Evolved Open-Endedness in Cultural Evolution: A New Dimension in Open-Ended Evolution Research

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Abstract

The goal of Artificial Life research, as articulated by Chris Langton, is "to contribute to theoretical biology by locating life-as-we-know-it within the larger picture of life-as-it-could-be" (1989, p. 1). The study and pursuit of open-ended evolution in artificial evolutionary systems exemplifies this goal. However, open-ended evolution research is hampered by two fundamental issues; the struggle to replicate open-endedness in an artificial evolutionary system, and the fact that we only have one system (genetic evolution) from which to draw inspiration. Here we argue that cultural evolution should be seen not only as another real-world example of an open-ended evolutionary system, but that the unique qualities seen in cultural evolution provide us with a new perspective from which we can assess the fundamental properties of, and ask new questions about, open-ended evolutionary systems, especially in regard to evolved openendedness and transitions from bounded to unbounded evolution. Here we provide an overview of culture as an evolutionary system, highlight the interesting case of human cultural evolution as an open-ended evolutionary system, and contextualise cultural evolution under the framework of (evolved) open-ended evolution. We go on to provide a set of new questions that can be asked once we consider cultural evolution within the framework of open-ended evolution, and introduce new insights that we may be able to gain about evolved open-endedness as a result of asking these questions.

Keywords: Cultural Evolution, Open-Ended Evolution, Evolved Open-Endedness, Zone of Latent Solutions, Cumulative Culture

1 Introduction

Genetic evolution appears to be open-ended: taking advantage of environmental regularities, gene expression and regulation can generate a potentially infinite number of traits and trait variations. Such evolutionary open-endedness has been characterized by a constellation of overlapping features, yet can generally be understood as the ability of an evolutionary system to produce a continuous stream of novel units (T. Taylor et al., 2016). For those trying to create and understand open-ended evolutionary systems the goal is (and should) not be to replicate genetic evolution, but instead to understand the underlying principles and dynamics of evolutionary systems in general. This undertaking requires knowledge of the clearest example of an open-ended evolutionary system that we have available to us: genetic evolution; but also the development of artificial evolutionary systems that fully embrace the principles of life-as-it-could-be (Langton, 1989). Such artificial evolutionary systems depart from the rules and principles of Darwinian genetic evolution while still meeting the general requirements of an evolving system. Nevertheless, Darwinian genetic evolution still provides a touchstone to draw inspiration from and provide justification for the decisions made when producing artificial systems. Having only one solid example of a real open-ended system is a problem: it limits one's ability to consider other possibilities and explore more widely in efforts to understand, develop and analyse open-ended evolution. However, it is increasingly being recognised that there is another evolutionary system from which one can find inspiration: cultural evolution (Borg & Powers, 2021; Marriott et al., 2018).

A population of individuals possesses culture if these individuals' acquisition of behavioral traits or beliefs is at least in part influenced by any kind of social learning, and where the traits or knowledge are shared by at least some members of the population, often across generations (Whiten et al., 2022). Cultural evolution is then just the change among cultural traits over time. Although cultural evolution is often described as being analogous to genetic evolution (Cavalli-Sforza & Feldman, 1981), there are clear differences in the way culture is inherited -1. whereas genetic evolution relies on typically two (sometimes one) parent(s), there are a potentially unlimited number of cultural "parents"; 2. where genetic transmission is almost exclusively transmitted vertically from parent to child, cultural transmission can also be horizontally or obliquely transmitted between conspecifics; 3. whereas genetic changes generally occur between generations, cultural change can also happen within generations (Mesoudi, 2011; Mesoudi et al., 2006). While these features distinguish cultural from genetic change, these do not imply that cultural inheritance is in any sense less (or not) "evolutionary", only that its dynamics may differ from those of genetic evolution.

Over the past 40 years there has been increasing recognition that culture and cultural evolution exist among animals (most prominently in birds and mammals) (Whiten, 2019, 2021a, 2021b), and that culture not only exists as a result of genetic adaptation, but also plays an important co-evolutionary role in guiding genetic evolution (Uchiyama et al., 2021; Whitehead et al., 2019). This co-evolutionary relationship between genes, culture, and the environment is sometimes known as "triple inheritance" (Laland et al., 2000). Nonetheless, while many animal species exhibit culture it is clear that human cultural evolution is different. Several dividing lines between human and animal cultures have been proposed, but the most prominent of recent formulations holds human culture to be distinctive in virtue of its cumulative nature – with human culture accumulating modifications over time with a ratchet-like effect of modifications building upon one another (Tomasello, 1999). However, as more observations of cultural evolution in other species have been made, it has become increasingly apparent that cumulative cultural evolution is not unique to human culture alone (Mesoudi & Thornton, 2018). This raises the following question: what, if anything, is unique about human cultural evolution?

To address this question we situate cultural evolution within the broader framework of open-ended evolution and argue that:

- 1. Culture is an evolving system, co-evolving alongside genetic evolution.
- 2. That within cultural species there are a range of "types" of cultural evolution; cumulative (tall) and non-cumulative (wide), unbounded and bounded.
- 3. That having a range of "types" of cultural evolution provides Artificial Life researchers with an opportunity to better understand evolutionary dynamics beyond what one sees in biology, and provides new angles from which to explore open-ended evolution.
- 4. That only humans demonstrate open-ended cumulative cultural evolution and that human cultural evolution has transitioned from a bounded to an unbounded evolutionary system in recent evolutionary history, thus providing us with a clear example of "evolved open-endedness."
- 5. That existing Artificial Life tools can and should be applied to the study of cultural evolution.

To address these points, we outline a number of core concepts from the wider study of cultural evolution before moving on to consider "open-ended evolution" and the role that the study of open-ended cultural evolution could play in better understanding evolutionary dynamics and the emergence of evolved open-ended evolutionary systems. A table of definitions for the key terms used here can be found in table 1.

Term	Definition	See
Cul-	Traits transmitted between and maintained	Cultural
ture	by conspecifics via social learning over a	Evolution
	number of generations	Society (2021)
		and Whiten
		et al. (2022)
Open-	An evolutionary process that is capable of	Gabora and Steel
Ended	producing a continuous stream of new	(2017) and
Evolu-	adaptive novel units, with no <i>a priori</i>	T. Taylor et al.
tion	limitations on the generation of such novelty	(2016)
Cumu-	A body of culturally transmitted traits that	Boyd and
lative	accumulate modifications over time with a	Richerson (1985)
Cul-	ratchet-like effect	and Tomasello
ture		(1999)
Un-	Continuous demonstration of new adaptive	Bedau et al.
bounded	novelty and/or the ongoing growth in trait	(1998) and
Evolu-	diversity. Term used interchangeably with	Channon (2006)
tion	open-ended evolution, but often used to	
	contrast with bounded evolution.	
Evolved	Open-endedness as the outcome of an	Pattee and
Open-	evolutionary process as opposed to an	Sayama (2019)
Endednessassumed pre-condition		

Table 1: Reference table of definitions for key terms

2 Cultural Evolution

What is culture and how does it 'evolve'? As suggested above, a population of individuals is said to possess culture if individuals' acquisition of behavioral traits or beliefs is at least in part influenced by any kind of social learning, and where the traits or knowledge are shared by at least some members of the population, often across generations (Cultural Evolution Society, 2021; Whiten et al., 2022). Defining culture in terms of transmitted behaviors and beliefs encompasses a wide variety of techniques and processes with physical effects on the world. These include extractive foraging techniques among chimpanzees (Sanz et al., 2010) or a method for lighting a fire (MacDonald et al., 2021). It may also encompass behaviors with communicative effects such as warning calls (Griffin, 2004), bird-song, or language (Janik & Slater, 2000). Further, the definition also incorporates population-level behavior such as methods among conspecifics for greeting and leave-taking (Baehren, 2022; Duranti, 1997) as well as normative behaviors such as styles of dress or decoration (Baehren, 2022; Richerson & Henrich, 2009). Again, per the definition, the key is that the acquisition of these behavioral traits or beliefs is influenced by social learning.

2.1 Does Culture Evolve?

The underlying principles of an evolutionary process do not, *a priori*, require the process to be physically embodied or biologically grounded. While familiar processes of biological evolution are grounded in the manipulation and modification of genes, cultural evolution (and evolution more generally) is under no such obligation. Consider Dennett's 1996 conception of evolution as being both algorithmic and substrate neutral. Evolution is algorithmic in the sense that if certain conditions are met, a certain sort of outcome is necessarily produced (Dennett, 1996, p. 48). Where there is reproduction with variation under selection at a population level, a certain kind of outcome is produced – in this case, the frequency of adaptive outcomes is increased in the population over time. In cultural evolution, 'adaptive' can ultimately refer to the cultural trait, and the effects that it has on its own reproduction through the effects it has on its bearers' behavior (Rosenberg, 2017), though the co-evolutionary nature of culture and biology, and the effect culture has on biology, cannot (and should not be) understated (Henrich & McElreath, 2007).

On consensus formulations, the target of reproduction is the informational content carried by some vehicle (whether this is expressed behavior, an artefact, or the instructions of a written account). Artificial Life has often equated such a characterization with the idea of a "meme": a discrete particulate unit of information that is copied intact between brains, analogous to the way that genes are copied between parents and offspring (Dawkins, 1976). However, cultural evolution does not require the process of reproduction and cultural inheritance to be understood in this strict sense. While the literature on this point is vast, Rosenberg (2017) provides a clear summary of the arguments: 1. Replication in biology has not always involved high-fidelity replicators – the major transitions in evolution involve explanations as to how evolution itself has gradually led to higher fidelity transmission processes, starting with the first replicating molecules that were not DNA with its accurate copying mechanisms (Maynard Smith & Szathmáry, 1995); 2. Even in genetic evolution, a single gene can rarely be equated with a single trait – the vast majority of biological traits result from complex interactions between the proteins expressed and regulated by many genes, so why should we demand in cultural evolution that a trait is the product of one discrete meme? 3. Many features of human institutions are adapted to preserve and proliferate cultural traits even under low individual copying fidelity. Variation is introduced in the form of the (re)combination of existing traits, innovation of new traits by individuals (which may involve rational thought), or copying error (loosely analogous to mutation in genetic evolution). Meanwhile, selection may occur in multiple ways. This includes biological selection – that is, the effect that cultural traits have on biological fitness (for instance, being led to belief that something is safe to eat when it is not). It also includes myriad cognitive forms of selection, which may include how memorable (Johnson et al., 2010) or easily communicated something is (e.g., more content-rich words are shorter) (Piantadosi et al., 2011). And if we accept that evolution is algorithmic, it follows that we are not bound to particular features of biological processes (e.g. sexual reproduction), nor are we bound to a specific substrate (e.g. DNA). Though Dennett's conception of cultural evolution is considered out-of-date to modern scholars of cultural evolution (Uhlíř & Stella, 2012), his fundamental argument applies to it nonetheless: the idea of an algorithmic process makes it all the more powerful, since the substrate neutrality it thereby possesses permits us to consider its applications to just about anything (Dennett, 1996). Which is, of course, true. That one can create an evolutionary process within a computer is evidence that the process itself need not be strictly biological, merely algorithmic (Lehman et al., 2020).

2.2 Co-Dependent Evolutionary Systems

Cultural evolution is deeply intertwined with biological evolution. While these evolutionary processes and their products can generate complicated co-evolutionary feedback loops, each evolutionary system can be understood, studied, and modelled separately (Boyd & Richerson, 1985; Mesoudi, 2011). For instance, as we suggest in more detail below, early hominin cultural evolution had substantial fitness in the form of ecological knowledge and technical production. Nonetheless, over time, cultural evolution has become increasingly unmoored from direct fitness effects, producing a wide range of behavioral, social, and technological change (Henrich, 2015). The reason for both the intimacy and relative independence of the two systems should be evident. The substrate of culture is biological: the brain.

Culture is thus bound to a biological substrate, but a substrate which is different from the classical understanding of genetic evolution in which traits are encoded (directly or indirectly) by genes. Gene expression may produce brains and (some) brains may acquire culture, but one cannot skip the middle step and claim that genes produce culture. While humans may be biologically prepared to acquire language (Fitch, 2011), they are not biologically determined to learn English, Farsi, or Korean. Clearly accessibility and exposure to certain kinds of inputs – the presence of English, Farsi, or Korean language cues – determine what language any given human ultimately produces. Or put another way, the acquisition, production, and transmission of language is largely influenced by social learning. And so we cannot simply claim that the process of cultural evolution is independent from biology - though we would not necessarily want to; what we claim is that biological and cultural evolution are interdependent.

The idea that cultural species, and particularly cumulatively cultural species such as Homo sapiens, have two interdependent systems of inheritance has been labelled 'dual inheritance'. On this account, human offspring inherit a genotype from their parents through sexual reproduction and they inherit a body of cultural information over the course of the post-natal lives via processes of social learning (Henrich & McElreath, 2007). And just as one's genotype has been dictated by a history of selection pressures acting on genetic variation, one's cultural inheritance is similarly shaped by selective pressures and the variation introduced through innovation, recombination, and error involved in social learning. Thus, in the same way that certain phenotypic features are adaptations – increasing the biological fitness of individuals – elements of culture may also be adaptations. Consider food taboos present in Fijian society (Henrich & Henrich, 2010; McKerracher et al., 2016) which apply exclusively to pregnant women. Despite the causal opacity of the underlying process, these taboos protect women from miscarriage. Alternatively, consider the ritualized process of cassava production. Again, despite the causal opacity of the underlying process, populations have developed practices that remove toxic cyanogenic elements which would have long-term health consequences if regularly consumed (Banea et al., 1992; Bradbury & Denton, 2011; Cardoso et al., 2005; McKerracher et al., 2016). Of course, it can also be adaptive to acquire cultural elements idiosyncratic to local cultures. Regardless of whether the practice of female or male circumcision has biological benefits, within a circumcising culture, it can be adaptive to demonstrate commitment to the group by engaging in such a costly signal. This can ensure inclusion and support by the group as well as prevent ostracism (Howard & Gibson, 2017; Sosis, 2004) – thus enhancing reproductive outcomes.

Cultural organisms do not only inherit genes and cultural information, but also an environment: that is, a habitat that has been selected, modified, and partly created by their ancestors (triple inheritance, see: Laland et al. (2000)). All organisms change their habitats through their actions – of which spiderwebs, termite mounds, or human-made earthworks are just a few notable examples – with more or less transitory effects. Such organism-modified environments are evolutionary relevant insofar as they modify selection pressures or transmission opportunities – what the evolutionary literature calls niche construction (Laland et al., 2000). Systematic and long-lasting modifications, such as beavers' dambuilding or human agriculture can have profound effects on both biological and cultural evolutionary processes of the species producing these modifications as well as others in the habitat.

While niche construction is not uniquely human, humans are distinctive in that most of their niche construction activities are cultural (e.g., building dams, drainages, bridges, schools, roads, mirrors, clothes). Over evolutionary time, the hominin lineage has created a cultural niche, which has not only affected their biological and cultural evolution by creating new selection pressures, but which has increasingly become crucial for their survival (Laland & O'Brien, 2011; Uchiyama et al., 2021). For example, the use of fire and cooking facilitated selection for larger brains alongside smaller guts and jaws. Yet without fire or cooking, hominins would be poorly adapted to their environments (Aiello & Wheeler, 1995). The second inheritance system – culture – can thus indirectly affect the first – genes – through niche construction. Genes and culture have co-evolved: cultural activities such as tool use and tool making have generated selection pressures for social tolerance and cognitive skills such as social learning, attention, working memory, and language, which in turn have opened up ever greater capacities for cultural innovations, social learning, and large-scale cooperation (Henrich, 2015), creating the biological and cultural conditions for the emergence of open-ended cultural evolution.

Cultural evolution is often faster than genetic evolution: cultural variants

can emerge and recombine quickly and repeatedly within the lifetime of its carrier, and can die independently of the death of the individual (Boyd et al., 2013). Alongside the speed of cultural evolution, humans' capacity for planning and foresight suggests that many human adaptations are cultural or have cultural origins (Uchiyama et al., 2021). Thus, cultural evolution cannot only produce solutions to (ecological) problems, but also create new opportunities and niches that cultural evolution can exploit - an autocatalytic process, resulting in the emergence of unbounded cumulative culture.

3 Open-Ended Cultural Evolution

As noted in the introduction, open-ended evolution is an umbrella term for a constellation of features associated with evolutionary change. These include the ongoing generation of novelties, adaptations, and evolutionary salient entities (T. Taylor et al., 2016). For simplicity sake, we hold that an evolutionary system can generate open-ended evolutionary change if it is able to produce a continuous stream of novel units (evolutionary individuals, traits) with no *a priori* limits to the generation of such novelties (Gabora & Steel, 2017; T. Taylor et al., 2016). As several commentators have noted (Bedau et al., 2019; Pattee & Sayama, 2019; Tennie et al., 2018) cultural evolution appears to be just such an open-ended evolutionary system.

More recently, cultural evolution researchers have used the term "openended" to describe what is unique about human culture (Tennie et al., 2018): not only is human cultural evolution cumulative, in that it generates cultural traits (e.g., behavior, knowledge) that build upon previous traits in ways that can (but not need to) become increasingly more complex and/or efficient over time, but it is also open-ended in that cultural solutions to problems do not need to be stuck at local optima, but can break free and further improve, for instance, by the harnessing of new affordances (Arthur, 2009; Derex, 2022). By focusing on the putative "uniqueness" of human culture, researchers have identified important transitions in the processes, cognitive capacities, and patterns of cultural evolution as hominins have evolved and changed over the past 8 million years.

In the next three subsections we make three distinctions between patterns of cultural evolutionary change: between cumulative and non-cumulative cultural traditions; between ""building-up" or *tall* traditions and the "building-out" of *wide* repertoires of traditions; and between bounded and unbounded evolution. These patterns of cultural evolutionary change are distinct, yet each is important to explaining the open-endedness of cultural evolution. In the final subsection we turn to consider how these distinct kinds of evolutionary patterns may have contributed to the evolution of open-ended cultural evolution in hominins.

In focusing on distinct kinds of evolutionary patterns, and tracing these back to changes in selection pressures, cognitive mechanisms, and social arrangements, the approach taken here differs from recent attempts at describing hallmarks of open-ended evolution (T. Taylor et al., 2016). Hallmarks are signals, such that if one encountered them, this is good evidence that the evolutionary system is capable of open-ended evolution. By contrast, our approach distinguishes patterns that are associated with evolutionary processes. These processes are critical to, but not necessarily sufficient for, open-ended evolution. Distinguishing these processes helps to identify those important for evolving open-endedness, as well as how the interaction between such processes may be important to the eventual emergence of a system supporting full-blown openended evolution.

3.1 Cumulative vs. Non Cumulative

A key distinction drawn by cultural evolution researchers is that between cumulative and non-cumulative culture. As many researchers see it, cumulative culture is central to explaining how human beings could have developed the sophisticated technical toolkits that allowed them to survive and thrive across varying – and sometimes extreme – ecologies (Grove, 2011; Henrich, 2015; Potts, 2013; Richerson & Boyd, 2005). Based on extensive human and non-human experiments, and a number of computational and mathematical models, Mesoudi and Thornton (2018) have suggested "core" criteria that cultural evolutionary process would have to satisfy in order to be classified as cumulative:

- 1. a change in behavior, followed by ...
- 2. ... transfer of the modified or novel trait via social learning, where ...
- 3. ... the learned trait results in an "improvement" in performance/fitness (cultural or genetic), with ...
- 4. ... the previous steps repeated in a manner that results in (sequential) modification and improvement over time.

However, we follow recent work in denying that "improvement" over time is a necessary feature of cumulative culture evolution, and instead favor a minimal formulation that sheds this requirement. On this minimal formulation, cumulative culture is simply the modification to, and retention of, socially transmitted cultural traits (Buskell & Tennie, in press). Because these retain modifications – and thus have histories – they can be considered "traditions". The histories of such traditions can, at least in principle, be reconstructed as sequences of step-by-step changes (akin to what Calcott (2009) calls "lineage explanations"). This minimal formulation better aligns cumulative culture with evolution theory, such that cumulative changes can generate not only adaptive changes, but also neutral and maladaptive ones (Buskell & Tennie, in press).

Contrasting with cumulative culture is non-cumulative cultural evolution. This does not retain modifications for one reason or another. This might be because there is no retention of past behavior, no introduction of modifications, or no kind of social learning. These situations might occur if individuals can only innovate new traits, cycle through a set of traits, and/or do not learn from one another. In these cases, histories of modifications will be non-existent, uninformative, or based in non-cultural inheritance systems.

3.2 Tall vs. Wide Evolution

In addition to analyses of the core criteria of cumulative cultural evolution (Mesoudi & Thornton, 2018), recent analyses have split up the concept of cumulative culture even more finely. These distinguish between processes that generate a disparate set of traditions ("cultural disparity") and those that lead to cumulative cultural change (and perhaps, increases in adaptiveness, efficacy, or complexity in particular traditions) (Buskell, 2018, forthcoming). One can interpret this distinction in terms of "building upon" traditions and "building out" to generate new traditions – or just *tall* versus *wide* evolution (for likeminded attempts at drawing this contrast see: Dean et al. (2014) and Tennie et al. (2009)).

Figure 1 provides a visual example of both tall and wide evolution, with tall evolution displaying a series of path-dependent adaptations that could only occur if the previous evolutionary steps had already arisen. Wide evolution, on the other hand, has no such dependency between adaptations: each trait is independent, such that their initial appearance follows no *a priori* sequence. In other words, one could re-arrange the wide axis but not the tall. Further refinements of the diagram would show the influence of recombination: where distinct "tall" traditions combine elements to generate new traditions.

Cultural evolution provides numerous examples of both tall and wide evolution. The tool use of chimpanzees provides a useful case study. Chimps are capable of innovating new tools given available resources, such as rocks to crack nuts, blades of grass for termite fishing, sticks for obtaining out of reach objects, branches for scooping algae out of water (Bandini & Tennie, 2017; Boesch & Boesch, 1990; Sanz et al., 2010). Each and all of these innovations can exist within a population of individuals, but the existence of one is not dependent on the existence of any other. Any of these innovations can be selected for and spread within the population independently of the others. Should modifications be added to these innovations – perhaps knapping the rocks, introducing an anvil, chewing and stripping the grass to produce ant-catching bristles – these would be potential examples of tall, cumulative evolution. This distinction between tall and wide evolution is useful insofar as capacities that underlie each come apart. This is clear from hominin evolution, where early capacities for social learning lead to wide knowledge bases of disparate ecological traditions prior to capacities (or opportunities) for building up any particular tradition into complex forms (Buskell & Tennie, in press; Sterelny, 2021) (more on this below).

In terms of capacity for open-ended evolution, there is no reason to believe that tall evolution is more likely to result in open-ended evolution than wide evolution. In fact, complexity is more likely to result from the intersection of both. Both formal models (Enquist et al., 2010; Kolodny et al., 2015; Winters, 2020) and cultural evolutionary theory (Buskell et al., 2019; Charbonneau, 2016; Richerson & Boyd, 2005) emphasize the role of cultural recombination as a potent force in generating new innovations: this occurs when distinct cultural traditions (or their constituent elements) are combined, and potentially exapted

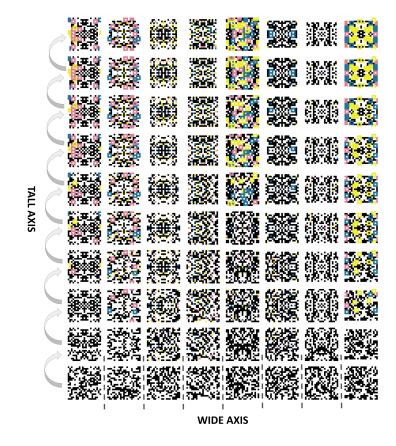


Figure 1: This figure illustrates our conception of *tall* and *wide* evolution. In step 1 (the first row) all possibilities are equiprobable, as they were generated by asking each patch in the field to turn from black to white with equal probability. Thereafter one of eight rules was applied over ten iterations. As can be seen, the changes along the *tall* axis are only possible *after* an initial, equiprobable seed was generated. Thus, changes are cumulative. Each column is independent, and 'movement' along the *wide* axis is not possible without violating the cumulative principle of *tall* evolution.

(Mesoudi & Thornton, 2018), to generate new traits. We expand upon this line of thinking below and go on to ask whether these variations in the progression of evolution (tall, wide, recombinative, exapted) are detectable within the "ALife test" introduced by Bedau et al. (1998) (also see, Channon (2001, 2003, 2006)).

3.3 Unbounded/Bounded Evolution

A conceptually distinct and contrasting set of evolutionary patterns is that between bounded and unbounded evolution. Bounded evolution occurs when abilities for transmission, retention, or the production of modifications are limited or absent. This leads to evolutionary exploration of a parochial, bounded space of traits. Unbounded evolution, by contrast, occurs when such abilities are present and when the environment facilitates evolutionary exploration—for instance, by being rich in natural resources which can be encompassed into technological production (Derex, 2022). This may be the same for social environments (which makes sense especially, given that these can be cultural outcomes as well as inputs).

To get a grasp on this distinction, it is useful to look at a domain in cultural evolutionary research where issues of boundedness or unboundedness arise. This is work on the so-called Zone of Latent Solutions (ZLS) Theory (Tennie et al., 2009), which has analysed the cultural and putative cumulative cultural traditions of non-human animals, especially great apes (hereafter; "apes"). Putative, because while several species of primates have clear capacities for social learning, work has suggested they have minimal capacities to build upon previous traits. The same may be true in other animals, such as birds and whales (Aplin, 2019; Perry, 2011; van Schaik et al., 2003; Whitehead & Rendell, 2015; Whiten et al., 1999). This suggests some "bound" on the cultural evolutionary capacities of these species.

According to the ZLS theory, many putative instances of ape (and perhaps other animals') cumulative culture are not, in fact, instances of cumulative culture. The ZLS theory holds that apes lack (or have minimal) capacities for generating and retaining modifications to learned traits. What explains apparent instances of cumulative culture in apes is "reinnovation": apes draw on a baseline repertoire of behaviors. A "baseline repertoire" is the suite of behaviors that any able-bodied member of the population would be able to produce on their own, without the need for social learning, given the right motivational, environmental, developmental, and cognitive circumstances. Thus, any behavior that could only be acquired through special types of social learning ("know-how" copying, see below) is outside the ZLS.

The ZLS theory thus suggests that the cultural evolution of apes is completely or largely bounded. Apes may have greater or lesser capacities to "build out" and acquire a wider base of socially facilitated knowledge. They may be able to "build upon" to generate tall, complex or adaptive cultural traditions. But these latter traditions will be limited to being built out of components from their baseline repertoires – they are 'latent solutions' – and sequences of those behaviors may be limited by other cognitive constraints. Empirical claims bear this out. To the extent that such capacities for accumulation do exist, they seem to be limited to specific domains, or to specific kinds of knowledge (Claidière et al., 2014; Sasaki & Biro, 2017). And there is now a wealth of data suggesting that cultural behavior in apes consists of latent solutions (Tennie et al., 2020).

It may be that the ZLS theory applies more generally to all non-human animals, or most of them. Breaking out of the ZLS into an unbounded exploration of possible innovations may thus be uniquely human. And though a full catalogue of important underlying processes is not complete, a key capacity seems to be abilities for copying "know-how" – that is, capacities for attending to, understanding, and reconstructing the elements and interrelationships of any particular behavior (including the making of artefacts). Other relevant capacities - at least for modern humans - plausibly include language, and special types of teaching.

3.4 Evolved Open-Endedness in Action

Within cultural species, we can differentiate between different types of cultural evolution: non-cumulative, bounded cumulative, unbounded non-cumulative, and unbounded cumulative. While cumulative culture does not appear to be uniquely human (Mesoudi & Thornton, 2018), unbounded cumulative culture plausibly is. Indeed, human cultural evolution appears to be the only instance of unbounded, cumulative cultural evolution.

Evidence suggests that the transition towards such cultural evolution has taken place over the last few million years. We thus have, in both archaeological remains and in our genes, the record of this transition into open-ended cultural evolution. Exploring this transition is valuable, for it offers a compelling insight into the problems, solutions, processes and complex evolutionary dynamics that can jointly explain the emergence of a new, open-ended evolutionary system. Though this is a particular instance, we suspect the concepts, tools, and ideas can be generalised.

This is not to say explaining the transition from primate ancestors to fully-fledged cultural hominins is easy. Anything but. Contemporary narratives point to a number of important changes that might have facilitated the evolution of a robust, quasi-independent system for cultural inheritance. These include changes in morphology (the bipedal stance, decreased gut size, increased crania), life history and population structure (social affiliation, intergenerational care, long developmental periods, extended family groups and social institutions), and cognitive attributes and machinery (greater executive control, social tolerance and attentiveness) (Aiello & Wheeler, 1995; Antón et al., 2014; Grove, 2017; Kaplan et al., 2000; Klein, 2008; Ostrom, 1990; Powers & Lehmann, 2013; Powers et al., 2016; Sterelny, 2012, 2021).

Just as important were cultural evolutionary feedback loops where early culture could facilitate selection for more and more effective social learning. Early hominin culture, for instance, generated an information environment seeded with cues as to how one should live. This includes "scaffolded" learning environments, where juveniles can learn in a relatively safe and low cost manner by interacting with the products of adult cooperation. These low-cost and safe learning environments could be increasingly supplemented with real-world experience, teaching, and experimentation as learners developed. Selection to improve capacities to navigate and explore this information domain would in turn lead to greater informational structure in the world—and thus to further selection. This general story is one of humans as "evolved apprentices" (Sterelny, 2012).

The story of how hominins escaped the "boundedness" of their primate relatives exploits this evolutionary feedback loop, increasing capacities for both tall and wide culture, and abilities to recognize "task-independent" properties of artefacts and behaviors that could be transferred and combined with other behaviors to generate new kinds of cultural traditions. These cognitive and cultural capacities could open up new evolutionary search spaces by exploiting novel affordances (Arthur, 2009; Derex, 2022). As a result, human technologies capture and put to use a collection of phenomena: for example, a car not only exploits the phenomenon that rolling objects produce much less friction than sliding ones (resulting in the use of wheels), but it also exploits the phenomenon that chemical substances (diesel, say) produce energy when burned (Arthur, 2009). This discovery and exploitation of new solutions to old problems allows a potentially unbounded form of cumulative culture. We see evidence for the opening-up of new evolutionary search spaces, and the exploitation of new solutions in numerous domains within patent records (Bedau et al., 2019).

Equally important is the way that human groups can support the increasing specialisation of skills and knowledge, the circulation of knowledge, and participation in collective endeavours—pitching in on large or temporally distributed projects that could never be completed by a single agent in their own lifetime. These social features in turn could contribute to the changes in cognition, life history, and information dynamics discussed above. This is part of what some have called—with various slight differences—the cultural intelligence hypothesis (Muthukrishna et al., 2018; van Schaik & Burkart, 2011).

As this makes clear, the transition between a limited form of social learning and the more complex and open-ended form currently enjoyed by humans is a complex story. Despite this, complexity researchers in archaeology, comparative psychology, paleoanthropology, psychology, philosophers, and many others have been able to make progress on disentangling distinct causal pathways, and to show how these can be put together again to explain the evolution of a distinct system of open-ended evolution: human cultural evolution (Boyd & Richerson, 1985; Tomasello, 1999).

4 Cultural Evolution, Open-Ended Evolution and Artificial Life

Culture and cultural evolution has a long tradition in Artificial Life, appearing amongst both the grand challenges (C. Taylor & Jefferson, 1993) and open

problems (Bedau et al., 2000) of the field, and spawning a regular workshop series at the Artificial Life conference (Marriott et al., 2018). It is therefore curious that open-ended cultural evolution has received relatively little attention as a possible avenue for fruitful research until recently (see Bedau et al. (2019)).

In the previous sections of this paper we have outlined many of the arguments and factors that we feel place cultural evolution firmly within the domain of open-ended evolution research. However, we also note a curious parallel between the work already taking place within the Artificial Life open-ended research community and the broader study of culture as an evolving system. A particular example of this can be seen in T. Taylor (2019), where three classes of novelty, all capable of generating open-ended evolution, are introduced: 1) exploratory novelty whereby existing traits are recombined to produce new novel adaptations, 2) expansive novelty resulting from the discovery and exploitation of new affordances, and 3) transformative novelty resulting from the discovery of new state spaces, possibly via the exaptation of current traits. Within the cultural evolution literature we can see clear parallels with each of these classes: exploratory novelty can be seen as a restricted process of cultural variation and accumulated modification within one domain or affordance (described as Type I cumulative cultural evolution by Derex (2022)); expansive novelty can be interpreted as an exploration of new affordances, expanding cultural evolution in to new domains (described as Type II cumulative cultural evolution by Derex (2022)); and transformative novelty can be viewed as movement into an n-dimensional state-space through the recombination and exaptation of existing cultural traits, enabling the creation and exploitation of new cultural and ecological niches.

It is therefore evident that open-ended evolution research in Artificial Life and cultural evolution research have been speaking about very similar things; the types of novelty discussed by T. Taylor (2019) and core aspects of cumulative cultural evolution outlined by Derex (2022) and Mesoudi and Thornton (2018) demonstrate such similarities. It should therefore be uncontroversial to suggest an open-ended evolutionary synthesis that combines genetic evolution, cultural evolution, and artificial evolution within a single theoretical framework. Combined with the exploratory work on open-ended technological innovation of Bedau et al. (2019), the inclusion of social and cultural transitions emerging from earlier biological transitions within the major transitions framework (Calcott & Sterelny, 2011; Maynard Smith & Szathmáry, 1995; Szathmáry, 2015), and the clear articulation of evidence for both biological and cultural mechanisms for the facilitation of evolved open-endedness (Pattee & Sayama, 2019), we see a strong argument for the inclusion of cultural evolution within the broader framework of open-ended evolution.

In the sections below we argue that the transition from bounded to unbounded evolution, that is evident within the recent hominin evolutionary history, shines an important light on how evolved open-endedness might be achieved. We go on to consider tall and wide evolution within the context of the Bedau et al. (1998) "ALife Test" and provide some initial thoughts on how this test could be further expanded to detect tall and wide adaptations in order to better delineate between the mechanisms driving (and halting) artificial evolutionary systems. Finally, we introduce a raft of new questions that the inclusion of cultural evolution under the framework of evolved open-endedness allows us to ask.

4.1 Transitions from Bounded to Unbounded Evolution

As we saw in section two, it is common to operationalize culture in informational terms: culture is information, embedded (or carried) by heterogeneous vehicles, that can be transmitted between agents (Richerson & Boyd, 2005). On this understanding, one thread tying together the evolutionary history of hominin populations is an increase in and improvement of culturally transmitted information (Boyd & Richerson, 1985). This general observation has led some researchers to claim that culture represents a "major transition" in the sense of Maynard Smith and Szathmáry (1995) and Szathmáry (2015), building off the idea that such transitions involve changes in the quality and reliability of information transition. For instance, Waring and Wood (2021) argue that human cultural groups are a new kind of evolutionary individual, suggesting that cultural selection pressures now vastly outweigh biological selection pressures in determining the course of human diversification and change.

Waring and Wood's arguments interpret the major transitions framework in a particularly strong way. This takes transitions to involve the stabilization of a new evolutionary individual, here, a cultural group (McShea & Simpson, 2011). But one need not understand the framework in this "unified" way (Michod, 1999). Instead, transitions may involve modifications of the "core elements of the evolutionary process itself" (Calcott & Sterelny, 2011, p. 4), irrespective of introducing a new level or kind of selection process (Godfrey-Smith, 2009). Thus, even if one is sceptical about cultural group selection (see, for instance, Chellappoo (2022)) one can usefully understand the introduction and refinement of cultural evolution using the ideas and machinery of the major transition literature (Calcott & Sterelny, 2011; Maynard Smith & Szathmáry, 1995; Szathmáry, 2015).

We conceive "open-endedness" through this more expansive understanding. It characterises an increase of informational content that can be (or is) transmitted in a given domain, potentially reflecting coordinated or piecemeal changes to the rate, increased quantity, or kind of variation that can be generated. In so doing, we follow Pattee and Sayama (2019): "[o]ver time both biological adaptations that enable more complex and open-ended social and cultural behaviors (bigger brains, opposable thumbs, changes in the shape of the larynx, ...), and cultural adaptations that open up access to new domains of knowledge (symbolic language, the scientific method, music and art, complex social institutions, ...) have been selected for in a clear demonstration of selection in favour of open-endedness, with this same selection pressure being seemingly absent in our closest genetic relatives".

4.2 Cultural Evolution and the "ALife Test" for Open-Endedness

Determining whether an evolutionary system exhibits unbounded evolutionary dynamics is still arguably the primary concern of open-ended evolution research. Without the ability to judge whether a system is open-ended, how can open-endedness be understood to any useful degree? Despite a general lack of use, we are of the opinion that the classification system of long-term evolutionary dynamics devised by Bedau et al. (1998) (sometimes known as the "ALife Test" for open-endedness) provides us with the best method for determining whether an evolutionary system exhibits unbounded evolutionary dynamics. However, we believe some of the key features of cultural evolution – wide vs. tall evolution, transition from bounded to unbounded evolution, and evolved open-endedness – may necessitate some refinement of the "ALife Test".

The three primary measures of evolutionary activity described in Bedau et al. (1998) are 1) the diversity of traits within the system at any given time, 2) the amount of "new evolutionary activity" observed in the system over time (i.e., the creation and maintenance of new adaptive traits), and 3) the mean cumulative activity of traits (i.e., the number of traits observed to date divided by the current diversity of traits in the system). For a system to exhibit unbounded evolutionary dynamics it would need to always demonstrate positive new evolutionary activity (i.e. new traits are being created and maintained), alongside either unbounded diversity (as time progresses the number of traits maintained in the system continues to grow) and/or unbounded mean cumulative activity.

What these measures of evolutionary activity do not take into account is whether the new activity is a result of cumulative (tall) evolutionary processes, non-cumulative (wide) evolutionary processes, or recombinative processes. These distinctions matter because they can begin to shed light on *how* a system has progressed toward, and ultimately achieved, open-endedness. For instance, would we expect to see a "building-out" of wide adaptations (as seems to be the case in hominin cultural evolution) before the emergence of tall accumulated modifications, ultimately leading to the combination of traits from disparate evolutionary lineages forming recombinative adaptations (wide evolution providing the raw material for exploratory and expansive evolution as per T. Taylor (2019))? Or are there numerous different pathways to open-endedness which can only be understood by breaking down the nature of the adaptive processes underpinning these evolutionary systems?

4.3 New Questions in Open-Endedness

Once we consider the implications and nature of cultural evolution from an openended evolution perspective we can begin to ask new and important questions about evolved open-endedness, human cultural evolution, and the underpinning dynamics of all evolutionary systems. These questions include, but are not limited to:

- Do the mechanisms underpinning cultural evolution more easily lead to open-endedness than those underpinning genetic evolution? Or vice-versa?
- What happens when a bounded aspect of an evolutionary system (e.g. animal cultural evolution) comes up against an unbounded aspect of the same evolutionary systems (e.g. human open-ended cultural evolution)? Is there a sudden pressure for evolved open-endedness to emerge amongst species that have so far only exhibited bounded cultural evolution? Or does the emergence of open-endedness always lead to the extinction of its bounded counterpart?
- Are there any bounded aspects of human cultural evolution? And could there also be bounded aspects of genetic evolution?
- Does an evolutionary system need to be cumulative to be open-ended, or is it possible to have non-cumulative open-ended evolution? Note: If major transitions are the primary behavioral hallmark of an open-ended evolutionary system, and major transitions build up incrementally from one another (each transition is dependent on subsequent levels) this would imply that open-ended evolution must result from a cumulative evolutionary process. But is it possible to generate open-ended evolution without cumulative major transitions and could major transitions be the result of numerous independent innovations?
- Are cumulative evolutionary systems always open-ended? The numerous cases outlined in Mesoudi and Thornton (2018) would suggest not, nor do the criteria for cumulative cultural evolution necessitate an open-ended system (or logically lead to the conclusion that open-ended evolution is an unavoidable end point).
- Is cultural evolution a suitable model system for open-ended evolution (Bedau et al., 2019) and evolved open-endedness (Pattee & Sayama, 2019)? And if so, what features of cultural evolution are common to all evolutionary systems capable of generating the open-ended evolution of novelty?
- Is an open-ended evolutionary synthesis which accommodates cultural evolution alongside genetic evolution and artificial evolution viable and/or desirable?

5 Conclusion

In this paper we set out to outline culture as an evolutionary system and argue for its inclusion within the broader framework of evolved open-endedness. In order to make these arguments we have provided numerous examples of the unique aspects of cultural evolution that make it a fascinating counterpoint to genetic evolution, but we also maintain a direct link between the core algorithmic features of evolution and cultural evolution. We went on to discuss the key features and dynamics of cultural evolution, including tall (cumulative) and wide (non-cumulative) evolution, transitions from bounded to unbounded evolution, dual and triple inheritance, evolved open-endedness, major transitions, and ZLS theory. Each of these features provide new insights into the nature of another model evolutionary system.

Going forward we believe two lines of enquiry are necessary to fully develop cultural evolution as an integral part of open-ended evolution research. 1) Following on from the work of Bedau et al. (2019), we believe an application of the "ALife Test" to the vast number of available cultural evolution datasets, across numerous species, would be informative for both the open-evolution community and the cultural evolution community. 2) Including mechanisms of cultural transmission and the unique features of cultural evolution within artificial evolutionary models – this may involve the modelling of culture as an independent system, or the inclusion of culture alongside genetic (and environmental) inheritance. To enable these two lines of enquiry we believe some work on the refinement of the "ALife Test" is necessary, as is the development of tall vs. wide vs. recombinative evolutionary theory, and more interdisciplinary dialogue between the fields of Cultural Evolution and Artificial Life.

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