

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 also led to confusion and controversy due to an under-examination of methodological assumptions and/or inconsistent use of terminology. The time is thus ripe for an assessment of recent progress in the study of the cultural reproduction of lithic technology. Here we review three central research topics: 1) culture origins, and the identification and interpretation of patterning at 2) intra-site, and 3) inter-site levels. This is followed by further thoughts on how to proceed from the current state of debate with theoretical and methodological pluralism.

Keywords: Cultural transmission, Social learning, Lithic technology, Archaeological evidence

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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 Despite this fundamental ambiguity, the culture concept continues to lie at the heart of basic units of archaeological taxonomy (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^{2,3} and psychological approaches to social learning.^{4,5} These influences have been immensely 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 three key research topics in lithic technology: 1) culture origins, and the identification and interpretation of patterning at 2) intra-site, and 3) inter-site levels.

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 Feldman³ first systematically advocated the comparability between genetic and cultural inheritance systems in their groundbreaking work, *Cultural Transmission and Evolution: A*

61 *Quantitative Approach*. In this book, they argued that the transmission of cultural knowledge
62 is analogous to genetic inheritance in that it involves copying (reproduction) with the potential
63 for modification (mutation), thus leading to variation and the potential for both random (drift)
64 and adaptive (selection) evolution. They also considered important disanalogies. This included
65 the distinction between the Darwinian selection of organisms through differential survival and
66 reproduction (fitness) and the *cultural* selection of traits through individual decisions with
67 respect to some form of cultural fitness (glossed as “appeal,” p. 19). However, the bulk of the book
68 was devoted exploring the disanalogy between the (almost) exclusively vertical transmission of
69 genetic material from parents to offspring and the rampant horizontal (peer-to-peer) and oblique
70 (non-parental elder to juvenile) transmission additionally present in cultural evolution.

71 Cavalli-Sforza and Feldman's original models were later modified and adopted in the ethnographic
72 case study of Aka pygmies, in which oblique transmission was subsumed under horizontal and
73 two new channels of one-to-many and many-to-one were introduced.⁶ This updated model
74 generated clear expectations (Table. 1) that could be readily translated into measurable traits in
75 artifact assemblages and thus served as the theoretical foundation for archaeological studies of
76 cultural transmission.⁷

77 Concepts of cultural fitness and adaptation were more fully explored by Robert Boyd and Peter
78 Richerson in their landmark *Culture and Evolutionary Processes*.² In this book, Boyd and Richerson
79 developed the Dual Inheritance Theory (DIT, now commonly known as gene-culture coevolution
80 theory) as a framework for considering potential interactions between cultural and biological
81 evolution. In DIT, culture change can happen in two ways. First, *natural* selection can act on
82 culture bearing individuals, in which case it is generally expected to increase the frequency of
83 adaptive culture traits. Second, *cultural* selection can occur on the traits themselves, in which
84 case biologically non-adaptive or even maladaptive traits can be favored. Cultural selection occurs
85 through the adoption choices of individuals, and biases affecting these choices (i.e., the “cultural
86 fitness” of variants) need not align with biological fitness. Boyd and Richerson thus conceptualize
87 cultural fitness in terms of psychological processes or dispositions they term “transmission
88 biases” that affect the likelihood of individuals adopting particular cultural traits. These include
89 “direct” biases due to inherent features (e.g., effectiveness, memorability) of the trait, “indirect”
90 biases based on characteristics of the model demonstrating the trait (e.g., success, prestige), and
91 frequency-dependent biases such as a preference to copy the most common trait (conformity).

92 Importantly for archaeology, DIT also considered the spatial dimensions of transmission, coining
93 the terms symmetrical (as an equivalent of vertical and oblique modes) and asymmetrical (as
94 an equivalent of horizontal mode) transmission across space. The operating forces of these two
95 mechanisms are quite different in that the former one is characterized by demic diffusion through
96 natal dispersal while the latter is not.

97 DIT holds that cultural evolution need not increase biological fitness in all cases, but nevertheless
98 posits that it frequently *does*. In fact, cultural evolution has been held up as the critical “secret”
99 to the demographic expansion and adaptive potential of our species.^{8,9} There has thus been
100 substantial interest in modeling conditions under which various transmission biases (often now
101 termed social learning strategies)¹⁰ would be expected to produce biological fitness enhancement.
102 For example, Boyd and Richerson² showed that conformity and prestige biases can increase
103 the probability of individuals selecting locally adaptive traits even in the absence of any direct
104 evaluation of trait merits. Under appropriate conditions, natural selection would thus favor these
105 transmission biases, leading them to become species-typical features of human psychology that
106 help to ensure the adaptive nature of cultural evolution. However, these biases would still be
107 insufficient to explain the production of locally adaptive variants to copy in the first place.

108 Boyd and Richerson address this with the concept of “guided variation,” now more frequently
109 termed individual learning. It is controversial to what extent individual learning relies on “blind”
110 trial and error vs. directed experimentation based on some form of causal understanding,¹¹ but
111 in any case it is expected to guide variation toward desired outcomes. If, in line with Human
112 Behavioral Ecology theory,¹² it is further assumed that humans generally act as biological fitness
113 maximizers then such learning will be biased toward the production of adaptive variants so long
114 as individuals have the cognitive, perceptual, and experiential capacity to identify the associated
115 fitness benefits.¹³ However, it is not clear that individual-learning objectives are necessarily any
116 more likely to be related to biological fitness than are social-learning adoption choices and the
117 concept of fitness as applied to cultural evolution remains under-theorized.¹⁴

118 The quantitative evolutionary approach pioneered by researchers like Cavalli-Sforza, Feldman,
119 Boyd, and Richerson has been immensely influential and productive for the study of human
120 culture and cognition in general^{9,15,16} and for archaeological approaches to understanding past
121 culture change in particular.^{7,17–19} However, applying the abstract, formal models of cultural evo-
122 lutionary theory to real-world archaeological data is not a straightforward process²⁰ 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, including the underlying “culture as information” paradigm that cultural evolutionary theory inherited from its population genetics origins.

1.2 Culture as Information

Evolutionary archaeology¹⁹ follows cultural evolutionary theory (CET) in conceptualizing culture as information held in the minds of individuals. As phrased by Richerson and Boyd:^{21: 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”²² 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 as well, 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.”^{23: 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*.²⁴ This approach has been especially popular among archaeologists interested in apprenticeship and the co-production of material, mental, and social structures more generally,²⁵ but the informational conception of culture as content to be transmitted or copied has remained dominant in CET and evolutionary archaeology.

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.²⁶ 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,”^{3: 5} the EES contends that “phenotypes are not inherited, they are reconstructed in development.”^{26: 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 “how the information came to be there in the first place.”^{27: 231} 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 culture reproduction and change beyond the social transmission of cultural information.

This is clearly exemplified by 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,²⁸ social structure²⁰ and institutions,²⁹ intrinsic features of¹³ and/or interactions between³⁰ technologies, and potential coevolutionary relationships between these diverse factors.³¹ Indeed, the CET literature is already replete with examples of material and 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.^{32: Table 11.2} 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. As in gene-centered approaches to biological evolution, the latter are expected to be expressed in purely terms of the population dynamics of information variation, transmission, and selection.

An alternative, EES inspired, approach would be to emphasize the causal power of such “proximate” mechanisms to actually 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 allow for optimization even in the absence of selection.¹¹ 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.³³ In humans, ecology, ideology, and economics can affect the nature, frequency, and retention of innovations³⁴ and particular technologies may be more or less evolvable due to the modularity vs. interdependence of component parts or procedures.³⁵

As with the EES more broadly, this 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 in the questions and objectives of different research programs.³⁶ This is equally true with respect to the study of cultural evolution. Richerson and Boyd^{21: 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.²⁰ This parallels the case with the EES, which may be most relevant and helpful to researchers interested in detailed explanations of particular evolutionary histories.³⁶ 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 theory of Bourdieu²⁴ and others has not generally been seen as amenable to practical application in evolutionary archaeology. One notable exception is Ingold's^{37: 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,²⁰ 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 Sperber³⁸ and colleagues.³⁹ 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 Richerson² but is a more inclusive concept that need not involve psychological factors affecting individual learning or lead to goal-directed enhancement.⁴⁰ Critically, 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.³⁹ 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,⁴¹ perceptual-motor constraints,⁴² social contexts,²⁹ and ecological interactions⁴³ 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,³⁹ 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”^{40: 3} yet to produce concrete archaeological predictions and applications comparable to CET.⁷

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.⁴³ 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 in a minimal sense (behavioral variation acquired and maintained by social learning) but humans are distinguished by our capacity for cumulative cultural evolution (CCE).⁴⁴ This capacity, thought to be rooted in unique human psychological adaptations for high fidelity social learning,^{5,16,45} 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.”^{8: 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”⁸ or crossing of an evolutionary Rubicon⁹ that put humans on a novel gene-culture co-evolutionary 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.”^{16: 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^{13,14} to archaeological criteria for diagnosing its presence.^{46,47} 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.^{2: 35} Boyd and Richerson⁴⁴ 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,⁵ these 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 behaviors⁴⁶ or suites of behaviors⁹ demonstrably beyond the inventive capacity of individuals. It would also be expected to produce evidence of increased rates of culture change and diversification^{21,46} and obligate reliance on teaching and/or imitation as mechanisms of cultural reproduction.^{5,45} 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 opportunity¹⁴ and, conversely, the fact that demonstrating that individual reinvention of a behavior is possible (for modern apes or humans) does not actually show that this is how the behavior was learned in the past.⁴⁷ Other issues are more conceptual and theoretical.

2.1 Requirements for CCE

As framed, the formal CCE concept depends on 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.¹⁵ This weakens the assumption that all instances of CCE required costly special purpose 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.⁴⁸ In fact, such individual reconstruction may actually enhance the fidelity of cultural reproduction,⁴⁹ which is a key factor promoting CCE.¹⁶ 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.⁵⁰ All of this calls into question the expectation that CCE capacity emerged in a single threshold event marked by archaeological evidence of teaching, 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 theo-

retical, experimental, and archaeological approaches to CCE origins,^{47,51,52} including especially the “Zone of Latent Solutions” (ZLS) hypothesis,^{45,53} which seeks to explain Paleolithic technologies in the absence of CCE capacity.⁴⁶ As originally framed,⁴⁵ the ZLS hypothesis distinguishes between non-human (“minimal”) cultural traditions maintained by convergent individual learning and low-fidelity social learning mechanisms, such as the direction of attention (stimulus enhancement) and product copying (emulation), and human cumulative culture, which requires “high-fidelity” *process* copying (imitation) and/or active teaching and norm enforcement. Note that this use of “imitation” to refer to body movement reenactment specifically differs from the looser use of the term as a synonym for social learning in the early culture evolution literature.⁵⁴ It is now recognized that imitation in this narrow sense may be necessary for the reproduction of arbitrary communicative or ritual behaviors but actually has relatively little utility for the reproduction of real-world technological skills,^{47,54} in which the emulation of products and outcomes (cf. “goals”) may be more important than the reproduction of idiosyncratic body movements. Consequently, the ZLS hypothesis has been modified⁵³ to move away from the problematic high vs. low fidelity distinction in favor of a dichotomy between “copying” and “non-copying” forms of social learning, with the former now including the copying of artifact forms (i.e., end-state emulation or “product copying,” previously considered low-fidelity).

This begins to approximate more traditional archaeological criteria^{47: 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 duration¹⁶ to allow innovation (guided variation) to accumulate.⁴⁴ Whether this is accomplished thorough observational copying or the persistence of structured trial and error learning situations^{13,49,55} is beside the point. In fact, the intentional provision of practice opportunities and direction of learners’ attention can also be considered as forms of teaching⁵⁶ and appear to be important for the reproduction of skills in small scale societies⁵⁷ including stone tool making.⁵⁸ The intention to scaffold learning in this way might depend on novel human social cognition,⁵ 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 situations¹³ as well as “information.” Such ecological inheritance is explicitly excluded from the CET culture concept,^{2: 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.”^{9,13} It is without question that humans culturally reproduce many such complex behaviors whereas these are rare or absent in other animals,⁵⁹ 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.^{47: 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 Richerson⁴⁴ explicitly attempted to explain iteratively increasing biological fitness but incorporated a reaction norm limit to individual learning that was verbally related to the increasing complexity of the fitness-enhancing skill, thus establishing an implicit link between fitness, complexity, and a more generic sense of improvement rather than mere increase. Subsequently, the CCE concept has often shifted to focus on increasing complexity *per se*⁵⁹ or been applied more broadly to discuss “improvement in performance as a proxy for genetic and/or cultural fitness.”^{14: 2} This elision from “increase” to “improvement” is dangerous for archaeology given the discipline’s long history of promoting racist and progressivist colonial hierarchies.⁶⁰

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 Thornton¹⁴ 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 archeologists.

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 coevolution⁴⁴ 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.²⁶ Given the danger of progressivist misinterpretation of the term "cumulative" and its established implication of improvement, it might 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 such as Achuelean handaxe production thus becomes a "problem" requiring special explanation, for example in terms of a lack of CCE capacity,^{46,52} genetic encoding of behavior,^{21,61} or transmission failures in small, dispersed populations.⁹ However, it is not entirely clear that CCE predominates even in recent human evolution.⁶² An alternative to this deficit model is to consider that stasis might also reflect locally optimal adaptation. In fact, archaeologists often consider stabilizing influences (cf. "factors of attraction" in CAT), such as design constraints⁶³ or the role of tools in larger behavioral ecological strategies.²⁸ 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 climatically-driven habitat shifts.⁶⁴ Finally, there are evolving organismal factors of attrac-

tion such as more general perceptual-motor and cognitive capacities^{42,47} or biomechanics and manipulative capacities⁶⁵ 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.

3 Identifying cultural reproduction at the intra-site level

Unlike the fierce debate over the learning capacities of early members within hominin lineage, it seems that the presence/absence of cultural transmission among subdivided populations of *Homo sapiens* is not a question worth reflection or discussion. Rather, the research attention in later prehistory has been shifted to the identification of social learning strategies and the mode of cultural transmission. Social learning strategies (SLSs) refers 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 This concept and the term transmission bias is usually used in an interchangeable manner, which is directly derived from the pilot work of Boyd and Richerson.² On the other hand, the mode of cultural transmission is deeply rooted in the research tradition developed by Cavalli-Sforza and Feldman,^{cavalli1981?} designed for describing the relationships between the demonstrators and learners (vertical/horizontal/oblique/one-to-many/many-to-one). It is worth noting that these two dimensions are discussed together here because they are theoretically interlocked and rarely separated in empirical studies presented below.

Many empirical cases within this line of inquiry primarily studied the projectile point technologies in North America using Pearson’s *r* Correlation Coefficient and Coefficient of Variation (CV) of simple morphometric data. Bettinger and Eerkens’s^{66,67} pioneer research comparing the regional morphological variation of Rosegate Points (1,350-650 B.P.) between central Nevada and eastern California are among the first trials of identifying SLSs in lithic assemblages based on DIT. 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. Specifically, they found the metric attributes of Rosegate points in central Nevada were highly correlated with each other, which was

429 interpreted as a result of the indirect bias in cultural transmission, namely wholesale copying
430 from a single successful or prestigious model. On the other hand, the poor correlations between
431 length, width, thickness, weight, and shoulder angle in eastern California were subject to guided
432 variation, or individual trial-and-error experimentation. A tentative explanation on the regional
433 difference of SLSs given by them is that groups living in east California may have acquired this
434 new bow-and-arrow technology from people with large social distance, “possibly a different
435 linguistic unit occasionally contacted through trade.”⁶⁷: 238

436 Mesoudi and O’Brien^{68,69} further investigated the same question through behavioral experiments
437 and agent-based modeling. In their studies, they asked human participants to modify five
438 attributes (length, width, thickness, shape, and color) of “virtual projectile points” to adapt
439 the changing “virtually hunting environments” under different learning conditions, including
440 copying the most successful, individual learning, and horizontal transmission. For simulated
441 agents, all others being equal, they have also added the strategies of copying at random, copying
442 the majority, as well as copying the average. First and foremost, their simulations did confirm
443 Bettinger and Eerkens’s⁶⁷ results that indirect bias will generate significantly higher correlations
444 between attributes compared with guided variation. More interestingly, they also found that
445 correlations between variables in “model-based” strategies (copying the most successful and
446 copying at random) are generally higher than those in “trait-based strategies (copying the majority
447 and copying the average),” but they doubt if this difference is visible in archaeological records
448 solely based on attribute correlations or measures of variation. Therefore, they proposed that the
449 criterion of fitness should also be included into consideration, meaning the strategy that can help
450 you better survive in the changing environments has the highest possibility of being adopted, and
451 their modeling results suggested that copying the most successful outperforms all other SLSs.

452 Another research by Eerkens and Bettinger⁷⁰ reflected on the choice of statistics and argued
453 that CV is a more robust statistical technique for measuring morphological variability in the
454 cases of cross-assemblage comparison and assemblages with small sample size. They have also
455 introduced the concept of Weber’s fraction from psychology, a threshold of human perception of
456 differences between two visible traits such as length, weight or area. In particular, two constants
457 in CV were provided as a reference framework of artifact standardization or variability: 1.7% as the
458 highest degree of standardization through human’s manual production and 57.7% as generated
459 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.⁷¹

Garvey's⁴³ recent analysis of Washita points from the Henderson site (A.D. 1,250-1,350) located in southeastern New Mexico followed this research agenda. However, what is slightly different is that her hypotheses are formulated in a well-motivated and context-specific manner. Based on the extant research on settlement and subsistence patterns of Henderson, especially zooarchaeological data, she argued that bison was central to its economy and social organization and could be possibly translated to certain successful hunters' reputational capital, forming the basis of indirect bias. In other words, many community members learned projectile point manufacturing technology from very few models. Alternatively, group-affiliative norms, or within-household vertical transmission, may be the stronger source of bias as it is located in a boundary zone between Pueblo farmers and mobile hunters of the southern High Plains and Edwards Plateau. It is expected that a higher degree of morphological variability will be displayed in projectile points under the vertical transmission with a larger pool of models. Subsequently, she 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 supported the latter hypothesis of within-household vertical transmission.

There are two limitations within this series of studies identifying the mode or bias of cultural transmission. First, be it correlation coefficient or CV, the analyses presented above depend on the morphometric measurements of formal tools' outline form exclusively. Due to the limited design space of artifact morphology, especially certain types of laminar technology, it is difficult to rule out the possibility of convergence without information exchange. 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. Realistically, human beings constantly get feedback on learning results and accordingly switch their learning strategies,

and individual learning is almost always necessary, 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 models⁴⁴ and experiments.⁷² Therefore, the identification of mixed SLSs represents an important future direction in this field. Third, as demonstrated by Premo⁷³ using agent-based modeling, population size should also be considered as a key role player in the interpretation of the coefficient of variation of a given continuous trait like lithic metric attributes, since different combinations of population size and transmission mechanisms can produce the same CV values.

Another parallel line of inquiry that is not directly rooted in formal cultural transmission models is the identification and measurement of knapping error. 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.⁷⁴ 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. 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 the frequent failures even for expert knappers.

Castaneda⁷⁵ 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 flint quarry would be an ideal place to study the transmission 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's⁷⁶ 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 greater occurrence of bulb/platform errors, termination errors, blade asymmetry, as well as unusual morphology.

At last, a rather recent effort by Maloney⁷⁷ 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.,^{78: S398} into the analyses of Kimberly Point's reduction sequence as compared with direct percussion point, showing the significant 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, 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.

4 Identifying cultural reproduction at the inter-site level

The identification of cultural transmission processes at the inter-site level is an exceptionally challenging task as multiple factors need to be carefully analyzed. Nevertheless, it can generally be dismantled into two scenarios that are not mutually exclusive, namely cultural diffusion (horizontal transmission across space) and demic diffusion (vertical transmission across space). In principle, it is expected that the similarity in lithic assemblages caused by cultural diffusion should be more distance-dependent, while demic diffusion predicts that the variability in stone tools should be correlated to the variability of ethno-linguistic groups.⁷⁹ For instance, Buchanan and Collard¹⁷ analyzed a continent-wide dataset of near-complete or complete Early Paleoindian (ca. 11,500–10,500 B.P.) projectile points (n=216) 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 first started with the digitalization of graphs and photos from old excavation reports, and these graphs were then translated to numerical data through landmark-based geometric morphometrics, namely the 11 landmark distance focusing on length, width and basal dimensions. For the purpose of size-adjustment, these metric traits were further transformed to “size-free” residuals by regressions on the first principal component derived from all the characters. In the subsequent cladistic analysis, the authors calculated the Permutation-tail probability (PTP), Retention Index (RI), as well as Consistency Index (CI) to determine the most parsimonious cladogram under various hypotheses, which turned out to be the cultural diffusion model. The phylogenetic analyses of projectile points also represent one of the most studied and published topics in the inference of inter-site cultural transmission.⁸⁰⁻⁸³

In terms of the implication of spatial proximity of material culture, Mackay et al.⁸⁴ adopted a somewhat similar approach when testing the role of cultural diffusion and environmental adaptation in the generation of lithic variability in 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,^{85,86} 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 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 Acheulian⁸⁷ and Gravettian⁸⁸, although it has been debated which modeling method is the most appropriate one in this type of analysis.⁸⁹

More recently, Valletta et al.⁹⁰ presented a novel approach to reconstruct the potential cultural transmission processes in different temporal and spatial scales based on the 3-D analysis of cores. They defined three quantifiable technological indices in order 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.”^{90: 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.

The direct contrast between demic diffusion and cultural diffusion has been rarely made in the cases of lithic studies. However, Fort’s^{91,92} analysis of the spread of agriculture in Europe may be illuminating here. In his model, it was hypothesized that cultural diffusion and demic diffusion has 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. 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.⁹³

Although currently there is no strong and direct empirical case study in demic diffusion of lithic technologies, it has been the default narrative embedded in the global dispersal of Anatomically Modern Human (AMH). To give an instance, it has been argued by Mellars^{94,95} 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 colonization of Eurasia by AMH around 50,000-45,000 years ago. This specific model of demic diffusion was objected by several other researchers.⁹⁶⁻⁹⁸ Likewise, there was a debate on whether the presence of overshot flaking in both Solutrean and Clovis can indicate the initial peopling of North America by Upper Paleolithic Europeans.^{99,100}

These disputes naturally introduce a scenario beyond cultural or demic diffusion, namely convergence.^{101,102} Put it differently, a similar cultural trait occurring in two different temporal and/or spatial frameworks can be a result of independent innovation instead of information exchange, which should be common considering the reductive nature and the limited design space of stone tool technologies. It has a particularly strong explanatory power when the technological continuity can be demonstrated within the same archaeological sequence, as shown in the case of the presence of Levallois products within Late Acheulian contexts at Nor Geghi 1, Armenia.¹⁰³ 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.⁹⁶ Nevertheless, it should be noted that various researchers use this concept to refer to cultural traits in different scales, including a generalized technology such as Oldowan core-and-flake technology, 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, a recent research by Smallwood et al.¹⁰⁴ tested the possibility of convergent evolution of Dalton and Scallorn points, two types of serrated projectile points on the Southern Plains-Woodland border 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, namely serration, in lieu of specific types of artifacts or reduction technologies, which could be subject to more intuitively obvious adaptive explanations. It is necessary to introduce the contextual information of these tool types first as it is an indispensable part of the story. The Dalton point and the Dalton complex it represents were dated to the Late Paleoindian period (ca. 12,500-11,300 B.P.), which is the first serrated bifacial point that occurred in North America. It is characterized by a lanceolate morphology with thinned concave bases as well as serration along its lateral edges. In another vein, the appearance of the Scallorn point, a small, narrow-

stemmed, and serrated triangular-shaped projectile point, is roughly 11,000 years later than the introduction of Dalton points. In the cladistic analysis, the authors examine 349 points covering 50 types including 12 Dalton points and 8 Scallorn points and found these two target types have a far evolutionary relationship. At last, this article raised a function-oriented explanation on the convergent evolution of serration as this trait can effectively cause wound tearing to track blood trails of smaller and quicker prey and help process the prey during butcheries.

It seems that convergence is the most plausible explanation when one considers two similar cultural traits that are extremely distant in time or space. However, convergence does not occur in a vacuum, meaning it is still affected by various social cues and assert influence over the cultural transmission processes. Similarly, it is unreasonable to claim that the similarity/dissimilarity among certain lithic assemblages can be exclusively explained by cultural or demic diffusion. The complexity of assemblage formation requires one to carefully evaluate the importance of various transmission and non-transmission factors ranging from paleotopography and land use strategies to population size and structure.

5 Future directions

It is admitted that inferring cultural transmission from lithic artifacts is a profoundly challenging task due to the mismatch between the resolution¹⁰⁵ and estimand¹⁰⁶ of theoretical model and empirical data, which is partly driven by the time averaging¹⁰⁵ and spatial averaging effects¹⁰⁷ of taphonomic processes. Nonetheless, the successful identification of these obstacles can guide us to develop more appropriate mesoscale models for archaeological research¹⁰⁸ and better recognize the matching empirical observables informed by middle range approaches like ethnography and experiments. At the methodological level, here are some future directions we see as promising. First, we should promote the large-scale lab collaboration on transmission experiments of lithic technology as demonstrated by the PaST.¹⁰⁹ Through these large-scale transmission experiments, we can also compare the learnability, or the chance of being transmitted accurately from demonstrator to learner, of different morphological and technological traits. Second, it is necessary to move beyond the 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.¹¹⁰ probably suggested this is not the most useful method in inferring cultural transmission. The identification of cultural transmission processes is intrinsi-

cally 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 reduction sequence into different domains such as platform maintenance, dorsal convexities management, elongated blanks production¹ 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 action of grammar proposed by Stout et al..¹¹¹ 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 transmission of lithic technologies.

This review briefly covers the major theoretical frameworks germane to cultural transmission, mainly dual inheritance theory, as well as the current thinking about its identifications and evolutionary implications in lithic artifacts. Specifically, it synthesizes different perspectives and empirical findings revolving around the following three key issues: 1) the debate over the origin of cultural transmission derived from the inconsistent terminology across literatures; 2) the identification of cultural transmission at the intra-site level; and 3) the identification of cultural transmission at the intra-site level. Unfortunately, many relevant topics are not presented here due to the time constraint, including at least 1) the psychological, cognitive, and neurobiological foundations of learning; 2) the life-history perspective of learning and the identification of children in stone artifacts; 3) the identification of novices and experts as well as knapping mistakes. It is also admitted that this essay is strongly biased towards anglophone scholarship and evolutionary approaches. Nonetheless, what has been presented above has already demonstrated the limitations of currently used proxies in archaeology and thereby a promising research niche waiting for occupation. The future of this field lies in the developments of more theory-driven and empirically testable models of cultural transmission, where middle-range approaches such as ethnography, experiment, and computation modeling have huge potentials to be explored.

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