accounting for characteristics of phenotypic evolution such as biased variation, rapid changes of form, the occurrence of nonadaptive traits, and the origination of higher level phenotypic organization such as homology and body plans (see Love [2003] and Müller [2008] and references therein). Most of the criticisms attributed the explanatory deficits of neo-Darwinism to its neglect of the generative processes that relate genotype to phenotype and to the exclusion of developmental theory from the evolutionary synthesis (Callebaut et al. 2007; Müller 2008).

Today, progress toward a general theory of invention and innovation is hindered by semantic inflation ("'innovation' and 'novelty' are two of the most overused and misunderstood words in evolutionary biology" [Erwin and Krakauer 2004: 1117]), problems of scale (e.g., mutations in homeobox genes and associated morphological changes that excite the epigeneticist may be dismissed as unimportant by, say, paleobiologists interested in larger-scale change), and the conflation of "invention as origin and fixation and innovation as consequence and success" (Erwin and Krakauer 2004: 1118).

Neoclassical Economics: "It's Exogenous, Stupid!"

Whereas classical political economists such as Smith, Ricardo, Mill, and Marx considered technological and institutional change (as well as demographical and other factors) as an integral part of their general theories of economic growth, they were expunged by the so-called fathers of the Marginalist Revolution of 1870–1874 (Walras in Switzerland, Jevons in Great Britain, and Menger in Austria). The Marginalist Revolution is often cited as a classic example of the phenomenon of *multiple discovery* (Lamb and Easton 1984; but see Ekelund and Hébert 2002).

The work of Schumpeter, the so-called father of innovation studies, must be placed and appreciated against the background of this tradition and, to a lesser extent, the classical tradition (Seligman 1971). For Schumpeter (1934), the root problem of any economic system is the attainment and maintenance of equilibrium. In his original model, economic activity was simply repetitive, so that the theory described a kind of circular flow. Into this model was injected a new production function—a new relation between input and output. This was generally realized by an innovator who was searching for greater profit than was available through normal channels. Schumpeter's definition of innovation included the introduction of a new *good*—one with which consumers are not yet familiar—or a new *quality* of a good and of a new *method* of production, which needs by no means be founded upon a *"scientifically" new* discovery but can also exist in a new way of handling a commodity commercially. His definition also comprised the opening up of a new market into which the particular branch of manufacture of the country in question has not previously entered, whether or not this market has existed before (niche construction); the conquest of a new source of supply of raw materials or half-manufactured goods, again irrespective of whether this source already existed or has to be created first; and carrying out the new organization of any industry, such as creating a monopoly position.

Schumpeter's linking of organizational, managerial, and social innovations with technical innovations has been rightly called revolutionary. However, for a contemporary understanding of (economic) innovation, "Schumpeter is not enough" (Freeman 1988; see also Fagerberg 2004): He paid little attention to the periphery of the world economy (what we have come to refer to as the "Third World"); he did not extend his analysis to international trade and the international diffusion of technology; he never formalized his models; and he compromised, we might say with hindsight, in that he had to reconcile his view of innovation, economic dynamism, and partial monopolistic appropriation of technological advances with his other view that equilibrium should still be defined in Walrasian terms.

Ubiquitous references to Schumpeter notwithstanding, a gulf has long separated his work from the neoclassical view. Freeman (1988) recalled that when Jewkes et al. (1958) wrote *The Sources of Invention*, they suggested three reasons for the general neglect of technical change by the economics profession: Economists were generally ignorant of science and technology and felt unprepared to venture into this unknown territory, they had few statistics at their disposal to guide them, and ever since the Great Depression of the 1930s they had been preoccupied mainly with cyclical fluctuations in the economy and the unemployment associated with them. The third explanation is particularly revealing: For Schumpeter, as for us, technical innovation is not a separate phenomenon but rather a crucial factor in the explanation of business cycles and the dynamics of economic growth generally.

While nominally accepting the importance of technical and institutional change, mainstream theory and most modeling have in practice divorced economics from these crucially important processes of change,

> relegating them to the status of "residual factors" or "exogenous shocks." . . . The various "growth accounting" exercises, even after allowing for an entire Kamasutra of variables, generally remain with a big unexplained "residual" . . . and fail to deal with the complementarities and interactions of these variables. . . . In general they are only a pale shadow of the growth theories of classical economics. (Freeman 1988: 2)

Concomitant with the neglect of technological change, neoclassical economic theory has failed to develop an illuminating formal analysis of entrepreneurship in the sense of the Schumpeterian innovator:

> The entrepreneur is at the same time one of the most intriguing and one of the most elusive characters in the cast that constitutes the subject of economic analysis. He has long been recognized as the apex of the hierarchy that determines the behavior of the firm and thereby bears a heavy responsibility for the vitality of the free enterprise society. In the writings of the classical economist his appearance was frequent, though he remained a shadowy entity without clearly defined form and function. Only Schumpeter and, to some degree, Professor [Frank H.] Knight succeeded in infusing him with life and in assigning to him a specific area of activity to any extent commensurate with his acknowledged importance. (Baumol 1968: 64)

Baumol (1968: 66) famously concluded that "the theoretical firm is entrepreneurless—the Prince of Denmark has been expunged from the discussion of Hamlet." In both simple and more sophisticated models of firm behavior, the firm must choose among alternative values for some well-defined variables such as price, output, and advertising outlay. Management is taken to consider the costs and revenues associated with each candidate set of values and to perform a calculation that yields maximum profit. "There matters rest, forever or until exogenous forces lead to an autonomous change in the environment" (Baumol 1968: 67). As an instrument of optimality analysis of well-defined problems, the extant theory of the firm is a theory of *management*—overseeing the ongoing efficiency of continuing processes—not entrepreneurship—locating new ideas and putting them in effect.

At the most fundamental level, neoclassical economics cannot come to grips with innovation and entrepreneurship because of the way it deals with *information.* The apex of neoclassical theorizing, the Arrow–Debreu formalization of competitive general equilibrium, is based on the hypothesis of perfect information—complete, perfect, and freely available knowledge of all prices and other characteristics of all goods and services traded on markets, now and in the future (Callebaut [2007] reviews Simon's "bounded rationality" alternative). This state of affairs explains why some economists have found it necessary to proclaim what for noneconomists is a truism—that agents cannot act on information they do not have. Simon has spent the best part of his polymath career pointing to "the discrepancy between the perfect human rationality that is assumed in classical and neoclassical economic theory and the reality of human life" and arguing that neither people's "knowledge nor their power of calculation allow them to achieve the high level of optimal adaptation of means to end that is posited in economics" (Simon 1992: 3). As Martens (2004: 19) points out, the perfect-information hypothesis "clashes with the very concept of innovation. Innovation implies that future knowledge is not presently available (otherwise it cannot be 'invented' or 'discovered') and presently available information is not generally and freely dispersed in the economy—in which case it would cease to be a unique piece of knowledge."

Logical Empiricism and the Abandonment of the Discovery Program

Discovery was an important methodological topic during the Scientific Revolution and after because employing the proper method of discovery was seen as an important mode of justification (Laudan 1980)—an idea that can actually be traced back to Aristotle (Hanson 1958a). By the mid-nineteenth century, two developments, which reinforced one another, tended to separate discovery from justification (Laudan 1980): a fallibilistic conception of theories ("the end of certainty") and acceptance of the view that "theories be evaluated wholly in terms of their consistency and their testable consequences and hence independently of the vagaries of their antecedent history" (Nickles 1980: 4).

The rise of the hypothetico-deductive method and concomitant abandonment of discovery methods per se—in particular, Peirce's "abduction" or "retroduction" (Paavola 2004; Simon 1977)—was consecrated in the dichotomy "context of discovery" versus "context of justification" dear to the logical empiricists (see chapter 2, this volume). It is often ascribed to Reichenbach, who introduced the distinction in the context of his explication of the logical empiricist's method of logical or rational reconstruction:

> We might say that [a logical reconstruction] corresponds to the form in which thinking processes are communicated to other persons instead of the form in which they are subjectively performed. . . . I shall introduce the terms context of discovery and context of justification to make this distinction.

> Then we have to say that epistemology is only occupied in constructing the context of justification. But even the way of presenting scientific theories is only an approximation to what we mean by the context of justification. Even in the written form scientific expositions do not always correspond to the exigencies of logic or suppress the traces of subjective motivation from which they started. (Reichenbach 1938: 6–7)

The further distinctions that are usually made in this respect—that the "psychological" ("sociological," "historical") is qualitatively different from the "logical," that discovery precedes justification, and so forth—cannot fairly be ascribed to Reichenbach (Glymour and Eberhardt 2008; Nickles 1980).

Popper (1959: 31) famously put the matter as follows in *The Logic of Scientific Discovery*, originally published in German in 1934: "My view of the matter, for what it is worth, is that there is no such thing as a logical method of having new ideas, or a logical reconstruction of this process." With few exceptions, this view remained the dominant one in the philosophy of science until Hanson (1958a, 1958b, 1960) questioned it and revindicated a place for a genuine "logic" of discovery.

The debate between the proponents of discovery and their foes, most notably Laudan, was documented by Nickles (1985), who insisted that "there is no *special* logic of discovery distinct from logic of justification" (Nickles 1985: 180)—the same logic can be used for both purposes. He also proposed the revival of a "generative conception of justification which goes beyond consequentialism to forge a strong linkage of generation (or rather, generalizability) with justification" (Nickles 1985: 177). Nickles (1985: 179) hinted at a naturalistic turn when asking whether "philosophers really have contributed much to practical theory of testing/justification."

Whereas Hanson unsuccessfully tried to resuscitate the old dream of a generative "logic," the Kuhnian challenge to the two-contexts distinction implied that nonrational elements persist even in the justification/testing of theories (Castle 2001). Whatever attention the discovery project still attracts seems to have more to do with the practical successes of automated "discovery" using classical artificial intelligence (Langley et al. 1987; Shrager and Langley 1990; Simon 1977) or connectionist approaches (Pennock 2000) than with sophisticated philosophical "arguments" (chapter 2, this volume). The philosophical naturalist will have to turn his or her attention to the social-scientific explanations of (multiple) scientific discovery that have been offered and try to make the best of them in the emerging, evolutionary framework.

It turns out, then, that Popper's romantic view of discovery belongs to the individualist *genius* account that has long been abandoned by students of cultural evolution, whereas anthropological and sociological thinkers from Kroeber (1917) on have articulated a zeitgeist account that could be quite easily recast in contemporary evolutionary terms, minus the original connotations of cultural determinism. Simonton's (1986) *chance* account, based on Monte Carlo simulations, could be made to conform to our current understanding of drift (as already conceived by Lamb and Easton 1984).

Conclusion: A Common Evolutionary Core

Biologists, economists, and philosophers of science have groped in multiple ways for novelty as "something that has not been there before." Such a quest presupposes criteria for sameness on the basis of which something can be established to be nontrivially different from things already in existence (Fontana 2001). Specifying these criteria has proven difficult in all three fields, but EvoDevo biology today seems to be on the most promising track.

In living systems, sameness results from common ancestry or independent convergent evolution. On one account, an organismal feature is novel if it is not homologous to any feature in the ancestral species (Müller and Wagner 1991). On this view, innovation represents a distinct kind of phenotypic change, differing from adaptive modification. The origin of novelty may be a result of different mechanisms than the mutations underlying variation and adaptations, and certain phenotypic changes may have more important and long-lasting consequences for evolutionary dynamics than mutational change. Whereas a central aim of the Modern Synthesis was the explanation of adaptive change as a population-dynamic event (viz., the correlation of phenotypic character variation with statistical gene frequencies in populations), EvoDevo seeks to explain phenotypic change through the alterations in the physical interactions among genes, cells, and tissues, whether they are adaptive or not (Müller 2007). EvoDevo thus represents a *causal-mechanistic approach* to understanding phenotypic change in evolution (Callebaut et al. 2007) that addresses many of the constituent features of phenotypic change, such as the generation of new structural elements (novelty), the establishment of standardized building units (modularity, homology), the arrangement of such units in lineage-specific combinations (body plans), and the repeated generation of similar forms in independent taxa (homoplasy). In addition, EvoDevo aims at explaining how development itself evolves and how the control of developmental processes is brought about by the interplay of genetic, epigenetic, and environmental factors. "With these goals, evo–devo moves the focus of attention to the qualitative phenomena of phenotypic organization and their mechanistic causes" (Müller 2007: 946).

Beginning with Veblen and Marshall, economists have been slow in moving beyond "the equilibrating and static theoretical system" to adopt an evolutionary approach (Hodgson 1993b: 406). They continue to be wary of "too literal" interpretations of the biological "analogy" (Nelson and Winter 1982; Witt 2003). In philosophy, most of the arguments deployed against evolutionary epistemology concerned "asymmetries" between biological and cultural evolution that have to do with the presumed uniqueness of human action and culture (Hull 1988).

The optimistic bet in the background of my comparison of biology, economics, and the philosophy of science is that the toolkit that EvoDevo offers today contains many more, and richer, resources than most advocates of evolutionary economics and evolutionary epistemology realize. For instance, the conflict between lawfulness and contingency (historicity) that Kroeber (1917), for one, identified correctly but could not resolve at the time is dealt with reasonably adequately in current evolutionary accounts under the labels of "path dependency," "inherency," and "generative entrenchment" (Callebaut et al. 2007). Or, economists' intuition that ideas, in order to be innovative, must be embodied by living people—which was explicated in a somewhat different context by Campbell (1979) in his account of "vehicles carrying knowledge"—could in principle be given a literal rendering in terms of hierarchical selection theory and EvoDevo. There is more to evolution than Dawkins.[3]

Notes

1. In fact, each of these communities can be decomposed into several clusters. The Web survey of innovation research carried out by Fagerberg and Verspagen (2006) among economists in 2004 and 2005 identified a large number of relatively small groups characterized by dense internal relationships defined along geographical and disciplinary lines. These smaller groups, however, are embedded in larger transnational clusters that are kept together by weak ties. I suspect that a rather similar picture would obtain for the anthropological and biological communities with an interest in innovation.

2. In the same vein, Stadler et al. (2001) have proposed to extend the explanatory level for phenotypic evolution from fitness considerations alone to include the topological structure of phenotype space as induced by the genotype–phenotype map.

3. I provide positive elements for the rapprochement envisaged here in Callebaut (n.d.).

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III CULTURAL INHERITANCE

7 The Evolution of Innovation-Enhancing Institutions

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This chapter applies an integrated approach to decision making and cultural evolution to examine the development of population-level differences in innovativeness. In referring to a group's *innovativeness*, I aim to highlight some of the factors or processes that favor both the generation of more *inventions* (meaning useful or adaptive novelties) and the spread those inventions through the population, making them, in this terminology, *innovations* (see chapter 1, this volume). My discussion has several parts. To lay a foundation for subsequent arguments, I begin by summarizing research showing how evolutionary theory can direct and inform our understanding of decision making, social learning, and cultural evolution. Building on this, I then examine how a population's size and its degree of *cultural interconnectedness* can influence rates of both innovation and invention.

After using a simple model to illustrate the relative importance of cultural interconnectedness compared to individual invention for the spread of innovations, I discuss a combination of ethnographic, historical, and archaeological cases to explore the relative importance of "mother necessity" and "heroic genius" versus recombination, lucky mistakes, and the accretion of small changes in driving invention (see chapter 15, this volume). This discussion suggests that, at best, "necessity" is neither necessary nor sufficient to explain invention and that invention processes are dominated by incremental additions, recombinations, and lucky errors, but not usually by revolutionary insights. This means that inventiveness is, at least in part, a product of large populations (which generate more lucky errors) and greater cultural interconnectedness.

Finally, I examine how greater interconnectedness in a population gives rise to a large-scale cooperative dilemma. Although some partial solutions to this dilemma have emerged across our species, only some societies have evolved the informal (and later formal) institutions—that is, cultural systems of reputation, signaling, and punishment—that favor the wide sharing of information, ideas, and insights. Theoretical work has revealed three avenues to solving such *n*-person cooperative dilemmas, but all three generate multiple stable equilibria, meaning that while they can stabilize cooperative information sharing, they can also stabilize "information hiding and free riding" as well as other non-group-beneficial behaviors. In such circumstances, processes of cultural group selection, which operate through various forms of competition among groups, can favor the evolution of those institutional forms that best promote the open dissemination so crucial to innovation. This line of thinking proposes that cultural evolution has favored the emergence of institutions that increase cultural interconnectedness and thereby stimulate both greater inventiveness and more innovation.

Theoretical Framework

With the physical endowments of a tropical ape, humans have successfully spread to nearly every corner of the globe in a relatively short period, from the dry savannas and tropical forests of equatorial Africa to the frozen tundra of the Arctic and the humid swamps of New Guinea. Humans are unique in their range of environments and the nature and diversity of their behavioral adaptations. Many local genetic adaptations exist in our species, but it seems certain that the same basic genetic endowment produces arctic foraging, tropical horticulture, and desert pastoralism—a constellation of adaptive patterns that represents a greater range of subsistence behavior than what is shown by the rest of the primate order combined.

The behavioral repertoires that permit such diverse adaptations to this range of environments are principally socially learned and represent cumulative cultural products that have been assembled and honed over generations (Henrich 2008). The tools, skills, and bodies of folk-biological knowledge on which foragers from the Arctic to the Kalahari rely are acquired developmentally, principally by observing and listening to older members of their social group. The same goes for food-preparation skills, many food preferences, and medical know-how (Billing and Sherman 1998; Lancy 1996). Numerous accounts of travelers, often experienced European explorers, stranded in places such as Australia, Amazonia, or the Arctic illustrate just how ineffective our rationality, evolved modules, and fitness-maximizing mechanisms are when they lack the relevant culturally transmitted input. In these cases, individuals freeze, starve, dehydrate, or mistakenly poison themselves while seeking to escape seemingly harsh environments in which any local adolescent equipped with a culturally inherited body of know-how could have easily survived (Henrich and McElreath 2003; Richerson and Boyd 2005). Even something as ancient and basic to human survival as making fire cannot readily be acquired without observing someone with expertise, a point emphasized by the fact that some isolated human foraging societies have lost this knowledge (Gott 2002; Holmberg 1950; Radcliffe-Brown 1964).

There seems little doubt that this emphasis and reliance on cultural learning extends to human social behavior. In both the laboratory and controlled field experiments, children and adults will readily acquire a wide range of social behaviors by means of imitation even when it is costly. In human societies, especially small-scale groups, complex kinship and political relationships, overlapping status differences and honor systems, marriage rules and preferences, and subtle notions of proper etiquette create culturally constructed obstacle courses that can be successfully navigated only by those with extensive cultural knowledge. As any ethnographer will attest, before a would-be Machiavellian can manipulate others to his or her own selfish ends, this individual has to master the local cultural systems, values, and expectations. Only then can he or she effectively "work" the system. One must be an excellent cultural learner *before* one can be an intelligent Machiavellian.

Building on the above insights, three decades of theoretical work applying the logic of natural selection to understanding our capacities for learning and decision making, and in particular to our capacities for social learning, has effectively shifted culture and cultural evolution into a larger, Darwinian framework for studying psychology and history (Boyd and Richerson 1985; Cavalli-Sforza 1971; Cavalli-Sforza and Feldman 1981; Henrich and Henrich 2007; Richerson and Boyd 1978, 2005; Shennan 2002). For our purposes, this approach provides a framework for first generating hypotheses about some of the microlevel psychological details of cultural learning and then constructing formal models of population processes that aggregate up from theoretically and empirically grounded microlevel decision mechanisms to population-level patterns. Below I apply this framework to understanding innovation.

Microlevel Processes of Decision Making Generate Culture

The general potency of human cultural learning, as well as several of the specific predictions arising from the above-mentioned approach, are substantiated by large bodies of experimental work in both social and developmental psychology, as well as by recent work in experimental economics. I point to only some of the highlights, to give a sense of the empirical underpinnings.

After more than two decades of research on cultural learning ("observational learning" or "modeling"), psychologist Bandura (1977) summarizes the spontaneous potency of cultural learning and its broad impacts on thinking and behavior:

> Modeling has been shown to be a highly effective means of establishing abstract or rule-governed behavior. On the basis of observationally derived rules, people learn, among other things, judgmental orientations, linguistic styles, conceptual schemes, information-processing strategies, cognitive operations, and standards of conduct. . . . Evidence that generalizable rules of thought and conduct can be induced through abstract modeling reveals the broad scope of observational learning. (p. 42)

> Observers display the same amount of observational learning regardless of whether they are informed in advance that correct imitations will be rewarded or are given no prior incentives to learn the modeled performances. (p. 38)

More specifically, the application of evolutionary theory to the questions of from *whom* individuals should learn, *how* they should integrate information gleaned from different individuals, and *when* they should rely on social learning versus individual experience (or rational calculation) has generated a series of hypotheses that find support from a wide range of experiments and field data. The approach suggests that learners—in order to most efficiently acquire adaptive behavior in noisy or stochastic environments—ought to be selective in terms of to whom they pay attention for the purposes of cultural learning. They should prefer those with greater skill, success, knowledge, health, and prestige,[1] while also using cues of self-similarity such as gender, size, and ethnicity to help ensure that what they learn is fit for their personal attributes and current or future social roles (see Henrich and Gil-White [2001] and Henrich and Henrich [2007] for reviews of the evidence).

The approach suggests that learners should aggregate information using conformist, or blending, algorithms (Boyd and Richerson 1985; Henrich and Boyd 1998, 2002), which reduce errors in learning (by averaging them out) and facilitate the extraction of useful information. Evidence from psychology (Asch 1951; Coultas 2004; Henrich and Gil-White 2001; Insko et al. 1985), archaeology (Mesoudi and O'Brien 2008a, 2008b), and economics (Apesteguia et al. 2007; Kroll and Levy 1992; Pingle 1995; Pingle and Day 1996) supports these predictions.

In addition to specifying to whom learners should pay attention and how they should integrate information gleaned from different models, this approach predicts how environmental uncertainty or problem ambiguity (problem difficulty) should impact the use of, or reliance on, social learning versus individual learning or cost–benefit evaluation. Consistent with these models, findings from psychology, anthropology, and economics indicate that as uncertainty rises, or as the difficulty/ambiguity of the problem increases, individuals' reliance on social learning increases (Davis 1984; McElreath et al. 2005; chapter 3, this volume). The same experiments indicate that this increased reliance on social learning is even more pronounced when incentives are increased. That is, perhaps nonintuitively, adding incentives magnifies the influence and importance of social learning (Baron et al. 1996).

Such laboratory experiments illustrate another key point from the theoretical work (Boyd and Richerson 1995): Adding or improving imitative opportunities for individual learners increases the total payoffs of the group. When individuals make decisions based only on their private information and evaluations, the group average is usually far from the optimum behavior. However, when imitation is permitted, the group's mean moves closer to and often approximates the optimum profit-making behavior (see chapter 11, this volume). This suggests that individuals are most likely to use imitation when they perceive (more or less accurately) their own skills or information to be worse than those they can copy.

These laboratory findings include numerous experiments involving monetary stakes, but we must also assess whether these theoretically derived insights are consistent with findings from the spread of novel technologies and practices in the real world. The vast diffusion-of-innovations literature has for six decades focused on understanding why novel techniques, technologies, and practices sometimes spread and other times do not (see chapter 1, this volume). Underpinning many of these investigations is the question of why some populations sometimes appear highly resistant to adopting what appears to be, in terms of economics or health, a beneficial novelty. Summarizing some of the principal findings from this extensive literature, Rogers (1995: 18) writes as follows:

> Diffusion investigations show that most individuals do not evaluate an innovation on the basis of scientific studies of its consequences, although such objective evaluations are not entirely irrelevant. . . . Instead, most people depend mainly upon a subjective evaluation of an innovation that is conveyed to them from other individuals like themselves who have previously adopted the innovation. This dependence on the experience of near peers suggests that the heart of the diffusion process consists of the modeling and imitation by potential adopters of their network partners who have adopted previously.

None of this is meant to suggest that costs and benefits, or individual evaluations of costs and benefits, are irrelevant or even unimportant. One individual in a community might, for a variety of potential reasons involving luck or individual initiative, obtain particularly high-quality information about the effectiveness of a new technology and adopt it. The adoption might result, for a farmer, in greater success in the form of higher crop yields. Our farmer's neighbors, impressed by the high yield, might imitate several of his techniques, including the new technology. As a consequence, the new technology may diffuse through the social networks of the community until all have adopted it. In this stylized example, all of the individuals in the community save one acquired the invention by imitating high-payoff individuals, and thus imitation is the heart of the process, but these learners exploited the superior cost–benefit information of one person.

Here is the take-home message: Because humans often rely heavily on learning from others, especially in incentivized situations involving ambiguous costs and benefits, a general approach to understanding innovation should take seriously the cultural nature of our species. Given that the invention or adoption of a novel practice or technology necessarily involves uncertain or ambiguous costs and benefits, owning to the lack of any direct experience from which to acquire such information, it seems plausible that social learning may be even *more* important for a theory of innovation than it is for other aspects of human decision making.

Innovation Is Fundamentally a Cultural and Social Process

Here I examine innovation and invention as cultural and social processes (recall that I partitioned invention and innovation at the outset). I first present a simple formal model that allows us to explore the relative contributions of independent invention, cultural learning, and the diversity of learners' associations to the spread of a novelty through a population. The findings, which are consistent with other more extensive explorations elsewhere, illustrate that "cultural interconnectedness" is crucial for innovation. I then examine inventions as incremental accumulations that depend crucially on recombination, happenstance, and luck and not so much on either individual heroic genius or mother necessity. Building from this discussion, I suggest that, given the importance of both recombination and luck in the invention process, both cultural interconnectedness and population size will be important for understanding both invention rates and innovation rates.

Cultural Interconnectedness

We can construct a simple model that connects individual decisions to create or adopt a novelty with the frequency of adoption of the novelty in the overall population. By partitioning individual invention and social learning, the model allows us to examine what kinds of characteristics make a population more innovative. Here, as above, inventions are useful, effective, and adaptive novelties that individuals create, whereas innovations are novelties that have successfully diffused through the population.

Consider a large population of identical individuals in which each develops a novelty with probability ε. If individuals do not invent the novelty themselves, they can observe k other individuals and can acquire it culturally from each, with probability λ, which captures a combination of individuals' cultural-learning abilities (vis-à-vis the thing being learned), the details of the novelty that make it more or less likely to spread, the effects of the novelty on individuals that might make them more likely to be paid attention to or learned from, and the willingness or ability of the other individual to transmit the novelty. Using this, we can compute the overall probability that each of our individuals acquires the novelty (see van Schaik and Pradhan 2003):

$$p = \varepsilon + (1-\varepsilon)\left(1-(1-\lambda p)^k\right)$$

Given that our individuals are identical, p also represents the expected frequency of individuals in the population who adopt the useful novelty after all learning is completed. If p is close to one, we can say the invention has spread widely and the group has *innovated*. Figure 7.1 is a plot of the numerical solutions to this equation for a range of values of k (along the horizontal axis) for three different values of ε. Note first that higher values of k (more associates to learn from) create a dramatic and highly nonlinear increase in the probability of acquiring the novelty, that is, of generating an innovation. For low values of k, the probability that any one person will adopt the trait is small, which implies that the final percentage of trait adopters in the population will be small. For example, when ε is 0.10 (a 10 percent chance of individual invention) and $k = 2$, the probability that an individual will acquire the novel trait is 12 percent. This means that, on average, only 12 percent of the population will eventually acquire the novelty.

However, for values of k greater than about 12, over 90 percent of the population will adopt the novelty. The shape of these curves shows what would empirically appear as threshold effects, especially when the trait is difficult to invent by experimentation or experience (low ε). Consider the curves for $\varepsilon = 0.01$ and 0.001. For values of k less than

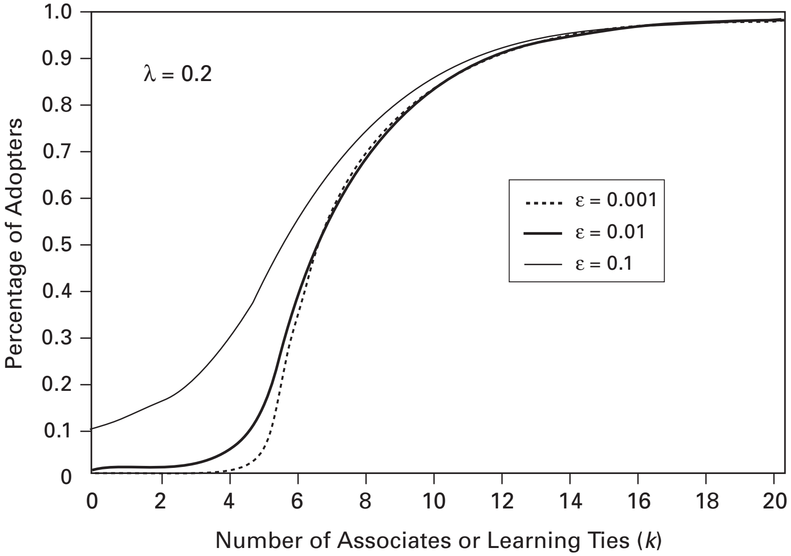

Figure 7.1
Plot of the relationship between *k*, the number of associates for a learner, and the percentage of adopters in the population once all individual and social learning is complete, for three value of ε (ε is the likelihood of individual invention, and λ is a measure of the effectiveness of cultural transmission between individuals).

about 5, few people adopt the novel trait. However, by the time *k* has reached 10, nearly 85 percent of the population is adopting it. Between $k = 5$ and $k = 7$, *p* spikes from about 0.05 to 0.58. This indicates that small differences in the number of people from which one can learn something can make a huge difference in the equilibrium percentage of the population adopting the novelty.

Figure 7.1 also shows that for high values of *k* there is relatively little difference in the curves despite the large difference (two orders of magnitude) in ε. A situation in which $\varepsilon = 0.10$ means that an individual has a 100 times greater chance of acquiring the trait by himself or herself, by means of, say, experimentation, than when $\varepsilon = 0.001$. Interestingly, however, as *k* gets larger, ε makes less and less difference on the value of *p*. By the time *k* reaches 12, this 100-fold difference in ε is almost entirely wiped out by the power of cultural learning stretching out and interconnecting minds. This suggests that in a large, well-interconnected population, people could get less inventive without much appreciable change in the population's innovativeness.

To understand the importance of this, imagine two different populations that, for reasons of geography, cultural beliefs, or cooperative institutions, have different values of *k* but are otherwise in identical situations (same λ and ε), captured by the $\varepsilon = 0.001$ curve in figure 7.1. Suppose the two populations have $k = 4$ and $k = 12$, respectively. On the ground, an observer of these groups would see that essentially no one (0.4 percent) in the first

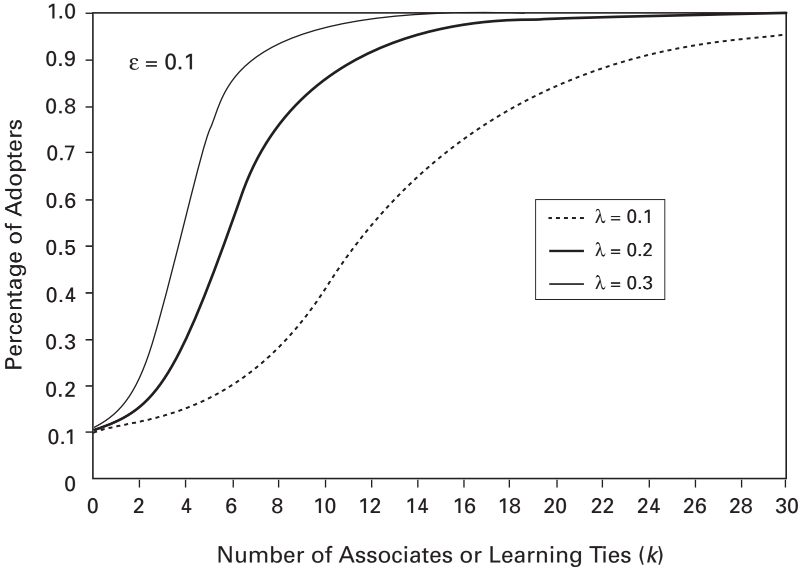

Figure 7.2
Plot of the relationship between *k*, the number of associates for a learner, and the percentage of adopters in the population once all individual and social learning is complete, for three values of λ (λ is a measure of the effectiveness of cultural transmission between individuals, and ε is the likelihood of individual invention).

population has adopted the novelty, whereas over 90 percent of individuals in the second population have adopted the innovation. If the analyst happens to think that the novelty is "smart" or "rational," then population 2 may seem "more inventive," "smarter," or "more rational" than population 1, which of course it is not, given that we specified that ε is the same in both populations. Population 2 is just more social in some sense.

Increases in λ, our parameter measuring the effectiveness of cultural transmission between individuals, also have a larger impact than similar increases in ε. Figure 7.2 is a plot of the relationship between *k* and *p* for three values of λ. While it makes little difference whether *k* is small or large, λ shows substantial effects for intermediate values of *k*. For example, when $k = 6$, *p* goes from 20 percent for $\lambda = 0.1$ to 56 percent for $\lambda = 0.2$ and to 84 percent for $\lambda = 0.3$. Comparing figures 7.1 and 7.2 for the relative effects of ε versus λ illustrates the importance of open channels of cultural transmission in favoring innovation.

The take-home message from this analysis, which is supported by more extensively studied evolutionary models (Henrich 2004b; Shennan 2001; van Schaik and Pradhan 2003), is that a group's innovativeness is determined more strongly by its cultural interconnectedness (including the effects of both *k* and λ) than by the individual inventiveness of its members (ε). Assuming that the probability of invention is not too small relative to the total population of potential inventors, groups that invest in cultural interconnectedness (sharing of ideas) will be substantially more innovative than groups that invest in raising the inventiveness of members.

These insights have numerous potential applications. At a continental level, larger land masses oriented on an east–west axis may favor the flow of cultural information, and farming know-how in particular, among distant populations (Diamond 1997; McNeil 1991). They may also explain the dearth of technological complexity in Australia vis-à-vis Eurasia, as well as differences between Africa and the Americas on the one hand and Eurasia on the other. At regional levels, they may help explain the differences between populations isolated on islands versus continental populations and may even explain the loss of technological know-how in Tasmania over the last 10,000 years (Henrich 2004b, 2006b; Rivers 1926; chapter 9, this volume). The approach may also provide a cultural evolutionary explanation for the florescence of material culture during the so-called "Human Revolution," suggesting that observed cultural efflorescence may have resulted from rising population sizes, densities, and/or greater interconnectedness and not from genetic changes. This further hints that anatomically modern humans and Neanderthals, who had similarly sized brains, may have varied only in their sociality (k), not in their inventiveness (ε).

On the Origins of Inventions: Mother Necessity, Mistakes, and Recombination

The above suggests that individual inventiveness likely plays a smaller role in innovation than cultural interconnectedness, but I want to further argue, mostly by reiterating arguments made by many others, that invention is not quite what many tend to think. I have four interrelated points on this front: (1) necessity is not the mother of invention, (2) most inventors are not singular heroic geniuses but make only small additions to existing accumulations, (3) these minor additions are rarely entirely new but instead usually represent only novel recombinations or cross-domain extensions of existing ideas, and (4) many of these useful additions or modifications result from lucky errors or chance interactions.

The idea that necessity is the mother of invention is an important assumption in much processual archaeological (chapter 1, this volume) and anthropological theory (Johnson and Earle 1987), as well as in economics. In anthropology, the idea seems to be that when environmental circumstances shift, population increases, or external threats arise (warring groups), the innovation engine in a society and/or its members (depending on the specific paradigm) kicks into gear and soon the appropriate novel technologies, practices, or forms of social organization emerge. Often implicit in this is the notion that the individual's own welfare is threatened or declining, causing the individual to shift and invest more in invention by taking more risks that will, on average, result in more inventions (Fitzhugh and Trusler 2009).

This economic logic supposes that as the incentives shift sufficiently to favor alternative practices or technologies, individuals switch and invest in the alternatives. My goal in this section is not to argue that "necessity" is never a factor in innovation or that incentives are irrelevant but instead to suggest that, at best, necessity is only one of several progenitors of innovation and not a necessary one at that. I discuss how many great inventions were initially rejected, suggesting that problems don't always find inventions but that inventions often find previously unrecognized problems (see chapter 14, this volume).

To begin, there may be a flaw with the economic logic of mother necessity. Incentives, from the perspective of an omniscient observer, may favor an alterative technology (or practice) or a more complex version of a particular technology, but for the adaptive learner, that novel technology does not yet exist, so the learner has no way to assess its relative costs and benefits (see chapter 2, this volume). Not only does the learner lack any experience with which to assess the incentive differences, he or she has not even thought of it yet and can't have any idea of the cost associated with figuring it out (Henrich 2006b). Learners know a lot about the costs and benefits of what they are currently doing but little or nothing about those of novel alternatives that they might consider switching to, let alone the costs of figuring out those alternatives (Henrich 2002). Although this is a bad situation for a cost–benefit analyst, it is the typical situation that cultural learning was "designed" by natural selection to handle.

Another theoretical concern is that if environmental shifts or population pressure have, for example, made current subsistence techniques less fruitful, an individual may have *less*, not more, time or energy to invest in invention. Invention investment may, in fact, decline in such circumstances. In modern economies, for example, firms invest in both their current product lines and research and development in boom times, but they halt R & D in tough times—not the other way around as the above logic would suggest (Hargadon 2003).

Risk-sensitive models of decision making show that if an individual's chances of survival fall below a threshold, such that, on average, he or she dies, that individual should adopt a risk-prone strategy; however, it's far from clear in a world with cultural learning whether such a strategy involves investing by means of individual learning in invention. Rather than "turning down" individual risk aversion in a utility or fitness calculation, natural selection could alternatively favor recalibrating cultural-learning strategies by shifting from conformist biases in transmission toward anticonformist biases (Henrich and Boyd 1998) or by reducing within-group ethnic learning biases (McElreath et al. 2003). Such shifts in cultural learning help reduce the likelihood of sticking to locally failing strategies, make learners more sensitive to even smaller differences in perceived payoffs between themselves and others, and open up the learner to acquiring useful novelties from other groups.

My own reading of the empirical record on these issues suggests that when faced with population pressure, environmental shifts, or external threats, people do sometimes innovate; however, more often they emigrate, suffer, and/or die. Diamond (2005) chronicles the innovation failures and the resulting collapse of the Maya, Greenland Norse, and Easter Islanders. The Greenland case is particularly instructive because we know that whereas the Norse gradually starved to death and vanished in response to climate change, local Inuit populations who were in contact with the Norse possessed adaptive technologies that allowed them to not only survive but expand. This means that the Norse could have adapted but did not. Below are six other provocative cases that seem to challenge the idea that necessity is the driver of invention:

1. Foragers living in Australia for 60,000 years (Testart 1988) failed to develop (or perhaps lost) any technologies involving elastically stored energy (e.g., the bow and arrow, musical bow, bow trap, or spring snare), kinetic energy (e.g., lasso and bola), or compressed air (e.g., blowpipe and dart, musical instruments).
2. New Guineans, although they used bows and arrows, never adopted fletching of any kind for their arrows.
3. The wheel appears to have been invented only in Eurasia (Basalla 1988). One could argue that other places lacked large domesticated animals that made wheels particularly useful, but wheelbarrows and pulleys are still pretty useful, and "llama carting" is a recreation today. Dogs, which were and are ubiquitous, can pull carts as well. In the nineteenth and early twentieth centuries, dogs were used to pull people and milk carts in northern Europe.
4. The Inca managed a vast empire, stretching from Columbia to Chile, without writing. It's difficult to imagine there was not a "need" for writing.
5. Some human languages lack systems for counting above three, basic color terms, words for "right" and "left," and grammatical operators to create conjunctive clauses (Everett 2005; Levinson 2003).
6. Zero appears to have been invented only twice in human history, once in India and once by the Maya. Most societies adopted zero soon after encountering it, although Europeans resisted zero for centuries (Seife 2000).

Beyond such macroscale cases, the same argument can be made for individuals' failures to innovate when faced with dire circumstances as noted above. For example, elsewhere (Henrich and McElreath 2003) I have laid out an account of Burke and Wills's ill-fated expedition into the Australian outback. This historical narrative illustrates both the futility of fitness-maximizing calculations in the absence of culturally inherited information and the tendency for humans, even arrogant Europeans, to rely on social learning over individual learning and experimentation for survival when the pressure is really on.

The available laboratory experimental findings, however limited, also converge to restrict the applicability of the "mother necessity view." As discussed above, when problems get tough or the world gets uncertain, student subjects faced with problems or puzzles with monetary incentives in the laboratory shift their reliance away from their own private evaluations and information and toward social-learning strategies. That is, they invent less and copy more when the world gets uncertain or problems get tough.

Besides the ambiguous role of necessity in yielding invention, a close look at the emergence of some well-known inventions illustrates (1) the importance of small additions by many contributors, often over long time periods, with a relatively small role for singular heroic geniuses; (2) the degree to which seeming novelties really represent only new recombinations or cross-domain extensions of existing ideas or technologies; and (3) the centrality of lucky errors or chance interactions in inventions, and not sui generis independent insights. I leave a complete defense of these views to the existing historical works (Basalla 1988; Diamond 1997; Hager 2007; Hargadon 2003; Meyers 2007; Sneader 2005; Williams 1987) and rely on six illustrative examples:

1. Eli Whitney's "revolutionary" cotton gin merely modified existing long-staple cotton gins, which were already widely available in the southern United States to extend their processing ability to short staple cotton. These gins go back hundreds of years to Indian gins called *charka*, which used the same principles as Whitney's gin (and actually looked similar). Similar gins are seen in twelfth-century Italy and fourteenth-century China.
2. Establishing the germ theory of disease required obtaining pure cultures of bacteria. In the nineteenth century, dozens of researchers were trying to figure out how to do this, without success. After years of work, Robert Koch solved the problem when, while cleaning up his laboratory, he ran across half of a boiled potato that had been carelessly left for a few days. Koch noticed the growth of discrete reddish dots at different places on the white potato and realized that he needed to use a solid, not liquid, medium to culture the bacteria. He went on to link specific pathogens with specific diseases (Hager 2007). The discovery of this process could not have occurred without a carelessly left boiled potato.
3. Thomas Edison's "invention" of the incandescent light bulb only improved on many other such bulbs patented between 1841 and 1878 by a wide variety of inventors. Of course, if you are from Britain, Sir Joseph W. Swan is the inventor of the incandescent light bulb, whereas if you are from Russia, it is A. N. Lodygin (Conot 1979; Diamond 1997). Moreover, Edison's bulb emerged from his Menlo Park laboratory, meaning it was actually the product of a team effort (Hargadon 2003).
4. The Wright brothers' invention of the airplane recombined existing manned gliders with unmanned powered airplanes (Diamond 1997). The trail of the evolution of flight goes back at least to Chinese kites in 400 B.C.

5. James Watt's "invention" of the steam engine occurred in 1769 after he repaired a Newcomen steam engine constructed 57 years earlier. This engine was modified from Thomas Savery's design of 1698, the components of which trace to seventeenth-century Europe and thirteenth-century China. After dissecting the steam engine, famed historian Joseph Needham concluded that "no single man was the father of the steam engine; no single civilization either" (Basalla 1988).

6. The discovery of penicillin and the dawn of the age of antibiotics began when Alexander Fleming returned from holiday to find that his Petri dishes had been contaminated with mold. Seeking to clean up his chronically messy laboratory, he dumped the whole batch of dishes into a sink, where they sat until he retrieved an unsubmerged disk to show a visitor. He happened to notice that whereas the mold was growing fine, the staph was retreating. Penicillin was discovered due to luck, energized by messiness. Fleming's published inquiry was then promptly ignored for a decade.

Invention and innovation are fundamentally evolutionary processes. Given that nearly all inventions build on existing ideas and often involve the recombination of existing concepts, methods, or materials, often fortified or integrated with a dose of lucky mistakes or happenstance, the overall inventiveness of a social group or population depends on the number of individual minds available to create recombinations, generate insights, and get lucky, as well as on their cultural interconnectedness (see chapter 8, this volume). This implies that the more minds in one generation, the more novel recombinations, insights, and lucky mistakes will exist for the next generation to recombine, refine, and extend across domains. The more innovations in existence, the greater the opportunities for recombinations and the more inventions are possible. Because the elements of any recombinant are acquired by learning from others, the more individuals one can potentially learn from, the greater the opportunities for creating novel recombinant inventions.

Consistent with this idea, business scholars now argue that companies should design themselves specifically to bridge multiple technological domains, especially to stimulate innovation by means of recombination (Hargadon 2003). Similarly, psychologists argue that living and adapting to foreign cultures increases creativity (Maddux and Galinksy 2006).

If both a population's size and its degree of cultural interconnectedness increase innovation rates, then we should expect certain kinds of practices and technologies to have an especially large impact on innovations, particularly those that permit or increase the flow of information within or across groups. Anything that permits faster or easier communication should, all things being equal, have an impact on innovation rates, such as transportation (horses, ships, roads, trains, and planes), communication (shared language, writing, mail, books, journals, literacy, telegraph, telephone, and Internet), and peaceful social relationships—although in wartime, espionage seems to energize innovation (McNeil 1982).

Solving the Public-Goods Problem Energizes Innovation

The technologies, practices, and relationships mentioned above can potentially increase both the effective population size and/or the degree of cultural interconnectedness; however, there remains a core motivational dilemma in creating innovations. Implicit in being "interconnected" lies a willingness to share what one has figured out (or stumbled upon) with others, or at least a willingness not to actively seek to prevent others from observing or learning what one knows. The overall group or population is often best served, in terms of either fitness or innovation rate, if everyone shares his or her ideas and inventions as openly as possible, thereby maximizing the flow of inventions, accumulations, and recombinations. However, individuals or groups (in a population of other groups) have incentives to learn as much as they can from others while keeping their own ideas and insights to themselves. These incentives turn the problem of innovation (creating and spreading inventions) into a classic cooperative (public-goods) dilemma with a big free-rider problem.

Prestige Deference Is a Dyadic Solution to This Dilemma

Elsewhere Gil-White and I (Henrich and Gil-White 2001) have examined how natural selection, acting to refine our capacities for cultural learning, has partially addressed this cooperative dilemma. We propose that learners essentially pay those from whom they want to learn (e.g., highly successful and skilled models) with prestige deference. This deference comes in many forms and includes small gifts, willingness to help, coalitional support, and public praise for the chosen model (resulting in more deference from others). In exchange for this deference, the chosen model permits the learner to hang around and observe what he or she does close up. Such models may give tips or even perform certain actions in a manner that facilitates observational learning. We call this the "information-goods theory of prestige" because information, in the form of learning opportunities, is exchanged in dyadic relationships for prestige deference. We argue that this approach explains much status-related behavior and is the only approach that makes the necessary connection between the empirically observed patterns of behavior—deference, status, ethology, and imitation. Supplementing the evidence we presented in our paper, more recent support has emerged in studies of human emotions, including pride, awe, respect, and elevation (Algoe et al. 2006; Keltner and Haidt 2003; Tracy 2007).

Institutions of Apprenticeship Are Built on This Psychology

This aspect of our evolved-status psychology likely forms the foundation for the widespread institutions of apprenticeship that have emerged independently in many human societies. Apprentices seek to learn particular skills (e.g., metal working, weaving, or pottery) while working under the strict, often slavish, direction of a master. In addition to the apprentice's labor, which may be required for years, the master may also require direct payment in money or goods and may have other stipulations, such as requiring the apprentice to swear not to set up a shop in the master's own town or not to reveal the master's secrets. Agreements among masters, and formal laws in some places, limit the number of apprentices that any one master may accept. The apprentice's learning is usually strictly imitative, with the explicit goal being to copy the master exactly (Coy 1989).

The institution of apprenticeship, while permitting the cultural transmission of complex skills, does not maximize the flow of adaptive information among individuals in the population in a manner that will maximize the population's innovation rates. Given that in addressing the underlying dilemma apprentices are usually limited in number and can serve only one master, there is little chance for the diffuse interconnectedness, accumulation, and recombination that energize invention and drive higher rates of innovation. The society, though not the masters, would be more innovative if masters freely distributed their knowledge, were permitted as many apprentices as could be handled, and did not require a longer period of servitude than necessary to acquire the requisite skills. Students could move among masters as they wished, comparing and recombining elements from different masters.

Solutions to the Larger-Scale Cooperative Dilemma Required

The kind of culturally interconnected population that I have argued above will best promote both innovation and invention requires solving a larger scale, *n*-person cooperative dilemma. Rather than dyadic cooperation of the prestige and apprentice systems, cultural systems that can create higher degrees of stable *n*-person cooperation, and in which individuals share widely what they know and invent, will energize population rates of both invention and innovation (see chapter 8, this volume). Cultural evolutionary models targeting these larger-scale problems of cooperation have so far provided three classes of potential solutions, one based on an interlocking reputational system that ties *n*-person cooperation together with other dyadic social interactions (e.g., Panchanathan and Boyd 2004), a second based on costly punishment of noncooperation and on the punishment of nonpunishers (e.g., Henrich and Boyd 2001), and a third that exploits cooperation as a form of signaling that distinguishes higher-quality partners from lower-quality partners (Gintis et al. 2001).

The first approach depends on a reputational system in which failure to cooperate results in acquiring a bad reputation such that others can withdraw their help (or increase their hurting) during dyadic interactions that occur apart from the cooperative interaction. The second approach relies on and combines the coexistence of culturally transmitted influences on cooperation and punishment (of noncooperators and nonpunishers), the reliance of learners on conformist transmission as the payoff differences between alternative strategies approaches get smaller, and the geometrical decline in payoff differences between prosocial strategies (involving cooperation and punishment) and selfish strategies (defection and nonpunishment) as one ascends to high orders of punishment.[2] The third approach assumes that individuals vary in a nonobservable quality desired by potential partners and can use cooperative or punishing behaviors to differentiate themselves.

All three solutions can solve, to varying degrees, the cooperative dilemma of information sharing laid out above. However, analyses of all three approaches demonstrate that the mechanisms always stabilize a wide range of individually costly, non-group-beneficial behaviors and have an equilibrium at full defection. All three could stabilize, for example, practices such as female infibulations, footbinding, and taboos on nutritiously valuable foods, as well as cooperative house building and widespread information sharing. This means that all three require a mechanism of *equilibrium selection* (Henrich 2006a) beyond what is presented in the basic models. That is, to be a complete solution, they require some process that can pick out the group-beneficial equilibrium from the myriad of noncooperative alternatives (see chapter 11, this volume).

Cultural Group Selection Solves the Equilibrium-Selection Dilemma

One important mechanism involved in equilibrium selection is *cultural group selection* (Boyd and Richerson 2002; Henrich 2004a)—a label for a class of processes that arise from the interaction of, and competition among, social groups. The idea is that different groups will culturally evolve to different stable states involving the above mechanisms as well as potentially many other mechanisms or combinations that theorists have not yet dreamed up. Although internally stable, these different equilibrium, or institutional, forms will vary in their facilitation and promotion of information sharing and cultural interconnectedness. Social groups with institutions that favor innovation, as a result of greater interconnectedness or larger populations, will outcompete, as a result of cumulative cultural adaptation and technological evolution, those groups lacking such institutions (those at other equilibria).[3]

Societies Lacking Institutions for Diffuse Information Sharing

One line of evidence for this approach comes from ethnographic studies of the small-scale subsistence farmers whose seeming “conservatism” in adopting potentially beneficial novel technologies and practices has long puzzled policy makers and development economists (Hoffman 1996). My research among the Mapuche of southern Chile shows that farmers know little of their neighbors’ successes or the details of their practices. Mapuche farmers’ lack of knowledge regarding others’ success suppresses the effect of our adaptive cultural learning mechanisms, which target the transmission of success-enhancing practices, techniques, or technologies. Even if success differences were noticed (as in crop yields), any transmission will be error ridden and therefore less effective.

This lack of knowledge no doubt results from several factors, although both interviews and observational data indicate that chief among these is that farmers actively hide information (new techniques) because they believe that if others know of their successes or innovations they (the successful innovator) will be envied. Such envy could result in physical harm to them and their families, in the form of illness, injuries, crop failures, and other forms of bad luck. Similarly, individuals who appear "too interested" in the business of other households face reputational damage, as they may be perceived as motivated to spread gossip that will result in envy and harm to the family. Although my Mapuche findings are more quantitative than most ethnographic work, the general image of how the belief–reputation system works and how it might suppress innovation and diffusion is quite consistent with economically similar populations in diverse geographic locations (Banfield 1958; Foster 1967; Redfield 1953).

The cultural beliefs connecting envy and harm, which are amazingly widespread, have also long been associated with perceptions of the world as a zero-sum game, meaning that if you are doing better, then I and everyone else have to do a bit worse (Foster 1965, 1974). This perception (and sometimes this reality) is accompanied by a cultural system of reputation that gives deviant innovators a bad reputation, which could subsequently result in possible losses in dyadic exchanges and social ostracism. Such innovators are seen as seeking to obtain more than their fair share from a fixed pool of possible benefits. If they get more, everyone else gets less. Such combinations of beliefs can form a self-stabilizing cultural system because deviants, even if they reject the cultural beliefs themselves, are still motivated to avoid standing out, innovating, or appearing to be successful. These kinds of cultural beliefs may dramatically suppress innovation and the rates of cumulative cultural evolution.

This suggests that societies with cultural systems that connect envy and harm to witchcraft, suppress success displays, imbue curiosity with malevolent intentions, and perceive the world as a zero sum will be outcompeted and assimilated by societies with cultural beliefs and reputational systems that favor information sharing and open the pathways of cultural transmission. Although research is just beginning on this question, I suspect that such envy–witchcraft cultural systems are "easy to think," in some sense, as they take advantage of several aspects of our evolved cognition (Boyer 2001). They readily evolve in certain ecological and economic circumstances (e.g., sedentary farming) and, once in place, are quite stable.

Broadening the Spectrum: Culture–Gene Coevolution

We can take this line of reasoning back one more step: Cultural evolution, driven by cultural-group selection, may help explain the evolution of our sophisticated cognitive capacities for social learning and the emergence of cumulative cultural evolution. Many species have some form of social learning, and some even show limited forms of imitation (see chapter 3, this volume). However, no other species, with the possible exception of birds and cetaceans relative to song transmission, has nontrivial amounts of cumulative cultural evolution (Rendell and Whitehead 2001). Formal evolutionary models have suggested that there exists a "fitness valley" between capacities for relatively simple low-fidelity social learning and the sophisticated cultural learning strategies found in humans

(Boyd and Richerson 1996). The evolutionary problem is that sophisticated cognitive processes dedicated to cultural learning cannot pay for themselves in a fitness sense until there are lots of adaptive cultural behaviors in the world that could be acquired with high fidelity. This problem is exacerbated by the cooperative dilemma described above if only one's close kin (e.g., mom) are willing to share their behavioral repertoire (Henrich 2004b; van Schaik and Pradhan 2003). This limits rather tightly the range of behavior one can possibly acquire with the expensive cognitive machinery of cultural learning.

Chimpanzees, for example, show cultural traditions in the wild (Whiten et al. 1999) and do reveal some weak imitation abilities (Whiten et al. 2003, 2005), yet chimpanzees do not seem to accumulate nontrivial bodies of culturally acquired know-how (see chapter 3, this volume). Most chimpanzee cultural transmission is limited to mothers and their offspring. As noted above, formal evolutionary models indicate that this lack of cultural interconnectedness will inhibit cumulative cultural evolution, especially when transmission is of low fidelity.

Thus, the question is, how might natural selection have bridged this fitness valley to create both sophisticated cultural learning and its consequent cumulative cultural evolution? I propose that if we begin with a human ancestor that is a "weak imitator" (like any of the great apes) and possesses the cognitive abilities to acquire, however incompletely, some social behavior by means of imitation and that lives in sufficiently large groups, then cultural evolution could favor stable information sharing within the local group by any of the three mechanisms described above. These mechanisms do not require any cumulative cultural evolution, only a willingness to let all members of one's group observe one another performing practices or skills that they might want to learn.

Once such a local behavioral norm arises culturally, formal models show that the conditions favoring cumulative evolution are relaxed (Henrich 2004b) and the same weak imitative abilities that failed to produced cumulative cultural evolution before may now begin to generate cumulative products. Once cumulative cultural products begin to emerge, two things can ensue: (1) The fitness valley is crossed, allowing natural selection to improve cultural-learning capacities in order to take advantage of the emerging cumulative cultural products in the group and the generally increased availability of things to learn, and (2) the cumulative cultural products produced by the group will allow it to compete with other social groups, thus spreading both the cultural norms of information sharing and the genes for more sophisticated cultural learning.

Conclusion

My main points can be summarized as follows:

1. Innovation is fundamentally a social and cultural process. A population's degree of innovativeness need not be connected to the inventiveness of its members, given that a

highly interconnected population can have high innovativeness even when it has relatively low inventiveness.

2. Given that invention is strongly influenced by recombination and luck, both larger population size and greater interconnectedness will, all things being equal, increase inventiveness and innovation.

3. There is an inherent large-scale cooperative dilemma in generating high degrees of cultural interconnectedness, and thus achieving high rates of innovation, that can be solved only by the evolution of cooperative institutions. Without such institutions, populations are limited in their ability to create interconnectedness and generate innovations.

4. The rate of innovation we observe in the modern world is a product of long-term cultural evolutionary processes driven by competition among groups. Many human groups, now and historically, did not readily share cultural information the way we routinely and unconsciously do.

5. The cultural evolution of behavioral norms that increased groups' cultural interconnectedness may have ignited an autocatalytic culture–gene coevolutionary interaction in which accumulating cultural information continually ratcheted up the strength of natural selection on genes to build brains for acquiring and storing culturally transmitted information.

Notes

1. Prestige in this sense represents the aggregate of group members' evaluations of who is skilled, successful, and knowledgeable, that is, worthy of imitation. In a world of imperfect information, other people's evaluations are an important source of information for refining one's own evaluations of from whom to learn.

2. Such models are structured such that strategies of cooperation and defection apply to "order 1," nonpunishment and punishment of defector to "order 2," nonpunishment and punishment of nonpunisher at "order 2" to "order 3," and so on. Thus, the famed "second-order free-rider problem" focuses attention on sustaining the punishment of defectors.

3. Given that the situation we are discussing here involves competition among stable equilibria, the concerns often expressed about the plausibility of the genetic group selection of altruism do not apply (Henrich and Henrich 2007).

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8 Fashion versus Reason in the Creative Industries

R. Alexander Bentley

Almost by definition, creative expression involves the transmission of information between individuals, with the continual production of new ideas, a minority of which rise to prominent genres or paradigms. In the creative industries, which rely on public dissemination, the process can paradoxically be seen as a competition to "cooperate," in the sense of a race to be credited for sharing the most information. In academia, publishing pressures drive researchers to compete for citations and other forms of wide-reaching, academically sanctioned publicity (Hull 2001), particularly in the era of the Research Assessment Exercise (in Britain) and comprehensive citation databases such as ISI Web of Knowledge that can summarize an academic's career at a single command. As a result, academic competition for citations increasingly resembles other modern creative industries predicated on the volume of "hits" (Bentley 2007a)—how many comments a blog received, how many tickets were sold, how many copies of a song or video were downloaded, or how many friends have linked to a MySpace page.

In many instances, competition for popularity or prominence drives diversification and the construction of new niches. In academia, the intense pressure to publish and to be cited has led to the proliferation of new journals on almost every conceivable topic (e.g., Svetlov 2004). Similarly, in cyberspace there are more and more new Web-based venues for uploading videos, blogs, pictures, and social-network home pages. Our modern opportunity to disseminate our own creative endeavors may be unprecedented on such a mass scale, but on the personal or village scale, individual creative expression through craft design extends deep into prehistory. This motivates the study of creative "industries" in both prehistoric and modern contexts, as covered in this volume.

Innovation and Networks

Creative industries are practiced by people in social contexts (e.g., Bentley 2006; Earls 2007; Guimerà et al. 2005; O'Brien et al. 2005). In the Internet age, these contexts are increasingly envisaged as networks, with each creative output (Web pages, media, academic publications) seen as a "node," its influences (cited references, related Web pages) as "outgoing links," and the works influenced by it (or referring back to it) as "incoming links." Since the late 1990s researchers, particularly in physics, have applied generalized network analysis to a range of creative industries (Newman et al. 2006).

A challenge for network analysis, however, has been how to deal with change, given that formulation of a network usually presupposes a structure to interactions. Once a network is in place, the connections of today determine (often strongly) what will happen tomorrow, such that change must be implemented as a *modification* to the preexisting network. However, in creative fashion and knowledge production, yesterday is often much less important than tomorrow, and interactions are usually quite different from one day to the next.

Change is not just a modification but the very essence of the creative process (e.g., Bentley 2006; O'Brien 2008; Ormerod 2006; Shennan 2002). Change, in fact, is also central to evolutionary theory. As Dennett (1996) argued in *Darwin's Dangerous Idea*, the tools and insights from over a century of evolutionary research can be applied to almost any process of change that involves entities transmitting their attributes to other entities through time.

In the creative industries, this transmission process is essentially one of copying what others do, in which creativity contributes new behaviors that eventually replace the old ones through being copied. Imitation is one of the hallmarks of the human species, and while our propensity to "copy strips of words" famously irritated Orwell (1946), our remarkable ability to imitate is, for better or worse, a prerequisite for culture itself. Even academic scientists who do their research within complex collaboration networks (Guimerà et al. 2005) are prone to copying ideas from one another (Bentley 2006; O'Brien et al. 2005; Simkin and Roychowdhury 2003, 2007). Counterintuitively, when things become increasingly free and subject to fashion, the simple tendency to "do as the Romans do" can nonetheless lead to homogeneity in collective behavior, conveying the illusion of conscious conformity or imposed control.

With mechanisms of variation, transmission, and selection, knowledge creation is entirely suitable for evolutionary analysis, particularly in evaluating the degree to which ideas are selected versus randomly copied. It is useful to model a highly simplified spectrum ranging from ideas that are copied randomly among people as fashions to ideas that are selected for inherent qualities (Bentley 2007b). Characterizing innovation along this fashion–selection spectrum yields crucial insight into the dynamics of how certain behaviors increase or decline. As the spectrum becomes broadly defined, the approach can be made incrementally more complex through incorporating additional model parameters tested against their real-world equivalents in the empirical data (Bentley et al. 2008).

Identifying selection is fundamental to understanding the nature of production of knowledge, particularly what proceeds in predictable directions as opposed to drifting upon the tides of fashion. If elements are randomly drifting, for example, it may make little sense to invest much effort in trying to predict where things will lead, as a recent experiment concerning popular music downloads demonstrated (Salganik et al. 2006). Conversely, we may seek to impose a selective process where it is unexpectedly found absent, as in scientific publishing, where we would hope that there is selection for quality and validity.

We can examine databases to test differences between genres over the short, modern, and long prehistoric timescales and within several different niches of knowledge production. It can be quite effective to propose only two simple hypotheses, which can be quantifiably tested for a given case study:

1. Ideas are randomly copied from one agent to another, with continual innovation.
2. Ideas are selected based on inherent meaningful value.

Given the hypothesized dichotomy, the major question in each case study is where certain behaviors lie on the spectrum between random copying and selection. If we use random copying as the null hypothesis, then we can identify selection against the null before characterizing it specifically. Practically speaking, the random-copying model does not require that people make choices without any reasons at all but instead only predicts that the statistics of all their idiosyncratic choices, at the population level, are comparable to random copying.

A century ago, economists made an extreme, but convenient, assumption about human decision making: It is rational, omniscient, and utility maximizing. Symmetrically, random copying is an opposite extreme: The random-copying model allows us to ask what would we expect if everyone simply copied each other, with occasional innovation? It does not mean that the forms of creative expression are themselves random, as they must obviously be intelligible, but that they exist within a large set of possible forms, none of which is inherently more useful than any other. In analogy to population genetics, these choices can be considered “neutral” traits, in that what is chosen has no inherent value relative to other options (Gillespie 2004; Hahn and Bentley 2003). For example, whether a mother names her girl “Mandy” or “Marla” would depend only on who and how many already have the name rather than on any qualities of the name itself.

Remarkably often, random multiplicative processes can be invoked to explain broad patterns of fashion change. Prehistoric designs, trendy academic jargon, and mass-media trends demonstrate the continual flux and empirical patterns of random copying (Bentley et al. 2004, 2007; O’Brien 1996; Salganik et al. 2006). When we look at closer scales within this flux, however, diverse opinions will exist as to what constitutes fashions versus more substantial material, with little means of objective evaluation.

Once this null model of random copying is established, it is possible to identify selection specifically in favor of novelty, validity, or conformity, for example (see chapter 7, this volume). For the “selection” end of the spectrum, we have a wealth of models of

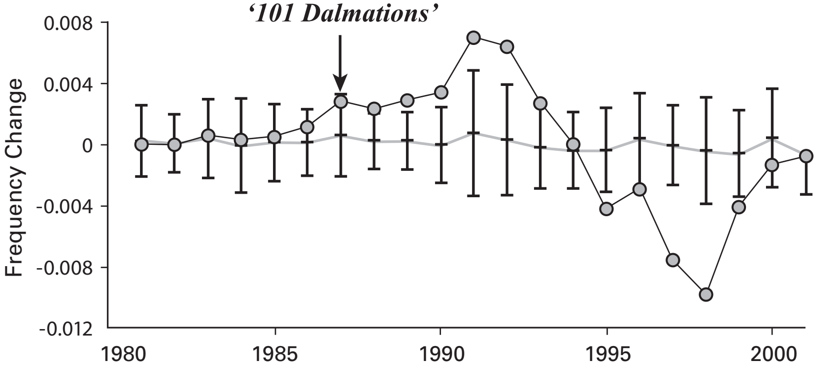

Figure 8.1
Changes in the popularity (frequency) of Dalmatians (filled circles) versus the mean change among all other purebred dog breeds (error bars showing ±2 standard deviation ranges) in the United States. Against the latter as background, the "celebrity effect" of the Disney movie *101 Dalmatians* in 1984 is clearly visible.

independent decision makers who weigh the costs and benefits of their options while subject to various biases of influence (e.g., Gintis 2007). This applies well to behaviors that serve some adaptive purpose, that is, that matter to human values or to the spread of a useful idea (e.g., Henrich 2001; Rogers 1962; chapters 7 and 12, this volume). Even a display of fashion, if it carries some meaningful signal (e.g., mating potential), can be seen as subject to cost–benefit decisions (Bliege Bird and Smith 2005). Generally speaking, with independent rational selection, creative culture should converge on the collective priorities of individuals rather than drift constantly (Surowiecki 2004).

Against this background, some interesting phenomena become visible. In one study, my colleagues and I (Herzog et al. 2004) used the expectations under random copying as the background on which to fit data on dog-breed popularity in the twentieth century. The rapid rise and fall of Dalmatians was clearly visible just after 1984 (see figure 8.1). The reason for the spike in Dalmatian popularity was surely the rerelease of the Disney movie *101 Dalmatians*. However, not all movies have this "celebrity effect," and the point is that we were able to identify the Dalmatians as a special case only because we had the null model of random copying (drift) to test against.

Ultimately, we might seek to explore how much we can explain through random processes, at each scale, before resorting to post hoc "reasons" such as individual selection for one thing or another. The scale of analysis is thus a key variable. For example, although choices of baby names at the scale of the entire United States is indistinguishable from random copying (Hahn and Bentley 2003), it is also evident that different ethnic groups select from different pools of names (Fryer and Levitt 2004). Therefore, with selection evident between groups, it could well be (and remains to be studied) that within each group, random drift could predominate again at that even finer scale. In this sense, the random-copying model helps us identify the scale at which selection is exerted, which may help to define the groups themselves.

A Case Study: Fashion versus Selection in Academic Publishing

Ideally, science is the systematic process of testing multiple hypotheses, but as practiced by real people, it is also distinctly social. Academics do their research within complex collaboration networks (e.g., Guimerà et al. 2005) and are prone to copying ideas from one another. Diverse opinions exist as to what constitutes trendy ideas versus more meaningful research paradigms; however, there is yet little means of evaluating this objectively.

Evolutionary theory offers a means of modeling these aspects of scientific process (Hull 2001). By applying basic population-genetic analogy to citations-database research, we can characterize the use of modern scientific keywords in terms of a continuum between the copying of fashionable ideas at one extreme (akin to the neutral model of random genetic drift) and the independent selective testing of hypotheses at the other (akin to selection, falsifying the neutral model). Among our several cases, we test differences between subfields older versus younger and within the physical sciences versus the social sciences. In doing so, we find some remarkable regularities, suggesting that the physical and social sciences are equally “trendy” when it comes to the comings and goings of popular keywords.

Following the discussion above, two simple hypotheses for the evolution of academic vocabulary are that vocabulary is randomly copied from one paper to another, with continual innovation, or vocabulary is selected based on the inherent meaningful value of the words. The question is one of degree, with variation expected along this basic continuum. Using random copying as the null hypothesis, we seek to identify selection against the null without characterizing it specifically, although the most obvious form would be selected for validity of the words that usefully describe something real and relevant to the topic. Selection versus random copying becomes the primary axis on which to characterize the process, and predictable patterns in the data can characterize their degrees of importance for a given academic field of study. If this can be achieved, it would then be possible to identify secondary effects, such as a bias in favor of novelty and against conformity.

Again, by using “random copying” as the null model, I do not mean that the words themselves are random, as they obviously will be intelligible, but that they would exist within a large set of possible keywords, none of which is inherently more useful than any other. Analogous to the neutral model of population genetics (Gillespie 2004), randomly copied keywords would be value neutral.

The random-copying model can be modeled as follows. We start with a set of N individuals, which are replaced by N new individuals in each generation. Over successive generations, each of the N new individuals copies its variant from a randomly selected individual in the previous generation, with the exception of a small fraction, μ (less than 5 percent) of the N new individuals, who invent a new variant in the current generation. In applying this to keyword use, we consider N to represent the number of keywords in a given time period rather than the number of articles, which vary in their number of keywords. This ensures that each "individual" corresponds with exactly one variant.

This model is simple to simulate (Hahn and Bentley 2003; Neiman 1995) yet provides richly complex results that produce at least three useful predictions relevant to cultural drift:

1. Individual frequencies through time: If we track individual variants through the generations, their frequencies (relative popularities) will change in a stochastic manner as opposed to either a directed or completely random manner. More specifically, the haploid neutral model predicts that the only source of change in variant frequencies over time is random sampling, such that (Gillespie 2004)

$$V = \frac{v(1-v)}{N}, \tag{8.1}$$

where V is the variance in frequencies from one time step to the next and $v \leq 1$ is the relative frequency of the variant as a fraction of N, the maximum possible number of variant copies per generation. For small v, $v(1-v) \sim v$, which after rearranging equation 1 indicates that $NV/v \sim 1$. This means that departures from the neutral model may be identified by values of NV/v substantially different than one. If the values were much less than one, there might be some stabilizing selective phenomenon reducing variability, whereas values much greater than one could occur for different reasons, such as a variant steadily rising or decreasing in frequency as a result of selection. The point is that the NV/v value provides a means of identifying selection so that when we apply "reasons" for change, we can be confident the change is not simply a result of random drift.

2. Frequency distributions: Like many "rich-get-richer" processes (under random copying, the chance of being copied is proportional to current frequency), the variant frequencies exhibit a long-tailed distribution, which for small values of μ can follow a power-law form (Bentley et al. 2004; Hahn and Bentley 2003; Kimura and Crow 1964). This is one of the less diagnostic predictions, as a variety of mechanisms can generate power-law and related distributions (Newman 2005). With selective bias for novelty, for example, we would expect newly invented variants to rise quickly from obscurity and fall precipitously after reaching some threshold of popularity, as well as a truncation of the tail of the variant frequency distribution such that very high frequencies are absent. Alternatively, there might be a conformist bias, resulting in a "winner-take-all" distribution, whereby one word has a higher frequency than predicted by the power law for the rest of the words.

3. Turnover: There is continual turnover in the variant pool. If the variants are ranked in order of decreasing frequency, the turnover, z, in that list over successive generations (time) depends much more strongly on μ than on N, such that

$$z \approx \sqrt{\mu}, \tag{8.2}$$

where z is measured as the fraction of turnover in the list (Bentley et al. 2007). In contrast to random copying, under selection the population size, N, should correlate positively with the turnover rate in the ranked list of most-popular variants.

Using these predictions as the null model, we can identify selection as departures from these patterns, depending on the kind of selection operating.

Data

In order to perform our analysis, we need a working definition of a subfield of academic publishing. If belabored, this could be quite a difficult task—many definitions would be too subjective, variable, or broad (e.g., certain papers in "evolutionary anthropology" might often have more in common with "developmental biology" than with other subfields of anthropology). A more promising definition is the scientific "paradigm" (Kuhn 1962), which encompasses all the scientific papers that were in some way inspired by a certain highly influential paper. The citing papers may occur in a range of different journals, but they will all share the defining characteristic of citing the highly influential work. I recognize the ambiguities (e.g., differences in importance of the seminal work among all papers citing it), but at least this definition applies consistently across our examples, without the subjectivity that many other definitions would require.

I chose four highly cited seminal works, two from the natural sciences and two from the social sciences. To determine the effect of time, from the pair in each category I include one work about 30 years old and another about 10 years old. This provides two comparisons: older versus younger fields of study and social sciences versus physical sciences. From the physical sciences, we have a paper by Barabási and Albert (1999) that introduced a quantitative model of "scale-free networks" and had been cited over 2,000 times (as listed on the ISI database) and a paper by Witten and Sander (1981) that introduced the physics model of "diffusion limited aggregation" and had been cited over 1,300 times. From the social sciences, I selected a paper by Nahapiet and Ghoshal (1998) that reviewed the influential concept of "social capital" and had been cited over 460 times and a book by Bordieu (1977), cited over 2,700 times, that introduced concepts of agency and structuration into the social sciences. These publications are abbreviated below as PS99, PS81, SS98, and SS77 (where PS stands for "physical sciences" and SS for "social sciences").

For each defined data set, I sorted the keywords data from the ISI database by publication year.[1] Keywords were taken only from the article title and the keywords chosen by the authors (not the ISI "Keywords plus," which is an automated condensation of the cited references). Before exploring patterns, I removed the following common words from the data: "a," "an," "and," "as," "by," "for," "from," "in," "its," "of," "on," "the," "to," "using," and "with." Aside from these, no other common words were present in high enough frequencies to significantly affect the top five most popular or the frequency distributions.

Results

Figure 8.2 shows the number of keywords, N, for each case study per year as well as the number of new keywords per year, $N\mu$. Table 8.1 shows the mean values for the period 2002 through 2006, which I chose because it is shared by all four case studies and is long enough after the start of the younger paradigms to create sufficient sample size. In all cases, the quantities N and $N\mu$ parallel each other (see figure 8.2), indicating a relatively consistent invention rate, μ, in all cases. A "new" keyword is defined as one that had not yet appeared in the record. I began recording at 1994 for the older works and on the date of publication (1998, 1999) for the younger works. As the corpus of previously used words grows with time, the invention rate declines (see table 8.1). The invention rate for all cases was between 14 percent and 18 percent by the end of the sampling period (see table 8.1).

In terms of cumulative turnover among keywords (see figure 8.3), we can see a gradation from the continual turnover expected under random copying with innovation to the cessation of turnover expected under selection. Among the papers citing the younger, physical science paper (PS99), the turnover in the top five keywords begins steadily in the

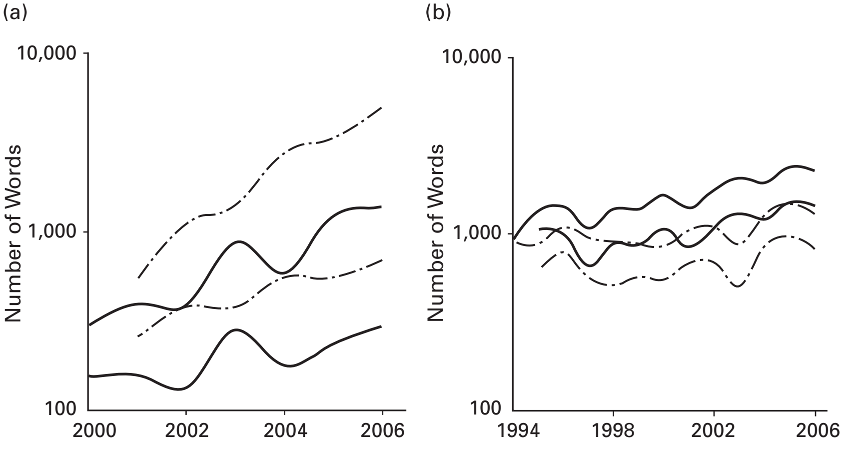

Figure 8.2
Number of vocabulary words used and new words introduced among keywords in the two case studies for articles (a) about 10 years old and (b) about 30 years old. In each plot, the social science case is shown by the bold solid line and the natural science case by the lighter dashed line. For each case study, the upper curve shows the total number of keywords used per year, and the lower curve shows number of new keywords introduced per year.

Table 8.1
Averages from 2002–2006 with range of observed μ over the interval

Work	Words N	Vocabulary	Inventions $N\mu$	μ (%)
Bordieu (1977)	1,671	1,036	441	24–18
Witten and Sander (1981)	1,050	566	192	17–16
Barabási and Albert (1999)	2,660	979	511	35–14
Nahapiet and Ghoshal (1998)	885	431	224	35–14

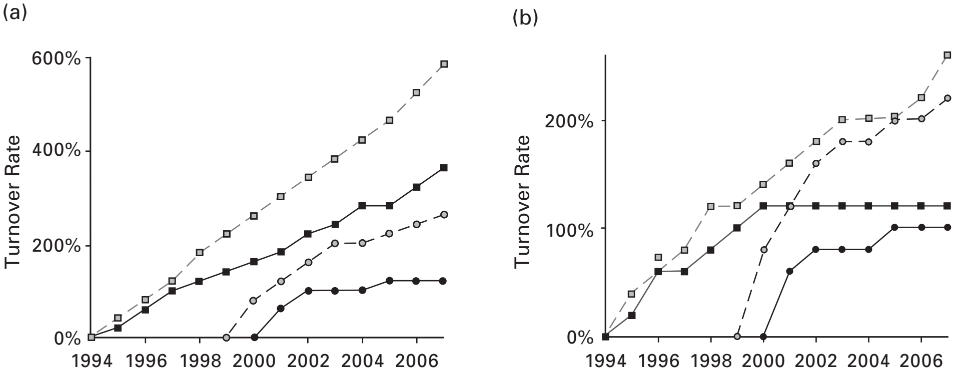

Figure 8.3
Cumulative turnover in the top five keywords, as the fraction of the top five. Filled symbols and solid lines show physical sciences; open symbols and dashed lines show social sciences. In (a), words reentering the top five are counted as turnover, whereas in (b), turnover refers only to words making their first appearance in the top five. For the older paradigms (Bordieu 1977; Witten and Sander 1981), the count is begun at zero in 1994; for the newer articles (Barabási and Albert 1999; Nahapiet and Ghoshal 1998), the count begins the year after publication.

early years but then levels off to virtually no turnover in the past several years. At the other end of the spectrum, keywords in the older, social science case (SS77) show a high and steady turnover throughout the sampling period, long after its publication and many years beyond which the other case had leveled off. In the older natural science case (PS81), turnover is continual when words reentering the top five are counted (figure 8.3a), but the turnover ceases when repeats are not allowed (figure 8.3b). This pattern appears to reflect recurrent ups and downs of the most frequent words, in and out of the top five, such that they register as turnover only if repeat entrants are counted. It could reflect selection if, for example, a set of words had been selected as more useful than any others, but within that set of top words there was drift.

Figure 8.4, showing the changes in frequencies of the top five keywords of 2006, helps explain the turnover patterns. The lack of turnover in PS99 is demonstrated by the striking ordering of the individual word frequencies through time (see figure 8.4a). In fact, sorting

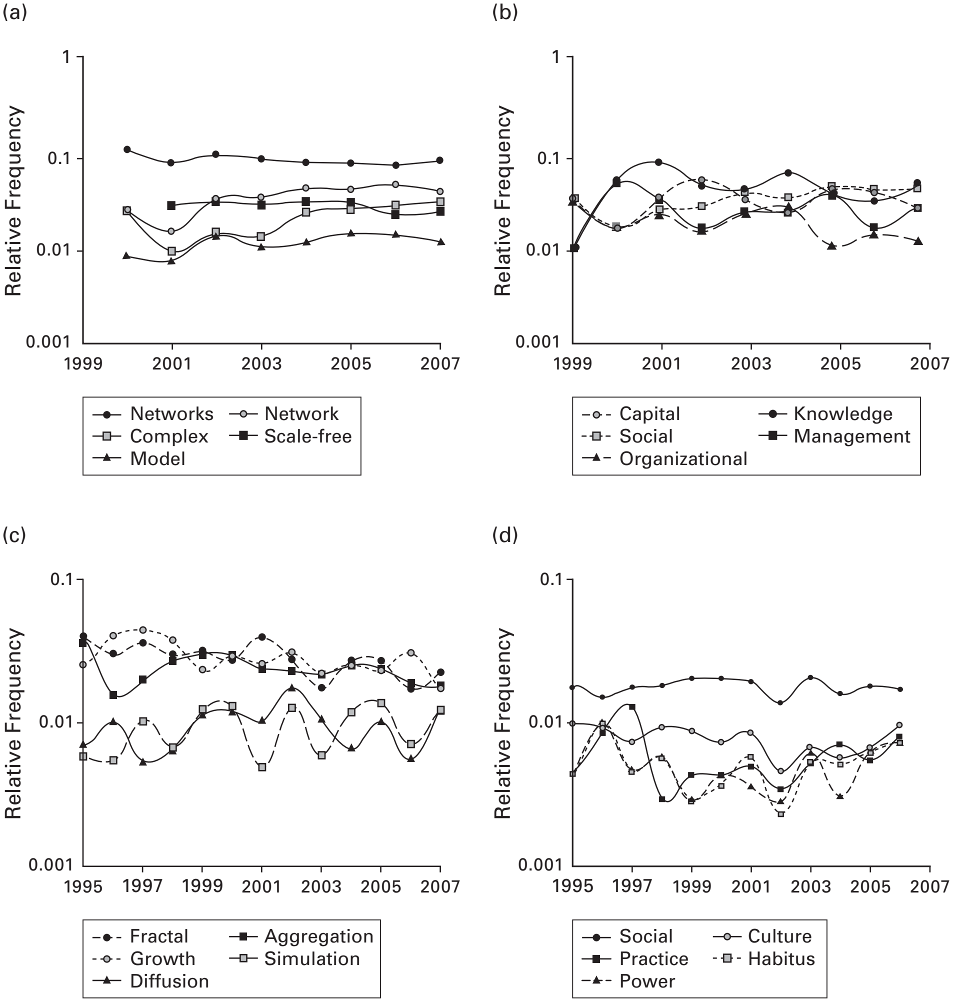

Figure 8.4
Relative frequencies of individual keywords from one year to the next, among papers citing (a) Barabási and Albert (1999), (b) Nahapiet and Ghoshal (1998), (c) Witten and Sander (1981), and (d) Bordieu (1977). The set of words chosen to display contains the top five keywords of 2006. Note the *y*-axes are logarithmic on all plots.

is such that the keyword network occupies a clearly distinct frequency ranking from the singular network, with the other entries similarly locked into their positions among the top five. This degree of sorting is not present in the other cases, except for the clear supremacy of the number-one keyword (social) in the case of SS77. As suggested from the turnover pattern, PS81 does appear to exhibit a group of three keywords (fractal, growth, aggregation) that are consistently on top as a group, but there is drift within that group (see figure 8.4c). Given the patterns seen so far, it would appear that PS99 shows the most selection, followed by PS81, SS77, and SS98.

As mentioned above, however, we must factor out the effect of the number of keywords N in each case. This is achieved with the ratio NV/ν, which should approximate unity under the neutral model, so we can use it as a comparable measure of variability. Table 8.2 shows the value of NV/ν for the top five keywords of 2006 that were also tracked in figure 8.4. Averaged over these five variants, NV/ν differs more by age of the paradigm than by subject matter—higher for the younger (~2.3) than for the older (1.3–1.4) paradigms. Among the older paradigms, drift seems to be the primary operation—even for PS81, if the top three words have been selected, they are now drifting within that selected group.

Among the younger works, however, the high variability scores may come for different reasons. Table 8.2 also demonstrates noticeable variation in the scores for each word. In the PS99 case, the word “complex” (word 3, score = 5.8) appears to have been selected for, as it doubled in frequency from 2002 to 2006, beyond what would be expected from random drift. Also in the PS99 case, “networks” (word 1) declined steadily as “network” (word 2) increased, such that their variability scores are near 2. By contrast, words in the SS98 case do not show such directionality in their change, and the high variability scores for four of the five words (see table 8.2) is a result of their fluctuating frequencies over the time interval (see figure 8.4b).

Table 8.2 reveals other interesting details. In the SS77 case, words generally get more variable moving down the rankings, which suggests a possible conformist bias in that the more frequent words have been preferentially selected. In the PS81 case, the word “aggregation” (word 2, score = 0.3) is considerably less variable than “diffusion” (word 5, score = 2.7), even though the seminal paper was about diffusion-limited aggregation.

Table 8.2
Variability scores (values of NV/ν) for the top five words tracked in figure 8.4 over the years 2002–2006

Work	Word 1	Word 2	Word 3	Word 4	Word 5	Average
Bordieu (1977)	0.82	1.13	1.10	1.46	1.75	1.3 ± 0.4
Witten and Sander (1981)	1.52	0.34	0.71	1.55	2.69	1.4 ± 0.9
Barabási and Albert (1999)	2.10	1.82	5.85	1.28	0.59	2.3 ± 2.1
Nahapiet and Ghoshal (1998)	2.73	2.75	0.97	2.66	2.19	2.3 ± 0.8

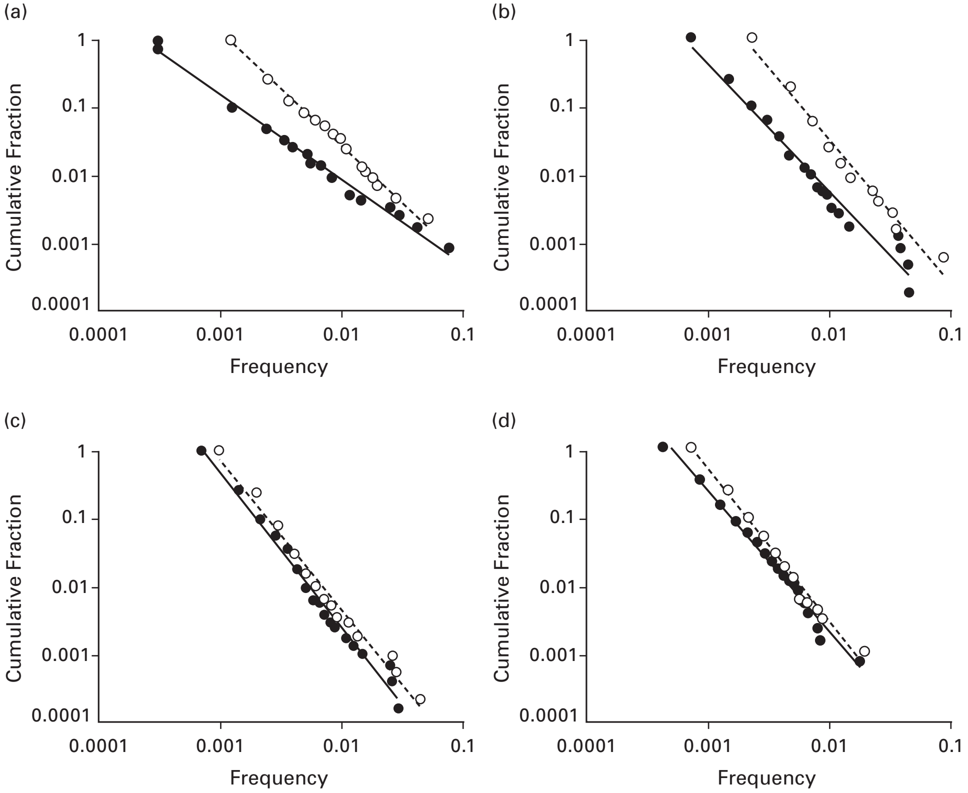

Figure 8.5
Cumulative frequency distribution of all keywords, for two time intervals, 2001 (open circles, dashed line) and 2005 (filled circles, solid line), for papers citing (a) Barabási and Albert 1999, (b) Nahapiet and Ghoshal (1998), (c) Witten and Sander (1981), and (d) Bordieu (1977). Double logarithmic axes, with lines showing best fit power-law slopes in 2001 and 2005, respectively, are as follows: (a) 1.67, 1.25; $r^2 > 0.99$; (b) 1.70, 1.75; $r^2 > 0.98$; (c) 1.58, 1.41; $r^2 > 0.881$; (d) 2.23, 2.05; $r^2 > 0.984$.

Finally, we look at the frequency distributions of keywords for two different time slices—years 2001 and 2005 (see figure 8.5). All show essentially a power-law form. For each age pair, the power-law slope of the social science case is steeper than for natural sciences (figure 8.5). Simulations of the neutral model (Bentley et al. 2004) indicate that the power-law slope increases with the number of inventions, $N\mu$, per generation. Whereas mean number of inventions is higher for SS77 than for PS81, the invention rate for PS99 is actually higher than for SS98 (see table 8.1). In fact, PS99 is again exceptional compared with the other three cases, as it is the only case for which the power-law slope changes substantially from 2001 to 2005 (see figure 8.5). These patterns support the case for selection in consideration of the rapid growth in references to PS99 and consequent increase in N and $N\mu$ over the time period (see figure 8.2). Even as more keywords were added to the PS99 pool, the distribution became more unequal (see figure 8.5a). A likely explanation is that the core ideas expressed in PS99 (e.g., complex networks) were being selected for in other fields of study.

Departures from the power law support the case for selection of groups of several words. In two cases, SS98 and PS81 (figure 8.5b and 8.5c), there appears to be selection for the top three or four words (and they are the same words in 2001 and 2005 for both cases), such that their frequencies are almost the same rather than following the power law.

Discussion

Some basic evolutionary analyses, with parallels in population genetics, can be used to characterize different forms of innovation and transmission of discrete cultural elements (Cavalli-Sforza and Feldman 1981). In the case of academic-language use, it shows that some academic fields are clearly characterized by a high degree of drift resulting in continual and unpredictable change in vocabulary, whereas in others it is quite different, with words under selection, such that the predominant vocabulary becomes increasingly crystallized and unchanging over time.

In my application to four examples of academic paradigms in the journal literature, I found that one could characterize relative differences in the degree of selection versus drift in keyword use. Over a several-year interval, the natural sciences paradigms (PS81 and PS99) reflected a greater degree of selection in cessation in the turnover of their top five keywords, with the younger case (PS99) showing clear sorting of those keywords by frequency, and the older case (PS81) suggesting the selection of a top group of several words that created a departure in the tail of the power-law distribution of keyword frequencies. Selection appears strongest in the younger natural science example because its keyword frequency distribution became more unequal (smaller power-law exponent) over time, with top words growing in popularity despite an increasing number of new keywords added to the pool of choices.

In contrast, the social science examples showed more indications of drift, consistent with the neutral model. These indications included continual turnover in the top five keywords, steeper power-law distributions (higher exponent) than their natural science counterparts of similar age, and high variability in the frequencies of individual keywords. Unlike the younger natural science paradigm (PS99), keyword frequencies in the younger social science example (SS98) varied stochastically rather than directionally.

The use of evolutionary analysis also made it possible to identify different dynamics among individual keywords, suggesting some individual words were subject to stronger selection than others. These effects could be identified and compared only once the effects of population size and relative frequencies were factored out, because frequency variance over time decreases with population size and increases with frequency for small frequencies. Hence, without having some idea of these variables, it is difficult to distinguish purposeful selection from random drift.

Conclusions

As humans behaving within heterogeneous networks of information, we may often have the impression that a certain genre of culture is trendy, conformist, or rigidly unchanging, and yet rarely do we employ an objective means for supporting such intuitions, much less understand how they came about. As much of this volume should demonstrate, basic evolutionary theory, long invoked to explain change through time in biology, provides objectivity for characterizing culture change.

An alternative, objective approach is the revitalized efforts at social modeling within the physical sciences, particularly in network science. However, if we view culture change as a historical science rather than a law-like one such as classical physics, then evolution may be the only theory to explain cultural variation and transmission in a causal way (e.g., Mesoudi et al. 2006; O'Brien 2008; Shennan 2002). The direct analogy between people and particles (or network nodes) in "social-atom" models (Buchanan 2007) depends on the assumed rules of interaction, which often stray too far from reality (Riede and Bentley 2008). Whereas variation in physics is often treated as "noise," it is the essence of an evolutionary approach. Current evolutionary theory inherits the insights of over a century of studying what amounts to change among entities that pass on their similarities to others through time. Our two conference organizers have been among the leaders in applying this to studies of culture change, particularly in archaeology (e.g., O'Brien 1996, 2008; Shennan 2002).

The selection–fashion dichotomy that I have advocated is perhaps more palatable in today's world than it was in previous decades, when labor unions were strong, the Internet was a novelty of U.S. government agencies, and academic publication was still done on real paper. Now, however, after the rapid rise and fall of dot-com equities, YouTube videos, MySpace personalities, and countless throwaway books, ideas of random copying and drift are much easier for people to digest. In fact, the evolutionary approach is spreading. Since the mid-1990s, growing numbers of physicists have started explicitly applying analyses of dynamic, historical processes of change—such as network evolution, complex adaptive systems, information cascades, sudden state changes, and extreme events—toward models of social change (e.g., Bentley 2007c; Bentley and Maschner 2008; Buchanan 2007). Similarly, some economists are beginning to focus on the flux of variation in open systems rather than the maintenance of equilibrium in closed systems (Ormerod 1998, 2006). I can only imagine what the future of innovation studies will look like.

Note

1. About 10 percent of the citing papers were omitted as a result of ambiguity in the publishing date listed in the database.

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9 Demography and Variation in the Accumulation of Culturally Inherited Skills

Adam Powell, Stephen J. Shennan, and Mark G. Thomas

In this chapter we introduce a simulation-based extension to an analytical model of cultural skill transmission presented by Henrich and Boyd (2002; Henrich 2004). Their original model derived the conditions necessary for a culturally inherited innovation, or cultural skill, to accumulate in a single population under a learning process that is both incomplete and inaccurate. Our simulation model extends these results by placing a modified version of their learning mechanism into a semirealistic human demographic setting with the aim of applying it in the context of the Upper Paleolithic transition. This was a pivotal period in human prehistory—the first sustained appearance of behavioral modernity—in which dramatic geographic and temporal variation in cultural innovation is evident. Although the invention of novel cultural skills or behaviors typical of the Upper Paleolithic is likely to have been stimulated by demographic pressures, cognitive advances, and environmental challenges, our simulation model is concerned solely with the long-term accumulation, or loss, of such cultural inventions. We propose that it is the maintenance, and not the invention, of novel traits that is of real interest and that this maintenance is limited by demographic factors. Our model is able to determine the demographic conditions necessary for a cultural skill to be maintained (or accumulate) over a period of many generations, and we argue that Late Pleistocene demography would have been an important factor in the appearance of the cumulative and complex cultural innovations characteristic of behavioral modernity.

The Upper Paleolithic transition, which occurred in Europe and western Asia ~45 thousand years ago (kya; Mellars 2005) and later in southern and eastern Asia (James and Petraglia 2005), Australia (Brumm and Moore 2005), and Africa (referred to as the Late Stone Age [Ambrose 1998a]), is seen by many as marking the origin of modern human behavior. This transition is characterized by a significant increase in both technological and cultural complexity, including the first consistent appearance of symbolic representation, and is often interpreted as evidence of the first "fully" modern human populations.

Bar-Yosef (2002) summarizes the main features characteristic of the Upper Paleolithic as follows:

- Rapid shifts in core-reduction techniques, leading to a proliferation of different microlithic stone tools, with blades largely replacing flakes.
- The use of bone, antler, and ivory in production of both functional tools and ritual artifacts.
- The systematic use of grinding/pounding stone tools to process plant food.
- Regular use of various body decorations from a wide variety of materials (including shells, teeth, ivory, and ostrich-egg shells), possibly signaling increasingly complex and/or frequent social interactions.
- The invention of improved hunting technology, such as spear throwers, bows, and boomerangs, potentially bringing much higher rates of hunting success.
- The appearance of art, both abstract and realistic, in the form of painting, engraving, and carved figurines.
- Unequivocal ritual burial, although there is also evidence of sporadic use of grave goods in Middle Paleolithic burials such as at Skhul V.
- A significant increase in the transfer distance of lithic and valuable raw materials.

In Europe and western Asia, this relatively rapid transition is widely thought to coincide with the expansion of *Homo sapiens* into a region previously occupied by Neanderthals (Bar-Yosef 2002; Zilhão 2007), leading to a period of coexistence of the two human lineages before the eventual extinction of the latter ~30 kya (Stiner and Kuhn 2006). For Africa, however, the idea of a short "seminal" transition has been contested by many authors, as there is evidence of many of these "markers of modernity" appearing at multiple sites across Africa well before 45 kya, possibly as early as 75–80 kya (Bar-Yosef 2002; Henshilwood et al. 2004; McBrearty and Brooks 2000), and most recently claimed for more than 160 kya in southern Africa (Marean et al. 2007). Yet these are sporadically maintained and are, in all cases, lost until the Late Stone Age, starting ~40 kya, when they again appear and become prevalent.

Archaeological evidence from South Asia and Australia appears more similar to the African case, with only sparse evidence of modernity—ornamentation, use of ochre, and possible rock art—occurring soon after the initial human expansions into the regions and becoming widespread only much later—~20 kya (Brumm and Moore 2005) in Australia and ~30 kya (James and Petraglia 2005) in southern Asia. Conversely, it has been argued that some late Neanderthal populations show features of behavioral modernity independent of any contact with modern humans (Conard 2005; Zilhão 2007).

Notwithstanding the oversimplifications made in the above outline, one important large-scale question remains: If, as is now widely accepted, anatomically modern humans (*H. sapiens*) originated in Africa between 150 kya and 200 kya (Lahr and Foley 1998; McBrearty and Brooks 2000; White et al. 2003), why was there such a long delay before the first consistent archaeological evidence for modern human behavior? One approach (Klein 2000) is to argue that the transition, or "human revolution," was a result of some kind of biological–neural mutation ~50 kya, which led to an increase in cognitive capacity, thus allowing an explosion of cultural and technological innovation.

Critics of this theory point to the low likelihood of this putative mutation having occurred independently in the many geographically separated human populations that would have existed at this time, given that there is no evidence for a second wave of Old World colonization by a group with such a mutation. Other authors (e.g., Lahr and Foley 1998; McBrearty and Brooks 2000) argue that the unambiguous evidence of modernity displayed in the African Middle Stone Age suggests that *H. sapiens* had the requisite cognitive capacity to be considered "fully modern" almost from the time of origin.

Some of the most notable examples of this African evidence associated with early modern humans are the (probably) hafted hunting weapons made of geometric blades of the Howiesons Poort industry in southern Africa (~55–70 kya; Lombard 2008), the series of barbed bone harpoon points at Katanda, Democratic Republic of the Congo (~90 kya; McBrearty and Brooks 2000), and the bone awls, pieces of ochre with abstract designs, and marine-shell personal ornaments at Blombos, South Africa (~74 kya; Zilhão 2007).

The arrival of anatomically modern humans in Australia (then part of the extended continent Sahul) dates to ~40–50 kya (Hudjashov et al. 2007; O'Connell and Allen 2004). Given that mastery of seaworthy technology would have been necessary to make the clearly intentional crossings of the Wallacean archipelago, a major ecological boundary, we can suggest that by that time *H. sapiens* had attained a modern level of cognition.

Numerous authors (Brumm and Moore 2005; James and Petraglia 2005; Lahr and Foley 1998; McBrearty and Brooks 2000; Shennan 2000, 2001; Zilhão 2007) view the emergence and consistent maintenance of modern cultural artifacts as a product of underlying demographic and associated sociological processes, although there are differences in the specific mechanisms invoked by different authors (see below). The basis of this view is the temporal correlation between the expansion and maintenance of modern human culture and the indication of major demographic expansion.

Our knowledge of late-Pleistocene demography remains extremely poor even in the best known regions of the world, but there is much evidence that populations were small in Africa and Eurasia until c. 50 kya, after which they are likely to have expanded rapidly. Stiner and Kuhn (2006) point to the narrow diet breadth and lack of impact on demographically sensitive small-game resources during the Middle Paleolithic in the circum-Mediterranean area as an indicator that population levels remained low. This is corroborated for some regions by site numbers (Lahr and Foley 2003; van Andel et al. 2003). Stiner and Kuhn (2006) propose that during the Middle Paleolithic, human populations responded to resource fluctuations by localized depopulation, and they suggest that human-population patterns corresponded to what we know about the population dynamics and low levels of large nonhuman predators.

Genetic evidence also points to marked increases in human populations in the late Pleistocene (Harpending et al. 1993; Rogers 1995; Sherry et al. 1994), and it has been argued that in Africa this expansion is associated with the improvement in climatic conditions associated with the end of Oxygen Isotope Stage 4 (Ambrose 1998b). The idea that there is a connection between demographic and cultural patterns and that both are affected by climate has been strengthened by recent work in Australia (Brumm and Moore 2005; O'Connell and Allen 2007), which seems to show a pattern similar to that seen in Africa but at a much later date. Thus, although Australia was colonized by modern humans ~40–45 kya, it shows only sporadic evidence of such phenomena as ornaments and burials for at least the next 20 millennia. It is only after 20 kya that they start to become more frequent and only in the early Holocene that they really become established, a pattern that seems to correlate with an order of magnitude increase in population size (Haberle and David 2004; O'Connell and Allen 2007). In this case, the improved climatic conditions of Holocene Australia are considered to be the most plausible causal factor (O'Connell and Allen 2007).

Models of the Relationship between Culture and Demography

Although many authors have postulated a link between the size of human populations and variation in the extent of cultural elaboration, the precise mechanism involved is unspecified in many, if not most, cases. However, three specific proposals have been made, none of them necessarily mutually exclusive. Several authors (O'Connell and Allen 2007; Stiner and Kuhn 2006; Vanhaeren 2005) propose that as populations increased, there would have been selective pressure for increasing use of various kinds of cultural-signaling mechanisms to strengthen social networks or to mark various kinds of identity, for example. In contrast, the two other models focus on processes of cultural transmission.

Some authors (e.g., Boyd and Richerson 1985; Cavalli-Sforza and Feldman 1981; Lumsden and Wilson 1981) have argued that human culture can be considered as an inheritance system, in some ways analogous to genetic inheritance, which is subject to evolutionary processes. They show that we can view human culture as a set of traits or behaviors that can be transmitted between individuals through a process of social learning, where "naive" copiers make inferences about the underlying behavior or trait based on its outward expression by a cultural model.

Of course, the mode of cultural transmission is different from that of genetic inheritance, as cultural traits can be transmitted not only from genetic parent to child (vertical transmission) but also from nonparental members of a group (oblique transmission) and between peers (horizontal transmission). Variation in these cultural traits is generated either at the learning stage, through mistakes in the inferential process (random copying error), by deliberate innovation, or by combining the traits of multiple cultural models, when the trait is expressed by the copier (a cognitive process).

An important component required of any evolutionary system is that of the differential success of variants in a population; in the case of cultural evolution this is driven by a number of mechanisms. These "forces of cultural evolution" (Boyd and Richerson 1985) include "cultural drift," which causes fluctuations in cultural-variant frequencies over time due to sampling error in populations of finite size; "guided variation," in which individuals modify their socially learned cultural variants through their own process of trial and error; and "biased transmission," where learners adopt a cultural variant preferentially (nonrandomly) as a result of (1) some intrinsic quality of the trait, (2) behavior itself ("directly biased transmission"), (3) a perceived quality of the cultural model that possesses it ("indirectly biased transmission"), or (4) the relative frequency of the variant in the population ("frequency-dependent biased transmission"). Thus, change over time in the frequencies of different cultural variants and their subsequent material expression in the archaeological record can be viewed as a result of these various processes of cultural evolution acting on socially learned traits, skills, or behaviors.

A review of the ethnographic literature (Shennan and Steele 1999) on the learning of craft skills shows that transmission in hunter–gatherer populations is almost exclusively vertical/oblique and is in many cases between parent and offspring of the same gender. This finding is consistent with the results of a model-based treatment of African cultural variation (Guglielmino et al. 1995), which found that the more conservative modes of cultural transmission (vertical/oblique) best explain the distribution of variation observed. It seems reasonable to assume that the mode of transmission of cultural skills within Late Pleistocene human populations would have been comparable to these contemporary hunter–gatherer groups.

In Shennan's (2001) simulation model based on Peck (1996; Peck et al. 1997), the mechanism that linked population size and variation in (beneficial) cultural accumulation was drift. It was shown that when cultural-innovation processes take place and the results are passed on by a combination of vertical and oblique transmission, larger populations have a major advantage over smaller ones. Members of larger populations are, on average, both biologically more fit and more attractive as models for imitation by virtue of the fact that the deleterious sampling effects present in small populations decline as population sizes increase. When populations are small, innovations that are less beneficial reproductively and less attractive to imitate are more likely to be maintained within them, that is, they have a greater "drift load."

A different transmission model, one based on the varying difficulty of learning different skills and the associated probability of achieving an improvement, was proposed by Henrich and Boyd (2002) and applied to explain the well-known pattern of cultural loss in Holocene Tasmania (Henrich 2004). This analytical model showed that under certain conditions, dependent on the population size (discussed below), the "cumulative adaptive evolution" of a cultural skill can occur, whereas in other circumstances a process of devolution and cultural loss will follow. Here we extend this model by using semirealistic stochastic simulations that reflect plausible human demographic conditions during the Pleistocene and take into account some of the drift issues highlighted in Shennan (2001).

The Henrich and Boyd Model

The model assumes a population of N adults, that is, "encultured" individuals, $i = 1, 2, \ldots N$, each of which has a z value, z_i, a measure of its ability at some cultural skill, such as making arrowheads. Every adult individual is also characterized by a variable, f, that specifies the relative likelihood of being chosen as a cultural model by members of a subsequent generation. The authors (see Henrich [2004] for full details) make use of the Price equation, a means of delineating the processes at work within any evolutionary system (Frank 1995; Price 1970), to measure $\Delta\bar{z}$, the change in the average z value in the population over time:

$$\Delta\bar{z} = Cov(f_i, z_i) + E(f_i \Delta z_i) \tag{9.1}$$

The two terms on the right-hand side can be thought of, respectively, as the change in the average z value resulting from cultural selection, that is, the propensity to copy successful or skilled people, and the change resulting from the inaccurate transmission process. Where $\Delta\bar{z}$ is positive, "cumulative adaptive evolution" is occurring, with the average ability at the cultural skill increasing over time within the modeled population. In order to replicate the "incomplete and inaccurate" processes of inference, copiers in subsequent generations never exactly replicate the z value of their models. An individual attempting to copy a model with z value z_i gains a value drawn from a Gumbel distribution (Henrich [2004] notes that the specific form of distribution does not qualitatively affect any derived results) with mode ($z_i - \alpha$) and dispersion parameter β, meaning that the transmission process is, first, systematically biased, as, on average, a copier will end up with a z value less than that of his or her model by an amount α, and, second, "noisy," so that there is a small probability (the area under the distribution greater than the model's z value), monotonically related to β and inversely related to α, that copiers will gain a z value greater than that of their model.

The model stipulates that all social learners choose the most-skilled member of the previous generation as their oblique model, and the following equation is derived:

$$\Delta\bar{z} = -\alpha + \beta(\varepsilon + \ln(N)) \tag{9.2}$$

The first term on the right represents the deleterious effect of systematic bias, and the second describes the opposing, favorable effect of random noise (ε being the Euler-gamma constant ≈ 0.577) and is a proxy measure of the area of the distribution greater than the

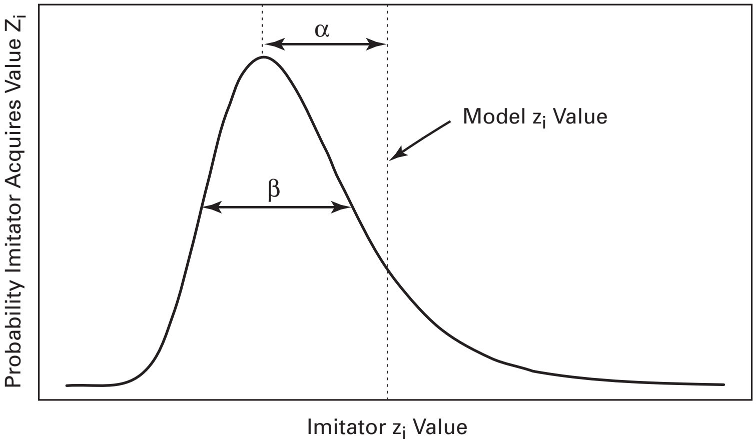

Figure 9.1
Gumbel distribution for incomplete and inaccurate transmission process.

model z value (see figure 9.1). To find the conditions under which cultural transmission will result in adaptive accumulation, the authors set $\Delta\bar{z} > 0$ and rearrange (9.2) to get

$$N^* > e^{\frac{\alpha}{\beta}-\varepsilon} \tag{9.3}$$

where N^* is the critical number of social learners necessary for a specific process of imitation defined by (α, β). (See figure 9.2.)

The main conclusion of interest here is that the cumulative adaptive evolution of a culturally inherited skill is dependent on the size of the pool of social learners N, so a larger population (subject to the same level of noise in the imitation process) would be able to accumulate and maintain a more "complex" skill. As the critical conditions for adaptive evolution depend solely on the ratio α/β, and if we assume that all modern human populations, on average, would have been subject to similar levels of random noise during the inheritance of cultural skills, we can effectively combine the two parameters α and β by setting $\beta = 1$ and then simply adjusting the parameter α to simulate cultural skills of varying "complexity."

One assumption inherent in the model is the unfailing ability of naive individuals to accurately identify the most skilled member of the preceding generation as an oblique model—an assumption that rapidly becomes unrealistic as the size of the adult population increases beyond the size of a sustainable social network. By imbedding an extended version of the transmission process previously described (to include both vertical and oblique transmission) into a semirealistic simulation that estimates conditions during the Late Pleistocene—that is, a number of geographically separate subpopulations connected

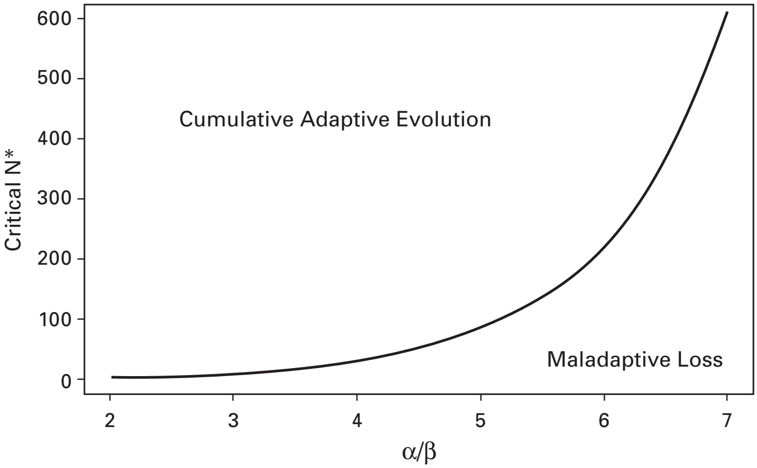

Figure 9.2
The conditions necessary for cumulative adaptive evolution.

by migratory activity—we can relax this assumption and further investigate the effects of early human demography on the accumulation of cultural skills. In the following sections we introduce and detail the simulation model, present the main theoretical results, and discuss their possible implications in future debate on the nature and causes of the appearance and accumulation of modern human culture.

Model 1: Extending the Analytical Model

Our underlying simulation model consists of a number of subpopulations, *G*, placed at random in a two-dimensional simulated world. Each subpopulation contains *N* adult individuals, and all subpopulations are connected by migratory activity. In every generation of the simulation, the model goes through the following steps:

1. Within each subpopulation a generation of offspring, also of size *N*, is created.

2. Genetic parents are chosen for each offspring by randomly sampling the adult generation with replacement.

3. Naive offspring then undergo a process of "vertical transmission," where they receive a z value by learning from their genetic parents according to the transmission process described by Henrich and Boyd (2002) and detailed above.

4. A proportion, P_{ob}, of these offspring then undergoes a process of "oblique transmission," where they replace their z value with one learned from the maximally skilled member of the adult generation in the subpopulation (the *oblique model*).

5. The now-"encultured" offspring generation then fully replaces the adult generation within each subpopulation.

6. A proportion, P_{mig}, of these new adults then migrates, with each migrant being placed in a new subpopulation by a Gaussian random-walk-like process.

Each simulation is initialized by giving all individuals in all subpopulations a z value of 10.0, then running forward for 50 generations, and after the final generation, calculating the world mean z value. This value is compared to the starting world mean (10.0) to determine whether this simulation results in "adaptive cumulative evolution," i.e., $\Delta\bar{z} > 0$. To account for stochastic variation in simulation outcomes, we perform multiple iterations, making this calculation at the end of each iteration. We then calculate the mean z value across iterations and deem the parameter set to be "cumulatively adaptive" if it is greater than the mean starting z value, i.e., >10.0.

We recognize that the time spans we are considering are 10,000–20,000 years (around 400–800 generations), but preliminary tests showed that 50 generations was in most cases sufficient to determine whether the parameter set would result in cumulative adaptive evolution or maladaptive loss—with mean z values either increasing monotonically without bound, decreasing monotonically to zero (at which point the cultural skill is irretrievably lost), or reaching a relatively stable equilibrium value. The model is also relatively conservative, in that it currently disregards the likely autocatalytic/positive feedback loop, where increasing ability in some cultural skills would lead to improved demographic conditions (by means of improved reproductive success/resource utility), which would, in turn, further increase skill accumulation.

The parameters of interest in this model are the number of subpopulations, G; the size of each subpopulation, N; the proportion of offspring to undergo oblique transmission, P_{ob}; the proportion of each subpopulation available to migrate, P_{mig}; and the "complexity" of the skill, α. Because of the difficulty in accurately estimating demographic parameters during the Pleistocene, we turn to a review of contemporary Australian aboriginal hunter–gatherer populations (Birdsell 1973) to draw some estimates for N. Two regularly occurring distinct social structures of differing size are identified. The first is the "band," an independent and autonomous patrilineal unit commonly comprising 25–50 individuals (usually an extended familial group), and the second, the "tribe," comprising around 500 or so individuals related by linguistic or dialectal similarity and forming a generally endogamous unit.

To complement these two contemporary ethnographic estimates, there are also analyses emerging from biological anthropology (Dunbar 1992, 1993) that may shed light on the question of early human subpopulation sizes. Dunbar argues that social-group size in primates is likely to reflect the cognitive capacities of the individuals comprising it, as there is thought to be a cognitive upper limit on the number of social interactions that can be maintained and thus a limit on group size. Extrapolating a relationship between neocortex ratio and social-group size in nonhuman primates to humans gives a prediction for ancestral group size in the region of ~150.

We need to bear in mind that the value of N in our simulation refers to the total number of social learners in the offspring generation and that, as we are assuming that 50 percent of each group is subadult and that a cultural skill is inherited by same-sex offspring, this represents roughly a quarter of each actual subpopulation size. Based on the previous estimates, we have simulated over values of N between 5 and 100, corresponding to total group sizes of ~20–400, recognizing that actual Pleistocene group sizes are likely to have been weighted toward the lower end of this range.

In estimating the migration rate, P_{mig}, we make use of an earlier Birdsell (1968) study giving an aboriginal intertribal marriage rate of ~15.7 percent, which corresponds to a migration rate of around 0.074. This is consistent with another Australian aboriginal study that yielded estimates of between 0.07 and 0.21 (Tindale 1953; see Eller et al. 2004). Even if Pleistocene subpopulations were comparable in size to contemporary hunter–gatherer groups, it is likely that subpopulation densities and intergroup interactions prior to the emergence of Late Stone Age/Upper Paleolithic technology were significantly lower than the contemporary estimates for migration rates. We therefore simulated over a range of migration rates, P_{mig}, between 0.001 and 0.15.

Although oblique transmission, and prestige-biased transmission in particular (Henrich and Gil-White 2001), is undoubtedly important in the transmission of cultural skills (Guglielmino et al. 1995; Shennan and Steele 1999), it is difficult to make realistic estimates of the extent to which it occurred. For this reason, we have simulated P_{ob} over the entire range of 0.1 to 1.0 (in increments of 0.1). The number of subpopulations, G, likely was subject to significant fluctuations during the Pleistocene, for reasons outlined above, so we simulated for a wide range of G, from 1 up to 500.

Preliminary simulation results indicate that as G increases beyond ~100, there is only a small increase in mean z value, suggesting that a “saturation point” is reached with regard to skill accumulation. Given this, and making the reasonable assumption that the number of interconnected human subpopulations during the Middle Stone Age was likely to have been at least this large, we fix $G = 100$ in future simulations. These simulations also showed that adjusting the value of N has no qualitative effect on the results, so fixing $N = 25$ from here on entails no loss of generality.

Simulation results are presented in figures 9.3 and 9.4 and show that the degree of skill accumulation increases with increasing oblique transmission probability (see figure 9.3), increasing migration rate (see figure 9.4), and decreasing complexity (as measured by the α value). The shaded regions give the parameter sets that result in cumulative adaptive evolution, i.e., mean final z value > 10.0.

This model defines the migration rate at the global level (P_{mig}), operating for all subpopulations irrespective of the local subpopulation density. As a result, it is impossible to ascertain the effects of having different subpopulation densities in different regions of the

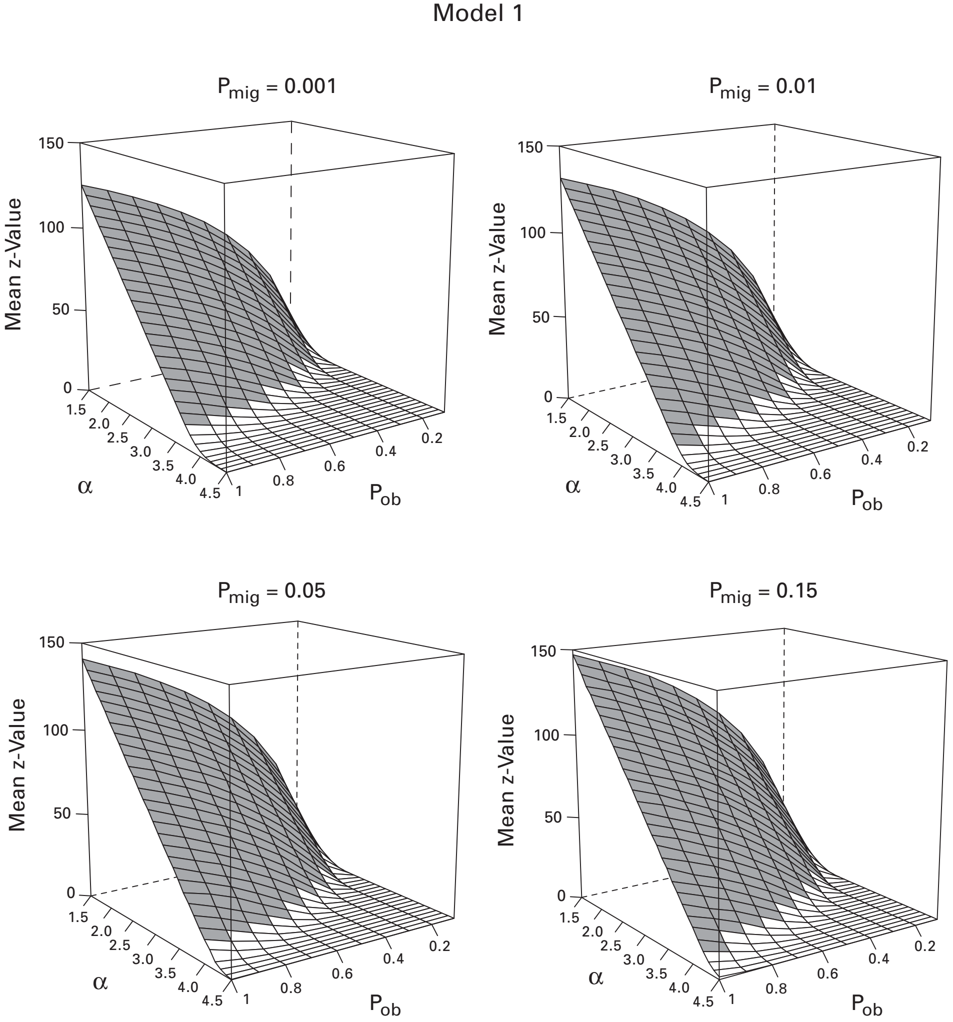

Figure 9.3
Model 1 simulation results, showing mean z values for combinations of parameters α and P_{ob} (oblique-transmission probability), given for four different migration rates (P_{mig}). Shaded regions indicate parameter sets resulting in cumulative adaptive evolution, that is, mean z value > 10.0.

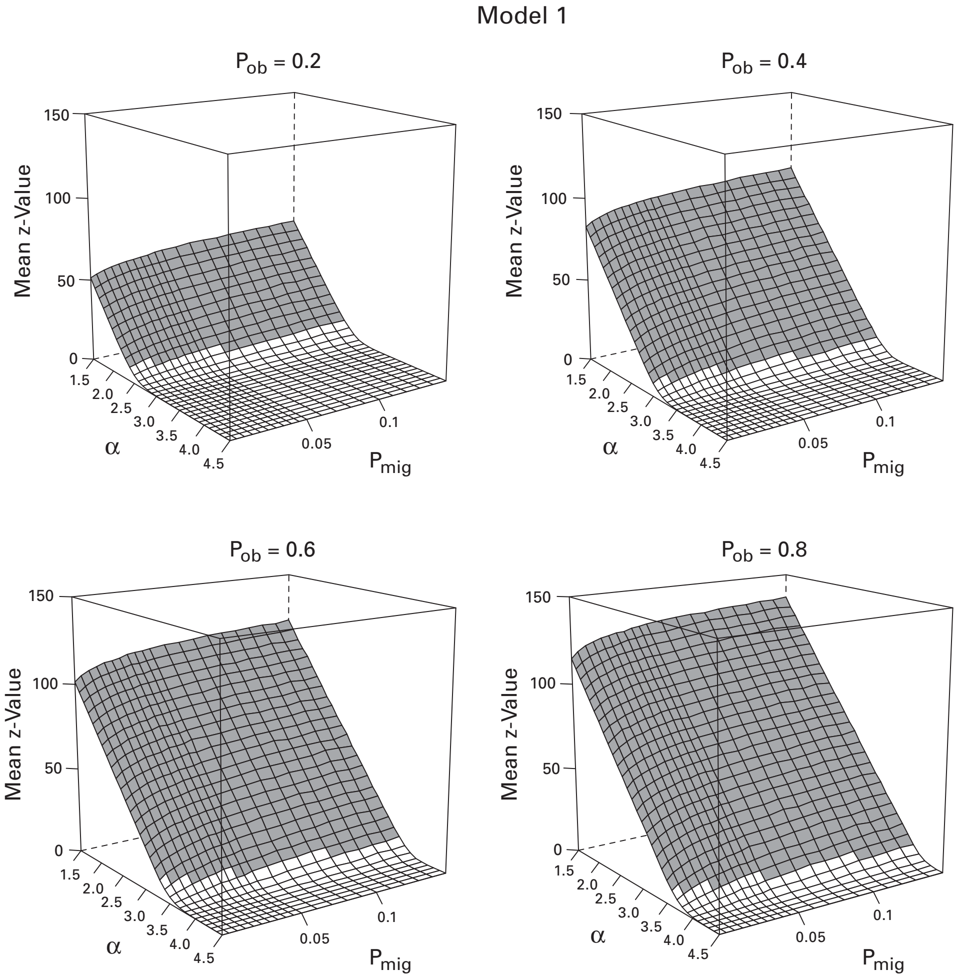

Figure 9.4
Model 1 simulation results, showing mean *z* values for combinations of parameters α and P_{mig} (migration rate) given for four different oblique-transmission probabilities (P_{ob}). Shaded regions indicate parameter sets resulting in cumulative adaptive evolution, that is, mean *z* value > 10.0.

same simulation world. A far more realistic model would explicitly link local migration rates to local subpopulation density. To this end, we have added an extra level of complexity to our simulation model as detailed below.

Model 2: Subpopulation Density–Dependent Migration

The migration process in this model is now explicitly dependent on subpopulation density. We define the global density of subpopulations, D, and adjust the dimensions of the simulation world so that we get ~100 subpopulations, a value for G we showed above to be reasonable. The model then creates a simulation world by placing, again at random, the subpopulations. At the migration step in the simulation, all adult individuals now undergo a Gaussian random-walk process, with the standard deviation of the Gaussian distribution defined by a new parameter, M_{sd}. The adult individuals that "hit" any other subgroup during this process are deemed to move to that group; otherwise, they are deemed not to migrate and to remain in their original subpopulation.

The parameter M_{sd}, which can be thought of as the "migratory range" of an individual, is defined as a proportion of the average nearest neighbor distance, $\bar{r}_E$, between subgroups within the simulation world. A derivation presented by Clark and Evans (1954) gives this average nearest neighbor distance between randomly distributed subpopulations in terms of density as

$$\bar{r}_E = \frac{1}{2\sqrt{D}},$$

which is shown in figure 9.5.

If we note that around 99.7 percent of the probability density of a Gaussian distribution lies within ±3 standard deviations, we would expect that when $M_{sd} \leq 1/3$ many subpopulations would be effectively isolated from all others as migrants would be unable to reach them; therefore, their internal skill accumulation would be unaffected by the migration process. Test simulations—where we calculated the mean global migration rate—confirmed this and showed that for M_{sd} greater than ~0.3, the mean global migration rate approximately equals the global subpopulation density, D (see figure 9.6).

For our current purposes, we set M_{sd} well above this critical value at 1.0, that is, equal to $\bar{r}_E$, so we can be sure that few subpopulations are completely isolated and that the mean global migration rate, and thus the effect on the accumulation of cultural skills, will depend solely on the underlying global subpopulation density. We simulate for 50 generations, over a range of α values and again for the entire range for P_{ob} (0.1–1.0).

Simulation results for this model show (in broad agreement with model 1 results) that skill accumulation increases with increasing oblique-transmission probability (see figure 9.7), with increasing subpopulation density (see figure 9.8), and with decreasing complexity (as measured by the α value).

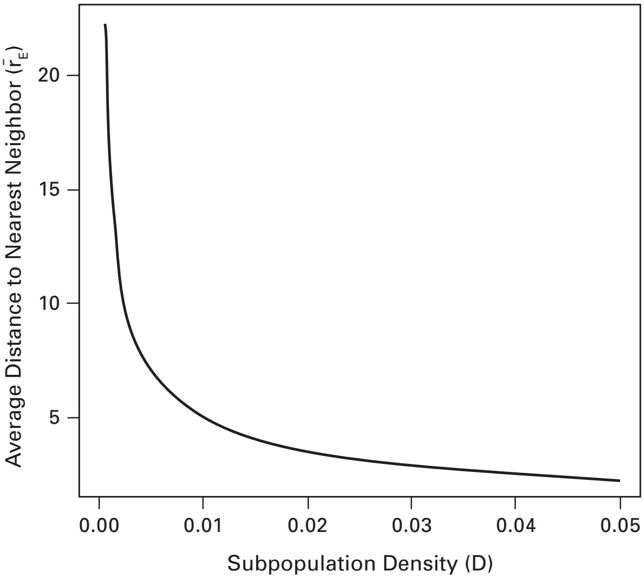

Figure 9.5
Average nearest neighbor distance between randomly distributed subpopulations.

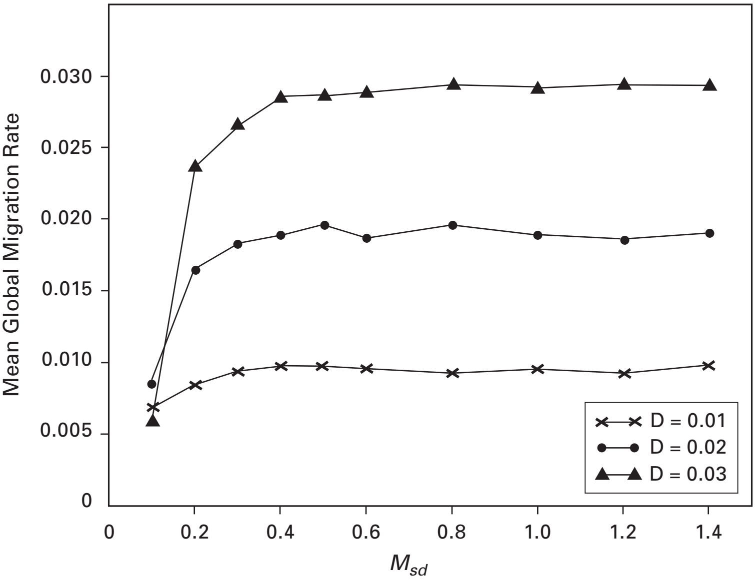

Figure 9.6
Mean global migration rate for increasing M_{sd} (migratory range) from test simulations. D = subpopulation density.

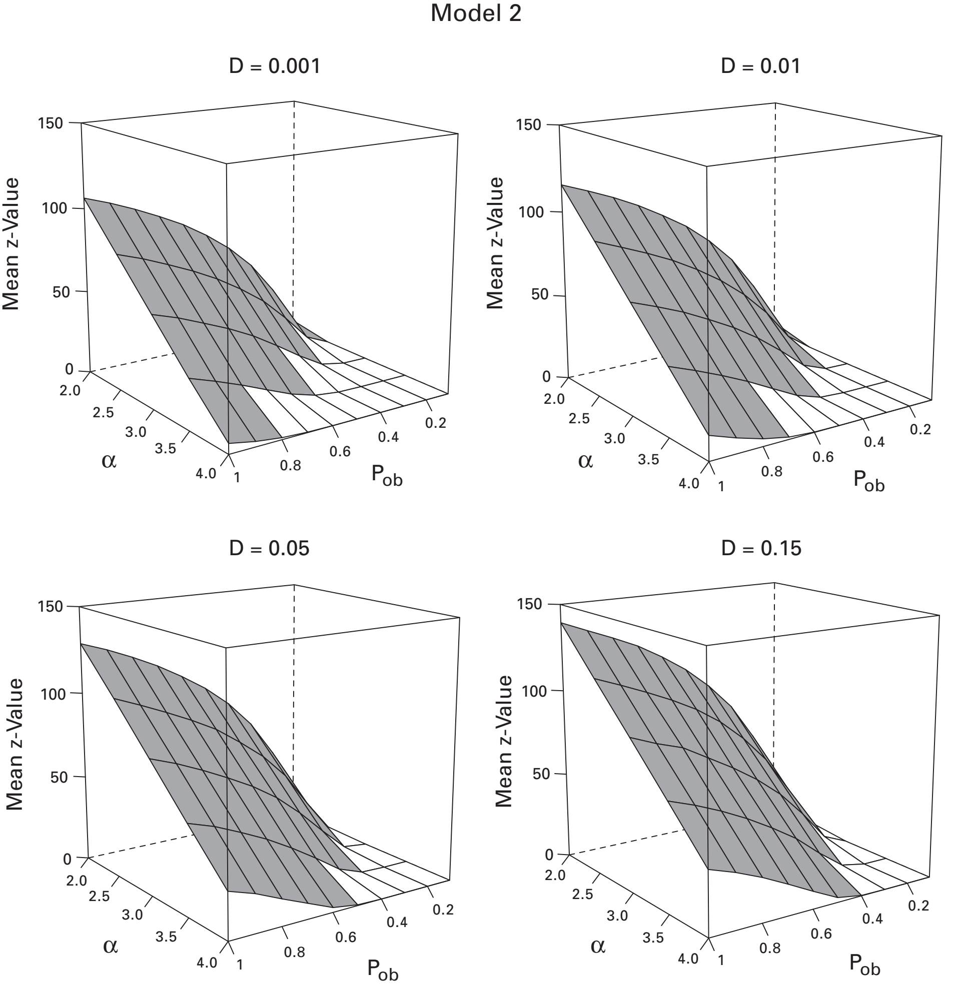

Figure 9.7
Model 2 simulation results, showing mean *z* values for combinations of parameters α and P_{ob} (oblique-transmission probability), given for four different subpopulation density (*D*) values. Shaded regions indicate parameter sets resulting in cumulative adaptive evolution, that is, mean *z* value > 10.0.

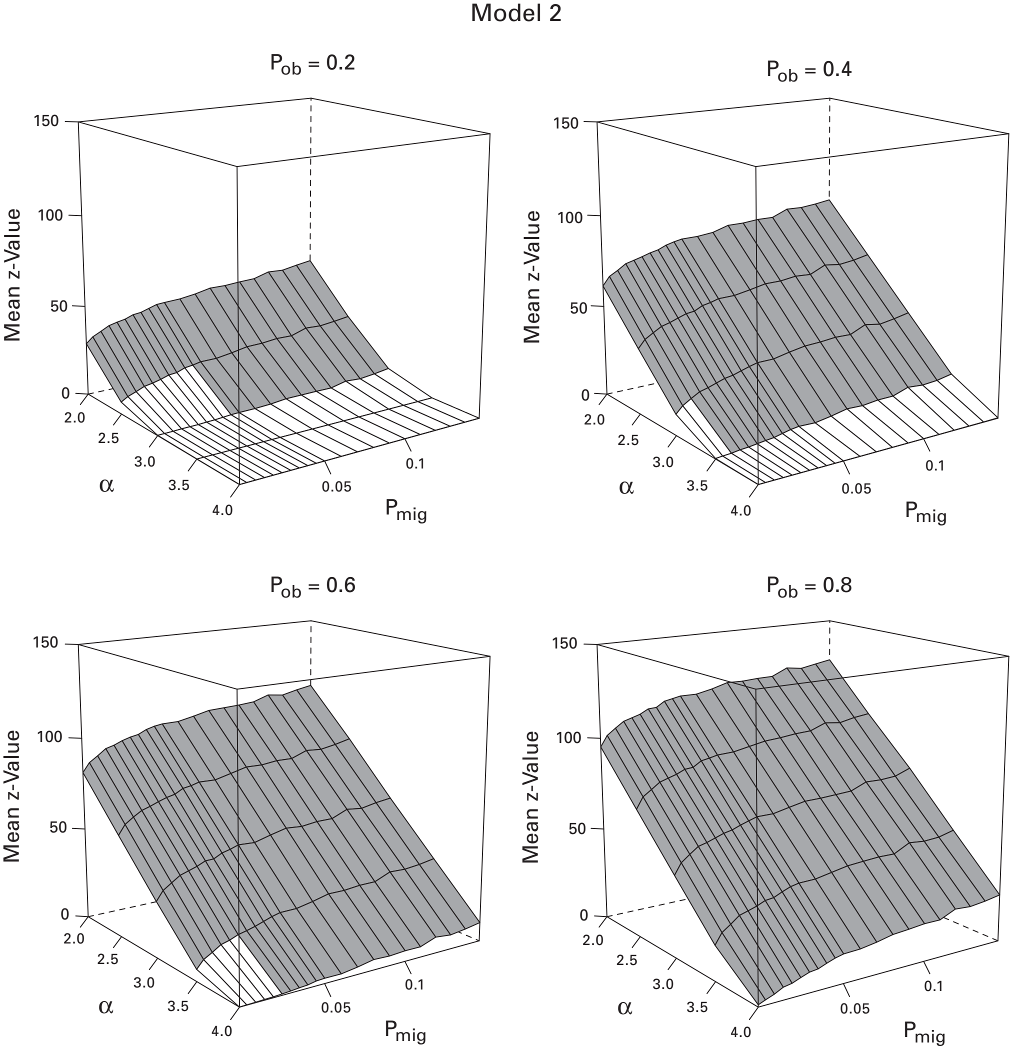

Figure 9.8

Model 2 simulation results, showing mean *z* values for combinations of parameters α and *D* (subpopulation density) given for four different oblique-transmission probabilities (P_{ob}). Shaded regions indicate parameter sets resulting in cumulative adaptive evolution, that is, mean *z* value > 10.0. P_{mig} = migration rate.

Model 2.1: Heterogeneous Subpopulation Density

A minor adjustment to the previous model allows us to investigate the effect of dividing the simulation world into two regions of different subpopulation densities. We partition the simulation world in half along the east–west axis and populate one half at a subpopulation density D_{high} and the other at a density an order of magnitude lower, D_{low}. In the following simulations, we set $M_{sd} = 1.0$ as a proportion of the average nearest neighbor distance, $\bar{r}_E$, in the lower density region, again to ensure that all subpopulations are connected by migration (including across the density divide). We set $D_{high} = 0.02$ and $D_{low} = 0.002$ and the dimensions of the world at 100 × 100, giving us a total of 110 subgroups, and simulate for a range of α values (2.0–4.0) and for values of P_{ob} (0.25, 0.5, 0.75, and 1.0) over 100 generations, performing 100 iterations for each.

In these simulations (data not shown), we find that skill accumulation is consistently higher in the higher-density region. As an example, we can fix $\alpha = 3.5$ and $P_{ob} = 0.5$ and look at the average z values in each region over time. Figure 9.9 shows that this difference is maintained over the entire (extended) duration of the simulation. The 95 percent confidence intervals, as estimated by taking mean regional z values for 100 iterations, show

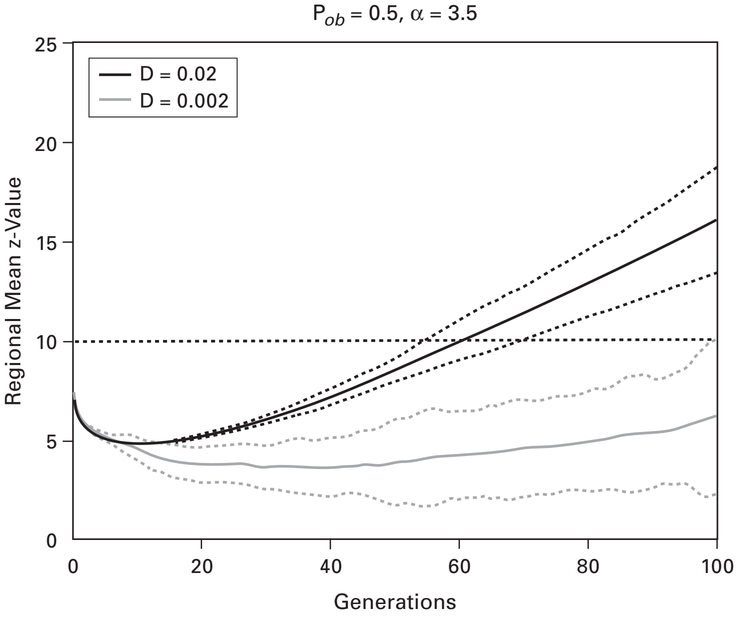

Figure 9.9
Example simulation result from model 2.1 (oblique-transmission probability [P_{ob}] = 0.5, $\alpha = 3.5$) with heterogeneous subpopulation density (D). Solid lines give the mean z value in each region; dotted lines give the 95 percent confidence intervals (from 100 iterations).

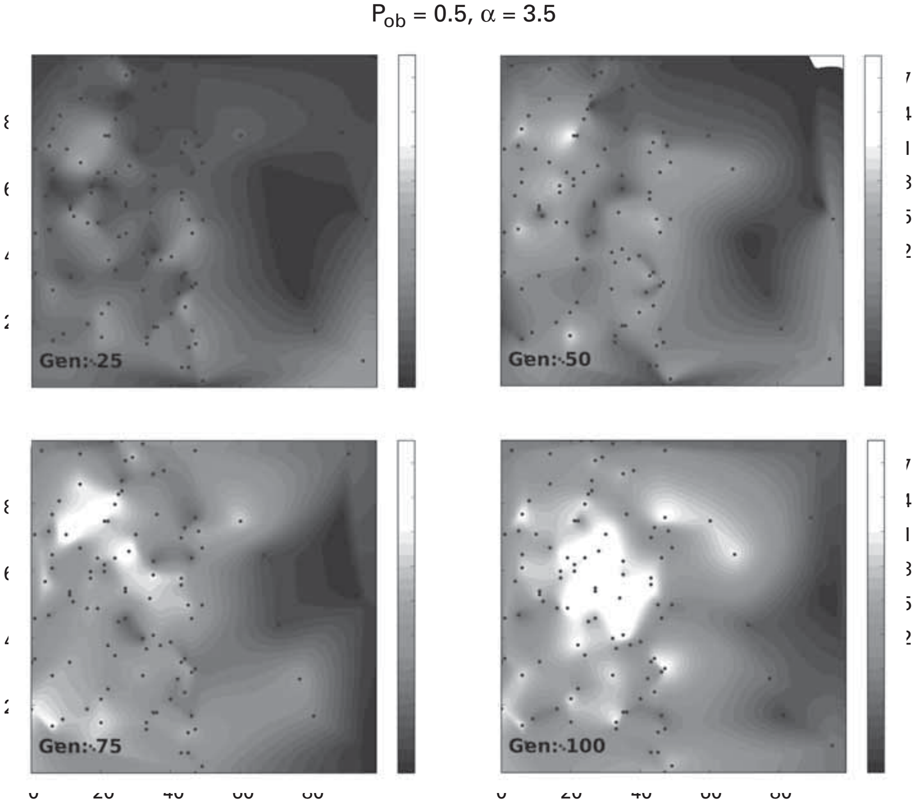

Figure 9.10
Spatial structuring of skill accumulation (model 2.1 example result) taken at 25-generation intervals. Subpopulations are shown as black points; mean *z* values are surface interpolated.

that the difference in accumulated *z* values between the different density regions becomes significant after less than 20 generations.

A visual illustration of this spatial structuring of skill accumulation can be seen in figure 9.10. In this example, a series of "snapshots" of a single iteration are taken at 25-generation intervals, and the subpopulation *z* values are surface interpolated to show "spatial skill accumulation."

Model 2.2: Heterogeneous Migratory Range

A further modification of the model allows us to divide the world into two regions of identical population density but differing migratory range, M_{sd}. This allows us to explore the effect of reduced migratory range on the accumulation of cultural skills in geographic space. We set $M_{sd,high}$ at 1.0 and $M_{sd,low}$ an order of magnitude lower, at 0.1. Figure 9.11

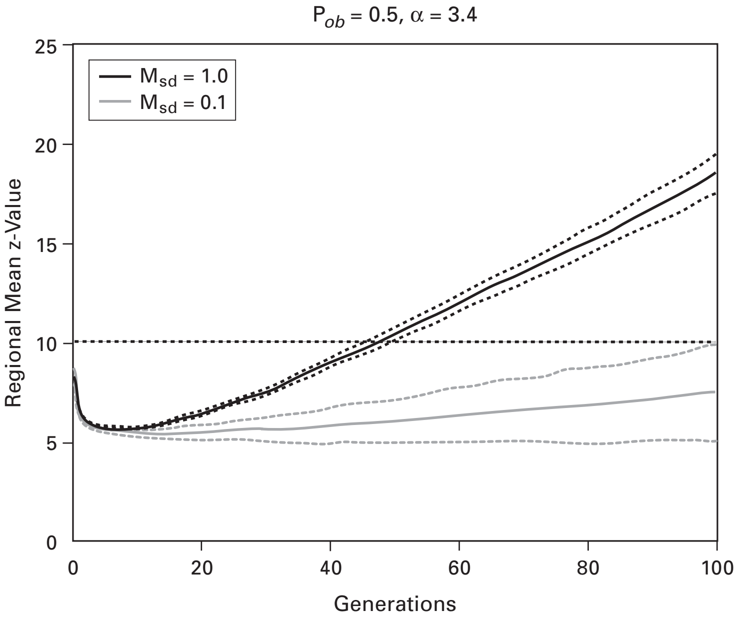

Figure 9.11
Example simulation result from model 2.2 (oblique-transmission probability [P_{ob}] = 0.5, α = 3.4) with heterogeneous migratory range (M_{sd}). Solid lines give the mean *z* value in each region; dotted lines give the 95 percent confidence intervals (from 100 iterations).

shows the results for $D = 0.01$, $\alpha = 3.4$, and $P_{ob} = 0.5$ across 100 generations and using 100 iterations to estimate the 95 percent confidence interval of *z* values for each region. As with the heterogeneous density simulations, we can see that the regional mean *z* value becomes significantly higher in the high migratory-range region after less than 20 generations. A surface-interpolation plot illustrating this spatial structuring of skill accumulation over time is presented in figure 9.12.

"Natural" Oblique-Transmission Methods

In all previous models, we parameterized the proportion of offspring undergoing oblique transmission (P_{ob}), which, as discussed above, is difficult to estimate from the ethnographic record. The identification of the oblique model was also assumed to be perfectly accurate, which ignores the likely difficulty of this process in the real world, even within the much smaller subpopulations we have modeled. To avoid these difficulties and to reduce the number of parameters in the model, we have developed a number of more "natural" processes for oblique transmission, which we surmise may more realistically reflect processes by which oblique models are chosen within human populations. Under these new methods, all offspring identify and select an oblique model with a degree of uncertainty and replace

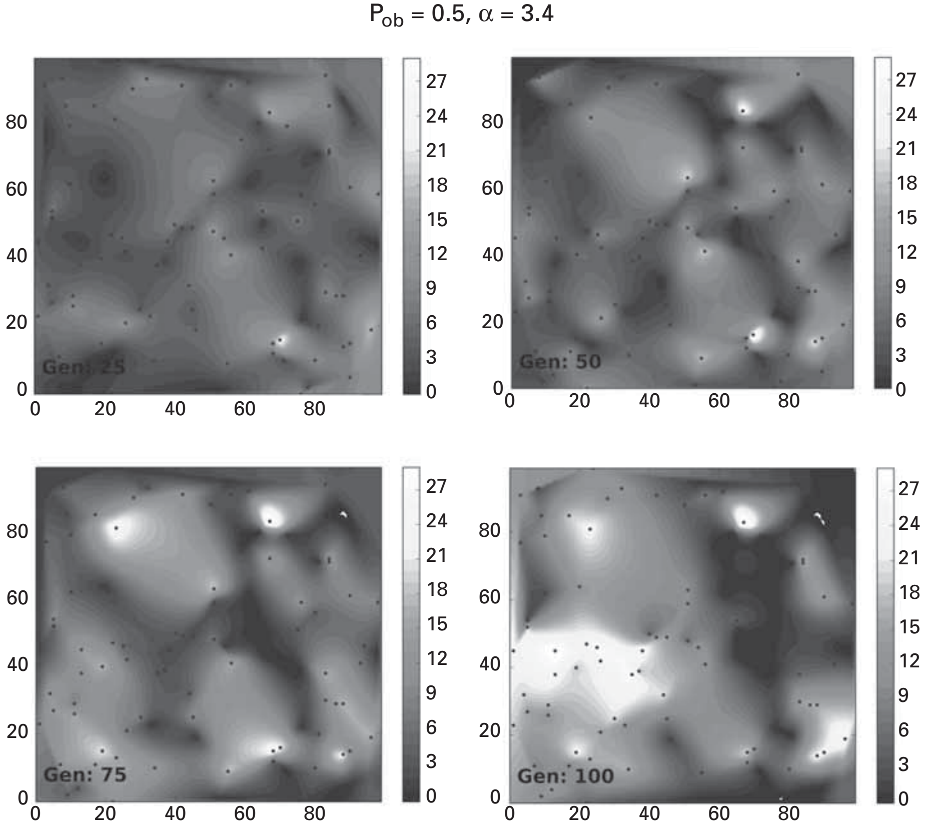

Figure 9.12
Spatial structuring of skill accumulation (model 2.2 example result) taken at 25-generation intervals. Subpopulations are shown as black points; mean *z* values are surface interpolated.

their current *z* value, that is, the one gained vertically from a parent, only if the value they gain from their chosen oblique model is greater.

In method 1, each offspring selects an oblique model from the adult generation, with probability proportional to the squared adult *z* value. In method 2, each offspring selects an oblique model from among only the adults with *z* values greater than what was already gained from a biological parent, with probability proportional to the magnitude of the difference. In method 3, each offspring selects an oblique model from the adult generation, with probability proportional to the difference between each adult's *z* value and the minimum adult *z* value in the subpopulation.

All simulations were run in a homogeneous simulation world, that is, where $M_{sd} = 1.0$ and with *D* kept constant both across the whole world and with each of the three alternative processes, so results can be compared, possibly allowing us to identify an efficient (or near-optimal), realistic cultural-learning strategy. We simulated for 50 generations, performing 100 iterations, for a range of subpopulation densities, D, and skill complexities, α, for each of the three "natural" oblique methods.

Results for the three methods again show the general result that increasing subpopulation density and decreasing skill complexity, α, leads to increased skill accumulation (see figure 9.13). Method 2 consistently results in greater mean z values, thus leading to cumulative adaptive evolution (the shaded regions), even for more complex skills and at lower subpopulation densities than either of the other two methods.

Discussion

Our results show that the level of cultural skill that can be maintained in subpopulations is related to the density/migratory activity of those subpopulations. In cases where densities/migration rates are low, cumulative adaptive evolution will never occur. Even in cases with higher densities and migration rates where it does occur, there is a significant period before accumulation begins, with potential consequences for population viability.

We also demonstrate that geographic heterogeneity in local subpopulation density/migratory activity leads to stable spatial structuring of skill accumulation, so that areas where skills accumulate can exist contiguously with areas of skill devolution over long periods of time.

The last set of simulations presented compared different "natural" strategies of choosing an oblique model within subpopulations, which recognize that individuals will not always be in a position to identify the individual with the maximum skill level. Results show that method 2—in which each offspring selects an oblique model from among only the adults with z values greater than what the offspring has already gained from a biological parent, with probability proportional to the magnitude of the difference—leads to cumulative adaptive evolution for more complex skills (characterized by a higher α value) and at lower densities than possible alternatives.

These results confirm and extend Henrich's (2004) initial results and show that the action of demographic factors on the results of cultural-transmission processes using plausible parameter values could indeed have had the effect on cumulative adaptive evolution that many others have postulated as central to the slow pace of cumulative cultural evolution prior to c. 50 kya and its greatly increased speed thereafter.

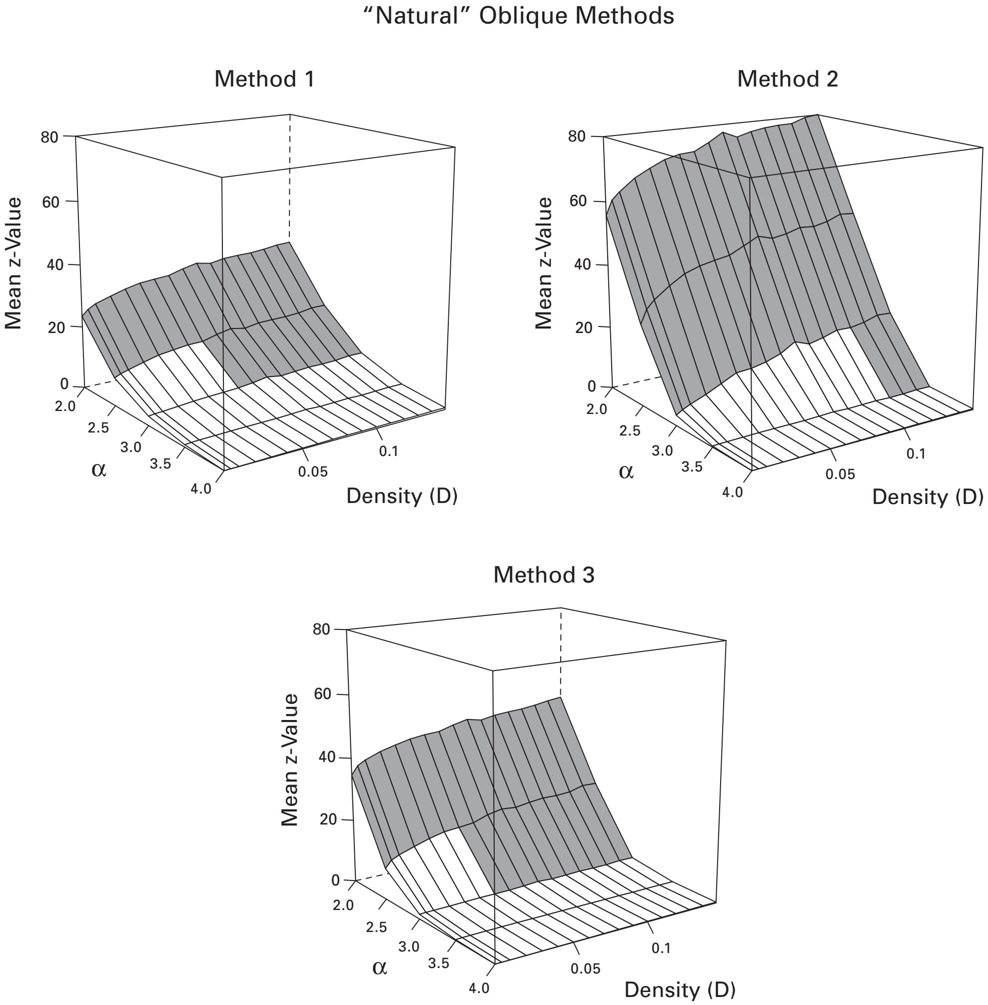

Figure 9.13
Simulation results for the three natural oblique-transmission methods, showing mean *z* values for combinations of parameters α and *D* (subpopulation density). Shaded regions indicate parameter sets resulting in cumulative adaptive evolution, that is, mean *z* value > 10.0.

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10 Cultural Traditions and the Evolutionary Advantages of Noninnovation

Craig T. Palmer

The old is the best, and the new is of the devil!
—Amish saying

White man got no dreaming.
—Australian Aboriginal saying

My message is a plea to recognize some adaptive value in tradition-perpetuating mechanisms and in the traditions they perpetuate.
—D. T. Campbell (1975: 1108)

People living in modern societies tend to value innovation highly. Diamond (2001: 28) has even called innovation "that most human of characteristics" and referred to the rapid increase in innovation seen around 35,000 years ago as the "Great Leap Forward." He views the creation of innovations not only as what makes us human but as what makes us distinct from other forms of life: "Had a visitor from outer space come to Earth before the Great Leap Forward, humans would not have stood out as unique among the world's species" (Diamond 2001: 33). Harris (1989: 64) goes even further, claiming that the increase in the rate of cultural innovation around 35,000 years ago was "a breakthrough as fateful as the transition from energy to matter or from amino acids to living protein" (see also chapter 9, this volume).

If so, then the Amish are a puzzle. This North American Anabaptist group, whose roots can be traced back to sixteenth-century Switzerland, spurns many forms of technological innovations. Instead of valuing innovation, the Amish place an extremely high premium on preserving the patterns of behavior they have copied from their parents or other ancestors—their cultural traditions. The high value the Amish place on preserving their traditions and their willingness to reject even economically advantageous technology in order to do so have earned them the name "People of Preservation" (Ruth 1991). This moniker serves to distinguish them from the people surrounding them who, according to Diamond and Harris, are representative of our species and deserve the name "People of Innovation."

If the Amish are unique with respect to the effort they put into reducing cultural change, they would be the poorest of choices to use in exploring innovation in cultural systems. I argue, however, that the Amish are actually *more* representative of our species with respect to the effort they put into *preserving* their cultural traditions than are the "People of Innovation" that make up the "modern" world. I will make this point by describing similarities between the Amish and traditional cultures in general, illustrated primarily by Australian Aboriginal peoples.

If the Amish are representative of the human attitude toward innovation during recent human evolution, our view of rapid cultural and technological innovation as the defining attribute of our species may need to be modified. This modification will necessitate incorporating mechanisms that preserve cultural traditions into evolutionary explanations of human cultural transmission. Current evolutionary explanations of culture tend to see cultural change as an active process involving activities such as "the hard work of invention" (Schiffer 2005: 485), the operation of various cultural transmission biases (e.g., Henrich 2001; chapters 1, 7, 9, 11, and 12, this volume), and random copying errors (e.g., Lipo and Eerkins 2005; chapter 8, this volume). The modification I am suggesting involves viewing the *absence* of cultural change as also being the result of an active process instead of merely a passive state that exists when the active processes of change are not taking place.

With reference to the active processes of change, Henrich (2001: 992) observes that "efforts to understand human behavioral change have produced a multiplicity of different approaches." The same cannot be said for efforts to understand the absence of behavioral change when cultural patterns of behavior are preserved. Richerson and Boyd (2000: 22) state that "among modern humans, the maintenance of complex traditions is not unproblematic," but they are referring only to the difficulties in maintaining traditions when very small populations become isolated. I suggest that the maintenance of traditions is always problematic because the preservation of traditional behaviors always requires hard work. If this is true, then a significant part of explaining innovation is explaining when innovation does *not* happen.

The goal of this reconsideration of the role of innovation in human evolution is not to replace current theories of technological innovation and culture change but to supplement them by proposing testable answers to two questions about cultural preservation:

1. How can patterns of cultural behavior remain essentially unchanged over many generations? That is, what are the proximate mechanisms preserving cultural traditions?
2. What was the evolutionary advantage, or advantages, of preserving cultural traditions over many generations?

My answer to the first question involves what VanPool (chapter 15, this volume) refers to as "metatraditions." I use the term "tradition" to refer to cultural (socially learned or "copied") behaviors "transmitted from ancestor to descendant, generally parent to child, [often] over many generations" (Coe 2003: 5), or simply "behaviors copied from ancestors." I use the term "metatradition" in the sense that Campbell (1975: 1108) did—as "tradition-perpetuating mechanisms." That is, metatraditions are traditional behaviors that enhance the faithful copying of other traditional behaviors from one generation to the next.

In exploring how patterns of cultural behavior remain unchanged, I look at similarities between the metatraditions that produce a relatively high degree of cultural preservation among the Amish and the Australian Aborigines. I then ask if metatraditions are, or at least were, universal. Failure to find metatraditions described in the ethnographic record, especially in descriptions of societies that have been relatively unchanged by modern technological societies, would indicate that metatraditions are not universal.

In answering the second question, I suggest that metatraditions present two distinct evolutionary benefits. First, they facilitate the replication of behaviors that were evolutionarily successful in past generations. This minimizes the occurrence of the infinite potential deviations from those traditional behaviors that are evolutionarily unsuccessful, while promoting the preservation of traits necessary for the gradual accumulation of innovations in succeeding generations. That is, metatraditions contribute to cultural evolution by helping to promote the "descent" part of the concept "descent with modification."

Second, the preservation of certain cultural behaviors is probably necessary for the formation of the extended networks of cooperating kin, including those typically referred to by anthropologists as "lineages" and "clans," that were crucial to the recent evolutionary success of our species. Preserving certain cultural behaviors, such as descent names or clan markings, is necessary for the formation of lineages and clans by definition because these are defined as a set of people who recognize each other as kin *because* they have inherited the same descent name (and/or emblem) from a common ancestor.

The essential role of tracing descent from a common ancestor in the identification of kin is emphasized by Evans-Pritchard (1940: 200), who observed kin are identified as individuals linked by one or more birth links through a common ancestor who forms "the apex of a triangle of descent." *Large* networks of kin can come to be identified only when something, such as a descent name or clan marker, is passed at birth from ancestor to descendant over many generations. Fox (1967: 122) describes this process by saying that when such multigenerational inheritance of cultural behaviors takes place, "large lineages of clans . . . grow up over time as the descendants of the original ancestor/ancestress" accumulate. Further, as Palmer and Steadman (1997: 44) point out, wherever descent names occur in the world, they identify as kin not only everyone with the same descent name but also anyone able to trace birth links to individuals with a given clan name. This is what enables Keen (2004: 174) to state that in Aboriginal Australia, discussed below, "kinship and society were co-extensive."

The necessity of cultural traditions in order to identify large sets of kin descended from distant common ancestors has implications for models of cultural transmission. Such models of possible correlations between forms of cultural transmission and the size of social groups are making significant advances in our understanding of recent human evolution (see chapter 9, this volume). Further refinements of these models could be made by incorporating the crucial role of tracing descent via cultural traditions in creating the kinship relationships between individuals that typically form the basis of the social relationships that constitute traditional human "groups." Failure to find such large networks of kin, and the mechanisms that I propose account for their creation, would negate my proposal.

Amish Metatraditions: The Ordnung

Amish rejection of many forms of technological innovation is not the result of a general passivity or lack of interest in technology. Nor do the Amish regard technology per se as evil or even undesirable. Rather, they take deliberate and elaborate steps to decide whether to adopt or reject any given technological innovation. These decisions are guided by a set of rules, usually unwritten, known as the Ordnung.

The Amish themselves view the Ordnung as a metatradition because it is "meant to convey the traditions of the community" (Wetmore 2007: 13). They see such a strong connection between the preservation of traditions and the preservation of valuable social relationships among kin that they say the primary goal of the Ordnung is to "pass down traditions, and build strong ties with one another" (Wetmore 2007: 13). This extreme value placed on social relationships and the traditional patterns of behavior that create and preserve them is the key reason behind the rejection of many technological innovations: "If they fear that a particular technology might disrupt their religion, tradition, community or families, they are likely to prohibit it" (Wetmore 2007: 14).

Although metatraditions do not have to involve religious behavior, religion often plays a prominent role. One reason for this may be that religious behavior is often distinguished by an individual's accepting another's influence by communicating acceptance of unverifiable supernatural claims (Steadman and Palmer 2008). Offspring who communicate acceptance of the supernatural claims made by their parents communicate to the parents a willingness to accept parental influence. The acceptance of parental influence, in turn, promotes the copying of traditions. The connection between tradition and religious behavior, that is, the communicated acceptance of supernatural claims, is so strong among the Amish that "to the participant, religion and custom [i.e., tradition] are inseparable" (Hostetler 1993: 11).

Myths and rituals among the Amish regularly include supernatural claims. Drawing on Malinowski's observations about the universal functions of myth, Hostetler (1993: 23) writes that in Amish society, "Myth institutionalizes the behavior of a society by enforcing traditions and norms." Traditional Amish stories also take the form of songs that "are based on the story of their martyrs, who the world hated" (p. 23) and tell how Amish ancestors chose to die instead of deviating from their traditions. This illustrates how acts of sacrifice not only serve as a means of communicating commitment to social relationships when they occur, as suggested by costly signaling theory, but also continue to promote cooperative social relationships in subsequent generations when the tales of sacrifice become traditional (Palmer et al. 2006).

Amish behavior in general is highly ritualized. When the enduring ritual behavior patterns of parents are copied and repeated by offspring, the ritual behavior becomes traditional by definition. Referring to certain of these patterns of behavior as "sacred" also plays a significant role in the metatraditions of the Amish because "changes that threaten sacred ritual are less acceptable than those unrelated to worship" (Kraybill 1989: 86). As a result, "custom tends to become sacred" (Hostetler 1993: 9).

The concept of the "sacred" may be inherently conducive to the preservation of traditions because, as Durkheim (1912) pointed out, sacred things are often set apart and forbidden, and being set apart and forbidden is likely to reduce the chances of change. Hostetler (1993: 90) concludes that Amish traditional culture "is strongly supported by the myths and beliefs of the society. . . . [and] the beliefs perform a conservative function in maintaining the social order."

Respect for living elders is another important Amish metatradition. The traditional encouragement of respect for Amish elders takes place within a network of kinship relationships. Within this kinship structure, respect given to elders is paramount: "Wisdom accumulates with age, and with age comes respect. Old people retain the respect of children and grandchildren. Obedience to parents is one of the most common themes in Amish preaching. . . . Since the wisdom of the aged carries more weight than the advice of younger men, the conservation of the entire community is assured and the religious ideals are protected from too much change" (Hostetler 1993: 14–15). To the Amish, "too much change" is change that disrupts traditional patterns of behavior in a way that damages social relationships among kin. Thus, the "Amish have made some adaptations to modernization, but . . . [have not allowed] technology and convenience to run away with their family and community" (Hostetler 1993: 125–126).

The technological innovation that best illustrates the hard work involved in maintaining the Ordnung is the telephone. Umble (1996) points out that the Amish have been engaged in a debate about telephone use since the nineteenth century. The debate is puzzling to outsiders who do not highly value traditions because the Amish "were not blind to the practical applications of the telephone" that made it "an instrument of progress" that would increase "both profit and pleasure" (Umble 1996: 112).

Despite a clear understanding of the tremendous advantages of telephone use, telephones were resisted by many Amish because they were seen as especially threatening to traditions and social relationships. Umble (1996) argues that this is because telephones threatened the fundamental pattern of face-to-face social interaction that was structured by rituals of worship, silence, work, and visiting and was anchored in the home. This threat to the very communicative mechanism most responsible for the copying of traditional behaviors was a threat to all traditions.

As a result of the effectiveness of the Ordnung, youngsters do what the old people did when they were young (Hostetler 1993). Hostetler states that among the Amish, "continuity of conformity and custom is assured" (p. 11), but this is clearly an exaggeration. Not only is the perfect preservation of a traditional pattern of behavior impossible, even a high degree of continuity can never be "assured." Culture and social institutions may work to inhibit changes, but innovations inevitably occur. There is also always the possibility of metatraditions losing their effectiveness and the rate of innovation increasing proportionately.

Umble (1996: 115) makes the insightful statement that instead of only reflecting the unique aspects of a peculiar religious group, the conscious effort the Amish put into avoiding many forms of innovation provides "a window into the dynamics of cultural change." The view from this window opposes the common assumption that cultural continuity is merely a consequence of the difficult process of innovation failing to be successful. It replaces that assumption with the view that cultural change may be a consequence of the difficult process of cultural preservation failing to be successful. This view is compatible with Campbell's (1975: 1105) observation that in cultural evolution, deviation from tradition "seems unproblematic" because "there has no doubt always been a sufficient raw dross of both haphazard and 'intelligent' variations on the social tradition to provide the 'mutations' or 'trials' the process requires, imperfect transmissions of tradition being only one source," whereas it is "retention and duplication" that is "more problematic."

The Amish illustrate how cultural patterns of behavior can be preserved through metatraditions, but this sheds only limited light on *evolutionary* questions about culture and technological innovations because Amish traditions have had only a relatively short existence. If the Amish really are no more than a peculiar exception, in the sense of being the only culture with metatraditions designed to preserve their traditional way of life, the argument I have put forth fails. The prediction of metatraditions once being a species-typical trait among humans, and currently more intact and effective in those societies referred to as traditional, is what makes my explanation a testable hypothesis instead of a "just-so" story.

Metatraditions in Aboriginal Australia: Ancestral Law

The set of metatraditions of Aboriginal peoples of Australia analogous to the Ordnung of the Amish is referred to as "Ancestral Law." Even in a study emphasizing the diversity of Aboriginal societies, Keen (2004: 244) states that "We shall see the people of several of the regions, perhaps all of them, shared a concept that can be translated as 'ancestral law' or the 'proper way,' having its origin in the intentions and actions of the totemic creator ancestors."

"Ancestral Law" is associated with the concept of "The Dreaming," a time when the original ancestors are claimed to have created the traditions that their descendants have been encouraged to follow ever since. Like the Amish, Aboriginal people themselves often emphasize the degree to which their culture is traditional. They see "Ancestral Law" as a metatradition promoting traditional patterns of behavior. The difference is that unlike the relatively recent existence of the Amish Ordnung, the metatraditions constituting the "Ancestral Law" of Aboriginal peoples may have helped maintain traditions for a much longer period of time. Although some change in behavior from generation to generation is obviously inevitable, there is no question that the change in Australia during the first 40,000 years of human occupation occurred at a much slower pace than what has been occurring in most societies during the last several centuries.

As is the case among the Amish, kinship in Aboriginal Australia was of considerable importance. Prior to colonization, kin-based relationships governed all aspects of social life (Keen 2004; Kendon 1988). The network of social relationships among kin that constituted Aboriginal society was the result of offspring copying the totemic names of one or both parents, generation after generation (Keen 2004).

Individuals with the same totemic descent name did not constitute local groups but instead formed a geographically dispersed exogamous category of individuals known as a clan by virtue of having the same totemic name that could be obtained only by descent from an ancestor with that name. The cooperative forms of behavior among members of these kinship networks was the direct result of Ancestral Law and its prescriptions for behavior being copied from one generation to the next.

Ancestral Law, like the Amish Ordnung, is largely religious. It involves communicated acceptance of various supernatural claims about ancestors. In describing the importance of the religious aspect of Ancestral Law, even among contemporary Aboriginal peoples who have experienced a long period of colonization, Berndt (1982: 1) stated that "although aboriginal societies have not 'come down into the present encapsulated, unchanged, in their traditional mantle' [that existed before colonization] change has been limited by factors, foremost among these is 'religion.'"

Traditional myths and other stories played a crucial role within the metatradition of ancestral totemism as they continue to do among the Amish. Clarke (2003: 16) states, "Whenever I have asked Aboriginal people to explain the Dreaming they have mostly responded in the same manner; it is the story of their old ways, how the land was formed, what they used to do and what they learned from their grandparents' generation about their Ancestors." Strehlow (1947) describes the considerable effort taken to preserve the myth in its traditional form through the centuries. Although there are many different types of Aboriginal myths, many clearly constituted metatraditions because they were charters for moral behavior, and moral behavior included the faithful copying of traditions (Hiatt 1975).

The telling of traditional stories or myths about the totemic ancestors was often accompanied by ritual. Morphy (1991: 285) reports that the *Yolunga* claim that all art "is an extension of the Ancestral Past into the present and one of the main ways in which ideas or information about the Ancestral Past is transmitted from one human generation to the next." Before dismissing such claims as mere talk, it is important to note that Mulvaney and Kamminga (1999) provide archaeological evidence for certain specific patterns of art, such as the Rainbow Serpent design, persisting in Australia for at least 6,000 years.

Castro and Toro (2004) emphasize that influencing children to copy the behavior of parents often requires hard work. This was clearly true among Aboriginal peoples, as Morphy (1991) describes how learning certain painting techniques may have taken up to ten years. Copying traditional stories and the associated rituals from one generation to the next also required considerable time and effort.

The association between the specific religious concept of the "sacred" and the metatraditions of Australian aborigines is suggested by Stanner's (1956: 51) observation that the term *Alcheringa*, usually translated as "sacred," can be literally translated as "men of old." If, as would seem likely, "men of old" refers to ancestors claimed to have lived in "The Dreaming," then we have another example of the close association between ancestors, the source of all traditions, and the concept of "sacred." From this perspective it is not surprising that Ranzijn and Bin-Sallik (2001: 170) claim that "Aboriginal elders previously enjoyed high respect as the custodians of the culture and were loved and held in high esteem by younger groups for their expertise and wisdom."

Were Metatraditions Universal?

The traditionalness of "traditional" cultures, as illustrated by the Aborigines, was obvious to many early anthropologists. Kroeber (1948: 256–257), for example, noted that "cultures are . . . inclined to be persistent. . . . Even in times of the most radical change and innovation there are probably several times as many items of culture being transmitted from the past as there are being newly devised." Perhaps Boas (1927: 156) was wrong in assigning an active role to culture as a cause of cultural persistence when he stated that culture acted as a "restriction of inventiveness," but the emphasis placed on the maintenance of sacred traditions in so many cultures makes this role of culture a possibility worth considering.

It is Frazer's (1922: 47) portrayal of life in traditional societies, however, that has had the longest lasting effect on how cultural anthropologists view traditions:

> No human being is so hidebound by custom and tradition as your democratic savage; in no state of society consequently is progress so slow and difficult. The old notion that the savage is the freest of mankind is the reverse of the truth. He is a slave, not indeed to a visible master, but to the past, to the spirits of his dead forefathers, who haunt his steps from birth to death, and rule him with a rod of iron. What they did is the pattern of right, the unwritten law to which he yields a blind, unquestioning obedience. . . . [In such a traditional society] the individual's lot is cast from the cradle to the grave in the iron mold of hereditary custom.

It is unfortunate that Frazer combined his description of the pervasiveness of traditional behavior in some cultures with such a negative judgment of those cultures. Frazer's disparaging view of traditional cultures has led to the perception that the word "traditional" is always derogatory because it implies backward, primitive, and inferior. This stigma has prevented an appreciation of the likely importance of metatraditions in human culture and evolution.

One of the strongest forms of evidence for the universality of metatraditions is that traditional religions universally promote the kinds of kinship cooperation that make the transmission of traditions possible (Steadman and Palmer 2008). A reexamination (Steadman et al. 1996) of ethnographic evidence for the supernatural claim that dead ancestors may influence their descendants and be influenced by their descendants found that this view might be universal. Shamans are also often claimed to communicate with dead ancestors and base their instructions of proper behavior on what they were allegedly told by the ancestors (Palmer and Steadman 2004). Coe (2003: 44) points out that "sacred is often the word used to refer to anything associated with ancestors."

Possible Evolutionary Benefits of Metatraditions

The widespread evidence of metatraditions in the ethnographic literature raises the question of why metatraditions may have been part of every known culture until several thousand years ago. I suggest there are two evolutionary benefits to traditions and the metatraditions that promote them, one beginning much earlier in human existence than the other. The earlier may have originated as our ancestors evolved into anatomically modern humans, somewhere in the period between 500,000 and 100,000 years ago. As the name "anatomically modern" implies, our ancestors must have had brains very much like our own, thus potentially capable of producing at least much of what Richerson and Boyd (2000: 2) refer to as the "stunning diversity" of cultural behaviors produced by people more recently.

Given that only a small fraction of the variety of the behavior patterns the brains of anatomically modern humans could have potentially produced each generation would have led to survival and reproduction, selection may have favored individuals who influenced their offspring to copy their behavior, as well as offspring capable of such copying. Richerson and Boyd (2000: 1) may be correct in asserting that the brain evolution leading up to that time may have resulted in a brain "built for speed" in the sense of being capable of large intergenerational changes in behavior. At some point, however, selection may have favored individuals who managed to keep that change on track, that is, sufficiently similar to what proved to be successful in the previous generation. A general lack of intergenerational behavioral change characterizes most organisms, including earlier human ancestors. However, a lack of intergenerational behavior change in an organism *capable* of vast intergenerational changes in behavior due to an ability to engage in an immense amount of social learning required fundamentally different mechanisms. I suggest meta-traditions may have been such a mechanism and thus contributed to the "descent" aspect of the Darwinian principle of descent with modification.

The second, and later, evolutionary benefit of traditions may have involved the previously described relationship between traditions and the social environment. Until very recently, the social environment of all humans consisted of webs of social relationships between individuals identified as kin. These webs cannot be explained by kin selection because they universally far exceeded the small set of closely related individuals, where kin selection would play a major role. As previously mentioned, although a great deal has been written by anthropologists about the nuances and variations of these large webs of kinship (lineages, clans, moieties, and the like), only one mechanism for their *creation* has been seriously put forth, and this mechanism *requires* traditional behavior.

Beginning at least several tens of thousands of years ago, the creation of the social environments of our ancestors required two types of traditions. The *identification* of large numbers of kin requires giving offspring some symbol that they are your descendants, such as a descent name, and influencing your offspring to copy your behavior (see Palmer and Steadman 1997).

Although there are other mechanisms that can produce cooperation, influencing these large numbers of identified descendants to *cooperate* with each other *because of their kinship relationship to each other* required a second tradition also found in all known traditional cultures. This second tradition consisted of parents influencing their offspring to cooperate with individuals identified as kin and to copy that behavior (see figure 10.1). The existence of such traditions is succinctly demonstrated by Middleton's (1960: 27) translation of a saying among the Lugbara of Africa: "the rules of social behaviour are the 'words of our ancestors.'"

The potential consequence of these two types of traditions' being copied over a considerable number of generations is illustrated by Fortes's (1969: 237) observation that the axiom of kinship amity "applies to all of the Tiv" and Keesing's (1975: 32–33) notation that "the whole population of some 800,000 traces descent by traditional genealogical links from a single founding ancestor." The ability of descent names to identify individuals as kin, and even to distinguish relative degrees of kinship distance between individuals by identifying a series of common ancestors, can have life-or-death consequences. For example, Fortes (1969: 237) describes how kinship distance identified through descent names regulates, among other things, a traditionally prescribed "graduated scale of weaponry and violence that is permitted in fighting. Close brother segments of a minimal lineage may use only clubs and stones in a fight; more distantly connected segments may use bows and arrows but must avoid killing; very distantly connected lineages fight with poison arrows and Dane guns, and aim to kill." Even much smaller extended networks of kin would be profoundly beneficial to survival and reproduction.

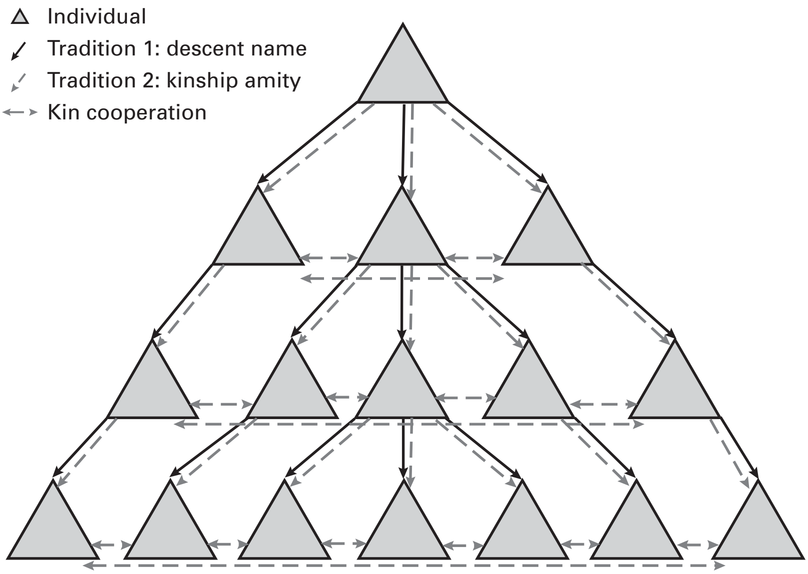

Figure 10.1
How traditional descent names identify large networks of codescendants and how traditions of moral codes influence codescendants to cooperate.

The widespread existence of large categories of kin identified through descent names is almost certainly the result of the transmission of traditions over a correspondingly large number of generations. The alternative notion that such categories of cooperating individuals could be instantaneously created during a single lifetime is so preposterous that it became the basis of Kurt Vonnegut's 1976 fictional novel *Slapstick: Or Lonesome No More*! As Cronk (1999: 129) explains, the character "Dr. Swain" runs for president on the promise to use "the computers of the federal government to recreate kinship networks like those of our ancestors . . . [including] 190,000 cousins, all obligated to help fellow clan members." Given the absence of a more plausible alternative explanation of how the kinship-based social environments of humans could have come into existence, the role of traditions maintained by metatraditions should at least receive serious consideration.

Conclusions

The goal of this chapter has been to expand the evolutionary view of culture so that it is seen as not just a powerful force in human behavioral change but also as a powerful force in the preservation of patterns of human behavior. Although this emphasis on cultural preservation may appear to be incongruous with much of the current thinking about innovation and cultural evolution, it actually is compatible (if not synonymous) with Darwin's original views on natural selection. Importantly, Darwin viewed that term as a substitute for what he actually envisioned as the cause of evolution—the principle of preservation. The importance of "preservation" to Darwin's theory about the mechanism of evolution is, of course, evident from its use in the subtitle of his 1859 book.

The power of Darwin's explanation of evolution has been greatly increased by advances in knowledge about how traits are preserved from one generation to the next. It seems reasonable to assume that advances in knowledge about how traditional cultural behaviors are preserved from one generation to the next would make a similar contribution to the study of cultural systems and the adoption of technological innovations. If the "principle of preservation," perhaps phrased for the sake of brevity as "natural preservation," had been the phrase that continued to be associated with Darwin's theory, the study of evolution today might be largely the study of "natural preservation."

If this were the case, a key concept in the study of cultural evolution might be "cultural preservation." Given that "tradition" is the word most commonly used to refer to patterns of cultural behavior preserved from one generation to the next, the study of cultural evolution might focus more specifically on the study of "cultural traditions" than is currently the case. In this fictional scenario, the title of this volume might change from "Innovation in Cultural Systems: Contributions from Evolutionary Anthropology" to "Innovation in Cultural Systems: Contributions from the Anthropological Study of Traditions." In such a volume, the appropriateness of a chapter titled "Cultural Traditions and the Evolutionary Advantages of Noninnovation" might be more readily apparent than is currently the case. Such a title would be particularly appropriate for a volume emanating from a workshop at the Konrad Lorenz Institute, because Lorenz (1975: 366) observed that "without cultural tradition," many structures of the human brain "would be as devoid of function as the wings of an ostrich, only more so."

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11 The Experimental Study of Cultural Innovation

Alex Mesoudi

Cultural innovation, like cultural evolution in general, can be profitably studied experimentally in the psychology laboratory. To illustrate this, I present two case studies in which experimental simulations of cultural transmission have provided insights into the processes of cultural innovation. First, Rose and Felton (1955) examined the effect of migration on the spread of different interpretations of inkblots within small groups, finding that invention was more frequent in closed societies, with stable group membership, than in open societies, where participants migrated between groups.

Second, Mesoudi and O'Brien (2008a, 2008b) simulated the cultural transmission of projectile-point designs in groups of participants, under the assumption that fitness was determined by an underlying adaptive landscape, where different inventions constitute peaks of different heights and successful innovation occurs when members of a population converge on the same peak. Participants used simple reinforcement learning to find locally adaptive point designs, but these designs rarely persisted once participants were allowed to engage in biased horizontal cultural transmission. After that, most participants converged on the point design of the most successful player (the highest peak in the adaptive landscape). In summary, experimental simulations can be used, in conjunction with other social science methods, to provide an interdisciplinary approach to the study of cultural innovation, as part of a unified science of cultural evolution.

How to Study Cultural Innovation

"Innovation" describes the processes by which a novel trait (an "invention") emerges and becomes fixed in a population (Erwin and Krakauer 2004). It has long been recognized that innovation plays a key role in biological evolution (Mayr 1960; Nitecki 1990), where it describes the emergence of novel phenotypic traits and their fixation within a species (see chapters 3 and 4, this volume). The recent proliferation of work that takes an evolutionary approach to human culture (e.g., Aunger 2000; Brighton et al. 2005; Henrich and McElreath 2003; Lipo et al. 2006; Mesoudi, Whiten, and Laland 2004, 2006; O'Brien and

Lyman 2002; Pagel and Mace 2004; Plotkin 2002; Richerson and Boyd 2005; Runciman 2005; Shennan 2002; Wheeler et al. 2002) suggests the need for a similar concept of "cultural innovation"—the processes by which a novel cultural trait emerges and spreads within a society.

Cultural innovation has long been studied to some degree within economics (Schumpeter 1934, 1942), anthropology (Barnett 1953), and sociology (Rogers 1995), but rarely in an objective, quantifiable manner. This changed in the 1980s with the introduction into anthropology of the population-genetics-inspired mathematical models of Cavalli-Sforza and Feldman (1981) and Boyd and Richerson (1985). Those studies demonstrated that the manner in which a cultural trait spreads though a population (and hence becomes an innovation) depends on the cultural-transmission mechanisms by which it is propagated, including vertical, oblique, and horizontal transmission (Cavalli-Sforza and Feldman 1981); one-to-many or many-to-one transmission (Cavalli-Sforza and Feldman 1981); conformist, anticonformist, and prestige biases (Boyd and Richerson 1985); and discrete or blending cultural inheritance (Boyd and Richerson 1985).

Different transmission rules will often generate distinct patterns of cultural change, such as stable intergenerational traditions (vertical transmission), rapidly changing fashions or fads (horizontal transmission), stable intergroup differences (conformity), or exaggerated cultural traits resulting from runaway selection (prestige bias). Models of cultural evolution therefore suggest that an understanding of cultural transmission—who copies what from whom, and how—will provide important insights into the spread of cultural innovations (see chapters 7, 9, and 12, this volume).

Although mathematical models are important tools for understanding cultural change, they are only as good as their assumptions. In this case, the assumptions concern cognitive biases that determine when people copy others (as opposed to learning individually), whom they learn from (e.g., high-status models or the group majority), how they learn (e.g., using language or imitation), and what they learn. This is very much the domain of psychology, and I suggest that laboratory experiments that draw on the methods of social psychology can be used to study these cognitive biases. In doing so, they provide important insights into the processes of cultural innovation and cultural evolution in general (Mesoudi 2007; Mesoudi and Whiten 2008).

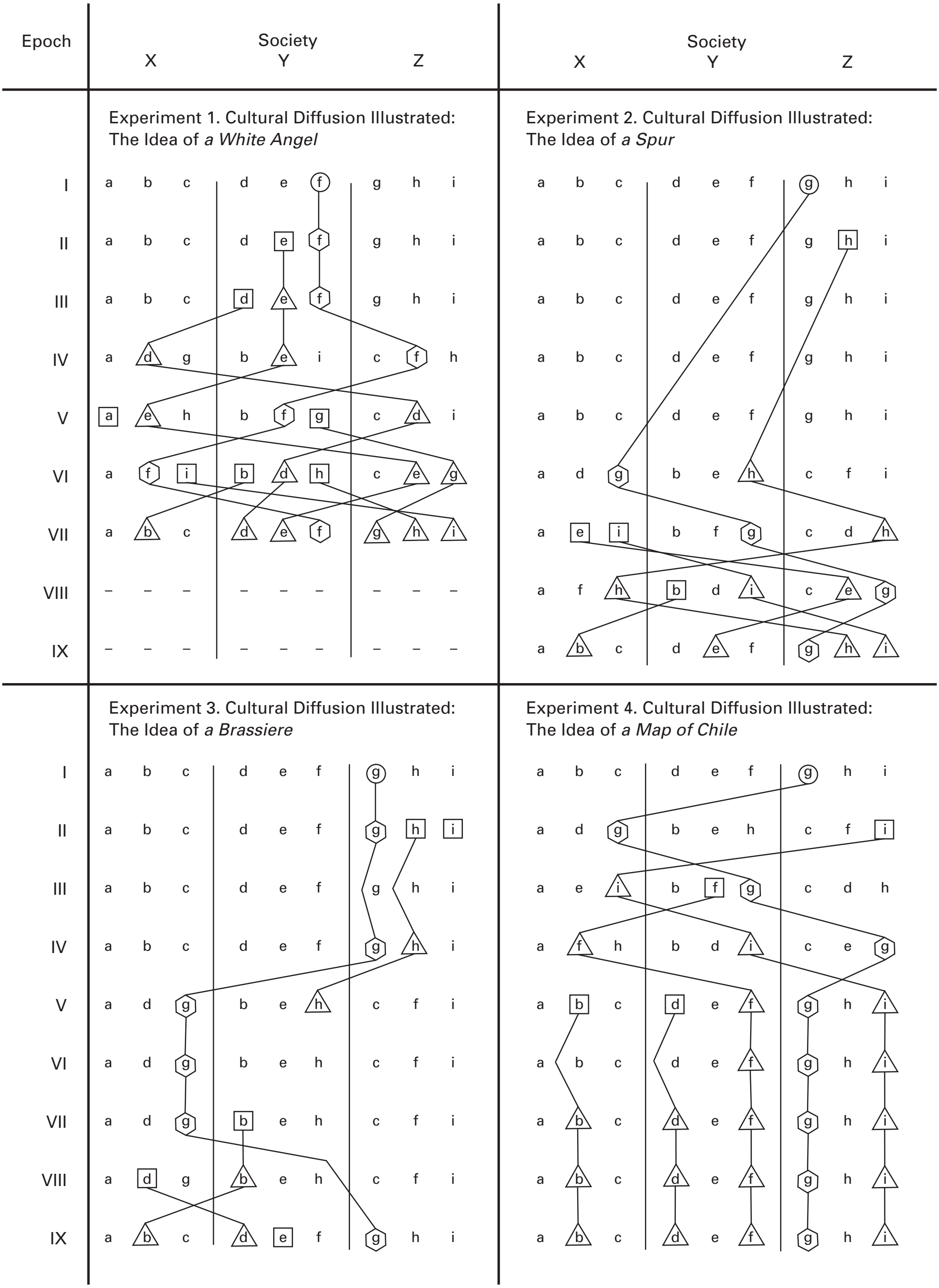
Although experimental studies that simulate cultural transmission and cultural evolution have been relatively rare in the past (but see Bartlett 1932; Insko et al. 1980; Jacobs and Campbell 1961; Rose and Felton 1955), there has been a resurgence of such studies in recent years (e.g., Baum et al. 2004; Efferson et al. 2007, 2008; Kameda and Nakanishi 2002, 2003; Kashima 2000; McElreath et al. 2005; Mesoudi 2008; Mesoudi and O'Brien 2008a, 2008b; Mesoudi and Whiten 2004; Mesoudi, Whiten, and Dunbar 2006). In a typical cultural-evolution experiment, participants in small groups (often called "microsocieties") engage in a predefined task or game designed to capture some simplified aspect of real-life cultural change. Over repeated experimental trials (or "generations"), the participants can, where desired by the experimenter, learn from one another, that is, engage in cultural transmission. Crucially, the experimenter can systematically control who learns what, and from whom and how, in order to examine the effects the various cultural-transmission biases described above have on broader patterns of cultural change.

There are several benefits that experimental methods can bring to the study of culture. Experimentalists can "rerun" history, allowing for the replication of findings; they have access to complete, uninterrupted, and unbiased data sets; they can manipulate variables; and they can randomly assign participants to different experimental and control groups (Mesoudi 2007). Of course, what experiments gain in control and manipulation (their high internal validity) they lose in their low external validity, that is, the degree to which they capture the actual cultural change that we wish to learn about. We can never be sure whether the artificial laboratory setting will properly capture the environments in which actual societies live; whether the simple experimental task will properly capture the challenges that actual societies face; whether experiments that last a maximum of a few hours can properly capture cultural change that occurs over years, decades, or centuries; or whether the often-biased participant pool (usually Western psychology undergraduates) will behave in the same manner as the people who were originally responsible for a particular aspect of cultural change.

These problems can be overcome by using experimental methods in conjunction with other methods rather than in place of them. By integrating ethnographic, archaeological, and experimental methods, together with other tools such as mathematical models and computer simulations, we can attain a more complete understanding of cultural change than is afforded by any one method alone. Indeed, the low external validity and high internal validity of both experimental simulations and mathematical models complement the high external validity and low internal validity of ethnographic and archaeological methods. I will return to this point later. Here, I turn attention to two case studies that highlight how innovation can be studied in laboratory settings.

Case Study: The Effect of Migration on Rates of Cultural Innovation and Invention

An early experimental simulation of cultural innovation was conducted by the sociologists Rose and Felton (1955) and provides several pointers as to how cultural innovation can be studied in the lab. Rose and Felton presented two Rorschach inkblots to three separate three-person groups of participants. During each trial, group members privately and separately wrote down what they thought they could see in each inkblot. Each group member, in turn, presented his or her interpretations to the other members of the group, who then rated the interpretations for plausibility both out loud and privately on paper. This process



Experiment 1. Cultural Diffusion Illustrated: The Idea of *a White Angel*

Experiment 2. Cultural Diffusion Illustrated: The Idea of *a Spur*

Experiment 3. Cultural Diffusion Illustrated: The Idea of *a Brassiere*

Experiment 4. Cultural Diffusion Illustrated: The Idea of *a Map of Chile* of private interpretation and public rating was repeated nine times (giving nine generations, or what Rose and Felton called "epochs").

The key question concerned not the content of the interpretations but how different interpretations spread through the groups and, specifically, how intergroup migration influenced cultural diffusion. Different phases of the experiment simulated two different group conditions: "open" and "closed." During closed phases, participants stayed in the same groups over successive epochs and repeatedly interacted with the same group members. During open phases, participants moved across groups. During each epoch of the open phases, participants moved from their parent group to a new group with different participants. Figure 11.1 shows how this social mobility was organized and how four exemplar interpretations (a white angel, a spur, a brassiere, and a map of Chile) diffused through the groups during successive epochs.

In their analysis, Rose and Felton classified each interpretation into one of four categories: (1) an invention—a novel interpretation generated by a single participant; (2) a habit—the repetition of an interpretation by its inventor in successive epochs; (3) a culture borrowing—an interpretation that has been copied from another participant; and (4) a culbit—the repetition of a borrowed/copied interpretation by the borrower in successive rounds (after Tylor 1871). Hence, Rose and Felton distinguished between the introduction of a novel form into a group, either through individual learning ("inventions") or cultural transmission ("culture borrowings"), and the subsequent persistence of those novel introductions ("habits" and "culbits," respectively), mirroring the modern distinction between invention and innovation.

Informal inspection of figure 11.1 underscores several points. First, we can see two modes of diffusion: (1) direct cultural transmission between participants within the same groups and (2) the diffusion of interpretations resulting from people moving between groups. This can be seen in the white-angel diffusion (Rose and Felton's experiment 1, top left panel of figure 11.1), which first spreads within society Y during the closed epochs I–III by within-group cultural transmission, before spreading with participants d, e, and f to the other groups during the open epochs IV–VII.

This contrast evokes debates in the anthropological literature (e.g., Ammerman and Cavalli-Sforza 1984; Sampietro et al. 2007) over whether agriculture spread across

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Figure 11.1
Rose and Felton's experimental design, with example traditions (from Rose and Felton, 1955). Epochs proceed down the vertical axis of each panel; letters (a–i) represent participants, who are divided into three groups, societies X–Z. The four panels show the diffusion of four different interpretations (white angel, spur, brassiere, or map of Chile) in four different experimental designs. Shapes indicate how each interpretation was classified, as either an invention (circle), culture borrowing (square), habit (hexagon), or culbit (triangle). Each panel shows a different form of migration: Experiment 1 has three closed epochs followed by four open epochs, experiment 2 has five closed epochs followed by four open epochs, experiment 3 has four closed epochs followed by another four closed epochs with different group membership (then a final return to the original groups), and experiment 4 has four open epochs followed by five closed epochs.

Neolithic Europe by cultural diffusion (the movement of ideas/technologies by means of cultural transmission) or demic diffusion (the movement of people, who bring novel ideas/technologies with them). Although archaeological and genetic data will provide the best, most direct evidence regarding this issue, such data are always fraught with difficulties of interpretation. Perhaps experimental simulations of cultural and demic diffusion, along the lines of Rose and Felton's study, might offer additional insight into this and similar debates.

A second informal observation obtained from inspection of figure 11.1 is that open societies facilitate the spread of interpretations across groups. As already noted, this can be seen in the top left panel of figure 11.1, where the white-angel interpretation appears in all of the groups during the open epochs IV–VII, as well as in the top right panel of figure 11.1, where the spur interpretation spreads across groups during only the open epochs VI–IX. One might consider this to be unsurprising—how could the same interpretation be found in more than one group if there is no communication or movement of people between those groups? But this ignores the possibility of independent invention in two unconnected societies. This did not occur in the diagrams shown in figure 11.1, and Rose and Felton do not mention it occurring in other trials, but it is possible that two people might see the same object in an inkblot, given the similarities in people's perceptual systems and semantic knowledge.

This issue—how to distinguish between traits that are shared because of descent from a common source versus traits that are shared because of independent invention (convergent evolution)—is explicitly dealt with by phylogenetic methods, which are increasingly being applied to cultural data sets (Lipo et al. 2006; Mace et al. 2006; O'Brien and Lyman 2003; O'Brien et al. 2008). Experimental simulations might provide insights into the reliability of phylogenetic methods by applying them to data generated in experiments in which it is known exactly who copied what from whom. Indeed, this has been done recently by Spencer et al. (2004), who applied phylogenetic analyses to lineages of manuscripts generated by participants in the lab in order to test the reliability of such analyses when applied to actual historical manuscripts (e.g., Howe et al. 2001).

A third observation from figure 11.1 is that interpretations sometimes went dormant, during which time they were not presented to the group but must have been remembered by the participants, given that they reappear during a later epoch. This can be seen in experiment 2 (top right panel of figure 11.1), where the spur interpretation disappeared during epochs III, IV, and V before reappearing in epoch VI and then spreading across the groups. This bears some resemblance to the manner in which recessive alleles can remain in a population of biological organisms with no observable phenotypic effects. It also highlights the fact that ideas can persist with no observable record of that persistence, which may present difficulties for historians or archaeologists when reconstructing lineages of cultural traits.

Following statistical analysis of their experimental data, Rose and Felton's somewhat surprising main finding was that the isolation of closed societies fostered invention (see chapter 8, this volume). As participants moved from group to group in the open societies, they tended to borrow from existing group members rather than invent novel interpretations. In the words of Rose and Felton (1955: 391), "in general, as mobility follows isolation, borrowing displaces invention." As they also note, this finding that closed societies foster invention counters the intuitive notion of "mobile and cosmopolitan urban populations having made the most cultural change" (p. 392), that is, that populations that encourage immigration and diversity (e.g., cosmopolitan cities such as New York or London) are culturally more inventive and creative than populations that remain isolated (e.g., the Amish [see chapter 10, this volume]), which are seen as culturally conservative and uncreative.

Perhaps, though, Rose and Felton's result is not too surprising in that being in the same closed group over successive epochs meant that participants could not simply repeat previously presented ideas. Instead, they had to come up with novel ideas, whereas participants who found themselves in new groups could forgo the difficulty of coming up with a new idea and instead copy the idea of a member of their previous group. This explanation has the benefit of hindsight, however, and highlights the potential value of laboratory experiments that simulate cultural processes such as innovation and transmission in questioning our intuitions and presumptions regarding cultural change, in this case the "bland presumption that social mobility leads inevitably to cultural creativity" (Rose and Felton 1955: 392).

It has to be pointed out that this was a highly simplified experiment with small numbers of participants and groups, and a form of culture—inkblot interpretation—that is by definition functionless, arbitrary, and subjective. It may well be that if this experimental design were repeated with functional cultural traits, we would see more creativity in open groups, as different functional components generated by different groups are combined, allowing cumulative cultural evolution (although whether this kind of recombination is classed as "invention" or not is another matter). Alternatively, much of culture can be classed as neutral and has been shown to change randomly (see chapter 8, this volume), so perhaps inkblots are not too inappropriate for simulating actual cultural change.

Finally, Rose and Felton found that habits and culbits showed different patterns of change: Habits tended to increase more in open societies than in closed societies, whereas culbits increased uniformly irrespective of the society type. This finding highlights the importance of a particular cultural form's origin, individual or social learning, for its subsequent persistence, although it is unclear what is causing this particular difference.

In summary, the pioneering study conducted by Rose and Felton (1955) illustrates how experimental laboratory simulations can provide valuable insights into the processes that govern cultural invention and innovation. These researchers showed how to distinguish methodologically between invention (the emergence of a novel cultural form) and innovation (the persistence of that cultural form), and they highlighted the importance of distinguishing between the origin of these kinds of cultural traits by showing that traits that originated in individual learning exhibited different patterns of change from those that originated in social learning. Consequently, their conceptual distinctions between inventions, culture borrowings, habits, and culbits may be useful in future studies of cultural innovation—not just experimental studies but also analytical, observational, and historical studies.

Rose and Felton's counterintuitive finding that invention was favored in closed societies and curbed in open societies highlights the importance of empirically testing what may appear to be obvious assumptions regarding human culture (e.g., closed societies are less creative than open societies). Further experimental studies might test the effect of social mobility on nonarbitrary cultural traits that allow functional improvement or cumulative cultural evolution, or test the effect that variables other than social mobility have on patterns of invention and innovation, such as task difficulty or ethnic markers.

Case Study: Innovations Can Spread as a Result of Biased Cultural Transmission in Multimodal Adaptive Landscapes

Rose and Felton's (1955) study demonstrates how to simulate the spread of largely arbitrary cultural traits in the form of inkblot interpretations. It seems likely, however, that many cultural innovations, particularly technological innovations, are not entirely arbitrary, such that their spread and persistence will depend to some extent on their cultural fitness. By "cultural fitness," I mean the properties of a culturally transmitted artifact, such as its functional efficacy, cost, durability, or social significance, that affect the artifact's probability of subsequent persistence and transmission relative to other similar artifacts. In an experimental study conducted in collaboration with Mike O'Brien (Mesoudi and O'Brien 2008a, 2008b), we set out to explore experimentally this relationship between an artifact's fitness and its invention and innovation. Specifically, we simulated the cultural transmission of projectile-point technology, drawing on an archaeological study of prehistoric Great Basin projectile-point cultural transmission conducted by Bettinger and Eerkens (1999).

In our study, groups of participants played a simple computer game in which they designed their own "virtual arrowheads" and tested them in a "virtual hunting environment." Participants entered the attributes of their arrowheads—length, width, thickness, color, and shape—and then received feedback on the success of their designs, in terms of calories obtained during a hunt, equivalent to an arrowhead's fitness. The closer the arrowhead design was to a prespecified optimal design, the higher the feedback score. The aim for the participant was to achieve as high a score as possible by finding the optimal design in the environment. This could be done in two ways (see figure 11.2)—by individual learning or by biased cultural transmission.

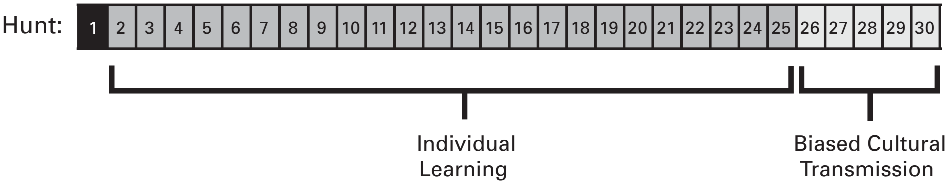

Figure 11.2
Experimental design of Mesoudi and O'Brien (2008a), showing the 30 trials (or "hunts") comprising one session.

Following an initial trial (during which the participant could copy the final point design of a previous participant, although this is not relevant to the present discussion), participants engaged in 24 trials (or "hunts") of individual learning, where they could use trial and error to find the optimal arrowhead design. Each hunt represented one opportunity to modify and test the arrowhead design. Then, during the final five hunts, participants could additionally engage in biased cultural transmission. They were shown the cumulative scores of other members of their six-person group, each of whom was playing the same game in the same environment, and the participant could choose to view and copy the arrowhead design of one of those other group members. Thus, participants could engage in biased cultural transmission by preferentially copying the player with the highest score (resembling Boyd and Richerson's [1985] "indirect bias" or Henrich and Gil-White's [2001] "prestige bias" [see chapter 7, this volume]).

One goal of our study was to explore how the nature of the underlying fitness functions, which were used to calculate the feedback scores given to the participants, affected arrowhead designs during different phases of the experiment. Specifically, we wanted to test the idea that the spread of technological artifacts will be governed by the shape of an underlying multimodal adaptive landscape. The concept of an adaptive landscape is commonly used in evolutionary biology (Arnold et al. 2001; Simpson 1944; Wright 1932) to represent the design space of all possible combinations of multiple phenotypic characters, where the height of the landscape represents fitness. If a landscape is multimodal, then there are multiple "peaks" of different heights, each representing a locally optimal phenotype of different fitness. Any deviation away from any of these locally optimal peaks would result in lower fitness. There may, however, be higher peaks elsewhere in the landscape that can be reached only by traversing low-fitness valleys. Hence, populations of organisms can get stuck on locally optimal but globally suboptimal peaks.

Applied to cultural evolution, the fitness of a cultural artifact would be determined by its location in an equivalent adaptive landscape. This landscape would represent all possible designs within a design space, with different peaks representing different locally optimal artifact designs (similar to Lake and Venti's [2009] conceptualization of bicycle design space, although adding a consideration of fitness).

With respect to the topic of this volume, I suggest that different locally optimal peaks in an artifact's adaptive landscape can be seen as different potential inventions. Innovations, on the other hand, can be seen as peaks at which the majority of actual artifacts in a population can be found, which may or may not represent the highest, globally optimal peak. In terms of learning processes, individual learning would constitute the exploration of this adaptive landscape by means of a random walk, leading to the discovery of one or more locally optimal peaks, or inventions. Biased cultural transmission, however, would allow people to jump across low-fitness valleys, from their locally adaptive peak to a higher peak found by a more successful individual, making this peak/design the innovation.

In our experiment (Mesoudi and O'Brien 2008a), we implemented a simple multimodal adaptive landscape to determine the fitness of the virtual arrowheads. The overall fitness of an arrowhead was the sum of the fitness contributions from four independent attributes: length, width, thickness, and shape as shown in figure 11.3 (the fifth attribute, color, had no effect on fitness). Shape was discrete, taking one of four values of different fitness. The others were continuous, ranging from one to 100 arbitrary units, and their associated fitnesses were given by bimodal fitness functions.

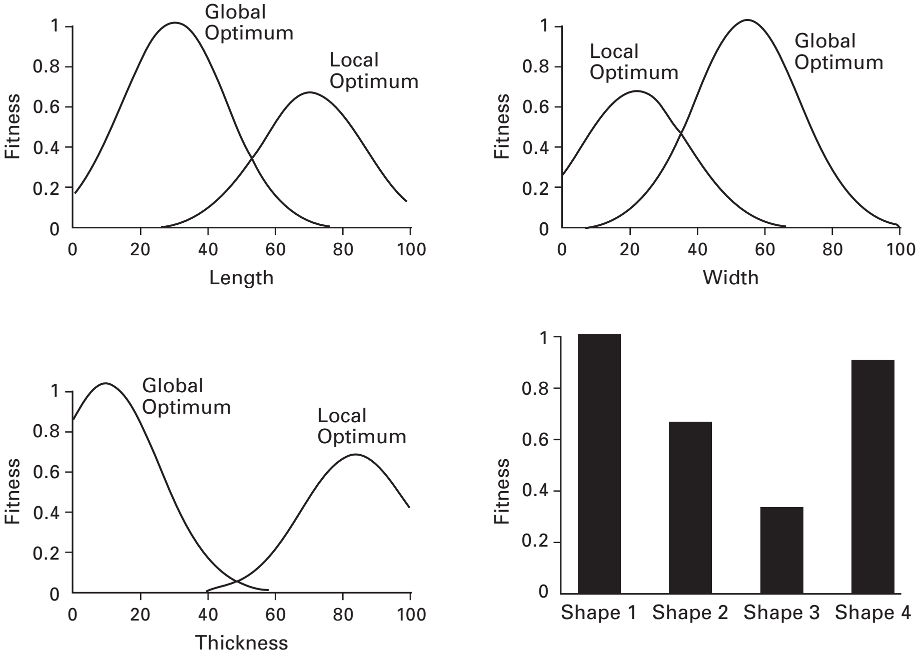

Figure 11.3
Fitness functions for the four functional point attributes used in Mesoudi and O'Brien (2008a). The overall score received by a participant was the sum of these four fitnesses. The three bimodal functions for length, width, and thickness combined to create a multimodal adaptive landscape.

Combining these three bimodal fitness functions specified a multimodal adaptive landscape that our participants could explore. For example, the highest peak in this adaptive landscape can be found where length, width, and thickness are all at their global optima. A slightly lower peak can be found where length and width are at their globally optimal values but thickness is at its local optimum. The lowest peak can be found where length, width, and thickness are all at their local optima. Any deviation away from each of these peaks (there are eight in total) results in a decrease in fitness and a lower score for the participant. Participants were not told anything about the underlying fitness functions, just as real hunters are not informed about presumed real-life technological-fitness functions.

We wanted to test the key prediction that during the 24 individual learning hunts, different participants will by chance diverge onto different peaks in the landscape and, because they are local optima, get stuck on these peaks. These are thus different "inventions" generated by our participants. Then, in the final five hunts, during which biased cultural transmission is allowed, we will see participants copying the most successful player, who has, perhaps by chance, found the highest globally optimal peak (or the highest peak found by anyone in that group). This is group "innovation." This scenario would therefore predict greater variation in the different participants' arrowhead designs following the individual-learning phase, because different participants will find different peaks compared to the biased-cultural-transmission phase, when the participants converge on the same peak. It would also predict lower mean fitness during the individual-learning phase because the different peaks will have varying fitness compared to the biased-cultural-transmission phase, when players can copy a more successful fellow player and all converge on that player's higher fitness peak.

These predictions were largely confirmed (for details, see Mesoudi and O'Brien [2008a]). Figure 11.4a shows that within-group variation dropped sharply once participants could engage in biased cultural transmission and copy other group members (the last five hunts), and figure 11.4b shows that mean fitness increased during this period. Further analyses supported the claim that the multimodal adaptive landscape was critical to the fitness advantage provided by cultural transmission relative to individual learning. Statistical analyses showed that the number of participants with point designs at the global optimum for each attribute was significantly higher immediately following the onset of biased cultural transmission than immediately before. Agent-based computer simulations of the same experimental task (Mesoudi and O'Brien 2008b) as well as subsequent experiments (Mesoudi 2008) confirmed that in a unimodal adaptive landscape, where there is a single optimal peak, biased cultural transmission does no better than individual learning. In sum, the shape of the underlying adaptive landscape was instrumental in, first, generating different inventions (representing different locally optimal peaks) and, second, favoring the emergence of an innovation (representing the globally optimal peak).

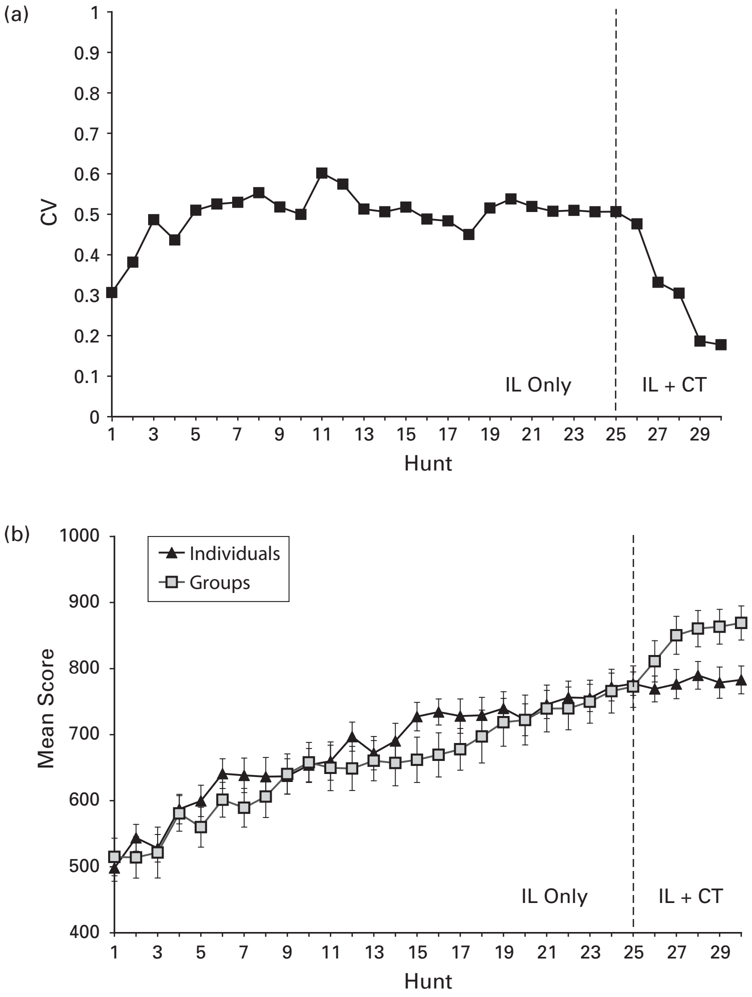

Figure 11.4
(a) Mean coefficient of variation (CV) for participants in Mesoudi and O'Brien (2008a). Data shown are the mean CVs for the continuous attributes (length, width, and thickness) for participants in groups of up to six. During hunts 2–25, to the left of the vertical dashed line, only individual learning was permitted ("IL ONLY"). During the final five hunts (26–30), to the right of the vertical dashed line, participants could additionally engage in biased cultural transmission ("IL + CT"). A sharp decrease in CV can be seen once cultural transmission is permitted. (b) Mean score per participant in the same experiment, separately for individual controls and participants in groups. Individual controls could not engage in cultural transmission during any hunt. The final five hunts feature a significant increase in mean score in the groups compared to the individual controls (F(1,43) = 4.76, $p < 0.05$).

How realistic is this assumption of a multimodal adaptive landscape underlying cultural innovation? With respect to projectile points specifically, Cheshier and Kelly (2006) recently summarized experimental evidence for trade-offs in point designs among such factors as accuracy, range, killing power, and durability, stating, for example, that "thin, narrow points have greater penetrating power, but wide, thick points create a larger wound that bleeds more easily" (Cheshier and Kelly 2006: 353). Functional trade-offs such as these would potentially produce multiple locally optimal point designs, with, for example, one optimal design maximizing penetrating power and another maximizing bleeding. As Boyd and Richerson (1992) suggest, many technological artifacts are likely governed by similar trade-offs between competing demands that may result in multimodal adaptive landscapes. Much work remains to be done to test this claim adequately, although experimental simulations might be useful in identifying the kind of data that is indicative of different cultural-fitness functions, which can then be compared with actual cultural data sets.

In general, viewing (a) different inventions as different fitness peaks and (b) biased cultural transmission as a means of traversing adaptive valleys that allows individuals to converge on higher peaks (much as Fisher [1930] viewed sexual reproduction) may provide important insights into long-term cultural innovation. For example, we might predict that the more peaks there are in an adaptive landscape, that is, the more alternative stable designs exist, the more difficult it should be to find the peak/invention that has the highest fitness. Similarly, the greater the fitness difference of alternative designs, that is, the differences in height of the different fitness peaks, the easier it should be to identify the highest peak/best design by means of biased cultural transmission and the more adaptive that biased cultural transmission should be relative to individual learning.

Population size would also be important: The larger the effective population size, the more likely it is that someone will find the highest fitness peak by way of individual learning, resulting in higher fitness in the entire population following biased cultural transmission (see Mesoudi and O'Brien [2008b] for computer simulations that confirm this effect of group size). We (Mesoudi and O'Brien 2008a) also found that when participants had to pay a cost to modify their point designs, that is, when individual learning was costly, cultural transmission was relatively more adaptive, consistent with the results of previous theoretical models (e.g., Boyd and Richerson 1995). Hence, we can predict that successful innovations are more likely to spread by cultural transmission when individual learning is costly.

Future experiments might simulate cultural evolution on differently shaped adaptive landscapes or where trait characters are linked in more complex ways, that is, cultural epistasis, as in Kauffman's (1993) Nk model of adaptive landscapes, as well as the higher-level combination of more distinct inventions, such as the combination of point designs and bow designs into a bow-and-arrow cultural complex. This introduces notions of modularity, which has been a recent topic of interest in biological innovation: "invention and innovation are about developing . . . new rules for combining biological and technological modules" (Erwin and Krakauer 2004: 1118; see also Callebaut and Rasskin-Gutman 2005), suggesting that principles from EvoDevo may be useful for the study of cultural innovation and cultural evolution (Mesoudi and O'Brien 2008c).

Conclusions

The preceding case studies hopefully have demonstrated that it is possible to simulate cultural processes in the psychology laboratory in a manner that can provide potentially useful insights into the mechanisms that underlie specific aspects of cultural change, including cultural innovation. Rose and Felton (1955) showed how to distinguish methodologically between invention (the emergence of a novel cultural form) and innovation (the persistence of that cultural form), and they tested the hypothesis that migration increases the frequency of invention, finding the contrary result that closed societies with no migration foster invention. Mesoudi and O'Brien (2008a, 2008b) showed that when the fitness of an artifact is determined by a multimodal adaptive landscape, then individual learning can cause artifacts to diverge to different locally adaptive states, that is, generate multiple stable inventions, whereas biased cultural transmission can cause artifacts to converge on a single globally adaptive form, that is, produce an innovation.

In conclusion, I reemphasize that experimental simulations of cultural innovation, or cultural evolution in general, are not intended to replace observational, ethnographic, historical, or archaeological methods. As noted at the outset, and echoing Larson's (see chapter 5, this volume) call for interdisciplinary research, all of these methods should be used together to tackle the same problems, such that they complement one another's strengths and shore up weaknesses. Experimental studies can provide tests of specific hypotheses under controlled laboratory conditions; ethnographic studies can provide naturalistic observational data; historical and archaeological studies can provide information regarding long-term patterns and trends; mathematical models can provide rigorous analyses of specific problems; and so on.

Although different branches of the social sciences have traditionally been isolated from one another, cultural-evolutionary theory provides an overarching theoretical framework that promises to integrate and unify the social sciences (Mesoudi, Whiten, and Laland 2006), just as Darwinian evolutionary theory integrated the biological sciences during the 1930s and 1940s (Mayr and Provine 1980). Indeed, the diverse contributions to this volume from anthropologists, archaeologists, biologists, philosophers, and psychologists provide encouraging signs that such a synthesis for the social sciences is not far off.

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12 Social Learning, Economic Inequality, and Innovation Diffusion

Anne Kandler and James Steele

Evolutionary models of innovation processes should address not just the origination phase but also the diffusion phase. Such models must be sensitive to socioeconomic context, where that context clearly affects the diffusion dynamics. Here we study the adoption dynamics of successful innovations, using as a model the sales of new consumer durables (televisions, washing machines, microwaves, and the like). Figure 12.1 shows the typical S-shaped adoption curve for such innovations. We consider the possible role of social-influence processes and of economic inequalities in determining the rate of growth in sales of new products of this kind and propose a new model that includes both social-influence processes and economic-inequality effects.

We start our consideration by contrasting two models of social-influence processes in innovation diffusion, one from marketing science (Bass 1969) and the other from dual-inheritance (DI) theory in anthropology (Henrich 2001). The Bass model of new product sales growth and the DI model of innovation diffusion both assume a homogeneous population of adopters, and both assume that the finite diffusion rate for learned awareness of the beneficial nature of the innovation is what prevents everyone from adopting it immediately. In both models, basic social-influence effects on levels of awareness are modeled as the rate term of a logistic growth process. The models diverge in their consideration of additional effects. Bass assumes that takeoff may be accelerated by an additional constant likelihood that an individual will choose to adopt independent of social influences ("innovativeness"). Henrich's DI model also assumes that takeoff may be accelerated by an independent-learning effect but introduces an additional frequency-dependent social-influence effect ("conformist bias") that actually delays takeoff.

For new products with significant cost, it is likely that adoption decisions are also influenced by price. In a community with money allocated unequally among individuals, people will have different reservation price thresholds for adoption. We therefore define an alternative approach, the "threshold heterogeneity" model. We demonstrate that where the price of a new product declines at the rate typically seen in new product life cycles, a population distribution of reservation prices based on empirical income distributions can produce the observed S-shaped diffusion patterns equally as well as the Bass and DI social-influence models.

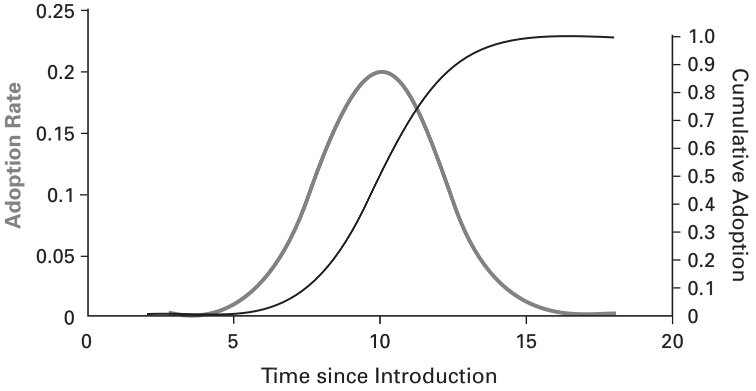

Figure 12.1
Typical adoption rate and cumulative adoption curves for new products.

To decide which of the considered models provides the most accurate explanation of the dynamics of adoption decisions, we need to consider additional information as well as sales growth. In his implementation of a DI approach, Henrich (2001) argued that biased-transmission processes must have predominated in the adoption decisions of populations of homogeneous agents in all empirical cases that show a sigmoid diffusion curve. Independent-learning processes cannot produce an adoption curve of this kind.

The assumption of agent homogeneity, however, is too restrictive and clearly inappropriate when studying adoption of costly goods in populations with high levels of economic inequality. A number of recent studies in the marketing literature have considered this problem (Golder and Tellis 1998; Van den Bulte and Stremersch 2004). They indicate that affordability is indeed an important criterion in individual decisions about when to adopt. For costly new products such as consumer durables, people are often aware of the product and its desirability long before they purchase it because they have had to wait for its price to come down to their own reservation price threshold.

To incorporate both social influences and affordability, we also propose a combined model. The key finding of this model is that although the adoption pattern will be determined primarily by social-influence processes where initial price is low and/or the subsequent price decline is rapid, the pattern will be determined primarily by affordability constraints when the initial price is high and the subsequent price decline is slow.

The Bass Model of Innovation Diffusion

Typically in the innovation-adoption literature from marketing science, diffusion of an advantageous new product by independent assessment of efficacy is expected to produce an r-shaped cumulative growth curve, whereas diffusion by imitation of prior adopters is expected to produce an S-shaped curve (Bass 1969). Bass's influential model proposes that the population of adopters can be divided into innovators and imitators and that the shape of the cumulative adoption curve will vary as a function of their relative importance. The Bass model includes an innovation coefficient, p, representing the fraction of the population that will adopt the innovation, regardless of the availability of demonstrators, and an imitation coefficient, q, representing the fraction of the population whose choice is determined by the number of previous adopters. The basic model states that

$$P(t) = p + qY(t),$$

where P is the probability of adoption by those who have not yet adopted at time t, and $Y(t)$ is the frequency of existing adopters at time t. This can then be expressed as a population rate of increase

$$\frac{\partial Y(t)}{\partial t} = (p + qY(t))(1 - Y(t)). \tag{12.1}$$

In cases where $q > p$, adoption will increase to reach an internal peak before declining, leading to an S-shaped cumulative adoption curve. In cases where $q \leq p$, adoption rates will be at their maximum initially and then tail off, leading to an r-shaped cumulative adoption curve. The empirical ratio q/p gives an index of the relative importance of innovativeness and of imitation in the diffusion of a particular new cultural trait and is a shape parameter for the cumulative adoption curve.

The Dual-Inheritance Model

A similar model of innovation diffusion is provided by DI theory. In this approach, it is assumed that the majority of human behavior is acquired through social learning (Boyd and Richerson 1985; Cavalli-Sforza and Feldman 1981; Henrich 2001). Following Boyd and Richerson (1985), we can distinguish among several different decision mechanisms affecting the adoption of traits:

- Guided variation—the selective retention of variants (including novel variants) found to be efficacious by individual trial-and-error learning.
- Direct-biased transmission—the selective copying of preexisting variants found to be efficacious by individual assessment.
- Indirect-biased transmission—the selective copying of variants from individuals with specific qualities and attributes deemed to make them fit models without assessing directly the efficacy of the copied variant.
- Frequency-dependent transmission—the selective copying of variants from individuals on the basis of their commonness or rarity without assessing directly the efficacy of the copied variant.

In the DI model (Henrich 2001), the temporal social dynamic of the spread of cultural variants by biased transmission can be modeled by the following differential equation:

$$\frac{\partial Y(t)}{\partial t} = \xi(P_1 - P_1 Y(t)) + \eta B(1 - Y(t))Y(t), \tag{12.2}$$

where $Y(t)$ describes the proportion of the population that has already adopted the variant at time t. The constants ξ and η represent the fractions of individuals in a population that rely on guided variation and biased transmission, respectively. The parameter P_1 is the probability of adopting the innovation through guided variation (Henrich 2001), and the parameter B represents the effects of the different forms of biased transmission on the spread of the variant. Given that we are interested in the adoption process of costly goods, we modify Henrich's treatment of guided variation so that the individuals are not allowed to revoke their adoption decisions if they cannot work out how to use the product effectively; that is, if they have purchased a good, they cannot return it.

In this context we have to distinguish between cases in which B is a constant and those in which B depends on the frequency, Y. In the first case, equation 12.2 includes the effects of direct and indirect transmission only, and the proportion of the population that has adopted at time t can be expressed explicitly by

$$Y(t) = \frac{1 - e^{-(\xi P_1 + \eta B)t}}{\frac{\eta B}{\xi P_1} e^{-(\xi P_1 + \eta B)t} + 1}.$$

Conversely, conformist-biased transmission, where the rate has a positive frequency dependence, can be included by setting

$$B = B(Y) = b(1 - a) + a(2Y(t) - 1)$$

(Boyd and Richerson 1985). The constant component $b(1 - a)$ models the influence of direct- and indirect-biased transmission, whereas $a(2Y(t) - 1)$ describes the influence of conformist-biased transmission. The parameter a is a measure of the strength of that conformist bias. As mentioned in Henrich (2001), a should be chosen to be rather small; otherwise conformist bias makes the spread of an initially rare variant impossible. In this case, equation 12.2 can be written as

$$\frac{\partial Y(t)}{\partial t} = \xi(P_1 - P_1 Y(t)) + \eta[b(1 - a) + a(2Y(t) - 1)](1 - Y(t))Y(t). \tag{12.3}$$

To illustrate the general spread dynamic given by equation 12.3, figure 12.2 shows cumulative adoption curves for different parameter constellations. The fraction of the population that relies on guided variation is assumed to be very small—P_1 has a value of 0.001, and the coefficients determining the rates of individual and of social learning,

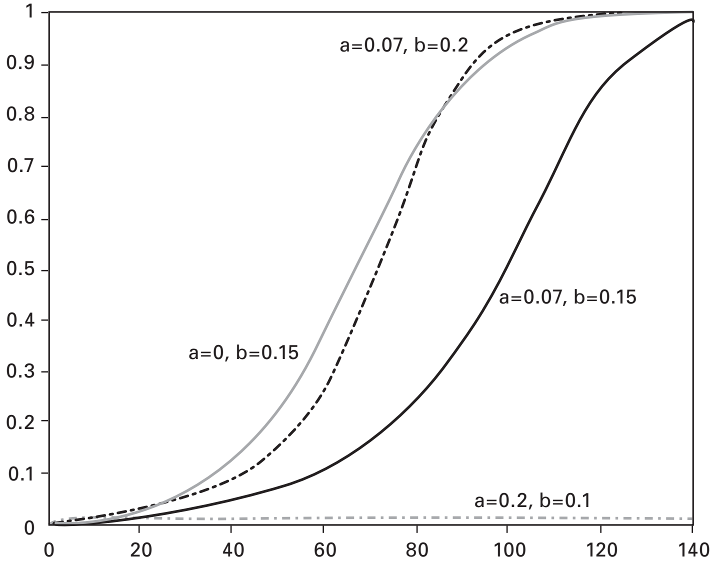

Figure 12.2
Cumulative adoption curves for different parameter constellations.

ξ and η, are both chosen to be 0.5. We can derive that a variant diffuses successfully by all the different transmission mechanisms if $B > 0$.

Figure 12.3 shows the course of the frequency-dependent transmission coefficient B in dependence of the frequency Y, and we see that the coefficients $B(Y)$ are always positive for the parameter constellations $a = 0$, $b = 0.15$; $a = 0.07$, $b = 0.2$; $a = 0.07$, $b = 0.15$, and in these cases the variant is adopted by the whole population. However, in contrast, if $B < 0$, the innovation is not supported by the whole of the social-transmission mechanism. The negative effect of conformist-bias transmission due to the rareness of the innovation at the beginning cannot be compensated by direct and indirect transmission biases, and the innovation will increase its frequency only by independent learning (see the cumulative adoption curve for the parameters $a = 0.2$, $b = 0.1$ in figure 12.2). Even a higher initial condition $Y(0) = 0.05$ is insufficient to maintain the variant in the population.

Further, comparison of the cumulative adoption curves with the parameters $a = 0$, $b = 0.15$ and $a = 0.07$, $b = 0.15$, which obviously differ only in the respective absence ($a = 0$) and presence ($a = 0.07$) of the conformist-biased component, shows that such frequency-dependent biases are able to produce long tails at the beginning. Conformist bias supports the spread of common variables but impedes the spread of rare variants. Consequently, it takes longer for a rare variable to spread if conformity is present as is reflected in the long tails at the beginning. In contrast, parameter b influences the steepness of the curve. The

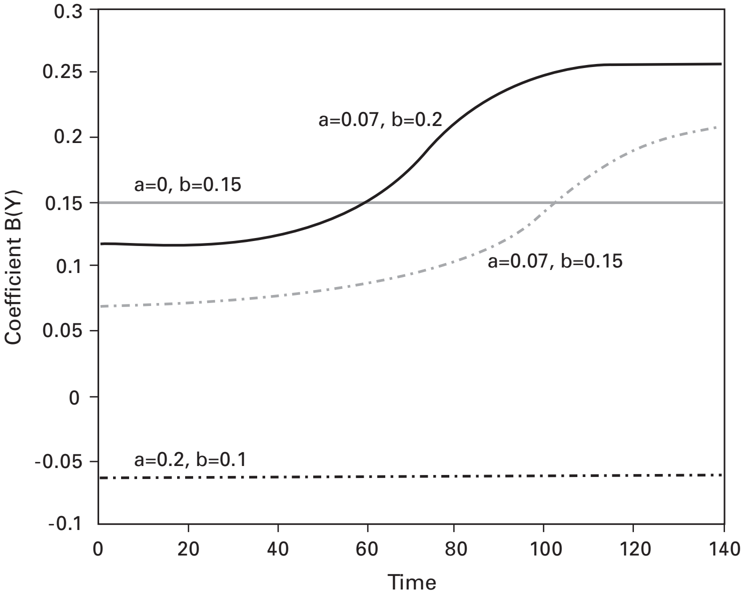

Figure 12.3
Transmission coefficient, *B*, for the different parameter constellations.

larger this coefficient, that is, the larger the effect of direct- and indirect-biased transmission, the steeper the cumulative adoption curve and the faster the variant spreads through the whole population.

Comparison of the Dual-Inheritance Model with the Bass Model

Both the Bass model and the DI model provide possibilities to describe the diffusion of an advantageous innovation in a population. In this section we explore how different or how similar the models are in terms of the adoption dynamics. If we compare the models without considering conformist bias, the cumulative adoption curves for the spread of costly goods obtained by the Bass model and the DI model coincide exactly. The Bass model defines the spread dynamic by equation 12.1, whereas the DI model without conformist bias determines the dynamic by equation 12.2. By setting

$$\tilde{p} = \xi P_1 \quad \text{and} \quad \tilde{q} = \eta B, \tag{12.4}$$

it is obvious that both equations are the same. This means that the fraction ξP_1 is equivalent to the parameter p in the Bass model—the fraction of the population that adopts the innovation independently and not as a result of any imitation process—and ηB is

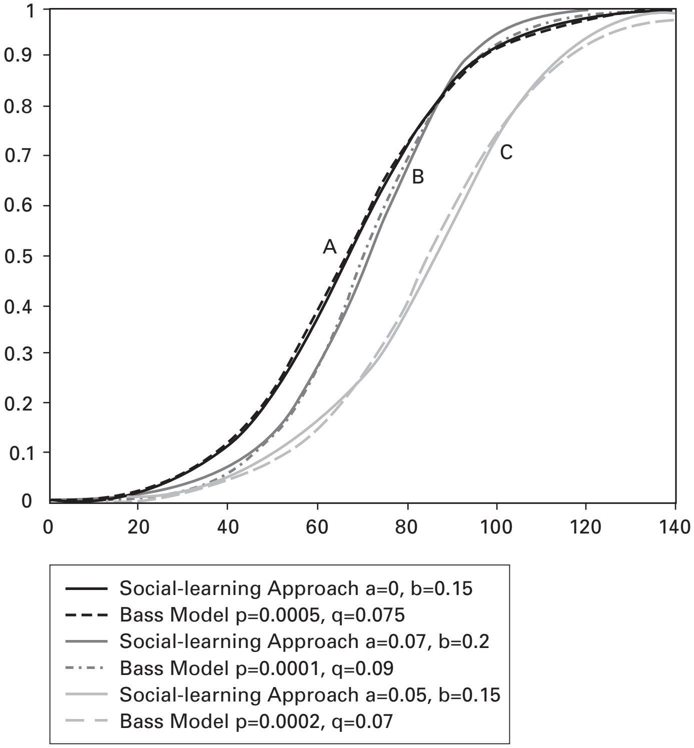

Figure 12.4
Comparison of adoption curves from the dual-inheritance and Bass models.

equivalent to the parameter q, which determines the strength of the imitation process. Figure 12.4 (curves labeled A) shows an example of this coincidence. With the parameters $P_1 = 0.001$, $\xi = \eta = 0.5$, $a = 0$, and $b = 0.15$, we obtain $p = \xi P_1 = 0.0005$ and $q = \eta B = 0.075$.

The situation changes if we include conformist bias, which is responsible for a long tail of the cumulative adoption curve at the beginning. Figure 12.4 (curves labeled B and C) shows the divergence of the DI model from the Bass model, which cannot reproduce this long-tailed pattern at the beginning. For these examples, however, the deviation between cumulative adoption curves remains less significant than the overall close correspondence.

Because of this coincidence, we consider in the further numerical examples only the DI model, given that the Bass model is equivalent to the DI model without conformist bias. From this point forward, we shall refer to the DI model as “the social-learning model.”

Alternative Explanation: Threshold Heterogeneity

The two previous models have the common assumption that the spread of an innovation is determined by a mixture of individual exploration and social learning. It is assumed implicitly that all individuals who want to adopt an innovation can actually do so. Having the spread of costly goods in mind, we emphasize that this is not always the case. Rather, only wealthy individuals will initially be able to afford an expensive innovation, whereas the others will have to wait until the price of the innovation drops below their individual thresholds for adopting it. Such "moving-equilibrium" effects are analyzed in probit models in the economics literature (David 2005; Geroski 2000) and are not accounted for in the social-learning model.

Based on the work of Van den Bulte and Stremersch (2004), we can examine this heterogeneity approach based on economic factors and show that both explanations—the social-learning model and the threshold-heterogeneity hypothesis—can lead to nearly the same S-shaped cumulative adoption curves.

In the following we assume that income is the factor that determines the adoption decision and timing and that income is unequally distributed through the population. The heterogeneity approach presumes that an individual, i, will adopt an innovation if its price is smaller than the individual's threshold, θ_i, the reservation price depending on the individual's income. We note that an unequal income distribution leads naturally to an unequal distribution of adoption-price thresholds. In this context, initial innovators are not the venturesome and daring individuals of the Bass model. Rather, they are the people who can initially afford the innovation.

Different considerations (Salem and Mount 1974) have shown that one means of approximating the income of a population, and consequently the price-threshold distribution, is by using a two-parameter right-skewed gamma distribution given by the function

$$f_\Theta(\theta) = \frac{\lambda^\alpha}{\alpha}\theta^{\alpha-1}e^{-\lambda\theta}, \quad \text{with} \quad \alpha, \lambda > 0 \quad \text{and} \quad \theta \geq 0. \tag{12.5}$$

The two parameters, α and λ, can be interpreted as measures of inequality and scale of the distribution.[1]

Different sets of these distribution parameters lead to different degrees of inequality, as shown in figure 12.5, where theoretical distributions of adoption thresholds for a new product of the form (5) with the parameters $\lambda = 6$ and $\alpha = 2, 3, 4$ are illustrated. The levels of income inequality can be quantified by the Gini income concentration coefficients[2] of 0.375, 0.313, and 0.273. It is obvious that the population's income is distributed most evenly for the smallest Gini coefficient, 0.273.

Assuming the income distributions shown in figure 12.5 as proxies for the adoption-threshold distributions, and with an exponential price decline for the new product over time,

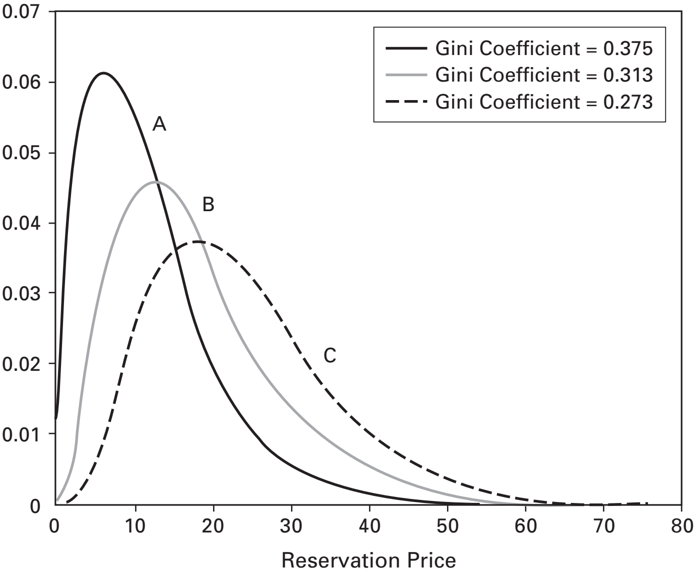

Figure 12.5
Price-threshold distribution for different degrees of income inequality.

the cumulative adoption curves (solid lines) in figure 12.6 are obtained. They are S-shaped, but here the shape reflects income heterogeneity and not contagion/diffusion. The interpretation of S-shaped curves in the social-learning model applies only in cases where there is population homogeneity in the economic factors determining the threshold for adoption subsequent to exposure. Figure 12.6 (solid lines) shows that different price-threshold distributions result in different adoption processes in a threshold-heterogeneity model. A more unequal income distribution implies that a larger proportion of the income will be earned by fewer individuals. This means that for a new product with high initial cost and a steady pattern of price decline, diffusion of the innovation through the population will take longer, given that the price threshold of the majority of the population will be lower.

In order to derive an analytical expression for the spread dynamic shown in figure 12.6 similar to equations 12.1 or 12.3 for, respectively, the Bass and the DI model, we use the cumulative-distribution function, $F_\Theta(\theta)$, of the price threshold, Θ, which can be interpreted as the proportion of the population with a threshold less than or equal to θ. Then,

$$F(t) = F_\Theta(\rho(t)),$$

where the price, $\rho(t)$, of the innovation is a decreasing function in time. As a further consideration, we assume an exponential price decline of the form $\rho(t) = \rho_0 e^{-bt}$, where the innovation has an initial price of ρ_0. In this case, we can determine the change, $dF(t)/dt$, in the proportion that has already adopted at time t by

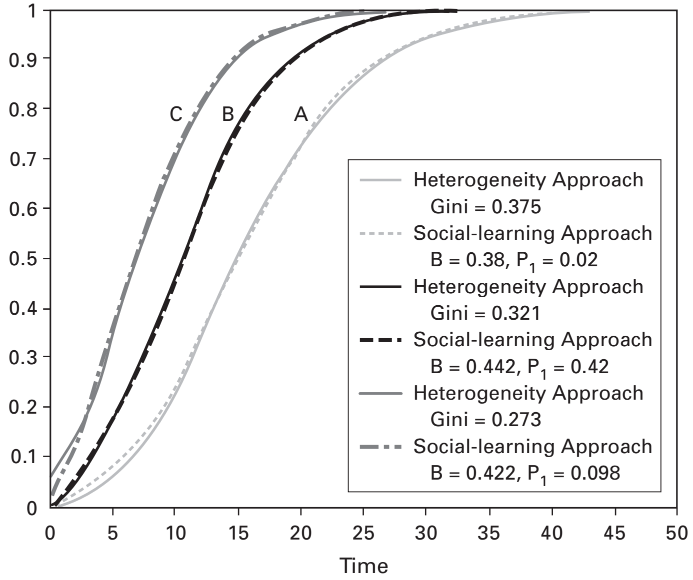

Figure 12.6
Cumulative adoption curves corresponding to data shown in figure 12.5.

$$\frac{dF(t)}{dt} = f(t) = -F'_{\Theta}(\rho(t))\rho'(t) = \frac{\lambda^{\alpha}}{\Gamma(\alpha)}\rho_0^{\alpha} b e^{-\alpha bt-\lambda e^{-bt}}. \tag{12.6}$$

We have formulated the analytical expressions for the time course of the adoption process based on the contrasting social-learning (equation 12.3) and threshold-heterogeneity hypotheses (equation 12.6), and now we compare the resulting cumulative adoption curves. Figure 12.6 shows that the shapes of the adoption curves can be similar. The solid lines represent the curves obtained by the heterogeneity approach with different degrees of inequality, whereas the dashed lines illustrate the spread dynamic produced by the social-learning approach under different transmission biases.

This raises the question of which values for the measure of income inequality and which transmission parameters, P_1 and B, lead to the same cumulative adoption curves. To answer this, we assume different gamma-distributed price thresholds with corresponding Gini coefficients of 0.273, 0.313, and 0.375 (as shown in figure 12.5) and a price decline for the innovation given by $\rho(t) = 45e^{-0.1t}$; that is, the initial price of the innovation is 45 and it then decreases exponentially. In the next step we determine the parameters that minimize (in a quadratic sense) distances between the function $Y(t)$ in the social-learning model and the function $F(t)$ in the threshold-heterogeneity approach. In mathematical terms, we look for the unique solution of the optimization problem

$$\min\|F(t)-Y(t)\|^2$$

Table 12.1
Considered parameter constellations

Heterogeneity Approach		Social-Learning Model	
Gini Coefficient	$\tilde{q} = B$	$\tilde{p} = P_1$	$\tilde{q}/\tilde{p}$ Ratio
0.375	0.010	0.191	19.19
0.313	0.021	0.221	10.32
0.273	0.049	0.211	4.34

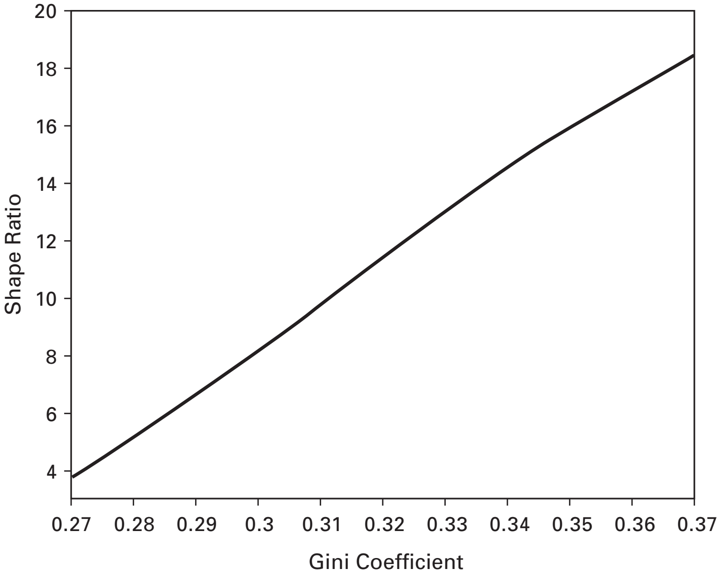

Figure 12.7
Proportionality relation between the shape ($\tilde{q}/\tilde{p}$) ratio and the Gini coefficient.

for all possible model parameters.

Table 12.1 shows the corresponding values of the parameters of the social-learning curves (with $\xi = \eta = 0.5$), which are the best quadratic approximations of the function $F(t)$. We find that $a = 0$ for all three examples, so the transmission parameter B reflects only the effects of direct- and indirect-biased transmission.

This analysis shows that curve forms in the threshold-heterogeneity model—forms that vary with income inequality, which we take as a measure of inequality of the reservation-price distribution—and in the social-learning model—forms that vary with the relative importance of guided variation and biased transmission—are directly proportional. This fact is illustrated in figure 12.7, where the shape ratios, $\tilde{q}/\tilde{p}$, and the

Gini coefficients are contrasted. The relation between these two parameters is almost linear.

A Combined Model

As shown in the previous sections, both models—one based on the social-learning hypothesis and the other on the threshold-heterogeneity hypothesis—provide good fits for S-shaped adoption curves. The social-learning model assumes that the spread of an innovation is determined by cultural-transmission biases in the population. The innovation favored by these transmission mechanisms will spread across the whole population. This approach assumes that every individual who wants to adopt is able to do so and that there are no external constraints on the adoption decision. In contrast, the heterogeneity model is based on such an external constraint and assumes that the adoption process is determined only by an individual's price threshold—the ability to afford the innovation. However, in this case it is assumed that all individuals in the population want to adopt the innovation as soon as possible.

For modeling the spread of costly goods, it might seem more appropriate to combine both hypotheses by developing a model in which the desire to adopt is influenced by social biases but where the timing of adoption is constrained by affordability. This leads to the following approach,

$$X(t) = Y(t)F(t) = Y(t)(1 - F_{\Theta}(\rho(t))), \tag{12.7}$$

where $F(t)$ is the cumulative adoption curve obtained by the threshold-heterogeneity approach and $Y(t)$ is the cumulative adoption curve of the social-learning model given by equation 12.3. This model assumes that acquiring a preference to adopt the innovation is independent of income. People are heterogeneous with respect to price thresholds for adoption but homogeneous with respect to mechanisms for acquiring the preference to adopt.

What about the spread dynamic of the combined model and the influences of different patterns of price decline? As stated before, the cumulative adoption curve of the social-learning model is by definition unaffected by changes in economic factors and stays the same in the following examples, where we compare the adoption curves of the social-learning model, the threshold-heterogeneity model, and the proposed combined model for different patterns of price decline. At first we assume that the price is constant over the entire time period. Figure 12.8 illustrates this situation, with a constant price, $\rho = 10$, an unequal income distribution indexed by a Gini coefficient of 0.375, and social-transmission parameters $a = 0.05$ and $b = 0.15$. The cumulative adoption curve of the threshold-heterogeneity approach is simply a constant, given that the price does not change from the initial value.

The cumulative adoption curve of the combined model shows an S-shaped pattern. It is dominated in the first time period by the social-learning model, but the economic constraints

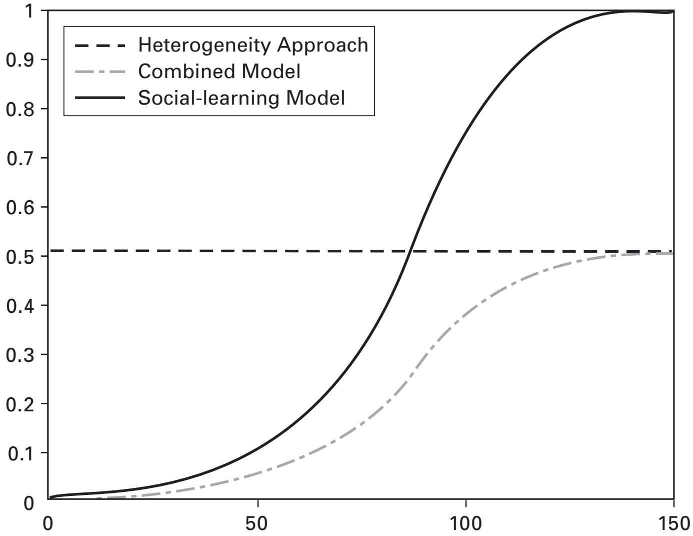

Figure 12.8
Comparison of the cumulative adoption curves for a constant price $\rho = 10$ with income inequality given by the Gini coefficient of 0.375, and transmission parameters $P_1 = 0.001$, $\xi = \eta = 0.5$, $a = 0.05$, and $b = 0.15$.

delay the spread of the innovation through the population. Given that the price is constant, only the part of the population whose reservation price is greater than or equal to 10 will ever adopt, and, as a result, the innovation will not spread successfully through the whole population, despite the fact that the whole population is aware of the innovation. This can be seen in figure 12.8, where the cumulative adoption curve of the combined model coincides with the cumulative adoption curve from the threshold-heterogeneity approach at the time where $Y(t) = 1$. By then, all individuals have been influenced to want to adopt the innovation, which means that the assumption of the heterogeneity approach is fulfilled, and the combined model is identical to the threshold-heterogeneity approach (compare equation 12.7 with $Y(t) = 1$).

In contrast, figure 12.9 shows the cumulative adoption curves if the price decreases exponentially from 45 to 10 and then stays constant. All other parameters are the same as in the previous example. Again, in a short time period at the beginning, the shape of the cumulative adoption curve of the combined model is dominated by the social-learning dynamic, but it coincides with the cumulative adoption curve from the heterogeneity approach at the time where $Y(t) = 1$. Because of economic constraints (the price will never fall below 10), the proportion of the population that will adopt the innovation is the same as in figure 12.8. However, given that the price has to decrease to reach the value of 10, the adoption process takes slightly longer.

The last example (see figure 12.10) assumes that the price decreases exponentially with no restriction; all other parameters are the same as in the preceding examples.

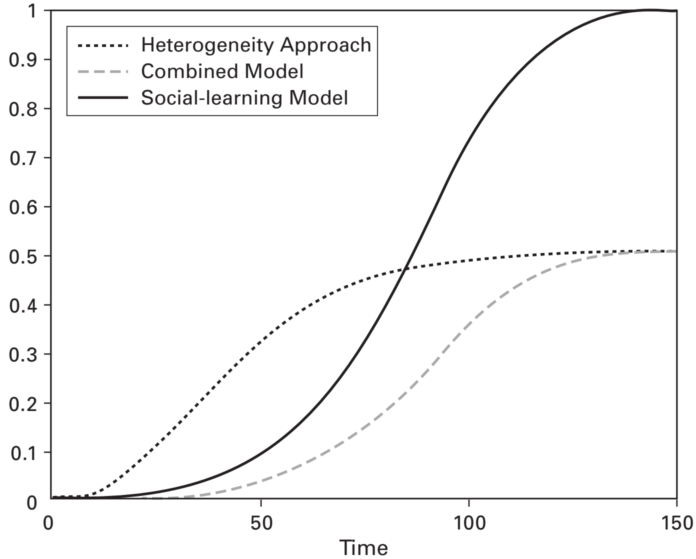

Figure 12.9
Comparison of the cumulative adoption curves for an exponential price decline from 45 to 10 with income inequality given by the Gini coefficient of 0.375 and transmission parameters $P_1 = 0.001$, $\xi = \eta = 0.5$, $a = 0.05$, and $b = 0.15$.

Figure 12.10a is obtained with price decline of the form $\rho(t) = 45e^{-0.05t}$. Notice that the income inequality has little influence on the spread of the innovation. The shape of the cumulative adoption curve of the combined model is dominated by the social-learning components. This is not surprising, given that the chosen initial price and the price decline will not produce a sufficiently long delay between the time where the richest individuals and the poorest individuals can afford the innovation. However, with more-costly goods, we consider a price decline of the form $\rho(t) = 100e^{-0.03t}$ (see figure 12.10b). Now, the initial price is nearly doubled, and the decline is slower. In this case "willingness" to adopt an innovation spreads faster than the individuals can actually afford it, and the shape of the cumulative adoption curve of the combined model is dominated by the threshold-heterogeneity components of the model, that is, the affordability constraints.

These examples demonstrate that economic factors have to be included where they would counteract or delay the spread predicted when only learning mechanisms are considered. To increase the realism of the model, we can relax the implicit assumption of the threshold-heterogeneity approach (see note 2), namely, that all individuals will have the same propensity for spending their income on an innovation. This means that we now incorporate the fact that the ratio between discretionary income and income is higher for wealthier individuals and tends to zero out for individuals with a small income. Figure 12.11 illustrates the approach. The dashed line shows the previous assumption of a constant propensity for

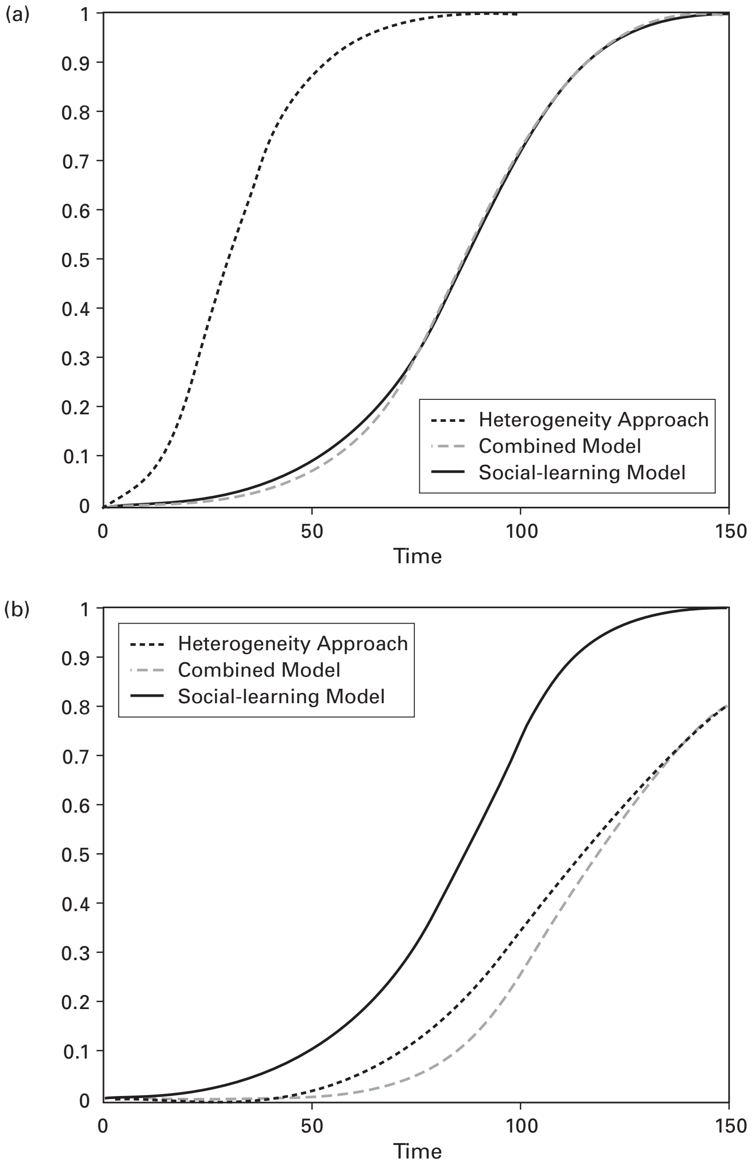

Figure 12.10

Comparison of the cumulative adoption curves for exponential price declines $\rho(t) = 45e^{-0.05t}$ (a) and $\rho(t) = 100e^{-0.03t}$ (b) with income inequality given by the Gini coefficient of 0.375 and transmission parameters $P_1 = 0.001$, $\xi = \eta = 0.5$, $a = 0.05$, and $b = 0.15$.

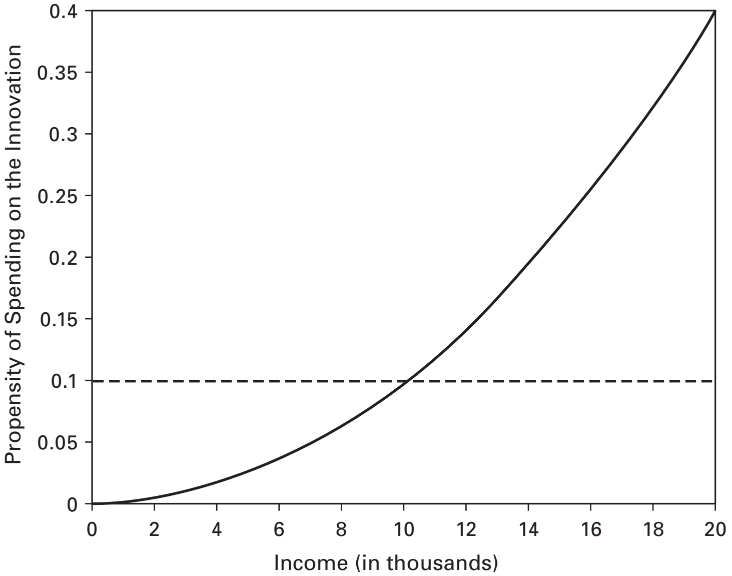

Figure 12.11
Proportion of income spent on the innovation.

spending, regardless of income. Now we assume a quadratic dependence between income and the propensity for spending (solid line). This leads to a higher number of adopters at the beginning but also decreases the proportion of the population that will adopt at late time points, compared with the situation of a constant propensity.

Figure 12.12 makes that effect obvious. The chained line represents the cumulative adoption curve for a heterogeneity approach with a constant propensity for spending, and the solid line shows the cumulative adoption curve produced by the income-dependent propensity given in figure 12.11. At the time period from $t = 0$ to roughly $t = 50$, the adoption curve of the "variable"-heterogeneity approach (solid line) is above the curve of the "constant"-heterogeneity approach (chained line) because the wealthier individuals tend to spend a higher proportion of their incomes on an innovation. As time goes by, the price of the innovation decreases so that more individuals can afford it. The "variable"-heterogeneity approach, however, assumes that the poorer the individuals, the smaller the proportion of their incomes they spend on the innovation. Therefore, the solid line is below the chained line for later times. This causes a long tail at the end.

The Case of Black-and-White Television Adoption in the United States

In the case of the adoption of black-and-white television sets in the United States, Wang (2003) argues that the observed delay reflects income inequality. When the new product

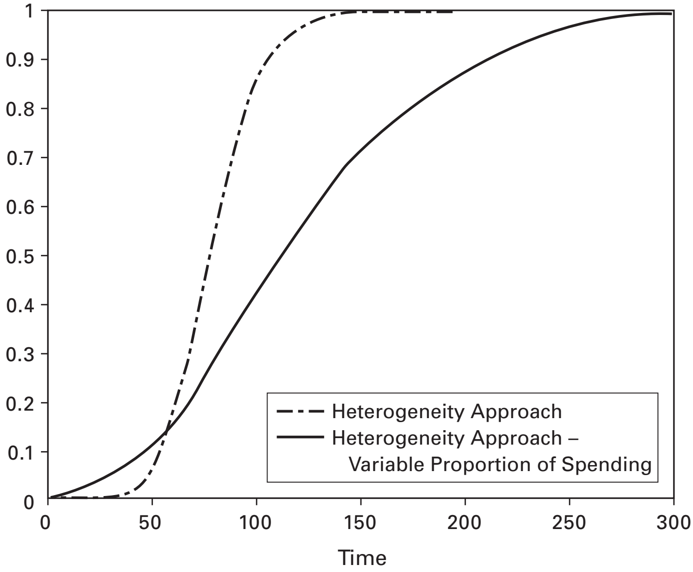

Figure 12.12
Cumulative adoption curves of the different approaches.

was introduced in 1946, high-income consumers tended to adopt it first. The price then fell with cumulative output, and demand grew as the product penetrated into lower income groups. Based on the considerations of Bayus (1993) for the time period from 1946 to 1960, we assume an exponential price decline for black-and-white sets of the form

$$\rho(t) = 1283e^{-0.087t}.$$

This implies that the initial price of a set at market launch was $1,283 and that afterwards a relatively steep price decline was observable. We adjust this to take into account the simultaneous growth in nominal per capita gross domestic product in the United States, which we take as a proxy for average nominal per capita income. Based on data for the period 1946–1971 in Johnston and Williamson (2007), we estimate the exponential rate of economic growth as $e^{0.045}$, which means that the price decline for black-and-white sets (as a fraction of average income) can be approximated as

$$\rho(t) = 1283e^{-0.1322t}.$$

The family-income distribution is approximated by a gamma distribution, and we use the parameter $\alpha = 2.49$ and $\lambda = 3.9 \cdot 10^{-4}$, estimated in McDonald and Ramson (1979) for the year 1960. The corresponding Gini coefficient is 0.34, which shows that family income in 1960 was relatively unequally distributed. Evidence suggests that the Gini coefficient was fairly stable and constant during the period of diffusion of this innovation.

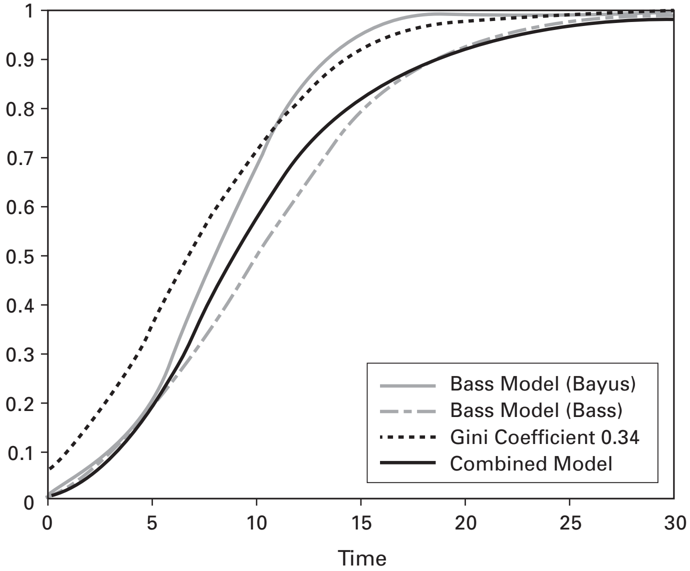

Figure 12.13
Cumulative black-and-white-television-set adoption curves for the Bass, threshold, and combined models. The Bass curves were fitted to actual sales data, whereas the threshold curves are based on income distribution and on the exogenous growth-adjusted price trend. Threshold was set as a constant fraction of income.

Bass (1969) estimated his model from sales data and obtained the coefficient of innovation, p, as 0.0279 and the coefficient of imitation, q, as 0.25. Bayus (1993) fitted the Bass model to the actual sales data and estimated the coefficient of innovation at 0.0159 and the coefficient of imitation at 0.39. We can use these data to model the diffusion rate for black-and-white sets using the threshold-heterogeneity model and employing the two Bass-curve fits as our targets for comparison. We note in passing that in contrast to the threshold-based curves, these best fit Bass curves are not constrained by any independent empirical data on the strength of imitative bias among adopters.

In figure 12.13, the dashed line represents the curves obtained by the threshold-heterogeneity approach, with $c = 1/11$ as the constant propensity of spending on television sets. This means that the individuals or families would spend up to about 10 percent of their annual income on their first set. Comparison with the two fitted Bass curves shows that the general behavior is similar, although it does not fit exactly. In contrast, the black solid line represents the cumulative adoption curve obtained by the combined model with the income distribution of the year 1960 for the threshold-heterogeneity approach and Bass parameters $p = 0.06$, $q = 0.3$. This means that compared with the pure Bass model as estimated by Bass (1969) or by Bayus (1993), the probability is slightly increased that an individual will decide to adopt the innovation independently of social influence.

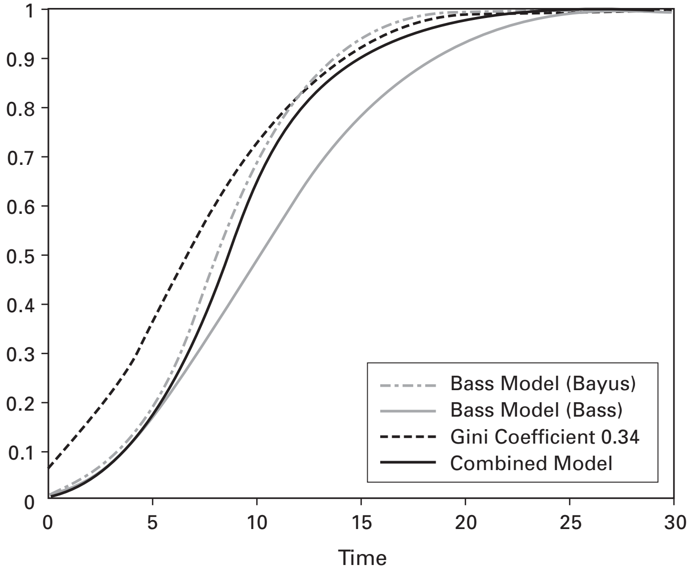

Figure 12.14
Cumulative black-and-white-television-set adoption curves for the Bass, threshold, and combined models. The Bass curves were fitted to actual sales data, whereas the threshold curves are based on income distribution and on the exogenous growth-adjusted price trend. Threshold was set as a variable fraction of income.

Figure 12.14 differs in that we assume a variable proportion of income as discretionary in the combined model, which now has Bass parameters $p = 0.035$, $q = 0.35$. It is evident that the threshold distribution predicts the correct timescale for the diffusion process and that the social-contagion component of the combined model improves the fit to the Bass curves by delaying takeoff in the higher income groups.

Summarizing, our empirical threshold distribution gives a good fit to the Bass sales curves for this case study, and the combined model improves that fit by introducing a social-learning element to explain the observed delay in takeoff. Overall, we infer that inequality in a population's income distribution is indeed likely to be an important factor in explaining the time course of new product diffusion.

The Diffusion of Hybrid Corn in the United States

Agricultural innovations might not be thought of as being subject to the same affordability constraints and price dynamics as consumer durable goods. Henrich (2001), however, has applied the social-learning model in such cases, suggesting that the observed long forward tail to the adoption curve for hybrid corn among Iowa farmers in the late 1920s and 1930s was a result of conformist bias. If we combine the social-learning dynamic with a

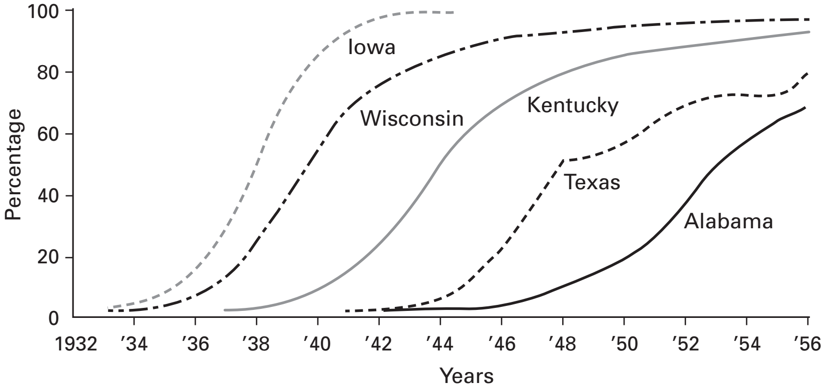

Figure 12.15
Percentage of total corn acreage planted with the hybrid strain by state (after Griliches 1957).

heterogeneous, variable-*c* adoption-threshold distribution, we obtain a cumulative adoption curve (combined model in figure 12.12) showing an S-shaped pattern with longer tails at the beginning (caused by the social-learning dynamic) and end (caused by the variable-*c* adoption-threshold dynamic). This characteristic of the adoption curve is also known from data on the spread of hybrid corn in the United States (see figure 12.15, especially the curves for Wisconsin and Kentucky).

Regarding these large-scale lag patterns, Griliches (1957, 1960) preferred an explanation in terms of unequal supplier effort, with commercial seed-corn suppliers initially targeting regions with large farm units and high corn acreage (and contiguous areas with similar climate, soil, and pest characteristics). However, there also may have been a contribution that resulted from heterogeneity in decision thresholds among farmers. For a business such as a farm, immediate-acquisition cost has to be measured not against disposable income but against future profit from the gain in yield. In the 1930s, commercially acquired hybrid seed corn cost almost ten times as much to adopters as homegrown seed corn (Griliches 1958), and the extra yield also imposed potential additional input costs (fertilizer, water, and extra labor for harvesting). The extra cost of hybrid seed represented a fixed cost per unit area, whereas yield varied (Dowell and Jesness 1939). It is plausible that late adopters included farms with lower typical corn yields, for which the high relative cost of the new strain was a significant factor delaying the adoption decision.

The same point is made by David (2005), by analogy with his analysis of threshold-heterogeneity effects on adoption timing for the mechanized reaper in the antebellum American Midwest (David 1966). The most recent and thorough examination of the hybrid-corn diffusion data is Young's (2005) acceleration analysis, which indicates a relatively poor fit of the data with the logistic adoption curve predicted by the Bass model. To our knowledge, an empirically derived threshold model has yet to be fitted to the detailed corn-diffusion data, although clearly this would be desirable.

Conclusions

In conclusion, we make some brief remarks on the implications of the above for evolutionary anthropology. If we discount any propensity for consumers to reject advantageous new products after adoption because they have misunderstood their use, then other than its optional conformist-bias element, the DI model (Henrich 2001) is identical to the Bass model (Bass 1969), which has been used extensively to analyze sales growth and life cycles of many well-documented new products. The Bass model is the subject of a massive amount of literature going back nearly 40 years, which includes many discussions of alternative drivers of the typical S-shaped sales pattern (including affordability). Anthropologists seeking such an empirical testing ground for the predictions of DI theory may find that much of the work has already been done by their colleagues in economic forecasting and marketing science (Chandrasekaran and Tellis 2007).

However, both the Bass and the DI models assume that agents are homogeneous with respect to the economic capacity to adopt. This is an oversimplifying assumption that does not recognize the evolutionary dynamics of complex societies with large economic surpluses in which wealth inequalities are characteristic and that can be modeled by quite simple mechanisms (e.g., the Law of Proportionate Effect [Gibrat 1931]). An evolutionary approach to innovation adoption in developed market economies, therefore, has to consider the evolutionary dynamics of economic inequality as well as those of social-learning processes.

Notes

1. The Gini coefficient is a statistical measure of the inequality of an income distribution introduced by Gini (1955). It is defined as a ratio with values between 0 and 1. The closer the coefficient is to 1, the more unequal is the distribution. In the considered case of a gamma-distributed income, the Gini coefficient is defined by $2B_{0.5}(\alpha, \alpha + 1) - 1$, where $B_{0.5}$ stands for the incomplete beta function (Salem and Mount 1974).

2. Given that determining an individual's price threshold is more difficult compared with determining an individual's income, it is common practice to model the price threshold, θ, by

$$\theta = cI \quad \text{with} \quad 0 \le c \le 1,$$

where I is the individual's income and c describes the propensity for spending money on the innovation (Wang 2003). For a constant, c, the price threshold resembles the observed income distribution, which means that it is gamma distributed and possesses the same degree of inequality (as expressed by the Gini coefficient). A constant propensity of spending for all levels of income is a very simplistic assumption and one that we relax in a later discussion.

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IV PATTERNS IN THE ANTHROPOLOGICAL RECORD

13 Technological Innovations and Developmental Trajectories: Social Factors as Evolutionary Forces

Valentine Roux

Historical (e.g., Duby 1962), anthropological (e.g., Creswell 1996), sociological (e.g., Mendras 1984; Ogburn 1957 [quoted in Akrich 1994]), and materials (e.g., Gille 1978) research has shown how technological change can unbalance a cultural system, causing its total reorganization and transforming it into a new system following its own dynamics. However, even if these studies sometimes explicitly show the relations between technical transformations and transformations of socioeconomic, legal, political, ideological, and demographic systems, the mechanisms by which technological changes are introduced are still poorly understood and continue to be the subject of debate (e.g., Akrich 1994). Here I discuss ways in which technological innovations are introduced and spread, that is, the mechanisms underlying the emergence and fixation of new technological traits, in order to better understand the impact of innovations on cultural systems.

The field of technology distinguishes among technological change, which is considered an emergent historical phenomenon and thus an unrepeatable scenario; the conditions for portraying these scenarios, which correspond to the production context of technological tasks; and the conditions for fixing the new features, which correspond to the transmission context (Roux 2003). These conditions are assumed to act as evolutionary forces, and studying them should give us insights into the evolutionary mechanisms of ancient cultures.

Study of the emergence and fixation of new technological features implies two levels of analysis: individual and collective. *Invention* occurs on the scale of the individual as opposed to *innovation*, which is the adoption of an invention on a collective scale (a current distinction generally adopted by technologists; see, e.g., Gille [1978] and van der Leeuw and Torrence [1989]). In other words, invention can be considered a cognitive activity on an individual scale, whereas innovation corresponds to a historical event. Below, I first deal with technological inventions and their order and mode of development as well as the possible role of the individual in the differential occurrences of inventions. Next, I examine the mechanisms underlying innovation and fixation processes.

Technological Evolution

Technological evolution is assessed by examining the trends of individual technologies and determining the modes that produce them. Is the passage from one technology to another characterized by incremental additions, or does it proceed by jumps? Accordingly, I distinguish between *continuous* and *discontinuous* inventions. The hypothesis is that if both kinds of invention can participate in technological evolution, the mechanisms underlying their emergence and fixation may vary.

Trend of Evolution: Cumulative Character and Order of Development

Studies in the history of technology show that techniques are cumulative in the sense that any transformation of a technique always incorporates previous knowledge (e.g., Creswell 1996; Deforge 1989; Gille 1978). In this respect, invention is often considered as an incremental modification or a combination of preexisting elements (e.g., Lemonnier 1993; Schiffer 2005; chapters 7 and 14, this volume).

Because techniques are cumulative, their evolution follows a certain order of development. The first stone tools were not created by indirect percussion but by direct percussion, the first pottery was made not with the help of rotary kinetic energy (RKE) but with muscular energy, pyrotechnologies did not begin with high-temperature technologies but with low temperatures, and so on. In other words, inventions always take place within the logical suite of historically detectable antecedents (Gallay 1986). However, the fact that techniques necessitate a certain order of development does not mean that this order is the same everywhere (Creswell 1996). Some groups can ignore certain stages and jump straight to more complex stages, given certain environmental or cultural factors.

This order of technological development, observed at a macroscale and independent of the historical trajectories of the inventions, can be characterized in evolutionary terms. The hypothesis is that the general trend is toward less expenditure of human energy (Creswell 1996; Deforge 1989; Gille 1978; Simondon 1958). Such a trend would correspond to "laws of evolution" (Deforge 1989; Simondon 1958), according to which techniques evolve logically from a state ("abstract") where the elementary operations underlying the manufacture of an object are first juxtaposed to a state ("concrete") where these operations are related and cannot be separated from each other, given their interaction in a synergistic fashion.

The analysis is based on well-documented lineages of objects that evolve from a stable technical principle and are established after an analysis of the genesis of the objects. In other words, they can be considered as a genealogy of physical principles (Creswell 1993, 1996). The corollary to the passage from the "abstract" to the "concrete" object is that, all things being equal, objects will evolve toward less volume, less weight, a lesser number of pieces, less response time, and a lesser price (Deforge 1989). This theory of the evolution of objects has been applied in archaeology by Boëda (2005) in order to better describe lineages of ancient lithic industries, to understand their evolution in structural terms, and to explain convergences as well as, for example, the emergence of blade technology.

As far as pottery-manufacturing techniques are concerned, in the Southern Levant one can trace an evolution of the coiling technique into the wheel-coiling technique (use of RKE for thinning and shaping coiled roughouts) into the wheel-throwing technique (use of RKE on a mass of clay). This latter technique, which appears as an entirely mechanized manufacturing process, can be considered an ultimate stage in the development of ceramic techniques using RKE in accordance with the "laws of evolution" proposed by Simondon (1958). Indeed, the different operations are exerted in synergy through the use of RKE. Such synergy is unique among pottery-production techniques, which are usually a series of independent operations, such as the wheel-coiling technique. Hence, there is a considerable gain of time (Roux and Courty 1998).

The necessity of establishing lineages of objects based on technological process for an appropriate understanding of their relationships—and therefore of the evolution of objects—has been well argued by Creswell (1993, 1996), who, in analyzing the evolution of mills, shows that the relationships based only on morphological features are inappropriate and misleading, whereas those based on technological process enable us to consider all the different variants that have occurred over the centuries. Before Creswell, Haudricourt (1987) argued that the genealogy of tools should take into account their physical properties. He suggested that the ancestor of the plow was not the spade or the stick but the rake, given its handling system that characterizes the plow as an instrument dragged and not hit. In support of this hypothesis, he pointed out that the first plows in Egypt and Mesopotamia were used at sowing time for work similar to that of the rake or the harrow (see chapter 1, this volume).

As far as pottery is concerned, if only morphological types are considered, the relationships mix morphological vessels that are formed using different techniques. Such relationships do not permit an analysis of the evolution of objects, which necessarily implies an analysis of the relationships between forms and techniques. On the other hand, if one takes into account the technological process, then the relationship diagrams will highlight, for example, relationships between objects with variations of forms but made according to the same technique or the lack of relationship between objects with comparable shapes. In archaeology, lineages of objects based on technological process are still to be created and represent one of the most compelling agendas in the study of cultural technology (O'Brien and Lyman 2003).

Mode of Evolution: Gradual versus Rapid

On the basis of numerous technological studies, Creswell (1994, 1996) suggested that innovation appears in two ways: (1) as an autonomous and progressive development not motivated by any specific social factors and responding mainly to technological rules and (2) as a development by jumps between stages determined by social mutations. In the first, innovations can be considered as progressive and continuous. They develop in response to their own technological tendency up to a certain extent, which is fixed by limits. In the latter case, the passage from one stage to another appears to follow a logarithmic function and not a linear one. Innovations can be considered discontinuous, going beyond the limits imposed by the internal logic of the techniques. They are not simply the combination or addition of preexisting elements but introduce new technological lineages (see chapter 1, this volume). The technological jump produced by these techniques can be assessed quantitatively and qualitatively.

Creswell (1993, 1994, 1996), in a study of mills used in the Middle East to extract olive oil, demonstrates that the evolution of techniques can proceed by jumps. He shows that there are two main thresholds in the evolution of milling techniques. The first consists of using traditional mills, which extract around two-thirds of the oil that is theoretically possible to obtain. These traditional mills, which present morphological variants, develop pressures between 1 and 5 kilograms per cubic centimeter, with an output of between 20 and 25 kilograms. The second threshold corresponds to the complete extraction of the oil using modern mills. These mills are hydraulic presses that develop, on average, 50 kilograms per cubic centimeter of pressure, with an output of around 30 kilograms. This output represents the upper limit of the quantity of oil contained in the fruit (around 25 percent of the weight).

As shown in figure 13.1, when one considers the pressures and the output of the traditional and modern mills, the group of traditional mills is far from showing a linear trend between zero and the group of modern mills. The passage from the first threshold to the second follows a logarithmic function. Hence, the general law proposed by Creswell is that technological evolution proceeds according to thresholds, not only by incremental

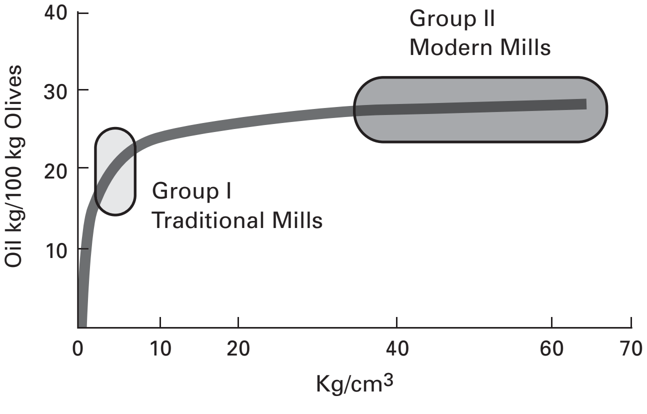

Figure 13.1
Jump from traditional to modern mills (after Creswell 1996).

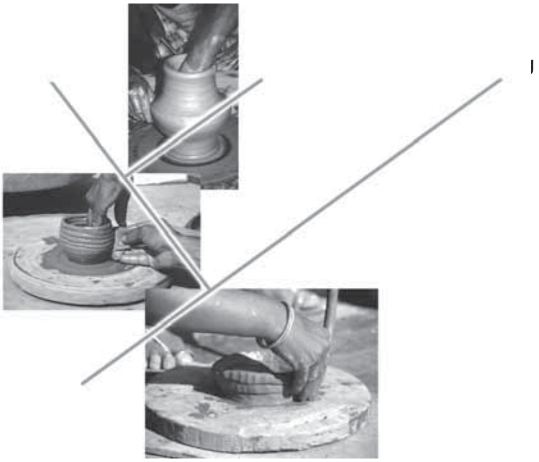

Figure 13.2
Historical development of pottery-fashioning techniques.

additions. By definition, each threshold corresponds to an invention, here called "discontinuous," which is characterized by the introduction of new physical principles in the technological process, that is, new principles of propulsion, and is limited in number, corresponding not to infinite recombinations of preexisting elements but to new starting points in the evolution of objects reaching the end of their evolution (Deforge 1989). Each threshold or discontinuous invention gives rise to new lineages of objects characterized by new physical principles. These new lineages coexist, at least for a while, with the ancestral lineages.

It follows that the diagrams obtained when searching to represent, for example, the evolution of ceramic-vessel lineages produced from the fifth through first millennia B.C. in the Southern Levant, are cladogenetic (see chapter 1, this volume), as shown in figure 13.2. There, each new fashioning technique gives rise to a new lineage alongside the ancestral one. Each corresponds to new physical principles: The wheel-coiling technique is characterized by the use of RKE (the new trait) for transforming clay walls made from assembled elements (the ancestral trait), and the wheel-throwing technique is characterized by the use of RKE (the ancestral trait) to transform a clay mass (the new trait) into a vessel.

Passage to the wheel-coiling technique is a first jump when assessed in terms of source of energy. The clay walls are now deformed under the combined energy of finger-to-palm pressures and RKE. RKE requires the wheel to revolve around an axis with a sufficient kinetic energy to resist the strength of the pressures. It has to reach a speed of around 80 revolutions per minute. The manufacturing time is divided by half. The jump is even larger for the passage to the wheel-throwing technique. The quantity of required kinetic energy

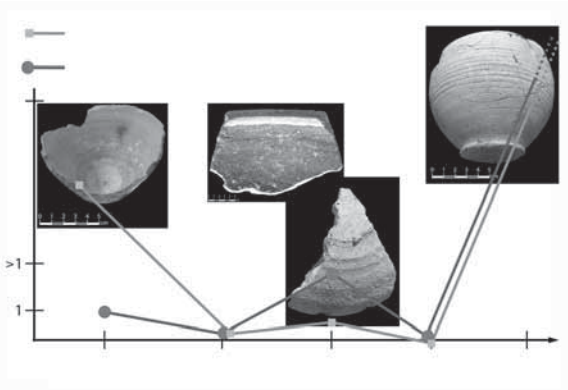

Figure 13.3
The developmental trajectory of the wheel-coiling technique in the Southern Levant, from the fifth to the second millennia B.C. EB = Early Bronze; MB = Middle Bronze.

for transforming a mass of clay into a vessel is much higher in order to resist the strength of the pressures on the clay mass. The wheel has to reach a speed of 150 revolutions per minute. The manufacturing time is divided by 20.

When considering the lineage of wheel-coiled vessels in the Southern Levant, techno-stylistic variants are observed. Different fashioning methods were invented, and new morphological types were wheel coiled in the course of centuries. The different fashioning methods correspond to modifications of the stage at which RKE was used (preforms or roughouts [Roux and Courty 1998]). In other words, they correspond to gradual variations following the same physical principle—the use of RKE on assembled elements (figure 13.3). Methods can be plotted linearly when one is considering strength of pressures and manufacturing time. Thus, there is no jump between these methods. They represent continuous inventions on the basis of the threshold introduced by the wheel-coiling technique. The spatial extension of continuous variants most often indicates frontiers between social groups—the groups where they developed (e.g., Gallay 2007; Lemonnier 1993; Stark 1998; Stark et al. 2008).

To sum up, empirical data suggest that technological evolution is made up of both continuous and discontinuous innovations—inventions by small-scale cumulative modifications not excluding radical jumps from time to time. The tempo of discontinuous innovations can be quite rapid. In the case of the wheel-coiling technique in the Southern Levant, this new technical feature is clearly identified in strata of numerous sites dating from the second half of the fifth millennium B.C., whereas the use of RKE for smoothing the surface of clay walls appears for the first time on a few vessels belonging to sites dating from the first half of the fifth millennium B.C. (Roux et al. n.d.).

Cognitive Activity and Inventions

I now consider the cognitive activity involved in discontinuous inventions in order to examine the possible role of the individual in technological evolution. The hypothesis is that the individual and his or her cognitive activity could act as a random factor in an evolution that otherwise follows, at a macroscale, a necessary order of development.

Following the ecological approach, coupled with referencing studies on the learning process of complex skills (e.g., Bril 2002; Gibson 1977; Reed 1988), invention can be considered as the result of an exploratory activity in the body–matter–energy system and the discovery, in the course of action, of the possibilities offered by the environment. Thus, invention of the wheel-coiling technique has been interpreted as the result of a dynamic interaction among the task (discovery of the use of RKE for making bowls), the body (discovery of the skills for forming a bowl with RKE), and the instrument (discovery of the properties of the wheel for producing RKE; Roux 2003).

As for the skills involved in discontinuous craft inventions, such as the ones involved in wheel fashioning, they can be viewed as phenomena that break with tradition. Indeed, recall that the difficulty in learning skills involved in any craft lies mainly in mastering the technique itself (physical modalities according to which raw material is processed), which implies controlling elementary movements, which vary depending on the finished products (Roux and David 2005). Learning and developing new elementary movements will imply a different tuning of the previously learned elementary movements. This will require rehearsal thousands of times (Bril et al. 2005).

From this point of view, the emergence of new techniques, characterizing discontinuous inventions, signals the presence of individuals who modified their elementary movements and developed new skills apart from those they learned previously. Thus, the wheel-coiling technique signals new skills different from the ones involved in the coiling technique; the wheel-throwing technique signals skills different from the ones involved in the wheel-coiling technique (Gelbert 1997; Roux and Corbetta 1990). Years of apprenticeship separate these techniques.

Stoneknapping is another discontinuous innovation that signals the development of new skills radically different from the ones involved in cracking open nuts—the possible ancestral lineage from which stoneknapping evolved—even though both tasks correspond to thrown percussion. They require, in particular, a level of movement tuning for controlling the conchoidal fracture (Pelegrin 2005; Roche 2005). These movements combine precision and force and are exerted according to a fine bimanual coordination. No ape or monkey seems to achieve such a combination (see chapter 3, this volume). They reveal capacities that are uniquely hominin (Roux and Bril 2005).

Who, then, were the inventors who were able to break with tradition and develop new skills? The learning process itself is carried out according to a model (the way of doing by a group for the purpose of obtaining a given finished product), which is the transmitter's way of doing something (Bril and Roux 2002). In this respect, there never is invention while one learns motor skills. At the end of the apprenticeship, skills necessary for reproducing the tradition, and only these skills, are literally “embedded.” The skills then participate directly in the maintenance of the tradition, in the sense that it becomes difficult for subjects to conceive of making things in other ways, given the cognitive and motor skills they have developed, which act as “fixers” of worldviews (Roux 2007).

However, recall that subjects can develop different levels of expertise (Bril et al. 2005). The expert is one who, when confronted with the constraints of the task, is able to achieve the technological process through a constant dynamic fit between the state of the object and the next step. In other words, the expert has an extensive capacity to detect the appropriate information resulting from the ongoing course of action coupled with the ability to incorporate the new information into his or her actions.

Moreover, expertise does not consist only of tuning as well as possible the properties of the system (the task–environment–organism system). The expert also is one who is able to force the system in one direction or another to adjust to new features (Bril et al. 2005). These new features can be “emergent performance problems” (see chapters 1 and 14, this volume), new situations (e.g., new raw material), or “disturbances” in the system (e.g., flaws in the material).

We would expect to find the invention process among experts who are most familiar with the task’s constraints (Ericsson and Lehman 1996), that is, experts who are able to explore body–material–energy properties, in this case going beyond the cultural representations that have formed their way of seeing and doing. These individuals are exceptional as much for their skills as for their rarity, as anthropological studies have shown.

In India, inventions in pyrotechnology I saw were made by the most skillful craftsmen, attested as such by their products and reputation. This could explain why, all other things being equal, some techniques appeared in certain areas of the world and not in others. Such is the case of the wheel-fashioning technique, which was never invented either in America or in sub-Saharan Africa, despite the knowledge of the rotary movement for finishing operations. I suggest that in these areas no individual developed the cognitive activity that led to the discovery and the mastery of RKE for transforming clay volumes—hence the hypothesis that individuals and their cognitive activities might be a random factor in the evolution of techniques. This random factor also could well explain phenomena of technological convergences.

The Dynamic of Discontinuous Technological Innovations

The question raised now is how technological innovation occurs—how an invention made at an individual scale becomes an innovation at a collective scale. It is the temporal course of these two interacting variables—the individual and the collective—that gives the technological system its faculty to adapt and bring about technological change (Roux 2003). More precisely, the phenomenon of innovation is the result of a dynamic process emerging from complex interactions among its constitutive components: (1) the technical task, here defined in terms of *chaînes opératoires* (e.g., Lemonnier 1993; Sellet 1993); (2) the environment, which provides the materials used in the technical task; and (3) the subject, who carries out the technical task and whose intention(s) are rooted in the group's sociocultural representations.

Properties of these various components possess constraints (whether physical–chemical, biomechanical, environmental, or cultural). Innovations play on these constraints and are initiated according to terms dependent on political, economic, social, and/or religious situations in which the demand for new objects plays a part. From this point of view, innovations invariably refer to particular historical scenarios. These scenarios, even though particular, should enable us to examine Creswell's general hypothesis that jumps in technological evolution are determined by social mutations. And they should also allow us to assess relationships between historical scenarios and their conditions of actualization, defined here as the context of craft production.

Discontinuous Innovations and Social Factors

As an example of a historical scenario, consider the emergence of the wheel-coiling technique. In the Southern Levant, wheel coiling appeared during the second half of the fifth millennium B.C., during the period called "late Chalcolithic," among farmer–pastoralist cultures whose material culture is especially remarkable for its innovations (in particular, new ceramic and metallurgic techniques). Throughout this period of about 300 years, wheel coiling was used for only a single morpho-functional category—small, open vessels with rectilinear walls, called "V-shaped bowls." These bowls are found as much on settlement sites as in sanctuaries or in mortuary contexts, where they are found systematically in primary and secondary tombs. A detailed study of the wheel-coiled bowls found on the site of Abu Hamid (Dollfus and Kafafi 1988), in the middle Jordan Valley, suggests that these bowls had a ceremonial function (Roux 2003).

The innovation of wheel coiling has been interpreted as having emerged from a complex interaction among an invention made on an individual scale, a favorable geological environment, and a demand at a collective level for objects of ceremonial value—a demand initiated by politico-religious changes and marked in particular by the emergence of chiefdoms (Levy and Holl 1988). Such a demand has been interpreted as emanating from an elite, given the function of the objects and the politico-religious context. In other words, in the Southern Levant the innovation of wheel coiling appears rooted in a demand initiated by an elite at a period when new sociopolitical structures were emerging.

This scenario has numerous analogues in various chrono-cultural periods in the sense that the main technical inventions known from the preindustrial era apply to objects that are related most often to an elite context. For example, the emergence of iron- and steel-related activities in the north of the Parisian Basin during the second Iron Age (fifth century B.C.), as with the wheel-coiling technique, appears as rooted in a demand initiated by an elite, as shown by Bauvais (2008), who argues that the first iron objects were mainly prestige goods placed in tombs (ornaments, armaments, cart wheels) at sites containing elite residences and made sporadically by itinerant blacksmiths responding to the demands of the elite.

Another example can be seen in the domain of agriculture, with the "traction complex"—yoke, plow, travois, and cart—which appeared in western European Neolithic cultures during the third millennium B.C. This innovation had a decisive economic impact, as it allowed a growing population to be better managed through increased productivity. At first, this innovation may have been the monopoly of only a part of the population, which seems to have used it to further strategies for control of political power. This hypothesis is based on the incorporation of the traction complex in symbolic rock art, which shows that the plow and wheel were first ideological and social phenomena related to the elites before being incorporated as common tools into a society's economic structure (Gallay 2006).

A similar phenomenon has been observed among peasants of historical periods (from the Middle Ages to modern times), known throughout history for their resistance to innovation. It appears that innovations were always made by elites, who then transmitted them to the peasantry (Mendras 1984). The elite were open to experimentation, and only they had enough economic margin to face the risk every trial entails (Mendras 1984).

These different historical scenarios suggest that (1) in traditional societies, discontinuous innovations are initiated by individuals having some form of power—religious, political, and/or financial; and (2) these innovations are actualized not for their techno-economic advantages but for symbolic and/or social reasons. This argues in favor of Creswell's (1996) hypothesis that continuous transformations in techniques can be more or less autonomous as part of an evolution, whereas discontinuous changes follow changes in society.

The concept of "change" is controversial, given that social groups are always changing. In Creswell's view, social mutations at the origin of innovations correspond to those moments where there are close interactions between society and techniques. Close interactions can also be at the origin of absence of change and preservation of traditional features (see chapter 10, this volume). In both cases, these interactions determine to a large extent the mode of evolution of technological systems. Thus, the emergence of discontinuous innovations supposes both elites originating new demands to meet social or symbolic needs and social components able to actualize the new demand. Such a mechanism can be explained by cognitive constraints weighing on traditional cultures, favoring cultural preservation.

Periods of close interaction can alternate with periods of looser interaction. Creswell (1994) talks about the cyclical nature of relations between technique and social processes.

In archaeology, the rate and nature of innovations testify to such a cycle. Indeed, some historical periods are characterized by numerous technological discontinuous innovations, such as the late Chalcolithic societies in the Southern Levant, whereas others are characterized mainly by continuous innovations, such as the Early Bronze I (fourth millennium B.C.) in the Southern Levant. Given the importance of the demands of the elite in the innovation process, the alternation between these periods could well be explained in sociopolitical terms.

The Spread of Discontinuous Innovations

It sometimes can take a few millennia for discontinuous innovations to become predominant. This is the case of the wheel-fashioning technique in the Southern Levant (Roux 2008). As we shall see, the rhythm of fixation of discontinuous techniques can be explained by the transmission context, the properties of which are determined by the environment of production, that is, the conditions for actualizing inventions.

In the Southern Levant, the wheel-fashioning technique was invented during the Chalcolithic period for the manufacture of ceremonial bowls. The Chalcolithic cultures collapsed in Early Bronze I (fourth millennium B.C.), and 75 percent of the settlements disappeared. The ceramic-material culture became characterized by strong regionalism and the appearance of new techno-stylistic traits (Miroschedji 1989). As for wheel coiling, it practically disappeared from the Southern Levant. In Early Bronze IB, the rotary instrument was present, but contrary to the previous periods, RKE was used only for finishing operations, not for thinning or shaping clay walls (Charloux 2002, 2006). Wheel coiling was again present in Early Bronze II and III.

The latter period, dating from the first half of the third millennium B.C., is marked by the presence of fortified cities with monumental construction. At Tel Yarmouth, a fortified town about 30 kilometers southwest of Jerusalem and principal site of the southern region of Southern Levant, two basalt tournettes have been found in the palace enclosure (Miroschedji 2000a, 2000b). Contrary to expectations, only 3 percent of ceramic objects were made with RKE, suggesting that few craftsmen used the tournettes. This low number of craftsmen persisted steadily throughout the period of the Early Bronze III, covering about 500 years. There was no borrowing of the wheel-fashioning technique, which would have helped to raise the proportion of vessels formed on the wheel (Roux n.d.). In Early Bronze IV (end of the third millennium B.C.)—a period of dramatic historical changes marked by the collapse of cities—wheel coiling disappeared again. The technique reappeared during the second millennium B.C., becoming predominant in the middle of the period (Middle Bronze Age II).

Thus, it took three millennia for the wheel-coiling technique to become widely adopted. It disappeared twice, once after the Chalcolithic period and once after Early Bronze III. This developmental trajectory and its nonlinearity can be explained by examining the craft-transmission context, which can be inferred from the context of production. For the

Chalcolithic period, a techno-petrographic study carried out on the scale of the Southern Levant showed that the craftsmen who formed bowls on the wheel were small in number, itinerant, and attached to an elite (Roux and Courty 2005). Wheel coiling was handed down within a restricted circle of craftsmen whose status was distinct from the other, more numerous potters at various sites in the region and who were responsible for the utilitarian pottery. In Early Bronze III, wheel coiling seems to again have been the prerogative of an elite—exclusive to some specialized craftsmen who, given the presence of tournettes in the palace, must have been attached to it.

In summary, craftsmen who used wheel coiling in the fifth and third millennia B.C. were a few specialist craftsmen who were attached to an elite and who reserved the technique for making objects for this elite. Most production did not benefit from the innovation, which resulted in a technological system characterized as fragile and closed and explains why wheel coiling disappeared twice and was so slow to develop.

Fragile versus Robust Systems

The fragility of a technological system can be defined according to the size of the network by which it is transmitted. If the network is too limited, the system is fragile and cannot resist strong historical events such as those that transform a society's socioeconomic structure. During the fifth and third millennia B.C., potters using wheel coiling were few in number. Consequently, the transmission network was limited in size, and when confronted with the various historic upheavals that ended the Chalcolithic and Early Bronze Age cultures, the network was broken and the technique disappeared.

In contrast, robust systems are characterized by transmission networks large enough for the technological feature to have sufficient redundancy to resist historical events (see chapters 7 and 8, this volume). Thus, when wheel coiling became prevalent and was transmitted by a large network, it resisted various events that agitated the Southern Levant throughout history. The importance of a transmission network's size for fixing technical innovations has been underlined by various authors (e.g., Henrich 2001; chapter 7, this volume), including primatologists who have shown that, among the different groups of nonhuman primates, the ones who develop and fix technical skills are those with the highest level of social tolerance between individuals, which ensures transmission networks solid enough to guarantee the skill's survival (van Shaik and Pradhan 2003; chapter 3, this volume).

Closed versus Open Systems

Closed systems make no exchanges with other systems. They are kept closed by a one-to-one relationship between producers and the technological task. This relationship acts as a nonexchange mechanism between the closed system and other systems. The result is an absence of technological-task transfers or borrowings between producers (the ones who make and the ones who might borrow) with noncompatible status and, consequently, rhythms of development that are very slow.

This was the case with wheel coiling during the fifth and third millennia. The technique was in the hands of a small number of specialized craftsmen and was not subject to any transfer (by the potters) or borrowing (by other craftsmen), remaining a fragile technological system for more than two millennia. This was also the case for metallurgy of the lost-wax technique. Invented during the Chalcolithic period exclusively for the fabrication of prestige metal objects—scepters, maces, and crowns (Shalev 1994)—the technique disappeared with the collapse of the Chalcolithic cultures, only to resurface during the second millennium B.C. A recent study by Y. Goren (unpublished) shows that the lost-wax technique must have been in the hands of priests, who worked in secret places and who reserved this technique for objects of a politico-religious nature. The lost-wax technique was invented and made a system in the same way as wheel coiling—innovation tied to an elite's politico-religious needs, one-to-one relationship between status of craftsmen and technical task, and a small transmission network. Its disappearance along with the end of the Chalcolithic politico-religious structure thus was to be expected.

Given the mechanisms explaining their emergence, discontinuous innovations generally are actualized into a closed fragile system—when emerging, they are in the hands of a few individuals aimed at making a restricted range of objects. It follows that, even though they present techno-economic advantages, discontinuous innovations can be subject to nonlinear developmental trajectories and a long fixation process.

Transformation of Fragile Systems into Robust Systems

There are two ways for systems to become robust: Either the closed system transforms itself into an open system, or the closed system develops at the expense of the technical tasks used by open systems on the same objects. As opposed to closed systems, open systems exchange on both the object level and the task level and therefore are not restricted in their development.

Transformation of Closed into Open Systems

Transformation of closed systems into open systems supposes that those involved in the innovations make a point of integrating them into usage by the majority. Changes in peasant societies are an excellent illustration of this mechanism (Mendras 1984). In these societies agricultural innovations were promoted by the elite (who were landowners and farmers), many of whom took interest in the progress of their estates and had far-reaching contacts that enabled them to introduce novelties into their region. The process of integrating innovations into the existing system generally included a test phase, a phase of proof of the experiment's success repeated year after year, and finally a phase of integration into common experience, which would then be transmitted from one generation to the next.

This progressive integration by the elite into common practice could be the mechanism by which, for instance, ceramic craft used at first in closed systems (e.g., in the Greek Neolithic [Vitelli 1989]) subsequently was used in open systems.

Expansion of Closed Systems

For closed systems to develop, innovative technical practices have to be applied to a wide range of objects used by the majority. In the Southern Levant, ceramic production made with RKE increased during the Middle Bronze Age II, along with expansion of the Canaanite cities and, probably, development of a market economy. Workshops using the wheel-coiling technique and making a large array of vessels progressively expanded, to the detriment of domestic production, which was then restricted to the making of cooking pots (Maeir and Yellin 2007).

More generally, from the recent periods forward, I suggest that all discontinuous innovations requiring lengthy apprenticeship tended to emerge, develop, and expand in closed systems. In multiple techno-economic-task societies, innovations characterized by a long learning period can expand within closed systems only as a result of the biobehavioral inability of individuals in the same sex or age grade to master a large number of tasks requiring several years to be learned. One of the immediate consequences of bringing innovations to technical tasks characterized by long learning times would be an escalation in the number of tasks carried out in closed systems and eventually, given their techno-economic advantages, their development in place of the open-system tasks, which were generally distributed among individuals belonging to different grades.

Conclusion

Technological evolution appears to be the result of both continuous and discontinuous innovations. The latter allow social groups to jump from one stage to another and to go beyond previous technological limits. They occur when there is a strong interdependency between techniques and societies. In this regard, the rate of discontinuous innovations cannot be reduced to the sole question of both a population's size and its degree of cultural interconnectedness. Organization of societies is another important social factor that appears determinant, notwithstanding the role of the individual, which can act as a random factor. In ancient times, it appears that technical innovations met needs that at first were not economic but rather social or symbolic as suggested by authors such as Cauvin (1994). They emerged in fragile, closed technological systems and developed slowly, according to nonlinear trajectories. They were fixed through their development into a robust system, whether closed or open. I suggest that in farmer–pastoralist cultures, when length of learning times imposed restrictions, new technical tasks developed in closed systems instead of open systems, thereby directly contributing to societies' growing complexity.

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14 Can Archaeologists Study Processes of Invention?

Michael Brian Schiffer

The archaeological record has long served as the sole source of evidence on the invention of many technologies. Thus, when studying a technology that originated in a prehistoric context, such as pottery making or copper metallurgy, researchers have taken note of its earliest appearance and charted its subsequent occurrences over time and space. The cumulative findings of two centuries of research have made it possible to answer the *when* and *where* questions about the invention of a great many prehistoric technologies. This is a significant accomplishment that has immeasurably enriched our understanding of the human past.

Having worked out the broad time–space parameters of numerous technologies, archaeologists are now apparently poised to elucidate the actual processes of invention—that is, answering the *how* and *why* questions about the behavioral origins of material variation. However, I argue here the counterintuitive position that the archaeological record seldom furnishes fine-grained, robust evidence on specific invention *processes*. Even so, because archaeologists are not tethered to the archaeological record, we can turn to other research strategies and other lines of evidence to help create invention models. This chapter develops that argument by (1) situating invention within the overarching context of technological change; (2) assessing the archaeological visibility of the major technological processes—invention, development, replication, and adoption; and (3) furnishing examples of invention models that have arisen in an expanded ethnoarchaeology, a research strategy that uses historical evidence.

On Technological Change

Technological change is defined here as changes in the kinds and quantities of artifacts made and used by people in a particular society or in a designated area (such as a region). This behavioral definition seemingly translates directly into archaeological-context terms: temporal change in artifact types and frequencies. However, it's not that simple. Archaeological observations document the end product of the operation of varied cultural and environmental formation processes, including reuse, reclamation, and deterioration (Schiffer 1987). As a result, evidence of technological change potentially can be conflated with traces of other processes.

In order to ameliorate these effects and to orient studies of invention processes, I recommend that we make three methodological moves. First, search for those archaeological deposits that might retain high-resolution evidence of inventive activities as in the primary refuse of highly mobile peoples (D. J. Seymour, pers. comm., 2007). Second, develop models by employing research strategies such as ethnoarchaeology, computer simulation, experimental archaeology, modern material-culture studies, and historical research. In these research contexts, the confounding effects of many formation processes are lessened. Third, formulate research questions in behavioral—not archaeological-context—terms. Thus, technological change is framed as *behavioral* change—alteration in activities. The focus becomes the activities that took place during the life history of a *kind* of artifact or a *kind* of technology, old or new (hereafter, I use "artifact" and "technology" interchangeably).

Life histories are segmented (for present purposes) into four major processes: invention, development, replication, and adoption. Each process—actually, a family of more specific processes—consists of activities, which, in turn, are composed of varied interactions among people, artifacts, and externs (the latter are unmodified phenomena of the natural environment). There are various kinds of interactions, including mechanical, thermal, chemical, and electromagnetic, and many interactions also involve human senses such as sight, sound, taste, and touch (Schiffer and Miller 1999). Interactions are enabled by performance characteristics, which are an artifact's activity- and interaction-specific behavioral capabilities. Thus, a cooking pot must possess sufficient thermal-shock resistance to survive repeated heating and cooling during activities of food preparation, and a flag must possess a particular color pattern to be visually identifiable in display activities as the symbol of a particular nation. In short, performance characteristics determine a technology's ability to carry out its utilitarian and symbolic functions in a given activity (LaMotta and Schiffer 2001; Schiffer 2000, 2005a, 2005b; Schiffer and Miller 1999; Skibo and Schiffer 2008; Walker et al. 1995).

The dominant global pattern of technological change over time, as inferred from the archaeological record, is that of increasing formal variation—more kinds of things. We tend to attribute this pattern to invention processes. Although invention is the source of new variants, the other major processes generally have the effect of *reducing* variation. That is, only some inventions are developed; only some developed inventions are replicated; and only some replicated inventions are adopted. Thus, the increase in artifact variation over time is, finally, the result of several technological processes taking place in the past, of which invention is but one.

In the life history of any technology, these processes can occur coevally and iteratively. Indeed, the models presented below make clear that inventive activities often arise during development, replication, and even adoption. However, whenever and wherever invention occurs, the products are subject to selection. Notwithstanding this behavioral complexity, I retain the simple linear model to make the presentation manageable.

Invention

Invention is the creation of an idea or vision for a technology having performance characteristics that differ from those of other technologies present in that society or area. The idea may be little more than the minor modification of an existing artifact, or it may be a vision breathtaking in its audacity, and it may be entirely original or be inspired by an import or by a technology seen somewhere else. Inventions are often materialized as prototypes, as models, or as descriptions and drawings. Invention produces the variants selected by development processes. (New variants that arise by accident and through errors in replication are also subject to selection, but handling these sources of invention is beyond the scope of this chapter.)

Development

Development involves problem solving, usually through trial-and-error experiments. People strive to refine the design of a selected technology so that it can meet the specific performance requirements—utilitarian, symbolic, or both—of an anticipated activity or activities (Schiffer and Skibo 1997; Skibo and Schiffer 2001, 2008; chapter 12, this volume). This entails spanning a "developmental distance" between a prototype (or model) and a technology that can competently perform a specific function or functions (Schiffer 2005b, 2008b). Traversing a developmental distance requires resources such as time, money, organization, labor, skill, tacit knowledge, raw materials, tools, facilities, and structures. In complex societies, a technology's proponents (e.g., inventors, entrepreneurs, engineers) may draw on family wealth and income, loans and gifts, government grants and contracts, and stock sales for securing resources such as labor and materials (see chapters 7 and 12, this volume). However, creating tacit knowledge and skill requires experience and, thus, time, and forming an organization requires a suitable societal framework, including permissive laws. These necessities cannot always be bought.

In small-scale societies, opportunities to obtain resources for covering a great developmental distance are far more limited and may require the participation, over long periods, of many local groups in a region. I have proposed elsewhere that this process, which might be termed "distributed development," appears to have enabled the transition from pit-house to pueblo dwellings in the prehistoric American Southwest (Schiffer 2005b; see also Schiffer 1992). During the century or so that this development process transpired, people in local groups—each perhaps consisting of a half dozen households—invented and tried out different kinds of dwelling and storage facilities, gradually acquiring knowledge about the performance characteristics of each variant throughout the activities of its life history. These performance characteristics—some learned rapidly, like ease of manufacture, and others learned after many years, like ease of maintenance—became common knowledge throughout the region.

Such information transmission was facilitated by, for example, exchange networks, exogamy, and religious sodalities. Eventually, the pueblo—masonry and adobe—was judged to have the most favorable mix of performance characteristics in the context of increasing dependence on agriculture, growing populations, and reduced residential mobility, and so it was selected by most groups when they built new structures. It is doubtful that any one local group could have mustered *in a very brief time period* the resources required for trying out a variety of new structures and ascertaining their performance characteristics in all relevant life-history activities.

In societies large and small, a short developmental distance can often be traversed by tinkering with an established recipe (Schiffer and Skibo 1987; chapter 11, this volume). Thus, an experienced potter can turn his or her skills toward making a larger vessel of an extant form–function type with minimal resource needs beyond time to practice. In contrast, building a canal-irrigation system in a society solely dependent on dry farming requires new tools and materials, much time and labor, and, significantly, new organizations for coordinating labor, maintaining the system, setting water policy, and resolving disputes. The functioning of the irrigation system may also necessitate new rituals, perhaps involving new artifacts, and activity-maintaining ideologies (see chapter 15, this volume). In the course of spanning a great developmental distance, trial and error leads to the accrual of new techno-science, socioscience, and ideo-science (Schiffer 1992), as people learn through experience what works and what doesn't in specific activity contexts. Development produces the variants selected by replication processes.

Replication

A technology ostensibly meeting its performance requirements may then be readied for *replication*. Replication of some technologies in large-scale societies often requires the creation of new manufacturing processes, new tools, new skills, and new organizations. In other cases, as in small-scale societies, replication may be easily handled by the people and organizations that already possess the appropriate skills, tools, and materials. Success at replication results in the reproduction, distribution, and marketing or exchange of the new technology, thereby producing the variants that are selected by adoption processes.

Adoption

In the *adoption* process, consumers have the opportunity to acquire and (usually) use the new technology. Consumers may be individuals or groups, including households and communities, churches and companies, and polities at every level. In considering whether to acquire a new technology, consumers—the final arbiters of a technology's replicative success (Leonard and Jones 1987)—compare its anticipated performance characteristics to those of any competing technologies and, most important, to the performance requirements of specific activities, ongoing or anticipated (see chapters 7 and 12, this volume). Technologies, it should be noted, are commonly adopted differentially by a society's individuals and groups, which may have varying performance requirements (Schiffer 2000, 2005a). Adoption decisions can be studied by means of a performance matrix, which displays, side by side, the performance characteristics of competing technologies in relation to activities (Schiffer 2000, 2005a).

Segmenting Life Histories

In some projects, I collapse development and replication into commercialization (Schiffer 1996, 2000, 2001, 2008b), whereas in other projects I subdivide commercialization into a half dozen or so very specific processes (Schiffer 2005b, 2008b). In view of this flexibility in segmenting life histories, the question is, how many processes should one identify before proceeding with a project? Obviously, this depends on the researcher's interests and priorities, and the answer may not be evident at the outset. However, a good rule of thumb is that the number of processes should mirror the number of consequential social groups participating in that technology's life history. Thus, we identify the general groups of decision makers who, acting as agents of selection, determine whether a technology's life history will continue (Schiffer 2008b).

Even in small-scale societies in which craft skills are widely shared in gender- and age-defined groups, different process-related groups decide whether to replicate and adopt an invention. For example, let's assume that a potter comes up with an entirely novel method of decorating serving vessels. Producer groups—the other potters in that society—can choose whether to replicate the new decoration on their own pots. Moreover, user groups, which include members of households and corporate groups, may decide to adopt the new pots, depending on whether the decoration's visual performance is expected to enable the vessels to carry out their symbolic functions during everyday meals, in religious rituals, and in feasting activities as well as or better than existing decorations. Obviously, inventor, producer, and user groups may have overlapping memberships, but the decisions are group and process contingent. Even in small-scale societies, collapsing technological change into just two processes, such as "invention and adoption" or "invention and innovation," is apt to be profoundly misleading.

Archaeological Visibility of Technological Processes

Although invention, development, replication, and adoption all contribute to technological change, these processes, I suggest, are represented unequally in the archaeological record. One might be tempted to propose that invention should be highly visible. After all, an invention process took place, somewhere, at the beginning of every adopted technology's life history, perhaps leading to a plethora of variants. However, the vast majority of inventions, *as one-of-a-kind items selected against*, are apt to leave only subtle archaeological traces, especially if their materials are immediately reused.

However, some unreplicated variants may be identifiable in well-known regions—for example, those having very large artifact samples from many excavated sites—as the unique or rare artifacts, including structures and other features, that fall outside existing typologies (Schiffer 2005b). It is possible that some of the uncommon artifacts over which we traditionally dote, and which have high newsworthiness, may be nothing more than singular creations—artisans giving free reign to their imaginations—that were never developed or replicated. Unique items, I hasten to add, can also be produced, for example, by children (Bagwell 2002; Crown 2002), other novices, and artists. In any event, we should pay close attention to unique and rare artifacts in well-known regions because some of these items may be attributable to invention processes. Although investigating invention processes in prehistory is likely to be difficult, any study's feasibility has to be assessed on a case-by-case basis.

Development processes may be somewhat better represented in the archaeological record than invention. As in the study of invention, the key to identifying the traces of development is to search well-known regions for unique artifacts, features, and structures. In addition, one might find traces of developed products that were not replicated, perhaps in work areas or workshops that retain primary refuse or in secondary refuse areas that resulted from simple and short waste streams (Schiffer 1987).

Once replication begins, we often find unambiguous traces of manufacturing processes in the form of waste products, rejects, raw materials, tools, and facilities. In general, replication ought to be represented far more consistently in the archaeological record than invention or development.

Adoption is the one process that consistently stands proud in the archaeological record. With the exception of poorly preserved artifacts, and those that were rare in the past, the adoption process of any technology is likely to yield many archaeological examples. After all, almost every artifact showing traces of use is evidence that that artifact type had been adopted.

Many previous studies of technological change have been flawed because researchers conflated the major processes. Typically, investigators assume that the archaeological record faithfully reflects invention, whereas they are dealing almost exclusively with adopted technologies, the final product of sequential selection processes. As a consequence, archaeologists, especially those employing diffusion theory, erroneously explain technological change exclusively in terms of invention and innovation, that is, the origin and spread of ideas. It is preferable to keep the major processes conceptually distinct and to handle each one by process-specific models, theories, laws, and heuristic tools (Schiffer et al. 2001). However, a number of critical variables, such as performance characteristics and performance requirements, may occur in models pertaining to different processes.

The following section presents examples of the kinds of models that archaeologists can build by employing an “expanded ethnoarchaeology” (Schiffer 2008a), a strategy using historical evidence. The long-term goal of these efforts is to create models that specify the general conditions and factors fostering inventive activities. By furnishing such expectations, these models can inform the study of technological change in archaeological cases. Moreover, when joined with information about formation processes, the models can furnish guidance about the kinds of deposits likely to preserve evidence of inventive activities (D. J. Seymour, pers. comm., 2007). (Promising invention models that have arisen in other disciplines, from psychology to economics, might be evaluated in an expanded ethnoarchaeology.)

Models of Invention Processes

I have found it productive to fashion models that explain bursts of inventiveness—the activities that yield a set of related inventions clustered in time and often in space. Thus, each of the following models denotes a kind of invention process that gives rise to spurts of inventive activities and is defined on the basis of specific boundary conditions—that is, it occurs in a particular “behavioral context” (LaMotta and Schiffer 2001).

Stimulated Variation

A very general model is that of “stimulated variation,” which specifies that selective pressures emanating from two selective contexts, immediate and extended, can give rise to bursts of invention (Schiffer 1996). The *immediate* selective context is the entire sequence of processes that take place during an already *adopted* artifact type’s life history, such as procurement of raw materials, manufacture, transport, distribution, storage, use, maintenance, reuse, and disposal. Any change in these activities can create selective pressures for invention. The *extended* selective context includes activities, agents, and mechanisms that are coupled by flows of energy, artifacts, or people to activities of the immediate selective context (Schiffer 1992).

Stimulated variation is set in motion when changes in selective contexts affect an adopted technology’s performance in one or more life-history activities. Indeed, a burst of inventiveness is likely to occur when potential inventors judge that the technology’s performance characteristics fall short of meeting an activity’s performance requirements. Often, these kinds of deficiencies are framed as problems to be solved or, on occasion, as opportunities to be pursued.

An example comes from the first era of radio, known as “wireless.” As wireless communication technologies—transmitters, receivers, and the like—began to enjoy adoptions for maritime and military activities during the first decade of the twentieth century, users learned that interference from other transmitters broadcasting simultaneously confounded point-to-point communication. Thus, the need for precise tuning of transmitters and receivers was identified as a pressing problem and stimulated a variety of inventions (Aitken 1976). The proximate cause of this burst of inventiveness was pressures in the immediate selective context—the unreliable performance of wireless apparatuses during use. In turn, these performance deficiencies arose because of the increasing adoption of wireless technologies manufactured by many companies in many nations, whose signals increasingly interfered with each other (extended selective context).

Stimulated variation created a spate of inventions for overcoming interference; some of these were developed and replicated, and a few were widely adopted. In other cases, however, every invention generated by stimulated variation is judged to be ineffective, and so other behavioral changes may be necessitated (Schiffer 1996).

Invention Cascades

The invention-cascades model (Schiffer 2005b), a close relative of stimulated variation, applies to *the development process of a complex technological system* (CTS). The latter is flexibly defined as any technology consisting of a set of artifacts—component parts—whose interactions among themselves and with people (and perhaps with externs) permit that system to function. Examples include irrigation systems, boats, and churches. People in small-scale societies also developed CTSs, such as particular hunting, gathering, food-preparation, and ritual technologies.

The cascade model posits that, during development, emergent performance problems, recognized by people as shortcomings in that technology's constituent interactions, provoke sequential spurts of invention. After each performance problem is solved by invention, people encounter new and often unanticipated problems, which initiate more inventive spurts, and so on. The result is a series of "invention cascades." The model's distinctive feature, which promotes its generality, is the premise that processes in a developing CTS's life history are the immediate contexts in which performance problems emerge and stimulate invention cascades for new component parts. Thus, processes such as fashioning a prototype, manufacture, use, and maintenance are suitable analytical units for investigating invention cascades.

In an analysis of the development of the nineteenth-century electromagnetic telegraph, I discussed the basic processes, which came to include creating the prototype, technological display, demonstrating "practicality," replication, marketing and sales, installation, use/operation, and maintenance. People addressing the performance problems encountered during these processes fomented numerous cascades and invented multiple variants of basic components such as senders, wires, relays, batteries, insulators, lightning protectors, and receiver-printers (Schiffer 2008b).

The cascade model indicates that the invention of prototype electromagnetic telegraphs, which was accomplished by many people in many nations during the 1830s, was merely a starting point in a long sequence of inventive activities. Indeed, the prototype, usually a telegraph that could be exhibited at work in a laboratory or display setting, served merely to attract resources for the development of a full-scale system. Once under way in earnest, the development process itself consisted of incessant inventive spurts that resulted, eventually, in replicable telegraph systems, a few of which were widely adopted.

The cascade model is a potent antidote to diffusionist explanations of technological change. This has been convincingly shown by Arnold (2007) in her rebuttal of a diffusionist explanation for the appearance of the *Tomol*, the oceangoing canoe of the Chumash, a southern California group. In this instructive case, she argues that even if voyagers had arrived in canoes that had been made across the Pacific—a point she does not concede—the Chumash still would have had to invent tools and acquire skills for using local materials to make their own versions of seaworthy canoes. This development process, she maintains, would have taken some time, requiring inventive spurts to solve emergent performance problems (see chapter 15, this volume).

In general, then, the transmission of information about, or examples of, a CTS made elsewhere cannot account for the invention-laden development process with its organization of people and artifacts needed to replicate copies locally (Pacey 1990). I hasten to add that neither the cascade model nor diffusion theory can explain *why* the development process got underway in the first place, *how* its resource needs were met, and *why* it was pursued to a successful conclusion (see chapter 2, this volume). Only by taking into account many contingent factors—for example, the presence of organizations able and willing to furnish resources to initiate and sustain development, and potential consumers' anticipated demand—can the archaeologist craft a deeply contextualized narrative that accounts fully for a CTS's development (Schiffer 2008b). However, the cascade model does specify that as long as development is proceeding, the CTS will be an incubator of inventive spurts giving rise to variants of component parts.

Cultural Imperatives

In a previous work, I defined a cultural imperative as "a product fervently believed by a group—its constituency—to be desirable and inevitable, merely awaiting technological means for its realization" (Schiffer 1993: 99; see also Schiffer 1991). The imagined product is usually visualized in terms of specific performance requirements. Members of the constituency, who may be a tiny minority in a society, seek to fashion their product employing any and all promising technologies that come along, regardless of their source. Sometimes these inventions are developed further, replicated, and adopted.

The shirt-pocket portable radio, which is my favorite example of a cultural imperative, was confined to a small group of mostly young, male electrical enthusiasts, beginning in the first decade of the twentieth century. The vision of a radio receiver small enough to carry around and play in a shirt pocket was perpetuated in hobbyist and electronic trade magazines. This publicity recruited new members to the constituency, alerted members to new technologies that might be exploited, and conferred bragging rights on the makers of the clever one-off radios featured in articles.

As new electrical technologies came along in later years, members of the constituency episodically churned out a flurry of new pocket radios. Thus, when crystal detectors were replicated in the first decade of the twentieth century, hobbyists immediately used them to build tiny radios, sometimes placing them in the cases of old pocket watches. Because these radios needed an antenna and ground connection, they were far from fully portable, and they could not be tuned. With the widespread commercialization of vacuum tubes in the 1920s, "pocket" radios incorporating these new components were far too large to fit into shirt pockets, and thus many inventors resorted to building more sophisticated crystal sets. Although some crystal radios built and commercialized in the 1920s and 1930s had rudimentary tuning, they retained those pesky wires for antenna and ground connections. They were shirt-pocket size but neither self-contained nor fully portable, and so they did not entirely satisfy the cultural imperative.

The first sets that met the performance requirements of a shirt-pocket radio incorporated subminiature vacuum tubes—about 3–4 centimeters long and about 0.5–0.8 centimeters in cross-section. Originally developed by Raytheon for hearing aids, these tubes saw extensive adoptions during World War II for use in military equipment, such as proximity fuses in bombs and in artillery shells. After the war, experimenters and several companies, including Raytheon, invented a plethora of shirt-pocket radios employing subminiature tubes. Raytheon went further, not only developing its own radio but also replicating it through a subsidiary company, Belmont Radio, in late 1945. The Raytheon engineer in charge of this project, Norman Krim, was a member of the shirt-pocket-radio constituency, had been an avid reader of hobbyist magazines during his youth, and became the principal advocate of this invention at Raytheon. The Belmont radio, played only through an "earplug," was entirely self-contained, but one wire to the earplug doubled as the antenna.

With the replication of transistors in the early 1950s, which had vastly better battery economy than vacuum tubes, experimenters created the first solid-state, shirt-pocket radios. In 1954, Texas Instruments invented one that was completely self-contained and had a built-in speaker. It was further developed by an Indiana company (I.D.E.A.) and marketed as the Regency TR-1. Within a few years, American and Japanese companies by the score developed and replicated countless new models, which were eagerly adopted by millions of consumers.

An essential condition of the cultural-imperative model is the presence of a constituency that is perpetuated over time. Equally important, however, is that the constituency be present in a society experiencing many technological changes. Otherwise, members of the constituency would have available few new components, materials, and processes that might be tried out for creating its pet product. In modern industrial societies, a constituency can consist of people and firms that are part of the military–industrial–academic complex, such as those advocating, and profiting from, efforts to invent fusion-power technology, a cultural imperative since the 1950s. Although the cultural-imperative model seems to account for certain inventive activities in industrial nation-states, I believe that it may sometimes apply to small-scale societies undergoing many technological changes, assuming the presence of cultural imperatives.

Component-Stimulated Invention

Component-stimulated invention is the flowering of creativity that sometimes follows the appearance of a new part or component (Schiffer 2008c). In capitalist–industrial societies, people commonly invent devices that employ or are built around a new component, such as the vacuum tube, transistor, laser, and computer microchip. I suspect that the process is more widespread, perhaps also occurring in small-scale societies.

This invention process is typified by the electromagnet (Schiffer 2008c). Beginning in the early 1830s, replication of the modern electromagnet immediately stimulated the invention of telegraphs, magnetos (a kind of generator), and motors. In addition to these celebrated offspring, it begat hundreds of lesser-known inventions prior to the widespread adoption of steam-driven dynamos in the 1870s. Drawing current from batteries, most of these inventions, ranging from fire alarms to musical instruments to facsimile machines, were materialized as prototypes and patented. However, relatively few were developed and replicated in the period 1840–1875. Nonetheless, these obscure inventions represent a noteworthy creative florescence, for the electromagnet was imagined as the core component in countless electromechanical devices.

There are two *idealized* patterns of component-stimulated invention. In the first, the component is conceived as a substitute for another in *extant* devices. For example, in its first decades the transistor was regarded mainly as a substitute for vacuum tubes, and so myriad transistor types were invented that mimicked the performance characteristics of specific vacuum-tube types. This pattern yields new designs of the component for existing applications and, often, redesign of other components with which it interacts. Thus, with the lower voltage requirements of transistors compared to vacuum tubes, some manufacturers took advantage of the opportunity to redesign other components such as resistors, capacitors, and inductors that could be miniaturized.

In the second pattern, the component is visualized as functioning in—indeed, making possible—*new* artifacts and CTSs, sometimes across a broad societal front. The engine of creativity lies in inventors' envisioning connections between a component's unique combination of performance characteristics and potential technologies that might exploit these for carrying out actual or anticipated functions.

People acquainted with the electromagnet, perhaps having seen it operating in the receiver-printer of a telegraph office, would have internalized its most salient performance characteristics. To wit, it (1) produces magnetism of potentially great strength, (2) turns on and off rapidly, (3) is actuated through wires at distances long or short, and (4) creates reliably and repeatedly precise motions of small amplitude through simple mechanisms. By matching these performance characteristics to the requirements of a technology that could solve a *perceived* problem in some realm of activity, an inventor might envision new devices and CTSs.

Although we might wonder which came first, the component or the problem, it is probable that *both sequences occurred*. Some inventors were captivated by the new component and sought applications; others began with a problem that they believed the new component could help solve. What matters most is that inventors, by repeatedly forming a nexus between problems and the component, came up with new technologies. (It should be obvious that this model can be easily generalized to cover inventions stimulated by the replication of a new product or new technology.)

Material-Stimulated Invention

Another potent fillip to invention is the appearance of a new material or material technology, such as chipped stone, pottery, iron, or Bakelite, that potentially can be fashioned into many forms serving many functions. In a case study of bone tools spanning the prehistoric and historic periods in the Northern Plains, Griffitts (2006) demonstrated that contact situations are especially conducive to material-stimulated invention. Indeed, we can be reasonably confident that indigenous artisans would have played with any new materials and processes that came their way, seeking to make artifacts that might meet the performance requirements of ongoing and anticipated activities. Material-stimulated invention should be a widespread process, especially in societies undergoing rapid social and technological changes.

Inventive spurts occasioned by the appearance of a new material ought to follow two idealized patterns. In the first, the new material is envisioned as a replacement for a material used in extant artifacts (Griffitts 2006). We can imagine, for example, that the first people in a society to acquire rudimentary pottery-making skills might have tried to form vessels in the shapes of basket, gourd, and skin containers and perhaps even fashioned zoomorphic forms to mimic carved stone or wooden effigies. Likewise, in the late 1830s, the inventors of electrometallurgy—the process of working metals through electrical deposition—formed varied objects, from medallions to printing plates, that traditionally had been made from other materials or by other processes (Schiffer 2008b).

In the second pattern, artisans dabble in making new kinds of artifacts, perhaps capable of performing new functions (Griffitts 2006). Potters might have tried to create vessels for holding materials that formerly lacked a specialized storage or heating container. By electrodepositing copper—the easiest metal to work electrically—early experimenters copper-plated numerous organic forms whose surfaces had been made conductive, including insects, fruits and vegetables, and lace, exhibiting the technology's promise to produce endless novelty items. They also created recipes for depositing gold and silver, which led to experiments in plating ornate objects made of base metals, altering their visual performance so as to mimic much pricier items (Schiffer 2008b).

In general, we can expect the appearance of a new material or material technology to provoke a burst of inventiveness aimed at making artifacts, old and new. And in societies undergoing rapid growth and change, artisans may have incentives to extend the reach of their technologies toward new applications ("producer pressure" [Schiffer and Skibo 1987; see also Schiffer 2001]). These experiments may be episodic, particularly if the new material technology itself undergoes changes in performance characteristics. In the course of trials, artisans acquire a richer understanding of a new material's performance characteristics in relation to manufacture, maintenance, and anticipated use activities of particular artifacts. The growth of this techno-science lays a foundation for further experiments and inventions.

Peer-Group Competition

By combining elements of Hayden's (1998) "aggrandizer" model with the general notion of "peer-polity interaction" (e.g., Renfrew and Cherry 1986), one can craft a model that identifies widespread conditions—peer-group competition—that might lead to bursts of inventive activities. The model is based on the premise that in societies where peer groups (of individuals, households, neighborhoods, sodalities, churches, corporations, cities, and nation-states) compete among themselves for resources, consumers, territory, political power, prestige, and so forth, inventive activities will take place to supply new technologies to serve emergent utilitarian and symbolic functions (see chapter 15, this volume).

We are all familiar with the institutionalized invention processes found today in the laboratories of corporations making everything from ice cream to nuclear reactors. Incessant competition drives invention as corporations strive to increase market share, come up with "the next big thing," or just generate salable patents.

Competing polities such as towns, cities, and nation-states promote inventions in, for example, roads, canals, ships, harbors, bridges, forts, palaces, public buildings, parks, monuments such as tombs and statues, paintings and murals, highly decorated serving wares, and, of course, armaments. Before any invention is developed, however, officials usually select from among a host of new designs and models proposed by the inventors, whether they be artisans, engineers, or architects. One example is the nineteenth-century competition among major maritime nations, especially between England and France, which led to the invention of new kinds of navigation aids (Schiffer 2005a). In the twentieth century, the missile and space races between the superpowers gave rise to numerous spurts of invention in areas of technology as diverse as nuclear weapons and solid-state electronics.

Clearly, peer competitions can be a very powerful driver of invention, as well as of development, replication, and adoption in societies at all scales.

Conclusion

In view of the scant archaeological visibility of inventive activities, it is tempting to conclude that we are not in a very good position to study them. Perhaps we should concentrate on investigating replication and adoption processes. However, avoiding invention processes would be a mistake, for a comprehensive understanding of technological change requires insights into processes that give rise initially to variation in artifacts. Thus, I maintain that archaeologists do need to build invention models. The examples in this chapter raise hopes that an expanded ethnoarchaeology—as one promising research strategy among many others—may furnish invention models of potential archaeological utility.

I have found it useful to build invention models that identify the factors in specific behavioral contexts that are apt to promote inventive spurts. Such models, along with a sophisticated understanding of formation processes, might enable us to seek and recognize any subtle traces of inventive activities that do survive in the archaeological record. Invention models also encourage us to ask new kinds of questions about the origins of material variation. Answering these questions, I suggest, can promote a better understanding of the hows and whys of technological change, past and present. Perhaps archaeological models can contribute to the discussions of modern technological change taking place across and beyond the academy.

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15 War, Women, and Religion: The Spread of Salado Polychrome in the American Southwest

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An old adage holds that necessity is the mother of invention. This is especially true when it comes to humans seeking to kill, or to keep from being killed by, their fellows. Innovation in, and spread of, military technology can be rapid and often represents a case where evolutionary forces can be directly linked to the generation of cultural variation and changes in behavior and technology. For example, the acceptance of the bow and arrow is tied to warfare (Blitz 1988; Wallace and Doelle 2001). As Blitz (1988: 135) observes, "groups confronted by hostile neighbors armed with the bow would be under significant pressure to adopt it themselves." In such cases, the evolutionary importance of technological change is quite straightforward.

Here we deal with war and technological change, but we focus specifically on its aftermath, when the causes of technological innovation and its acceptance are less obvious. In the late thirteenth and fourteenth centuries A.D., the Salado ceramic tradition spread across the American Southwest. This tradition is unique in that it crosscuts the three general archaeological traditions that have been defined for the region—the Anasazi, the Mogollon, and the Hohokam (see figure 15.1). Crown (1994: 37) notes that this crosscutting reveals "unanticipated convergence in [Southwestern] ceramic manufacturing traditions," but "the Salado polychromes seem to have been added to the longstanding repertoires of southwestern potters, so that potters continued to use their traditional techniques and styles to manufacture other vessel types after the Salado polychromes appeared." In other words, the Salado ceramic tradition linked people in previously distinct cultures but didn't replace these differences. Instead, cultural differences continued, but the Salado demonstrates a shift in social interaction such that distant people were symbolically and politically integrated in a way that they had not been previously (Crown 1994).

The dual nature of the Salado system, which emphasizes integration but maintains regional differences, has puzzled archaeologists, who have variously described the Salado as a tradition, a culture, a ceramic horizon, a phenomenon, a mirage, and an enigma. Archaeologists can't create trait lists separating the Salado from other cultural groups (Nelson and LeBlanc 1986), making it unique in the Southwest, where archaeologists are proud of their ability to identify and trace particular groups for millennia (e.g., Haury

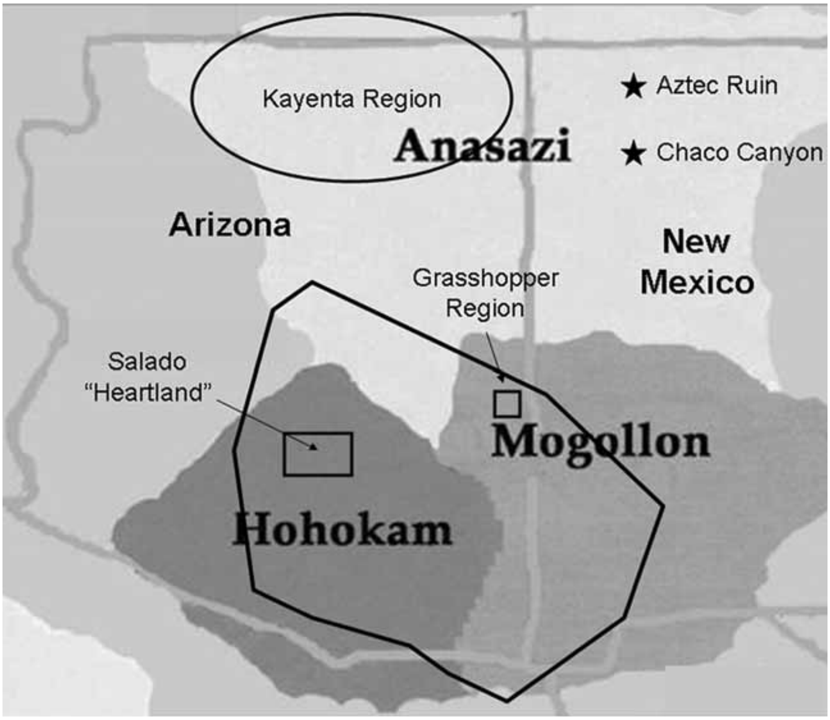

Figure 15.1
The Anasazi and Salado areas of the American Southwest.

1975). Archaeologists can characterize parts of the Salado phenomenon, but we haven't been able to place the pieces into a meaningful, coherent package.

At its core, the Salado is best characterized, and perhaps may *only* be characterized, as a pottery tradition (Dean 2000; Nelson and LeBlanc 1986; Ravesloot and Regan 2000), but the fact that so many people began to make uniformly decorated pottery within a generation demonstrates a significant cultural change in Southwestern groups. Although Crown (1994) presents strong evidence that the Salado wares reflect the spread of a religious system, the impetus and social significance of the pottery and its associated belief system are unclear. Here, then, is an enigmatic case of cultural invention and transmission: Salado pottery developed and spread quickly across 130,000 square kilometers of the Southwest, uniting diverse groups using shared symbolism. What are the cultural processes that led to its development and spread? And what do they tell us about how human cultures evolve?

We propose that the Salado was the result of intense female competition created by the influx of thousands (perhaps tens of thousands) of female war refugees and their children into central and southern Arizona and New Mexico. The extreme female competition resulted in immigrant women's developing and spreading the Salado religion, which emphasized unity and inclusiveness and drew heavily from their previous ceramic technologies. This religious system helped reduce female conflict and was most clearly manifested in pottery, a product made and used primarily by females. Although the Salado religion profoundly impacted the course of Southwestern prehistory, it isn't clearly reflected in the ritual activities of males, who are considered by Southwestern archaeologists (e.g., Crown and Fish 1996; Mills 2000) to be the primary ritual participants. It appears instead to have been a "mundane" religious system associated with the everyday life of women as reflected by the mundane use of Salado pots.

Late Prehistoric Warfare and the Salado Phenomenon

The late thirteenth and fourteenth centuries A.D. in the Anasazi area of the Southwest was a period of tremendous strife. Starting about A.D. 1250, large-scale village-on-village warfare (and perhaps even conflict between village alliances) became intense and led to the eventual abandonment of areas that had been occupied for millennia (LeBlanc 1999; Lekson 2002a; Wilcox et al. 2001). Armed conflict shattered the remnants of the Chaco–Aztec system that had culturally united much of the northern Southwest and led to the mass emigration of as many as 20,000 people (Lowell 2007). Violence led to the virtual abandonment of the Kayenta and northern Anasazi area (see figure 15.1; Fowles et al. 2007; LeBlanc 1999; Lipe 1995; Lowell 1991). Although some communities appear to have moved en masse (Lekson 2002b), many migrants moved into previously existing communities, perhaps joining distant kin or trading partners. A common pattern in these cases was an extreme gender imbalance reflected in mortuary remains; women tended to outnumber men two to one in many areas, and subadults were far more common than in previous groups (Lowell 2007).

Arrival of a substantial number of migrants relative to the indigenous population corresponded with a shift in settlement strategies, as populations began to aggregate in pueblos with defensive attributes, including protected plaza areas and defensive locations, and new architectural features such as platform mounds (Elson et al. 2000; Lowell 2007). Populations in some areas experienced perhaps as much as a tenfold increase as dispersed local populations and the new immigrants clustered into larger settlements such as Grasshopper Pueblo (see figure 15.1). Increased variation in pottery decoration and technology, female (but not male) mortuary practices, and hearth morphology (e.g., the apparent introduction of rectangular, slab-lined hearths) reflect a sizable influx of female refugees from the north (Lowell 2007), but evidence of increased variation in male-centered material culture such as ceremonial architecture (e.g., circular kivas used by the Anasazi) and projectile-point shape is absent (Lowell 2007).

Architectural and skeletal evidence indicates that immigrating women and children inhabited both previously built and newly constructed structures in the communities they entered, were forced to rely more heavily on wild crops than the indigenous inhabitants were, and had poorer nutrition compared to their contemporaries (Lowell 2007). Further, warfare appears to have followed these migrants, with increased conflict over one or more generations and eventual abandonment of communities as populations moved farther south (Elson et al. 2000; Lowell 2007). For example, portions of the Tonto Basin in central Arizona were occupied and abandoned in a span of 50 years from A.D. 1275 to around A.D. 1325, with most of the villages being burned and the populations moving elsewhere (Elson et al. 2000).

Starting around A.D. 1275, during and slightly after the peak of the immigration from the north (Crary et al. 2001; Crown 1994), the Salado ceramic tradition spread across the Southwest. Salado polychromes were locally made but have clear antecedents in the Kayenta and Tusayan Anasazi traditions from which the immigrants came (Crary et al. 2001; Crown 1994). Other than the pottery, distinctive characteristics of the Salado vary considerably (Dean 2000), as the mixture of cultural traits between immigrants and indigenous peoples produced differences across this vast region (Zedeño 1995).

Yet in the midst of this diversification, "uniform" Salado polychromes (Crown 1994: 90) were produced across 130,000 square kilometers. Salado polychromes (see figure 15.2) were perhaps first made in the Salt River and Gila River areas of south-central Arizona, but they rapidly spread throughout central and southern Arizona and New Mexico (Crown 1994; Lekson 2002b). They tended to be made at the household level out of locally available resources and through a variety of forming techniques, including those introduced by the immigrants as well as those previously used by indigenous artisans (Crown 1994, 1995). Further, Salado polychromes seem to follow, at least in part, individual potters as they moved across the landscape (Crary et al. 2001; Crown 1994; Lowell 2007).

Crown (1994) evaluated competing hypotheses concerning the social importance of the Salado polychromes and concluded that the pottery reflects the rise of a new religious system. In brief, she found that the pottery was made by local potters with a wide range of skill levels (as opposed to specialists making the pottery for elite usage and exchange); that Salado wares were produced and consumed at the household level for mundane use (as opposed to specialize ritual–elite use); that the pottery was highly valued but was not restricted to any particular age or sex cohort in burials; and that the redundant icons reflected a widely held belief system focused on the earth, sun, weather, impersonations of deities, and fertility but did not correspond with a single burial or ritual system. Ultimately, Crown (1994: 7) argued that "the pottery was accepted in association with a religious ideology, as reflected in the imagery. . . . Rather than an exclusive ideology associated with a cult of the dead or ancestor worship, the Salado polychromes reflect the presence of an inclusive ideology, a regional cult that helped to stabilize social relations during this time of change in the Southwest."

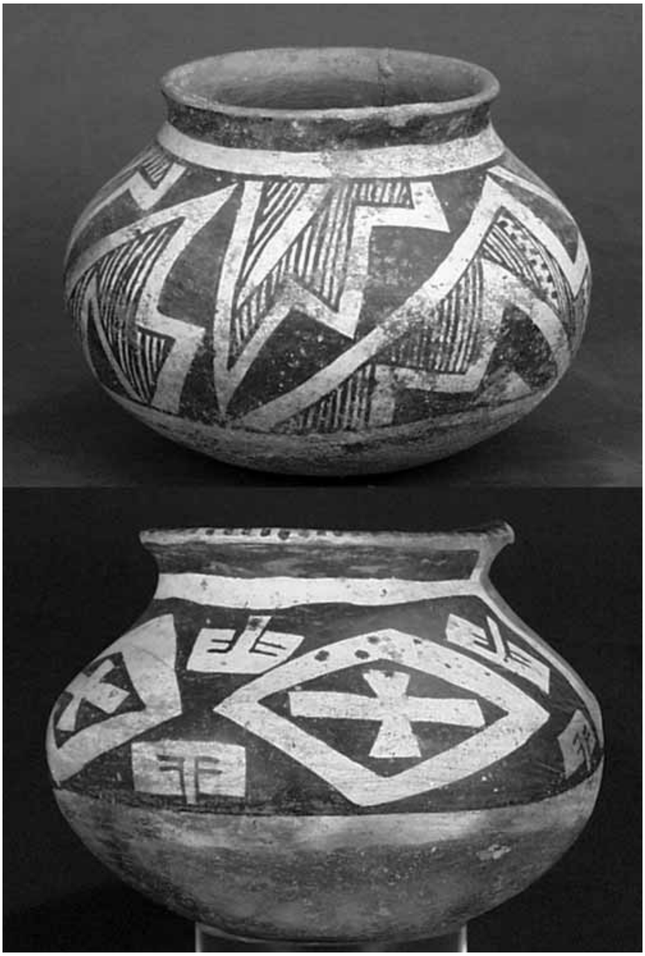

Figure 15.2
Examples of Salado polychrome (top vessel courtesy El Paso Museum of Archaeology, catalog number 59-9-588; bottom vessel courtesy Maxwell Museum of Archaeology, catalog number 65.24.118).

What is peculiar about this religious system is that it was not consistently reflected in ritual items and architecture associated with males, who typically dominated religious ritual in the prehistoric Southwest (Crown and Fish 1996; Lowell 2007). In fact, the only unambiguous indication of the spread of Salado religion is the pottery, a product that ethnographic analogy and archaeological evidence indicate was manufactured by women (Crown and Wills 1995; Mills 2000; Spielmann 2000). We propose that the Salado religion and its associated pottery reflects female-centered religious expression that developed and spread to reduce female competition in communities stressed by the immigration of thousands of women and their children into the area. The influx of these refugees had a profound, destabilizing impact on community structure, just as it does today (Zolberg et al. 1989). The social tension created by these marginalized women and their families would have been particularly intense, given that both the indigenous and immigrating groups may have been matrilineal. Marrying local males would not have helped integrate the immigrants, given that land and other resources were inherited through the mother's line.

Economic difficulties of the refugees would have been passed down to their (especially female) children, possibly for generations. (Even in a patrilineal–patrilocal system, the low economic and political status of the immigrants likely made them less desirable marriage partners.) In this context, unhappiness, scalar stress, and general intracommunity strife were intense in the Salado area, as illustrated in the rapid formation and abandonment of large villages, forced resettlement over generations as villages were destroyed, and the formation of defensive settlements and broad village coalitions (Elson et al. 2000; Lowell 2007; Simon and Gosser 2001; Tuggle and Reid 2001; Wilcox et al. 2001).

Female conflict is ubiquitous in primates (De Waal 2000; Geary 1998), and among humans it is often expressed by advertising qualities valued by men (e.g., beauty and status) and by indirect (typically verbal) aggression toward other females, often through gossip and social exclusion from cliques (Cambell 2004; Hess and Hagen 2006; Merten 1997). However, in contexts where men with substantial resources are in short supply, competition can intensify into physical, often deadly, conflict (Campbell 2004; O'Brien 1988). Such conflict has evolutionary implications for women, given their reproductive constraints and high parental investment relative to men in most cultures (Campbell 2004). Women consequently use a variety of mechanisms to help mitigate conflict and avoid or reduce the deadliness of direct physical confrontations, including formal political or religious coalitions to increase integration (e.g., the women's movement of Zimbabwe [Win 2004]). We believe this was the case with the Salado.

In Southwestern cultures where religion, politics, and economy are tightly integrated, a women's movement emphasizing religious integration (and sociopolitical integration by extension) would have been ideal for reducing conflict. This system of shared belief integrated both the indigenous and immigrant women across families and even villages, reducing the stress that threatened to split communities and potentially engulf another portion of the Southwest in catastrophic, unrelenting open war. After the rise of the Salado tradition, village life became more stable as aggregated communities lasted for longer periods of time (Lowell 2007).

The hypothesis that the Salado system reflects a female-based religious system created in response to war refugees accounts for the empirical record associated with the Salado. First, male ritual did not change substantially, given that females and their relationships were the focus of the Salado religion. Second, Salado polychromes demonstrate a strong emphasis on Kayenta and other Anasazi imagery because immigrant women from those economically and politically marginal regions would have been the first to develop and adopt a system that helped them integrate within and among communities. Third, the integration of women reflected by the Salado would not necessarily be reflected in other aspects of the material culture, which, in turn, accounts for the large cultural variation and lack of defining characteristics other than pottery associated with the influx of refugees and the subsequent spread of the Salado. Fourth, the earliest Salado corresponds with the arrival of the immigrants. Fifth, the development of the Salado religion corresponds with increased evidence of social strife and warfare.

Additionally, the hypothesis accounts for aspects of Crown's analysis that determined the Salado reflected a religious cult. Crown (1994: 5–6) outlined six predictions corresponding with the hypothesis that the Salado reflected a religion: (1) There should be evidence beyond pottery for the rise of a religious system; (2) the pottery should be restricted to ceremonial contexts; (3) the pottery should be associated with a single mortuary ritual; (4) pottery in burials should not reflect prior use for secular activities; (5) pottery designs should reflect a belief system using ubiquitous and redundant icons, which may also be reflected in other religious contexts such as kiva murals; and (6) vessel forms should be limited to those used for ritual consumption.

Surprisingly, given her conclusion that the Salado reflects a religious cult, Crown (1994) found little support for most of these predictions. Predictions 2, 3, 4, and 6 are not supported because the Salado wares take a variety of utilitarian vessel forms, are not restricted to mortuary contexts, are used prior to their inclusion in burials, and are associated with different mortuary patterns (Crown 1994; see also Ravesloot and Regan 2000). The only Salado pots in her study that are exclusively associated with ritual contexts are a single vessel from a kiva and two from a cache that might have a primary ritual role (Crown 1994: 108).

Crown (1994: 6) notes, though, that if the pottery was not restricted to ritual or mortuary contexts, which are likely male-dominated religious expressions (Crown and Fish 1996), then only expectations 1 and 5 are likely to be met, which is in fact the case in her analysis. Crown (1994: 223) concludes that the pottery's use in mundane contexts, as opposed to ritual contexts, indicates that the Salado religion was open to all who chose to participate. Such openness is concordant with the proposal that the Salado is associated with a women's movement to reduce conflict, as is the fact that some high-status burials have little or no Salado pottery, whereas other burials, including low-ranked burials, can have

Salado polychrome in abundance (Ravesloot and Regan 2000). Hence, the Salado religion was not focused on elites but was instead “a poor woman’s religion.”

The Invention and Spread of Cultural Traits

We opened this chapter with the adage that necessity is the mother of invention. In the case of the innovation and adoption of the Salado system, this does indeed appear to be the case. What might the evolutionary mechanisms have been that resulted in the generation of variation, including a religion-based women’s movement and its rapid diffusion across 130,000 square kilometers in the form of the Salado tradition? Schiffer (1996, chapter 14, this volume) has described “stimulated variation,” in which the invention of technological traits is completed through the initial creation of considerable variation and the subsequent winnowing of those variants that have the requisite performance characteristics that make them superior to other variants. This model is applicable to the origin of the Salado religion. The “necessity” that required the “invention” was the need to create and stabilize communities during a period of massive population upheaval and unprecedented violence resulting in significant immigration. As predicted by Schiffer’s model, tremendous cultural variation ensued (Zedeño 1995), with the Salado religion being one of the behavioral variants with outstanding replicative success (Leonard and Jones 1987) resulting from its performance characteristics, which helped integrate populations by mitigating strife, especially among females.

It is also clear that the Salado religion did not spring fully formed into the Southwestern scene because it was “required.” The cliché linking necessity and invention implies that humans will find solutions to problems they face, using their ingenuity and/or their inborn cognitive algorithms and abilities. If this were so, then the explanation for both behavioral variation and its acceptance is simply the presence of a need to which humans intentionally adapt (see chapters 2 and 7, this volume). Yet such an adaptationist perspective is belied by the warfare that created the refugees in the first place. Attempts to decrease conflict were tried in the northern Southwest without success. Lekson (1999, 2002a), for example, argues that the Aztec system that succeeded the Chacoan system (and was also reflected in religious iconography) was a failed attempt to politically unite the northern Anasazi.

Such failures do not mesh with adaptationist perspectives, in which selective forces directly dictate successful cultural responses. This fact brings two related issues into sharp focus: (1) Intentionality and agency are insufficient for explaining the structure and continuation of cultural variation, and (2) a Darwinian evolutionary system structures cultural transmission.

Archaeologists and other social scientists frequently emphasize intentionality to explain cultural variation (e.g., Cowgill 2000; Dobres and Robb 2000). Proponents of “agency-based” explanations hold that humans are socially embedded actors who optimize their resources as they feel appropriate, seek to form social networks and gain social power, frequently plan for the future, and otherwise try to intentionally adapt to their social and ecological surroundings—facts that are undeniable to all who study humans. The implication, then, is that the proper explanation for the generation and continuation of behavioral variation must reside in the socially embedded intentionality of the actors themselves (Cowgill 2000). Although humans are "imperfect, and often impractical people" (Dobres and Robb 2000: 4), it is undoubtedly true that some cultural variation is attributable to the intentional modification–production of behavioral traits resulting from human agency (see chapter 7, this volume), although "copying error" caused by incomplete and imperfect transmission of cultural traits also creates variation (Eerkens and Lipo 2005).

However, human intentions do not constitute an adequate explanation for the structure of behavioral variation (VanPool and VanPool 2003). Humans may, or may not, recognize inadequacy in their technology and other cultural traits, but they don't know what behavioral variants will provide solutions, if solutions are possible at all. Even when operating in the same social and ecological context, people will frequently derive different responses to the same problem, none of which may be effective, as illustrated by the failure of the thirteenth-century Anasazi to abate the intense warfare. People's motives and subsequent intentionality may superficially explain why variation is introduced, but it does not explain why specific solutions are effective and therefore why specific cultural traits continue to be replicated (VanPool and VanPool 2003). Further, unintended consequences of cultural variation can have far-reaching impacts beyond any individual's intentions (e.g., the increase in anemia associated with increased reliance on maize).

The open warfare of the northern Southwest spread to the Salado area, but the presence of cultural variation (the Salado religion) that helped integrate communities across the region decreased its disruptiveness and intensity. Yet a satisfactory explanation for the Salado cannot have as its major component the concept of intentionality, given that it is neither explanatorily necessary nor sufficient. Undoubtedly, people involved in the religious system "meant to" participate in it and perhaps they even "intended" to unify the community and reduce scalar stress through the shared religion (although this is impossible to establish archaeologically), but neither the success of the Salado nor the failure of the other efforts to increase inter- and intracommunity integration reflects primarily the actors' intentions. Salado religion was an adaptation for decreasing community conflict because it possessed performance characteristics that led to its continuation in the selective context of intense female competition and extreme scalar stress.

The lack of a connection between the selective environment in which people find themselves and the usefulness of cultural variation has profound implications for cultural evolution. Darwinian evolution operates when heritable variation that impacts the probability of survival and reproduction is generated independent of the selective environment (Leonard and Reed 1993; Lewontin 1970; Lyman and O'Brien 1998; Rindos 1989; VanPool and VanPool 2003). Given that cultural traits clearly are heritable and frequently impact an individual's survival and reproduction (as illustrated by warfare in the American Southwest), the independence between creation of cultural variation and selective pressures necessitates that Darwinian evolution is applicable to cultural traits. It follows that natural selection, drift, and other evolutionary mechanisms are the processes through which the generation and continuation of cultural traits can be satisfactorily explained (O'Brien and Lyman 2000; Shennan 2002).

Previous research indicates variation in some cultural traits reflects the strength of the selective forces, with strong selective forces resulting in limited variation compared to traits under weaker selective pressures (O'Brien and Holland 1992, 1995; VanPool 2001, 2003). The generalization can be expanded, however, to include considerations of the nature of the selective environment and the time that selection has had to operate. To begin with, variation in traits is expected simply because of the transmission process in both biological and cultural contexts (Eerkens and Lipo 2005). Transmission "errors" consistently generate variation in cultural traits. Some variation will be selected against because it creates performance characteristics inconsistent with the selective environment, which is the product of both social and ecological factors. The frequency of variation that isn't selected against—that is "favored"—will increase, creating adaptations through the process of natural selection (O'Brien and Holland 1995; VanPool 2002).

In stable selective environments, the generation of variation and its archaeological manifestation will be limited with respect to selectively important traits because changes are unlikely to be beneficial, given that variation in an adaptation is unlikely to improve it. However, in either a changing or erratic selective environment, such strong selective pressures will often be inconsistent or eliminated, allowing for the transmission of a comparatively greater amount of variation. In culture, a significant factor modifying selective environments will be changes elsewhere in a technological system as illustrated by Palmer's (chapter 10, this volume) discussion of the Amish and the telephone.

This likely underlies Schiffer's (2005; chapter 14, this volume) cascade events, in that minor changes, whether they are the result of ecological variation, social changes, or the introduction of new technological variation, shift the selective environment, which, in turn, initiates structural changes in traits that may not have even been recognized as related to the original source of variation and the selective pressures operating on it. Such unintended consequences further illustrate that human intentionality is of limited explanatory utility when discussing the generation and spread of cultural variants (VanPool and VanPool 2003). We consequently suspect that the process of selection and the structure of variation in cultural evolution will follow exactly the pattern outlined by Lake and Venti (2009), Lyman and O'Brien (2000), and Lyman et al. (2008): Variation will initially be great and will be winnowed over time as an adaptation is created.

Creating adaptations—descent with modification—necessitates intergenerational cultural transmission. In preindustrial societies, children typically are trained within family units, causing vertical transmission to be paramount (Guglielmino et al. 1995; Palmer et al. 2005; Shennan and Steele 1999; VanPool et al. 2008; chapters 1, 10, and 13, this volume). Continuation of the Salado religion for roughly 200 years demonstrates intergenerational transmission, but its spread within a generation was a product of horizontal transmission. The rapidity of the spread was a product of the cascade effect caused by a shift in the selective environment. Whether horizontal or vertical transmission is dominant in a particular case of cultural transmission is an empirical question whose answer will vary (e.g., variation in Salado pottery-forming techniques reflects vertical transmission as reflected by continuation of the previously existing forming techniques, but design variation was at least initially transmitted horizontally).

Further, we propose that the dominance of vertical or horizontal transmission is somewhat dependent on the selective environment. In a stable environment, metatraditions, as discussed by VanPool et al. (2008) and Palmer (chapter 10, this volume), may form as adaptations to encourage faithful vertical transmission and thus decrease behavioral variation that is likely harmful. These traditions will necessarily act as barriers to a cascade of technological innovation.

In contrast, drastic modification of the selective environment will likely weaken or eliminate metatraditions because it will lead to increased behavioral variation. This variation may result in the absence of consistent behavioral traits within a generation, which, in turn, will make cultural transmission of consistent behavioral traits between generations difficult and thereby change social relations such that the metatraditions no longer effectively facilitate vertical transmission. Natural selection may also work against traditional behavior and consequently select against continuation of the metatradition through the process of hitchhiking (Hurt et al. 2001). Thus, increased horizontal transmission and the (re)combination of traits that were part of separate cultural lineages will be significant parts of stimulated variation in nonindustrial societies. Such recombination is certainly evident among the Salado, as previously distinct cultures began to share a variety of traits.

Conclusions

We have outlined a historical narrative underlying the generation and spread of cultural variation that fundamentally altered Southwestern prehistory. Our argument is presented in more detail in VanPool and VanPool (2008) but can be abridged as follows: The rise of intense warfare characterized by the massacre of entire communities led to the spread of female refugees and their families throughout much of what is now central and southern Arizona and western New Mexico. This created a new selective environment that impacted those living in the communities, as intense female–female conflict was created by immigrants vying with each other and with native women for mates and resources. The result was intense intra- and intercommunity conflict. The arrival of the immigrants initiated what Schiffer (2005; chapter 14, this volume) characterizes as a "burst of variation" associated with a cascade of innovation. The increased behavioral variation was especially pronounced in activities associated with women and led to the formation of a uniform pottery style, Salado polychromes, that spread across a vast area containing previously distinct cultures.

We propose that the Salado pottery tradition reflects strong selective pressures operating on the expansive cultural variation. In this context, a women's religious system that emphasized integration had performance characteristics well suited to the selective environment and as a result had tremendous replicative success as it spread across much of the Southwest in a very short time (between A.D. 1275 and A.D. 1300) through the process of horizontal transmission and migration. The selective pressures limited variation in the ceramic tradition such that there was relative uniformity in icons and other aspects of decoration across the region, despite the fact that the Salado wares were locally produced and reflected previously existing and diverse morphological forms. Participation in the Salado tradition decreased intracommunity stress, which helped mitigate but certainly did not eliminate intercommunity stress, such that large, stable communities formed across the Salado region.

We propose that the patterns illustrated in the Salado case study are typical of the generation and transmission of cultural variation, and even in genetic evolution, as bursts of variation are associated with the opening of previously unavailable adaptive space. Cultural variation does occur in "bursts" and "cascade events" associated with changes in the selective environment, yet, as illustrated by the very fact that there are "bursts of variation," the generation of variation is not dictated directly by the selective environment. As a result, natural selection will reduce the range of initial variation to form adaptations, despite the fact that experimentation and copying errors will continually generate variation. In the case of the Salado, strong selective pressures led to the formation and spread of a cultural adaptation over an expansive area while greatly limiting variation within the cultural trait. Less severe selective environments may allow more variation than present in the Salado, but we suggest that this same pattern is typical of cultural evolution.

Acknowledgments

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Index