Inferring cultural reproduction from lithic data: A critical review

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Abstract

The cultural reproduction of lithic technology, long an implicit assumption of archaeological theories, has garnered increasing attention over the past decades. Major debates ranging from the origins of the human culture capacity to the interpretation of spatiotemporal patterning now make explicit reference to social learning mechanisms and cultural evolutionary dynamics. This burgeoning literature has produced important insights and methodological innovations. However, this rapid growth has sometimes led to confusion and controversy due to an under-examination of underlying theoretical and methodological assumptions. The time is thus ripe for a critical assessment of progress in the study of the cultural reproduction of lithic technology. Here we review recent work addressing the evolutionary origins of human culture and meaning of artifact variation at both intra-site and inter-site levels. We propose that further progress will require a more extended and context-specific evolutionary approach to address the complexity of real-world cultural reproduction.

Keywords: Cultural transmission, Social learning, Lithic technology, Archaeological evidence, Cultural Evolution, Extended Evolutionary Synthesis

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1 Introduction

From its earliest origins, archaeology has been concerned with identifying, documenting, and understanding past human cultures and their patterns of change through space and time. However, there has been little enduring consensus of what "culture" actually is or the processes by which it changes. Indeed, the history of the discipline has been one of ever-changing paradigm shifts, ranging from the early debate between migrationism and diffusionism in cultural history to the functionalism of processual archaeology and on to more recent evolutionary approaches.[1: 23-92] Despite this fundamental ambiguity, the culture concept continues to lie at the heart of basic units of archaeological taxonomy[2] (e.g., cultures, techno-complexes, industries, traditions, facies, etc.) across micro and macro levels. At the micro-level, shared practices in material culture within a population make it possible for some artifact assemblages to be identified as comparable units. At the macro-level, such sharing is the mechanistic underpinning of cross-unit cultural dynamics from both spatial (isolation and interaction/contact) and temporal (continuity and discontinuity) perspectives.

Although it is unlikely that a lasting consensus on the nature and workings of human culture will be achieved any time soon, recent archaeological approaches have been heavily influenced by the development of cultural evolutionary theory[3,4] and psychological approaches to social learning.[5,6] These influences have been productive, but the rapid expansion of contemporary evolutionary archaeology has not been without growing pains and points of theoretical, methodological, and terminological confusion. The time is thus ripe for systematic review and assessment of the state of the field. To this end, we provide a critical overview of evolutionary archaeology theory and review its application to the following research topics in lithic technology: 1) culture origins, and the identification and interpretation of patterning at 2a) intra-site, and 2b) inter-site levels. We focus on lithic technology to constrain the scope of our discussion and because the durability and abundance of stone artifacts throughout human evolution makes them particularly suitable for theory testing.

1.1 A brief history of cultural evolution

Contemporary evolutionary archaeology is largely an outgrowth of formal approaches to cultural evolution (hereafter "cultural evolutionary theory" or CET) developed in the 1980s through the application of mathematical models borrowed from population genetics. Cavalli-Sforza and Feldman[4] first systematically advocated the comparability between genetic and cultural inheritance systems in their groundbreaking work, *Cultural Transmission and Evolution: A Quantitative Approach*. In this book, they argued that the transmission of cultural knowledge is analogous to genetic inheritance in that it involves copying (reproduction) with the potential for modification (mutation), thus leading to variation and the potential for both random (drift) and adaptive (selection) evolution. They also considered important disanalogies. These include the distinction between Darwinian selection of organisms through differential survival and reproduction (fitness) and *cultural* selection of traits through individual decisions with respect to some form of cultural fitness (glossed as "appeal," p. 19). However, the bulk of the book was devoted to exploring the disanalogy between the (almost) exclusively vertical transmission of genetic material from parents to offspring and the rampant horizontal (peer-to-peer) and oblique (non-parental elder to juvenile) transmission additionally present in cultural evolution.

Cavalli-Sforza and Feldman's original models were later modified and adopted in the ethnographic case study of Aka foragers, in which oblique transmission was subsumed under horizontal and two new channels of one-to-many and many-to-one were introduced.[7] This updated model generated clear expectations (**Table** 1) that could be readily translated into measurable traits in artifact assemblages, especially in terms of the lithic morphological variability at the intra-group and inter-group levels,[8] and thus served as the theoretical foundation for archaeological studies of cultural transmission.[9]

Concepts of cultural fitness and adaptation were more fully explored by Robert Boyd and Peter Richerson in their landmark *Culture and the Evolutionary Process*.[3] In this book, Boyd and Richerson developed the Dual Inheritance Theory (DIT, now commonly known as gene-culture coevolution theory) as a framework for considering potential interactions between cultural and biological evolution. In DIT, culture change can happen in two ways. First, *natural* selection can act on culture-bearing individuals, in which case it is generally expected to increase the frequency of adaptive culture traits. Second, *cultural* selection can occur on the traits themselves, in which case biologically non-adaptive or even maladaptive traits can be favored. Cultural selection occurs through the adoption choices of individuals, and biases affecting these choices (i.e., the "cultural fitness" of variants) need not align with biological fitness. Boyd and Richerson thus conceptualize cultural fitness in terms of psychological processes or dispositions they term "transmission biases" that affect the likelihood of individuals adopting particular cultural traits. These include "direct" biases, also known as content-based biases, due to inherent features (e.g., effectiveness, memorability) of the trait, "indirect" biases based on characteristics of the model demonstrating the trait (e.g., success, prestige), and frequency-dependent biases such as a preference to copy the most common trait (conformity). The latter two categories are merged under the name context-based biases in more recent CET literature.[10]

DIT holds that cultural evolution need not increase biological fitness in all cases, but nevertheless posits that it frequently *does*. In fact, cultural evolution has been held up as the critical "secret" to the demographic expansion and adaptive potential of our species.[11,12] There has thus been substantial interest in modeling conditions under which various transmission biases (often now termed social learning strategies)[10] would be expected to produce biological fitness enhancement. For example, Boyd and Richerson[3] showed that conformity and prestige biases can increase the probability of individuals selecting locally adaptive traits even in the absence of any direct evaluation of trait merits. Under appropriate conditions, natural selection would thus favor these transmission biases, leading them to become species-typical features of human psychology that help to ensure the adaptive nature of cultural evolution. However, these biases would still be insufficient to explain the production of locally adaptive variants to copy in the first place.

Boyd and Richerson address this with the concept of "guided variation," now more frequently termed individual learning. It is controversial to what extent individual learning relies on "blind" trial and error vs. directed experimentation based on some form of causal understanding,[13] but in any case it is expected to guide variation toward desired outcomes. If, in line with Human Behavioral Ecology theory,[14] it is further assumed that humans generally act as biological fitness maximizers then such learning will be biased toward the production of adaptive variants so long as individuals have the cognitive, perceptual, and experiential capacity to identify the associated fitness benefits.[15] However, it is not clear that individual-learning objectives are necessarily any more likely to be related to biological fitness than are social-learning adoption choices, and the concept of fitness as applied to cultural evolution remains under-theorized.[16]

The quantitative evolutionary approach pioneered by researchers like Cavalli-Sforza, Feldman, Boyd, and Richerson has been immensely influential and productive for the study of human culture and cognition in general[12,17–19] and for archaeological approaches to understanding past culture change in particular.[9,20–24] However, applying the formal models of cultural evolutionary theory to real-world archaeological data is not a straightforward process,[25] and cultural evolutionary theory has itself continued to evolve. It is thus important to review potential points of confusion and/or refinement to this theoretical bedrock of contemporary evolutionary archaeology. Many of these relate to the underlying "culture as information" paradigm that cultural evolutionary theory inherited from its population genetics origins.

1.2 Culture as Information

Evolutionary archaeology[22] follows cultural evolutionary theory (CET) in conceptualizing culture as information held in the minds of individuals. As phrased by Richerson and Boyd:[26: 5] "Culture is information capable of affecting individuals' behaviors that they acquire from other members of their species through teaching, imitation, and other forms of social transmission." This conception echoes the "genes as information"[27] paradigm that characterized the mid-century Modern Synthesis (MS) of evolutionary biology and which itself reflected the contemporaneous ascendance of computer science and information theory. In cultural anthropology, this computational zeitgeist was expressed in symbolic approaches to culture as "an information-holding system with functions similar to that of cellular DNA" such that "the instructions needed for coping with the environment and performing specialized roles is provided by learned information, which is symbolically encoded and culturally transmitted."[28: 198] However, such symbolic approaches soon fell out of favor and were replaced by more enactive and embodied conceptions of culture as something people actually *do*.[29] This latter approach has been especially popular among archaeologists interested in apprenticeship and the co-production of material, mental, and social structures more generally,[30] but the informational conception of culture as content to be copied has remained dominant in CET and evolutionary archaeology. Thus, CET models typically treat cultural transmission as an effectively instantaneous process of replication or template copying explicitly modeled on genetic inheritance.

This is somewhat ironic, as CET has now become an important part of a so-called “Extended Evolutionary Synthesis” (EES) that explicitly questions the MS conception of biological evolution as the transmission and expression of genetic information.[31] Whereas the MS defines biological evolution as changes in the frequency of gene variants in a population, and CET correspondingly conceives cultural evolution as “changes within a population of the relative frequencies of the forms of a cultural trait,”[4: 5] the EES contends that “phenotypes are not inherited, they are reconstructed in development.”[31: 5] This active reconstruction (literally, re-production) is itself a source of adaptive variation and thus breaks down the classic MS distinction between “proximate” (e.g., ontogenetic) factors that merely inflect the expression of inherited genetic information and “ultimate” (e.g., natural selection) causes explaining their origins. This leads EES to emphasize a wider range of evolutionary causes (e.g., niche construction, developmental processes, non-genetic inheritance) beyond mutation, selection, drift, and gene flow. Applied to culture, such logic calls for attention to diverse causes of cultural reproduction and change beyond the social transmission of cultural information. The theoretical implications of this shift have attracted increasing attention from archaeologists in the past decade,[32–35] where niche construction theory became particularly relevant in the field of paleolithic archaeology.[36]

These implications are clearly exemplified in the case of technology, which is arguably the most studied cultural domain for both CET and evolutionary archaeology. Causal mechanisms potentially contributing to technological stability and change extend beyond learning processes per se to include relative costs and benefits in particular behavioral systems and ecologies,[37] social structures[25] and institutions,[38] intrinsic features of[15] and/or interactions between[39] technologies, and potential coevolutionary relationships between these diverse factors.[40] Indeed, the CET literature is already replete with examples of material and social causes of technological stability and change, including functional design demands, inflexible production processes and technological entrenchment, innovation cascades, market integration, environmental change, and more reviewed by Mesoudi et al.[41: Table 11.2] However, in the information transmission paradigm, such particular features are viewed as proximate mechanisms inflecting local rates and patterns of change rather than ultimate explanations for the origin of cultural diversity and adaptation.

An alternative, EES-inspired, approach would be to emphasize the causal power of such “proximate” mechanisms to drive evolutionary change. For example, there is some debate in the CET literature over whether technological innovation is usually blind and random (i.e., like genetic mutation) with optimization due to selective retention/copying (due to various biases discussed §1.1), or whether individual learning commonly acts to guide variation toward desired outcomes and allows for optimization even in the absence of selection.[13] A largely neglected third possibility in this debate is that proximate material and social conditions can also guide variation and affect retention. A simple non-human example is the way in which the durability of artifacts and locations associated with some forms of primate tool use can facilitate the reproduction of tool behavior.[42] In human societies, ecology, ideology, institutions, and economics can affect the nature, frequency, and retention of innovations[41,43–45] and particular technological systems may be more or less evolvable due to the modularity vs. interdependence of component parts or procedures.[46,47] Thus, the likelihood of dynamic interactions between biological and cultural evolutionary processes occurring over a wide range of spatial and temporal scales[15,48] should be a topic of particular interest moving forward, including the possibility that such interactions may help to explain patterns of stasis and punctuated change in the archaeological record.[39,40,48]

As with the EES more broadly, this critique of CET should not be construed as a repudiation of past work or even as presenting previously unrecognized mechanisms and/or empirical findings. In fact, one of the reasons the EES has been controversial is that its primary contribution is theoretical or even philosophical rather than empirical. The EES takes a stance on the nature and goals of evolutionary explanation whose relevance and appeal will depend on the questions and objectives of different research programs.[49] This is equally true with respect to the study of cultural evolution. Richerson and Boyd[26: 259] explicitly state that their definition of culture as information is a pragmatic one intended to promote productive research, rather than the only possible one. In this respect, it has clearly been successful. As with gene-centered approaches to biological evolution, the power of this informational approach stems from its relative simplicity, broad generalizability, and amenability to formal modeling. However, these broad strengths may be less well suited to explaining the precise causal-historical details of particular cases, especially when variables employed in formal models are difficult to relate to empirical measures of real-world data.[25] This parallels the case with the EES, which may be most relevant and helpful to researchers interested in detailed explanations of particular evolutionary histories.[49] Such a focus is more typically of evolutionary archaeology than it is of CET in general, but this has seldom been reflected in the theory and practice of the field.

For example, EES themes of developmental reconstruction and reciprocal organism-environment causation bear a conceptual similarity to the enactive and embodied approaches in cultural anthropology. However, the social theories of Bourdieu[29] and others have not generally been seen as amenable to practical application in evolutionary archaeology. One notable exception is Ingold's[50: 158] concept of a "taskscape," as "an array of related activities" carrying forward social life that is inextricably bound with the landscape. Building on this concept, Tostevin[1: 85] coined the term "taskscape visibility" to refer to "the relationship between where, when, and with whom a cultural trait, such as a flintknapping behavior, is performed and the possible cultural transmission modes available for promulgating the trait into the next generation." This concept is then combined with social intimacy to predict certain aspects of lithic technology, mainly blank production, can only be visible and thus learned within socially intimate people like those living in the same camp. On the contrary, tool kit morphology is visible to more socially distant people such as two hunter-gatherers shortly meeting each other when their foraging landscape is overlapping. This approach adds a concrete technological and ecological particularism to the more abstracted investigation of population size and structure effects that is well developed in CET,[25] but is correspondingly difficult to generalize and has not been widely adopted.

Another potential theoretical resource for evolutionary archaeology is the Cultural Attraction Theory (CAT) developed by Sperber and colleagues.[51] Again evoking EES themes, the core premise of CAT is that cultural traits are not straightforwardly transmitted or copied between individuals but must be actively reproduced. The particular processes and contexts of reproduction may then act as "factors of attraction" biasing the outcome in a particular direction ("convergent transformation") and resulting in either stabilization or directional change. Such convergent transformation would include the guided variation (trial and error learning) of Boyd and Richerson[3] but is a more inclusive concept that need not involve psychological factors affecting individual learning or lead to goal-directed enhancement.[52] CAT explicitly includes ecological (physical and social context) as well as psychological factors of attraction and theorizes culture change and stability as products of complex causal chains rather than biased information transmission.[51] As such it would seem to be well suited to accommodate evolutionary archaeology interest in topics such as the way that specific artifact production techniques, perceptual-motor constraints, social contexts, and ecological interactions can affect cultural evolution. This potential has yet to be realized, however, as CAT work to date has tended to focus on communicative (e.g., songs, jokes, stories) culture and psychological factors of attraction rather than broader ecological causes,[51] and on explaining stability rather than change. Modeling has supported the in-principle potential of convergent transformation to supplement CET as an additional mechanism of cultural stabilization, but it remains an "abstract notion"[52: 3] yet to produce concrete archaeological predictions and applications comparable to CET.[9]

Currently, then, there remains a disjunction between CET, with the broad explanatory scope and methodological advantages allowed by its simplifying focus on social transmission, and the more complex and particularistic array of causes and interactions relevant to understanding specific archaeological cases of culture change or stability.[8] Bridging this gap with a more extended synthesis of cultural and evolutionary theory will be a major undertaking and an important priority for future work in evolutionary archaeology. In the remaining sections of this review, we consider current confusions and controversies arising from this theoretical disjunction and provide modest suggestions toward resolving them. These issues are perhaps most salient in debates over the evolutionary origins of human culture.

2 The origins of human culture

According to CET, many animals have culture (behavioral variation acquired and maintained by social learning) but humans are distinguished by our capacity for cumulative cultural evolution (CCE).[53] This capacity, thought to be rooted in unique human psychological adaptations for high fidelity social learning,[6,19,54] allows for iterative improvement over generations eventually resulting in "well-adapted tools, beliefs, and practices that are too complex for any single individual to invent during their lifetime."[11: 10920] CCE capacity has been proposed as the secret of our success (i.e., geographic, demographic, and ecological expansion) as a species and its origin characterized as a "key event"[11] or crossing of an evolutionary Rubicon[12] that put humans on a novel gene-culture coevolutionary trajectory ultimately explaining "how our ancestors made the journey from apes scavenging a living on ants, tubers, and nuts, to modern humans able [to] compose symphonies, recite poetry, perform ballet, and design particle accelerators."[19: 2-3] There is thus intense interest in determining the timing and context for the onset of CCE in human evolution. However, many uncertainties remain, ranging from the definition of CCE[15,16] to archaeological criteria for diagnosing its presence.[55,56] These uncertainties reflect the challenges of applying abstract CET concepts and models to interpret concrete and particular archaeological patterns.

CCE theory is deeply rooted in the culture-as-information paradigm and in particular the idea that such information is costly to generate through individual learning but cheap to store, replicate, and transmit socially once acquired.[3: 35] Boyd and Richerson[53] showed that mixed strategies of individual (guided variation) and social (observational copying) learning can over generations lead to the evolution of fitness-enhancing skills that would have been beyond the inventive capacity (the "reaction norm") of individuals in the first generation (i.e., CCE). Drawing on literature from comparative psychology,[6] these formal models assume that observational learning of such complex skills is behaviorally cheap but reliant on developmentally/neurobiologically costly psychological mechanisms such as imitation and the shared intentionality that allows teaching. These costs create a barrier to the initiation of CCE in the form of an "adaptive valley" that must be crossed before CCE can start to produce the body of complex, difficult-to-learn, and useful cultural content that would allow these expensive mechanisms to pay for themselves. This potentially explains the rarity of CCE in nature and leads to the expectation that its emergence in humans was a threshold event initiating a process of sustained biocultural feedback.

Archaeologically, the crossing of this threshold would be indicated by the appearance of individual behaviors[55] or suites of behaviors[12] demonstrably beyond the inventive capacity of individuals. It would also be expected to produce evidence of increased rates of culture change and diversification[26,55] and obligate reliance on teaching and/or imitation as mechanisms of cultural reproduction.[6,54] However, there are challenges in applying expectations derived from this formal version of CCE to concrete archaeological data. These include pragmatic problems with actually demonstrating that a given behavior could not possibly be invented by an unassisted individual given sufficient time and opportunity[16] and, conversely, the fact that demonstrating the *possibility* of individual reinvention (for modern apes or humans) does not demonstrate that this is how the behavior was *actually* learned in the past.[56] Other issues are more conceptual and theoretical.

2.1 Requirements for CCE

As framed, formal modeling CCE in CET concept incorporates a presumed dichotomy between observational learning (cognitively expensive, behaviorally cheap) and individual trial and error (cognitively cheap, behaviorally expensive) that may not be supported. Indeed, there is substantial evidence that observational and individual learning rely on shared neurocognitive mechanisms.[18] This weakens the assumption that all instances of CCE require costly specialpurpose cognitive mechanisms for social learning. Conversely, many complex fitness-enhancing skills cannot be learned purely through "cheap" observational learning but must be reconstructed through costly individual practice in supportive material and social contexts.[57] In fact, such individual reconstruction may actually enhance the fidelity of cultural reproduction,[58] which is a key factor promoting CCE.[19] Transmission chain experiments on CCE have similarly shown that the importance of different information sources (e.g., experiential, observational, artifactual) depends on the particular task and context being studied.[59] All of this calls into question the expectation that CCE capacity emerged in a single threshold event marked by archaeological evidence of teaching,[60–62] imitation, and behaviors "beyond the inventive capacity of individuals."

The presumed importance of imitation and teaching to CCE capacity derives from the assumption that particular learning processes have an intrinsically high vs. low reproductive fidelity independent of specific circumstances. This is reflected in the ranked taxonomy of social learning mechanisms (e.g., stimulus enhancement < emulation < imitation) that has informed many theoretical, experimental, and archaeological approaches to CCE origins,[56,63,64] including the "Zone of Latent Solutions" (ZLS) hypothesis,[54] which seeks to explain Paleolithic technologies in the absence of CCE capacity.[55] However, this conception of fidelity is increasingly being recognized as problematic,[15,65,66] and the ZLS hypothesis has been modified[67] to discard the high vs. low fidelity distinction in favor of a dichotomy between "copying" and "non-copying" forms of social learning. Thus, the ZLS hypothesis no longer emphasizes body movement reenactment ("imitation" in the strict sense, note that this differs from the looser use of the term as a synonym for social learning in the early cultural evolution literature)[68] as a key requirement for CCE. Others have argued that imitation in this narrow sense may be necessary for the reproduction of arbitrary communicative or ritual behaviors but has relatively little utility for the reproduction of real-world technological skills[56,68], in which the emulation of products and outcomes (cf. "goals") may be more important than the reproduction of idiosyncratic body movements. Correspondingly, the ZLS now includes emulation and the copying of artifact forms (i.e., end-state emulation or "product copying") as potential mechanisms supporting CCE.

This begins to approximate more traditional archaeological criteria[56: 335] for identifying cultural reproduction on the basis of shared artifact morphology or production processes but remains committed to the classic CET dichotomy of individual vs. observational learning. Thus, only observational copying is sufficient to support CCE whereas non-copying forms of social learning (e.g., stimulus enhancement, or exposure to situations and materials) can only facilitate individual reinvention without cumulative potential. As discussed above, this assumption is questionable. Formally, all that CCE requires is the accurate reproduction of behaviors for a sufficient duration[19] to allow innovation (guided variation) to accumulate.[53] Whether this is accomplished through observational copying or the persistence of structured trial and error learning situations[15,58,69] is beside the point. In fact, the intentional provision of practice opportunities and direction of learners' attention can also be considered as forms of teaching[70] and appear to be important for the reproduction of skills in hunter-gatherer societies[71] and stone tool making in particular.[72] An explicit intention to scaffold learning in this way might depend on novel human social cognition,[6] but such processes can also occur unintentionally and might be a plausible mechanism for some cases of CCE.

In line with broader EES themes, it is increasingly recognized that learning occurs in constructed niches including the inheritance of material artifacts, physical contexts, and social situations[15] as well as "information." Such ecological inheritance is explicitly excluded from the CET culture concept,[3: 35-36] but factors such as the material transfer of tools or the evolution of social institutions for the specialization of labor may be equally important to the emergence of cultural traits "beyond the inventive capacity of individuals."[12,15] It is without question that humans culturally reproduce many such complex behaviors whereas these are rare or absent in other animals,[73] but it is not obvious that a process of iterated observational copying and trial and error learning is both necessary and sufficient to explain everything from bows and arrows to symphonies and particle accelerators. From this perspective, CCE may not be a unitary *process* or capacity with a discrete evolutionary origin so much as a particular kind of *outcome* that may involve diverse processes and causes across different instances. To address this complexity in the archaeological record, Stout et al.[56: 311-312] advocated a stepwise research program proceeding from the empirical assessment of reproductive fidelity for specific behaviors (e.g. reconstructed knapping techniques) through the use of ecologically valid experimental studies to infer learning processes and ultimately to the reconstruction of biocultural evolutionary processes affecting the behavior in question. However, even this approach to CCE as a product rather than a mechanism confronts important theoretical issues with defining the concept of "cumulative" evolution.

2.2 What is cumulative evolution?

The word cumulative means "increasing by successive additions," but it is unclear exactly what is increasing in CCE. The original model of Boyd and Richerson[53] explicitly focused on increasing biological fitness but incorporated a limit (reaction norm) to fitness increase through individual learning that was verbally justified by appealing to the (assumed) complexity of fitness-enhancing skills. This established an implicit link between biological fitness and behavioral complexity consistent with a more generic sense of cultural "improvement" rather than mere increase in some particular variable. Subsequently, the CCE concept has often shifted to focus on increasing complexity per se[73] or been applied more broadly to discuss "improvement in performance as a proxy for genetic and/or cultural fitness."[16: 2] This elision from "increase" to "improvement" is dangerous for archaeology given the discipline's long history of promoting racist and progressivist colonial hierarchies.[74]

There is a principled sense in which increasing biological fitness could be termed "improvement" but the same is not generically true of increasing complexity or maximization of particular performance characteristics. As Mesoudi and Thornton[16] discuss, the CCE concept is often applied to cultural traits with no apparent benefit to the bearer's inclusive fitness. They thus suggest it may be more appropriate to think of improvement in terms of "cultural fitness" as indicated by proxies such as wealth or status. However, if such proxies are not related to biological fitness, then characterizing maximization as improvement is only possible relevant to a particular cultural value system. Unless motivated by careful ethnographic work, the concept of cultural fitness risks being either circular (fit traits are those that reproduce successfully) or a naïve extension of researcher values. Such external evidence of cultural values is often unavailable to archaeologists.

The recognition of a distinct form of "cumulative" culture evolution emerged as a useful marker in a debate over the possibility of fitness-enhancing gene-culture coevolution[53] but, in hindsight, it is not clear that the CCE concept captures anything that is not already encompassed by concepts of inheritance, adaptation, and persistent evolutionary trends that have already been extensively theorized in evolutionary biology. CCE does involve a particular form of behavior-led evolution in that individual learning generates "guided variation" which is then subject to selection, however this is now encompassed by the broader EES concept of constructive development.[31] Given the danger of progressivist misinterpretation of the term "cumulative" and its established implication of improvement, care should be taken in its use. It might often be preferable to drop the C and just speak of cultural evolution in all its complexity and diversity.

In Paleolithic archaeology, the implicit (or explicit) framing of CCE as improvement produces an expectation that it should always occur when possible. The long-term stasis of technologies[75] such as Acheulean handaxe production thus becomes a "problem" requiring special explanation, for example as due to: 1) a lack of CCE capacity,[55,64] 2) the genetic encoding of technological behavior,[26,76] and/or 3) the occurrence of frequent transmission failures in and extinctions of small, dispersed populations.[12,77] However, it is not entirely clear that CCE predominates even in recent human evolution.[78] An alternative to this deficit model is to consider that stasis might also reflect locally optimal adaptation.[79] In fact, archaeologists often consider stabilizing influences (cf. "factors of attraction" in CAT), such as design constraints[80] or the role of tools in larger behavioral ecological strategies.[37] These perspectives generally expect successful strategies to be stable and thus focus more on explaining episodes of change in terms of extrinsic causes such as climate-driven habitat shifts.[81] Finally, there are evolving organismal factors of attraction such as more general perceptual-motor and cognitive capacities[56,82] or biomechanics and manipulative capacities[83] that might affect the relative costs and benefits of particular technologies. Most likely, each of these mechanisms and more have been relevant at different times and places in the Paleolithic and would have interacted in complex and historically contingent ways to produce the observed archaeological record. This calls for renewed attention to spatial and temporal variation within periods of purported stasis like the Acheulean[79,84] even if this variation does not follow a global trend of cumulative improvement.

3 Identifying cultural reproduction at the intra-site level

Unlike the fierce debate over the learning capacities of early members within the hominin lineage and their material correlates, research attention in later prehistory has focused on the inference of social learning strategies and the modes of cultural transmission from stone artifacts. As such, the following section will shift from theoretical debates to the evaluation of different research designs connecting what is predicted in the model and what is measurable empirically. Social learning strategies (SLSs) refer to "flexible rules that specify or bias when or how individuals should use social information, under various circumstances, to meet functional goals."[10: See Fig. 1 for a detailed classification scheme] As mentioned earlier, this concept and the term transmission bias are usually used in an interchangeable manner, which is directly derived from the pioneering work of Boyd and Richerson.[3] On the other hand, the mode of cultural transmission (**Table** 1) is deeply rooted in the research tradition developed by Cavalli-Sforza and Feldman,[4] designed for identifying the social relationships between the demonstrators and learners (vertical/horizontal/(oblique)/one-to-many/many-to-one) and predicting the dynamics and pace of cultural evolution under these different channels. It is worth noting that these two dimensions are discussed together here because they are theoretically interlocked and rarely separated in empirical studies using the accumulated copying error (ACE) model, which represents by far the most successful application of CET in archaeological research.

3.1 The accumulated copying error model

The central idea of the ACE model is straightforward. It states that small mistakes will be generated during the process of copying another's actions, either because of the imperceptible magnitude of the difference or the physical limits of perfect imitation even given correct perception. Through repeated cultural reproduction processes, these copying errors will result in a noticeable difference between the original artifact and later replicas.[21,22] Following the huge success of CET, the attractiveness of the ACE model lies in the fact that it generates clear predictions that can be tested directly against easily accessible lithic metric data, ensuring its broad adoption in archaeological research. In the meantime, it also suffers from its simplified assumptions on the agency of learners, the role of demography, and its negligence of technological attributes beyond gross morphology (e.g., outline form) as well as the possibility of mixing SLSs.

Many empirical cases within this line of inquiry studied projectile point technologies in North America, which are ideal research subjects of the ACE model because of their morphological stability and representativeness in the prehistory of the Western Hemisphere. Bettinger and Eerkens's[85,86] pioneering research comparing the regional morphological variation of Rosegate Points (1,350-650 B.P.) between central Nevada and eastern California is among the first attempts to identify SLSs in lithic assemblages based on CET. It is generally believed that this type of projectile points represents bow-and-arrow technology as opposed to atlatl-and-dart (Elko Corner-notched Point, 3,150-1,350 B.P.) technology, and their minimally overlapping chronologies indicate a rapid replacement of the latter with the former and a rather powerful mechanism of cultural transmission. Bettinger and Eerkens found the metric attributes of Rosegate points in central Nevada were highly correlated with each other, which was interpreted as a result of indirect bias in cultural transmission, namely wholesale copying from a single successful or prestigious model. On the other hand, the poor correlations between length, width, thickness, weight, and shoulder angle in eastern California were a product of guided variation, or individual trial-and-error experimentation. A tentative explanation on the regional difference of SLSs given by them is that groups living in east California may have acquired this new bow-and-arrow technology from people with large social distance, "possibly a different linguistic unit occasionally contacted through trade."[86: 238]

Mesoudi and O'Brien[87,88] further investigated the effects of SLS variation through behavioral experiments and agent-based modeling. In their studies, they asked human participants to modify five attributes (length, width, thickness, shape, and color) of "virtual projectile points" to adapt the changing "virtually hunting environments" under different learning conditions, including copying the most successful, individual learning, and horizontal transmission. For simulated agents, all others being equal, they have also added the strategies of copying at random, copying the majority, as well as copying the average. First and foremost, their simulations did confirm Bettinger and Eerkens's[86] results that indirect bias will generate significantly higher correlations between attributes compared with guided variation. More interestingly, they also found that correlations between variables in "model-based" strategies (copying the most successful and copying at random) are generally higher than those in "trait-based strategies (copying the majority and copying the average)," but they doubt if this difference is visible in archaeological records solely based on attribute correlations or measures of variation. Therefore, they proposed that the criterion of fitness should also be included in consideration, meaning the strategy that can help one better survive in changing environments has the highest possibility of being adopted. Their modeling results suggested that copying the most successful outperforms all other SLSs. Again, due to the difficulty of defining and operationalizing the concept of fitness using archaeological data as compared with model or experimental data, this proposal was hardly adopted in subsequent studies.

Another research by Eerkens and Bettinger[89] reflected on the choice of statistics and argued that CV is a more robust statistical technique for measuring morphological variability in the cases of cross-assemblage comparison and assemblages with small sample size. They have also introduced the concept of Weber's fraction from psychology, a threshold of human perception of differences between two visible traits such as length, weight, or area. In particular, two constants in CV were provided as a reference framework of artifact standardization or variability: 1.7% as the highest degree of standardization through human's manual production and 57.7% as generated under the random uniform distribution. A value lower than 1.7% would suggest the use of external aid such as a machine, while a value higher than 57.7% means artifacts within an assemblage are deliberately made to be distinct from each other. It is worthwhile to mention that a simpler version of 3% errors of artifact reproduction is commonly cited, based on which the minimal CV of 1.7% is calculated.[90]

Garvey's[8] recent analysis of Washita points from the Henderson site (A.D. 1,250-1,350) located in southeastern New Mexico provides a good example of the application of this approach in a well-motivated, context-specific manner of the kind we are advocating here. Based on the extant research on settlement and subsistence patterns of Henderson, especially zooarchaeological data, Garvey argued that bison was central to the local economy and social organization and thus could be related to certain successful hunters' reputational capital, forming the basis of indirect bias. This leads to the prediction that many community members learned projectile point manufacturing technology from very few models, resulting in low morphological variability. Alternatively, Garvey suggested that the location of Henderson in a boundary zone between Pueblo farmers and mobile hunters of the southern High Plains and Edwards Plateau might promote group-affiliative norms, or within-household vertical transmission. This alternative predicts a higher degree of morphological variability due to a larger pool of models. To test these predictions, Garvey first simulated the copying errors of projectile points under the conditions of 100 households and 4 generations of learning, which are based on the numbers of dwellings and site occupation time (100 years) inferred from radiocarbon data. Three levels of copying errors were simulated based on Weber's fraction (CV=3%, 5%, 10%). The comparison of simulated and archaeological data distribution provided convincing support for the hypothesis of within-household vertical transmission. Nevertheless, and like many other studies using the ACE model, this study's exclusive use of outline form ignores the effect of limited design space and prevents Garvey from exploring many interesting dimensions of technological learning ranging from raw material selection to platform preparation to functional preferences. The reconstruction of these details in skill reproduction requires careful examinations of debitage and debris, which often dominate a given lithic assemblage, and multiple lines of analyses including provenance analysis, use-wear analysis, etc.

In sum, there are three limitations within this series of studies identifying the mode or bias of cultural transmission. First, the analyses presented above depend on the morphometric measurements of formal tools' outline form exclusively. Due to the limited design space of artifact morphology, it is difficult to rule out the possibility of convergence without cultural interactions, which was never raised as a formal hypothesis for testing in studies focusing on projectile points presented above. To address this question, a more holistic approach taking the technological characteristics embodied in debitage into consideration is desired as advocated by Tostevin.[1] Second, a relatively simplistic and static narrative of SLSs was implied in those studies as if learners can only be subject to one type of transmission bias and there are no noisy signals at the population level. It is common that only two distinct SLSs are set up as mutually exclusive hypotheses, such as model-based copying versus guided variation[86] or model-based copying versus vertical transmission.[8] Realistically, human beings constantly get feedback on learning results and accordingly switch their learning strategies, and individual learning is almost always necessary,[15,58] especially for physical skills. It has also been formally shown that the flexibility of decision-making heuristics behind these changes can be highly adaptive in both mathematical models[53] and experiments.[91] Therefore, the identification of mixed SLSs represents an important future direction in this field.[10] Third, as demonstrated by Premo[92] using agent-based modeling, the population size was not but should be considered as a key factor in the interpretation of the coefficient of variation of a given continuous trait like lithic metric attributes,[93] since different combinations of population size and transmission mechanisms can produce the same CV values. More importantly, it points out the issue of equifinality in social and behavioral sciences, meaning the same behavioral pattern can be achieved through different processes and mechanisms. Given the inherently low resolution of archaeological data, it is a salient question in the inference of cultural reproduction that can only be partly reconciled through the methodological pluralisms as we advocated in this piece. Attention to the social reproduction of knapping skill, rather than artifact outline form per se, is one step in this direction.

3.2 The skill level approaches

Beyond the CET-informed studies on stone artifacts, there is a long-established research tradition in lithic analysis revolving around the apprenticeship and the evaluation of technical expertise of the knapper.[30,94,95,96: 78-103] Despite the fact that it is not directly rooted in formal cultural evolutionary models, it has the potential to be incorporated into the EES framework[96: 164-171] since studies within this pluralistic tradition often emphasize idiosyncratic and contextualized causes and interactions within a technological system. More specifically, researchers pursuing this line of inquiry develop different frameworks for the identification and measurement of knapping errors and/or standardized morphology. Occasionally, this line of inquiry also attempts to quantify the complexity of certain technologies, varying case by case. Emphasizing the embodiment of technology over the "culture as information" perspective, some recent studies focusing on skill levels managed to reconstruct the learning behaviors of past knappers through situating the close-reading of stone tools in a broader technological system, albeit in an ad-hoc manner.

For instance, the technological analysis of an Acheulo-Yabrudian assemblage in Qesem cave, Israel, suggested that some cores went through two phases of flake removals.[97] The first phase is characterized by a series of successful blade removals without creating hinges, while the second phase features hinges, steps, crushing signs as well as short removals. This phenomenon was interpreted as core sharing, where inexperienced knappers worked on cores previously produced by those experienced to better acquire the knowledge of stone tool making. It is a rather explicit form of scaffolding, emphasizing the direct interaction of demonstrator and learner aiming at facilitating the learning processes of the latter, a phenomenon that has been reported recurrently in ethnoarchaeological studies of stone knapping skill acquisition.[72,98: 149] However, another possible mechanism behind these two-phase cores could be that the difficulty of flake removal significantly increases when the core is reduced to a certain size threshold, leading to frequent failures even for expert knappers.

Castaneda[99] identified three levels of knapping skills, namely expert, advanced apprentice, and novice, based on a series of criteria on selection and execution errors at a Neolithic flint mine in Spain. Interestingly, multiple cores reflecting high skill level were abandoned for no apparent reasons or long before full exploitation were identified, which were interpreted by the author as a way of demonstrating the early steps of knapping techniques in a digestible manner to novices. Compared with other works using a similar approach, Castaneda's study emphasizes the role of raw material selection in the knowledge system and includes some new standards such as the convexity of the working surface. In the meantime, her approach lacks a clear measurement and quantification system of errors and thereby relies heavily on the analyst's subjective experience. Another major insight of this study is that a flint quarry would be an ideal place to study the reproduction of lithic technology given the relatively sparse distribution of appropriate knapping materials on the landscape and the immense cost of transporting them. This conclusion was confirmed by Goldstein's[100] knapping error frequency analysis of multiple obsidian blade assemblages from early pastoralist sites in Kenya, where assemblages closer to the quarry show higher error rate as manifested by the greater occurrence of bulb/platform errors, termination errors, blade asymmetry, as well as unusual morphology.

At last, a rather recent effort by Maloney[101] focusing on the quantification of time investment as a proxy of technological complexity is also worth attention. More specifically, he applied the concept of "procedural unit," defined as "mutually exclusive manufacturing steps that make a distinct contribution to the finished form of a technology" according to Perrault et al.,[102: S398] into the analyses of Kimberly Point's reduction sequence as compared with direct percussion point, showing the significantly higher time cost in the former technology. Nevertheless, no experimental or ethnographic data were given to justify the time estimation of each procedural unit identified. Drawing upon the classical models of technological organization, Maloney also made a series of predictions on how different combinations of raw materials cost and technological complexity will affect the mechanisms of social learning. First, there will be a positive relationship between the dependence of social learning and technological complexity. When raw material cost is high, the innovation rate is always low. When raw materials cost is low, complex technologies will possibly generate a higher innovation rate while easy technologies feature low error transfer of knowledge.

As compared with case studies guided by the ACE model, the skill level approaches incorporate more factors such as raw material economy,[99,101] land-use strategies,[100] and various technological components of artifacts. They also avoid the heavy reliance on formal tools as reflected in the former approach, which often account for only a small part of the whole lithic assemblage. Instead, cores[97,99] and blanks[100] are often given more attention since they are believed to be more informative in terms of the actual knapping process. Nonetheless, the absence of a standardized framework, at least for the same technological system, calls its replicability and generalizability into question, impeding its wide adoption in large-scale comparative analyses for the study of macroevolutionary processes.[48] To some extent, the contrast between the skill level approaches and the ACE model recapitulates the diverging research interests of EES and CET.

4 Identifying cultural reproduction at the inter-site level

Finally, there is research on variation at the intra-site level, which has largely focused on distinguishing the relative importance of cultural (horizontal transmission across space) vs. demic (vertical transmission across space) diffusion in explaining similarities between sites. Compared with intra-site level inference as presented above, the identification of cultural reproduction processes at the inter-site level is an exceptionally challenging task as multiple factors need to be carefully analyzed, especially the possibility of convergent evolution that will be discussed in more detail later. Based on a classical CET-informed study of contemporary cultural variation in Africa,[103] it is generally expected that the similarity in lithic assemblages caused by cultural diffusion should be more distance-dependent, with the assumption that the closest neighboring community should display the highest level of similarity, and vice versa. Conversely, demic diffusion predicts that the variability in stone tools should be correlated to the variability of ethno-linguistic groups. Leaving the rigor of this framework aside for now, it is commonplace to see the data required for inferring the demic diffusion is unavailable in archaeological contexts. In fact, the cultural diffusion hypothesis is often tested against alternative hypotheses like environmental constraint or land-use strategies in archaeological case studies. This fact again points to the complexity of translating insights derived from formal models to real-world empirical studies given the low quality of most archaeological data.[104]

4.1 Cultural and demic diffusion

For instance, Buchanan and Collard[20] analyzed a continent-wide dataset of near-complete Early Paleoindian (ca. 11,500–10,500 B.P.) projectile points using cladistics and tested several competing hypotheses on the formation of inter-assemblage variability of projectile points. First, the site type hypothesis predicts the correlation between projectile point morphology and site function (habitation, butchery, cache). Second, the cultural diffusion hypothesis expects the correlation of projectile point shape with geographic distance as a result of the horizontal transmission of technology among neighboring groups. Third, the environmental adaptation hypothesis posits that similar projectile points will occur in similar environments as a result of adaptation. To test these hypotheses, this study used landmark-based geometric morphometrics to reconstruct different cladograms under various hypotheses, suggesting that the cultural diffusion model is the most parsimonious one. The combination of geometric morphometrics and phylogenetic analyses of projectile points also represent one of the most studied and published topics in the inference of inter-site cultural transmission,[105,106] which is in parallel with another line of inquiry operationalizing the cultural distance through the presence/absence of certain lithic tool types.[107] However, it inevitably shares some similar limitations as the ACE model in terms of its heavy reliance on formal tool morphological data as we argued earlier.

The consequences of spatial proximity on material culture and their implications to reverse inference have always been the central issue of studies on the diffusion of culture. Mackay et al.[108] adopted a somewhat similar approach when testing the role of cultural diffusion and environmental adaptation in the generation of lithic variability in MSA and LSA southernmost Africa. They proposed that the source of innovation should represent the maximum diversity of tool forms, and there should be a negative relationship between the distance of two sites and their cultural similarity. If the environment is the dominant factor, the tool form is expected to track the environmental variation according to the previous point. Drawing on the formal modeling results,[23,109] they have also explicitly laid out the expectations of these two hypotheses at the single-site level. To be more specific, the frequency distribution of a supposedly stone tool innovation across archaeological layers should follow the sigmoid-shaped uptake curves when it is culturally transmitted, featuring a slow initial reception and then a rapid growth until saturation. When this innovation is adaptively neutral, it should follow a "battleship" curve derived from a ceramic drift model. Nonetheless, their work only presents a verbal model and no actual frequency curve data was tested against these formal hypotheses. In addition to the detailed phylogenetic or general comparative analysis of lithic assemblages across sites, archaeologists have also identified the diffusion of certain technology[80] and even the possible routes of transmission based on the chronology of its first appearance at certain sites and the distance between these sites, such as Acheulian[110] and Gravettian,[111] although it has been debated which modeling method is the most appropriate one in this type of analysis.[112]

A common feature of the case studies presented above is that they are all large-scale syntheses using second-hand data, but it is also possible to infer inter-site cultural reproduction from detailed technologies studies of just a few assemblages. This approach is recently demonstrated in an attempt to reconstruct the potential cultural transmission processes in different temporal and spatial scales based on the 3-D analysis of cores by Valletta et al..[113] They defined three quantifiable technological indices to identify cultural "lineages" and local learning communities, among which two indices are particularly relevant here in that they reflect different levels of transmission visibility. The first one is core reduction modality, measured as "the ratio between width of the reduction surface and core thickness" and generally operationalized into two types in this case study, namely the narrow-front and the wide-front. It represents the more visible trait that can be inferred from the end-product relatively easily, which is used to infer cultural continuity through time. The second one is longitudinal profile, calculated as "the average angle between the most regular portion of the relative striking platform and different, consecutive portions of the blank scar surface."[113: 150-152] This technological trait is argued to be only visible through the knapping actions and thereby indicating more strict contemporaneity and stronger social intimacy of the demonstrators and learners, justifying its use in the identification of different learning communities within a region. This study essentially shares the inner logic of Tostevin's taskscape visibility approach,[1] which includes a series of logically feasible but empirically untested assumptions in terms of the differential visibility of various technological traits. Nevertheless, determining what these traits actually indicate with respect to social intimacy and visibility requires more evidence from ecological valid experiments featuring real-world skills, authentic raw materials, a realistic training period, and a naturalistic pedagogy.[e.g., 82]

Although the demic-cultural divide seems to be an intuitive conceptual framework, the direct contrast between demic diffusion and cultural diffusion has been rarely made in the cases of lithic studies. However, Fort's[114] analysis of the spread of agriculture in Europe may be illuminating here. In his model, it was hypothesized that cultural diffusion and demic diffusion have differentiated speed in the spread of farming, where the former is slow while the latter is fast. This is a reasonable hypothesis because it should take a longer time for hunter-gatherers to fully replace their old subsistence practice with farming marked with the long-term payoff and delayed consumption. Meanwhile, farmers can quickly start to grow crops after moving to a new place. It can also be generalized to many other cultural traits due to cultural inertia, referring to a general preference of what already exists within a community and a resistance to technological innovations or novel social relationships. By mapping the early Neolithic sites in Europe and simulating the transmission speed with radiocarbon dates, he suggested that cultural diffusion was at work in Northern Europe, the Alpine region, and west of the Black Sea while demic diffusion can best explain the introduction of farming in Balkans and Central Europe, which was partially confirmed by ancient DNA data. A limitation of this method is that it requires large-scale high-resolution chronological data, making it difficult to be applied in Early and Middle Paleolithic assemblages which are beyond the scope of radiocarbon dating.[115]

Perhaps for this reason there are no strong and direct empirical case studies in demic diffusion of lithic technologies. Nevertheless, demic diffusion has been treated as a self-evident assumption behind some popular narratives of the global dispersal of Anatomically Modern Human (AMH), a tendency that has been argued to reflect the continued influence of a colonialist mindset in paleoanthropology.[74] With respect to lithics in particular, it has been argued by Mellars[116] that the similarity between geometric backed artifacts in the Howieson's Poort of South Africa, the Uluzzian culture in Southern Europe, and multiple Late Pleistocene assemblages in South Asia is a result of AMH diffusion into Eurasia around 50,000-45,000 years ago. However, this specific model of demic diffusion was critiqued by Clarkson and his colleagues,[117] among others. Likewise, the implications of Initial Upper Paleolithic, a broadly distributed archaeological phenomenon across Eurasia characterized by blade production with Levallois-like technological elements,[118] to demic diffusion and its alternative explanations have been a hotly debated topic during the past two decades[119–121]. Therefore, this is a promising topic for Paleolithic archaeology despite the problem of data quality and the lack of empirical valid research design. We would also like to caution here that without proper contextualization this line of inquiry can have some dangerous political implications, which have been used to justify the racist and colonist ideologies and deny the indigenous sovereignty.[122]

4.2 Convergence in lithic technology

These disputes naturally re-situate convergence as a central issue in the study of diffusion,[123,124] reminding one of the early critiques towards the hyper-diffusionism and hyper-migrationism. Simply put, a similar cultural trait occurring in two different temporal and/or spatial frameworks can be a result of independent innovation instead of information exchange. Such convergence is expected to be common considering the reductive nature and the limited design space of stone tool technologies. It is commonly assumed that convergence is the most plausible explanation for two similar cultural traits that are extremely distant in time[125] and/or space.[126] Another powerful criterion for identifying independent local evolution is the presence of technological continuity within a single archaeological sequence as, for example, in the case of the emerging presence of Levallois products within Late Acheulian contexts at Nor Geghi 1, Armenia.[127] In contrast, sharp technological discontinuities are more consistent with diffusion (demic and/or cultural).

Likewise, revealing the functional advantages of certain technologies like backed microliths and the shared environmental pressures can also make a strong case for convergence, following its original meaning in biology.[117] Nevertheless, a note of caution here is that the adaptiveness of certain traits does not necessarily exclude the possibilities of diffusion any more than the possibility of individual re-invention precludes actual reliance on social learning.[56] Ultimately, a broader geographical and chronological context is required for confident interpretation.

It should be also noted that various researchers apply the concept of convergence to cultural traits in different scales,[128,129] including a generalized technology such as least effort (cf. "Oldowan") flake production, or a specific technological solution like backing, or the contour of a specific type of tools, which may vary drastically in the probability of being invented independently. To illustrate the issue of scale, a recent case study by Smallwood et al.[125] tested the hypothesis of convergent evolution of Dalton and Scallorn points, two types of serrated projectile points in central North America using phylogenetics and geometric morphometrics. This study has a rather unique research design as what they tested is a single tool attribute, which could be subject to more intuitively obvious adaptive explanations, rather than more general types of artifacts or reduction technologies. The Dalton point is the first serrated bifacial point in North America (ca. 12,500-11,300 B.P.), while the Scallorn point, a serrated triangular-shaped projectile point, appeared roughly 11,000 years later than the former. A conventional, multi-trait cladistic analysis revealed that these two types have a distant evolutionary relationship despite sharing the particular feature of serration. Accordingly, Smallwood et al. suggested that serration may be an example of convergent technological evolution driven by the functional effectiveness of this trait in causing wound tearing that is useful both for generating blood trails to track smaller and quicker prey and facilitating the butchery of larger prey. Despite sharing similar analytical methods and research topics with several cases studies presented above, this study is distinct in that it focuses on a shared design feature contextualized by calculating the evolutionary distance of more neutral traits. We believe it has the potential of being applied to other regional and temporal contexts with minor modifications.

The boundaries between convergence, cultural diffusion, and demic diffusion can sometimes be rather fluid. Just like convergence in biological evolution, technological convergence can be made more or less likely by a range of factors, including cultural, ecological, and social inheritance contexts that may themselves be inherited (i.e., homologous) even if the technological trait itself is independently reinvented (cf. "deep homology" in biology). The product of convergence will in turn assert influence over the cultural reproduction processes. This essentially suggests the comparative nature of the concept of convergence since a technique that is locally evolved and argued to be a result of convergent evolution can itself become an origin point of diffusion in the surrounding area. When the reference point changes, one might need to reconsider the use of convergence in explaining a novel technological phenomenon. Unfortunately, it is quite often that archaeologists only care to demonstrate a new trait's independence to earlier contexts but not its potential connections with other contemporaneous or later contexts. Conversely, it is unreasonable to assume that the similarity/dissimilarity among certain lithic assemblages can be exclusively explained by cultural or demic diffusion rather than convergence. The complex reality requires one to carefully evaluate the importance of various reproduction and non-reproduction factors ranging from paleotopography and land use strategies to population size and structure.

5 Conclusions

Understanding the nature, origins, and processes of human cultural evolution is a vast enterprise calling for pluralistic approaches. We have argued that mainstream CET is a productive research paradigm with clear virtues in terms of its broad generalizability and amenability to formal modeling, but that it may be less well suited to investigating the causal-historical details of particular cases that are often the focus in evolutionary archaeology. We thus join others (Prentiss, etc.) in advocating a more "extended" evolutionary archaeology theory that emphasizes a wider range of evolutionary causes and replaces the formal simplification of cultural transmission as abstract information copying with a more complex treatment of cultural reproduction as an active, concretely grounded, contextually situated, and evolutionarily generative process.

Inferring cultural reproduction from lithic artifacts in particular is a profoundly challenging task due to the mismatch between the resolution[104] and estimand[25] of theoretical model and empirical data, which is partly driven by the taphonomic processes and biases of archaeological sampling. Nonetheless, the successful identification of these obstacles can guide us to develop more appropriate models for archaeological research and better recognize the matching empirical observables informed by middle-range approaches like ethnography and experiments. The very first step here would be acknowledging the complexity of cultural reproduction and moving beyond the paradigm of "culture as information" since information copying as the central mechanism of "transmission" does not accurately capture the actual demands and processes of learning.[15] This position motivates our terminological choice of reproduction over transmission in the title of this review paper.

At the methodological level, we believe it is promising to promote large-scale lab collaboration on ecologically valid experiments of knapping skill reproduction.[130] Through large-scale collaborative experiments, we can also compare the learnability, or the chance of being transmitted accurately from demonstrator to learner, of different morphological and technological traits. This solution also entails the need to move beyond morphometrics and develop more process-oriented approaches. To illustrate, the high similarity of flake morphometrics across different reduction sequences, from Acheulean to Clovis point, conducted by Eren et al.[131] probably suggested this is not the most useful method in inferring cultural reproduction. The identification of cultural reproduction processes is intrinsically bound with the measurement of similarity between two lithic assemblages. As presented above, the most common measurement is the outline form of certain types of diagnostic tools, which can be performed in a traditional manner or using geometric morphometrics. Another approach is to dismantle the reduction sequence into different domains such as platform maintenance, dorsal convexities management, elongated blanks production[1] and then make the comparison respectively. The data can be in simple presence/absence or continuous metric form. Both methods can be informative in many contexts. Another way to approach this issue could be the action grammar proposed by Stout et al.[132] With the aid of cutting-edge machine learning techniques, it is possible to perform the inverse inference from end-product to knapping actions and thus compare the structural similarity between assemblages. Combining these measurements, it is possible to increase the resolution of research in the cultural reproduction of lithic technologies. Again, the future of this field lies in the development of more theory-driven and empirically testable models of cultural reproduction, where computation modeling and middle-range approaches such as ethnography and experiment have huge potentials to be explored.

6 Table

Table 1: Hewlett and Cavalli-Sforza's model of cultural transmission.[7: 923] Note: Here Hewlett and Cavalli-Sforza used "horizontal transmission" to include both horizontal and oblique transmissions for simplicity, which is probably not endorsed by many researchers studying developmental differences,[43,96] although there is essentially a conceptual overlap between the modes of one-to-many/many-to-one and the ignored mode of oblique transmission.

Features | Modes	Vertical transmission	Horizontal transmission	One-to-many	Concerted or many to one
Transmitter	Parent(s)	Unrelated	Teacher/ leader/ media	Older members of social group
Transmittee	Child	Unrelated	Pupils/ citizens/ audience	Younger members of social group
Acceptance of innovation	Intermediate difficulty	Easy	Easy	Very difficult
Variation between individuals within population	High	Can be high	Low	Lowest
Variation between groups	High	Can be high	Can be high	Smallest
Cultural evolution	Slow	Can be rapid	Most rapid	Most conservative

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8 Author biographies

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