Paleolithic Punctuations and Equilibria: Did Retention Rather Than Invention Limit Technological Evolution?

CLAES ANDERSSON
Department of Energy and Environment, Division for Physical Resource Theory, Chalmers University of Technology, Göteborg 412 96, SWEDEN; claeand@chalmers.se

ABSTRACT

Although the ability to add knowledge and the ability to retain knowledge are both (trivially) preconditions of cumulative evolution, the latter has so far been largely neglected in cultural evolution. As we here focus on the ability of cultures to retain a long-term memory, what emerges is that the propensity for introducing error in information transmission between generations strictly bounds the volume of information that can be stably maintained over time. What is argued and demonstrated here is how this phenomenon could provide key insights about tempo and mode in Paleolithic technological evolution. The application of this patch to the basic Darwinian framework causes its predictions to shift in an interesting way: 1) a large and growing body of archaeological finds that seem outright mysterious today begin to make theoretical sense, and, 2) the importance and role of cognitive capabilities changes considerably as the ability to learn and teach (rather than to invent and comprehend) is emphasized.

INTRODUCTION

What is the similarity between the evolution of protobiological RNA replicators and the evolution of Paleolithic culture? Not much, for sure, but it is here argued that these two otherwise so different systems still share a fundamental structural similarity and that, because of this likeness, they both face the same "memory problem." This structural similarity can be summarized into two critical characteristics: 1) they both rely on a dynamics of information transfer between short-term memory carriers to achieve a long-term memory; and, 2) the rate of noise in this transfer is comparatively high. But to see what this means, and what expressions this memory problem can take, we must take a moment to look at what insights its research has provided in evolutionary biology.

The memory problem in question and its causes have been well researched in population genetics and since it is better understood as a non-linear dynamics phenomenon than as something inherently biological, many of the models that have been used are generic and highly useful also for our purposes. Its discovery and exploration began with a paper by Eigen and Schuster (1977) where the relationship between the length of genetic sequences and the rate of error in replication was investigated. It is obvious that if no mutations occur, then no adaptation is possible. But what happens if we adjust the mutation rate upwards? At first there are no surprises—the rate of adaptation increases. But then, all of a sudden, at a critical mutation rate, the whole system collapses in what is referred to in the literature as an "error catastrophe." What happens is that the system of short-term memory carriers can no longer maintain a long-term memory—not only can the system not adapt further, it also loses everything that it had previously gained. If you keep the mutation rate fixed and instead adjust the sequence length upwards, you invoke exactly the same effect. The conclusion is that mutation rates determine the amount of information that can be maintained over time.

The question thus becomes, did Paleolithic cultures somehow effectively solve their memory problem by (as happened for higher life forms) reducing the likelihood of errors to close to zero? Although social transmission error is harder to quantify, most would probably agree that they did not solve this problem. Even today we must carefully search and study our persistent, systematic, and widely available records to recall past events in any greater detail. This is so even within our own lifetimes and historical facts are constantly under the threat of being counterfeited even in the presence of living witnesses. If we then are dealing with Paleolithic cultures, lacking nearly all our external information media, over hundreds and thousands of generations, it would be very hard to argue that error in transmission could be practically neglected. To the contrary, by all indications it was substantial. From this perspective, Paleolithic technology evolution indeed does begin to look more like the evolution of primitive RNA replicators than like the evolution of higher life forms with their exquisitely sophisticated mechanisms for error correction.

So we have every reason to seriously nurture the idea that the rate of transmission error invoked the exact same phenomenon in Paleolithic cultural evolution as it does in biology, although of course in a different guise; i.e., that it imposed a bone hard constraint on evolution by limiting the amount of information that could be carried over long expanses of time. This constraint is here referred to as a "Glass Ceiling" (for reasons that will become clearer further on) against which ever so inventive and intelli-

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gent hominids would have to bump their heads. This paper hence joins in the recent choir (see, e.g., Powell et al. 2010; Palmer 2010) calling for more attention to *retention* of knowledge in cultural evolution.

We here introduce and provide this idea with some preliminary nurturing. What is proposed is that the Glass Ceiling effect is a constraint on technology accumulation that matches the description of what is missing from the Darwinian account of long-term patterns in technology evolution—both in terms of micro processes and macro patterns. This constraint would put a strict limit on the complexity of technological repertoires and its level would not be determined by intelligence but instead by the fidelity of information (and thereby knowledge, which will be discussed shortly) transfer between generations. With this rather minor patch to the Darwinian framework, a large and growing body of observations, which will be summarized shortly, become expected and unremarkable rather than impossible and outright mysterious—the predicted and the observed evolutionary patterns are considerably harmonized. We thereby move into focus the problem of how achieved knowledge is even retained in the first place, raising the possibility that looking to intelligence, inventiveness, and environmental factors alone for explaining tempo and mode in Paleolithic technological evolution could be a mistake.

The rest of the paper is arranged as follows. First, the width of the gap between theory and empirical observation of evolutionary patterns and events is briefly reviewed. Then, the use of a replicator dynamics as a model of long-term knowledge evolution is explained and defended, clarifying what is meant in this paper by terms such as *knowledge*, *information*, and *fidelity*. After that, a maximally abstract and transparent model, aimed at isolating the Glass Ceiling phenomenon, is introduced and analyzed. The question about what the Glass Ceiling would mean, and could lead to, on the level of the hominid and social groups is then discussed. After discussing some models addressing similar topics, the results are then used to yield a new theoretical take on observations that so far have not been possible to harmonize with evolutionary explanations.

POORLY EXPLAINED EVOLUTIONARY PATTERNS

It seems more accurate to say that the punctuated equilibrium view of Paleolithic technological evolution has been elaborated than to say that it has been weakened with recent better dating and more finds. What we see throughout almost the entire 2.5 mya history of preserved human technology are prolonged periods of non-directional change punctuated by brief periods of directional change, e.g., Hovers and Kuhn (2006). However, despite the improving empirical picture, it will be argued in this section that the major features of Paleolithic technological evolution remain poorly understood theoretically. As a consequence, even basic questions about causal relationships cannot be properly addressed. For example, how is environment, cognition, and culture linked to technology? What causes stasis and punctuation in technological evolution?

The predominating explanatory logic basically holds that physiological adaptations—visible in skeletal remains or not—provided hominids with a technological potential. The levels of technological sophistication that we see expressed during the major eras would then represent the best the hominids in question could comprehend and invent given their present cognitive capability. Consequently, transitions between the major eras would correspond to changes in cognitive capabilities. This is, of course, anything but a far-fetched hypothesis. After all, intelligence and complex technology together strongly characterize the *Homo* genus and they both emerged during the same period of time. Furthermore, since technology clearly seems to be highly adaptive, a rapid exploitation of any potential to invent better technology appears inevitable already on the most basic reading of Darwinian logic. It is unlikely that this view of technological evolution would simply be flat wrong in an uninteresting way. To the contrary, the challenge that it poses is strong and no serious attempt at explaining the evolutionary patterns of Paleolithic technology evolution can ignore it. As Klein remarks:

> "If the stratigraphic associations and age estimates at both sites [Katanda and Blombos Cave] are accepted, they could imply that modern human behavioral traits and modern morphology arose in Africa together, at or before 100 ky ago, and we will have to explain why novel behavior that was probably highly adaptive remained geographically localized for tens of thousands of years."(Klein 2000).

But there is more to motivate us to accept this challenge than just a few out-of-sync archaeological oddities. The body of observations that hang in theoretical limbo is substantial, and far from having gone away with better dating techniques, the dating and integrity of these finds have been largely confirmed and their numbers have swelled. First off, the physiological and cultural histories of the *Homo* genus are only somewhat in sync and less and less so the closer we get to present times (Ambrose, 2001; Foley and Lahr 2003). For example, and perhaps in particular, we seem to have two instances of technology emerging well after major changes in preserved physiology: 1) *H. ergaster* and the Acheulean; and, 2) *H. sapiens* and the Upper Paleolithic (UP)/Later Stone Age (LSA) (Ambrose 2001; Henshilwood 2004; Henshilwood and Marean 2006; Hovers and Kuhn 2006; Klein and Edgar 2002; McBrearty and Brooks 2000; Minichillo 2006). The lag between *H. ergaster* and the earliest Acheulean (Asfaw et al. 1992) is on the order of a few hundred millennia and the lack of large bifaces in association with Southeast Asian *H. erectus* has been attributed to *H. ergaster* spreading throughout the Old World before the emergence of the Acheulean (Ambrose 2001; Foley and Lahr 2003)[1]. The time lag between physiologically modern *H. sapiens* and the widespread cultural richness of the UP/LSA is at least around 150 ka (McDougall et al. 2005) but perhaps even longer (McBrearty and Brooks 2000).

Even if we postulate adaptations that do not show up in skeletal remains (see Coolidge and Wynn 2006; Diamond 1992; Klein 1995, 2000; Wynn and Coolidge 2004; and, for an overview, Klein and Edgar 2002), we still have grave problems such as early (and often recursive)[2] appearances of technology (Bar-Yosef and Kuhn 1999; Bednarik 2003; Belfer-Cohen and Hovers 1992; Delagnes and Meignen 2006; D'Errico et al. 2005; Henshilwood and D'Errico 2005; Henshilwood et al. 2002; Lombard 2005; McBrearty and Brooks 2000; McBrearty and Tryon 2006; Shea 2003), the so-called transitional *H. neanderthalensis* cultures of Eurasia (Hublin 2000; Floss 2003; Marks and Chabai 2006; Mellars 2000; Straus 2005; Zilhão 2006) and Holocene recursive technological evolution in modern *H. sapiens*, most notably in Tasmania where some (Henrich 2004) argue that the toolkit underwent severe maladaptive depletion following the geographical isolation of Tasmania about 10,000 years ago, after the last glacial period.

The old view that the major technological eras were rather uninteresting periods of little or no change also have been much elaborated recently. For instance, in a volume on the finer anatomy of the Middle Stone Age (MSA)/Middle Paleolithic (MP) (Hovers and Kuhn 2006), while contributors are nearly unanimous in the judgement that the period displays much temporal and geographical heterogeneity, they are at the same time in wide agreement that very little long-term trends and directions can be discerned. The observed pattern of change was characterized as "going nowhere fast"—technological elements appear and disappear, while the core Mousterian technology remains remarkably intact, in fact even down to minute details of the *chaînes opératoires* (see Bar-Yosef 2006).

But not only this, reasoning from expressed technology to cognitive capability also is fraught with both logical and empirical problems (see, e.g., Davies and Underdown 2006; Henshilwood and Marean 2003; Hovers and Belfer-Cohen 2006; Mellars 1991, 1996; Renfrew 2001). We do not have to look far for examples of this—nobody explains the technological chasm between today and the world a millennium ago by an evolution of cognitive capabilities and neither does anyone view the Paleolithic technology level of some primitive modern cultures as the result of a physiological inferiority of their members. The presence of such "unexploited potential," furthermore does not appear to be transitory or even unique to modern humans. It has been observed also in primate research, where chimpanzees have been found capable of types of behavior in captivity that they do not exhibit in the wild (see Belfer-Cohen and Hovers 2010, and references therein).

The problem is that these observations and logical problems, as strongly as they may speak, offer no comprehensive theoretical alternative; at least none that is not highly problematic from a Darwinian point of view (see, e.g., the foreword by Mellars in Hovers and Kuhn 2006). Observations do seem to suggest that the evolution of technological complexity remained under some strong constraint and that the cognitive ability to invent technology persistently remained higher than the typical expressed level of technology. But how could this be possible in terms of actual evolutionary dynamics? This is the strong challenge illustrated above with a quote from Klein (2000). This fundamental Darwinian challenge must be met on its own fundamental level and that is also where the present work attempts to meet it.

KNOWLEDGE AND INFORMATION DYNAMICS

The present work addresses these questions by pointing to a family of quite abstract phenomena that are inherent to a broad class of information transmission processes. As is evident from the introduction, pursuing explanations based on information transmission is far from novel in general, but as Eerkens and Lipo (2005, 2007) note, it is quite new in archaeology and paleoanthropology where they argue that such models hold a considerable untapped explanatory potential. In this section we argue why Paleolithic technological evolution can be studied in such a way.

Cultural knowledge comes to reappear from generation to generation in humans, who at birth possess no knowledge that is specific to the culture within which they will come to find themselves. Whether it is fruitful to speak of this recurrence as replication or not has no universal answer—it depends on the time scale and purpose of our inquiry. We here only seek to argue for the suitability of noisy replication as a model *for our purposes*; it is a different issue whether or not it is a good model for other purposes[3].

The crucial features of replication that we are after here have nothing to do with mechanistic carbon copying, and neither do they hinge on the presence of any such process at this or any lower levels. What we are after is the necessity for information to "make jumps" between short-lived physical carriers, the risk of failing to make such jumps and disappearing as a result, or to become altered, so to speak, in midair. A replicator dynamics embodies these features, isolates them, brings them out, and is, moreover, theoretically convenient given the theoretical body from which we will proceed.

What we specifically consider is technological knowledge and by this we mean the ability of hominids to perform actions directly or indirectly related to technology. For example, a knapper who has the ability to work a Levallois core we say has *the knowledge* to do this. Knowledge is passed on directly to others who sense the knower in various ways such as actions and speech, and indirectly via artifacts, sites, and features of the environment from which knowledge can be inferred. It seems safe to assume that many modalities of knowledge transfer were (as they now are) used together in mutually complementing and supporting communication systems. What we have to argue is that crucial parts of culturally persistent technological knowledge could have survived only by making these risky jumps. If so, constraints inherent to such an information dynamics would be constraints on technology.

The type of knowledge that we will be considering in the models in this paper is what we might call Knower-To-

Knower-Knowledge (KTKK), meaning knowledge components that can be gained only by personal contact with someone who possesses and expresses them; i.e., with a human cultural model. If we delimit tokens of technological knowledge, such as if we speak of "the knowledge to make an Acheulean biface," then few if any tokens will consist of only KTKK. But on the other hand, very few tokens will not critically depend on *some* portion of KTKK.

Why is this so? While there is no obvious bound on *how much* technological knowledge that could be maintained externally to the knower, it is easy to think of knowledge components that cannot be represented externally at all. To illustrate why there had to be KTKK in any relevant technological knowledge tokens (not least before writing and pictographic instructions), let us briefly consider a set of elements identified by van der Leeuw (1993, 2000) as being necessary and sufficient for the production of Paleolithic technology—*conceptualizations*, *tools*, *raw material*, and *executive functions*—of these we will consider the first and the last category.

Conceptualizations involve three sub-components: 1) *topology*, which concerns the shape properties of what is being created; 2) *sequence*, which is the conception of structuring the temporal and logical sequence of steps involved in the manufacture; and finally, 3) *partonomy*, which is the link between the parts of the object to be manufactured and the object itself. If we are barred from using writing and pictographic explanations (indeed even if we are not), it is hard to conceive of an exclusively external medium for communicating in full these conceptual aspects of technology manufacture. While conceptualizations can be heavily scaffolded externally by the presence of persistent end-results and steps along the operational sequence (e.g., finished and unfinished lithic tools in the context of a manufacturing site), language is eminently suited for expressing, structuring, and remembering sequences and systems as narratives that simply and economically tell us how to do.

Executive functions are the motor skills and strategies that allow the knower to move conceptualizations into the real world, something that obviously involves tools and raw materials both intimately and reciprocally. The communication of executive functions is even harder to imagine in the absence of teacher and apprentice in direct contact[4]. Indeed, externalization of executive functions remains a tough nut to crack even to this day, partly because more knowledge than we tend to think is supported by tacit components (see, e.g., Polanyi 1967) that are not just hard to verbalize and document but even to identify as possessed knowledge to begin with. No matter which craft you intend to learn, there is still no substitute to engaging in close interaction with a master—only then will crucial knowledge that neither master nor apprentice even recognize as knowledge make it through.

The passage of all the detailed facts, distinctions, judgements, and motor skills that went into enculturating and training a Paleolithic technology knower would be unthinkable without liberal use of KTKK. In other words, even if it is impossible to conceive of Paleolithic technology without the stigmergic external cues provided by sites, artifacts, and the environment, it is just as impossible to conceive of a technology knower who never met and learned from at least one other knower.

Mistakes are inevitably made and, for purely thermodynamical reasons (there are more ways to destroy structure than there are ways to build it), many of these are likely to be maladaptive. Also, deliberate changes, intended to be adaptive, often fail to be so and this is not least the case when the knowers lack a naturalistic understanding of the technological systems that they use. If we can revert to previous versions, maladaptive error may be a nuisance, but if we cannot do so, the nuisance turns into a slippery slope. Even when the loss of functionality for each error individually is low, the emergent patterns studied using the models to be introduced next remain (they shift quantitatively but not qualitatively). The basic reason for this is that even if small changes in technological practices have only small effects on the function of the outcome, this negligibility does not extrapolate trivially to a dynamics. Random walks stray helplessly from their points of origin, and when error mounts upon error in high-dimensional spaces the cumulative effects of even tiny errors rapidly become dramatic[5].

We furthermore need no special assumptions about the human brain to conclude that: 1) KTKK could come to rest only in brains; and, 2) brains die with their owners. Hence, KTKK could survive long-term only by jumping from older brains to younger brains, and technological knowledge was at the mercy of the integrity of this noisy dynamics.

Finally, with KTKK of the deep past (unlike with genes, computer files, or books) we do not have the luxury of having neatly measurable symbolical expressions at our disposal. It is however commonplace (Coolidge and Wynn 2006; Read and van der Leeuw 2008) to speak of the size of brain memory, measured loosely in units of number of events, items, relations, and so on, that can be stored and recalled. When we here speak of *volume of knowledge* it is, in the same vein, basically the number of things that have to be remembered by a knower before it can do what the knowledge refers to (e.g., the knowledge to make an Acheulean hand axe). We also say that there is a relevant sense in which we can speak of sameness of knowledge, most importantly in relation to its persistence (and lack thereof) over time. For example, if we observe the presence of Levallois flaking at one point in time and then verify its presence in a clearly recognizable form again 10,000 years later, it makes sense to say that this knowledge has "remained unchanged."

THE MODEL

We use the limited life span of humans to formulate a temporally discretized model whose time steps correspond to real time periods of sufficient length (say, 150 years) so that a lack of personal overlap in human KTKK carriers between the time steps allows us to use replication *as a model*—social dynamics between these discretization points is summed up as a success or failure to pass knowledge on over that period of time. The rate of success is rendered by a fidelity parameter, and while KTKK fidelity (as opposed to, e.g., genetic fidelity) is highly challenging to measure empirically, the work by Eerkens and Lipo (2005) does bring hope in this respect—there are systematic ways to quantify and measure at least some aspects of the variability of knowledge by proxy of their artifact manifestations.

Binary sequences, whose configurations represent KTKK content and whose lengths represent KTKK volume, are used as a simple knowledge model since this both suffices for the present purposes[6] and, moreover, allows us to remain close to the models following Eigen and Schuster (1977) and their results.

THE BASIC MODEL

A population of binary sequences is put under selection—sequences homogenous in 0s (the master sequence) are favored and those that are selected are replicated subject to the per-bit replication fidelity q. By this we do not aim to model selection for improvements (the best configuration is present from the beginning) but rather how selection *against* degraded short-term knowledge safeguards long-term memory.

What happens is basically that selection succeeds in retaining knowledge[7] long-term as long as q remains above a critical value that depends on the length of the adapting sequences. But as soon as q drops below this value, the memory of the system suffers a complete breakdown—this event is referred to in the literature as *the error catastrophe*. The critical replication fidelity in Eigen's model (Eigen and Schuster 1977; Nilsson and Snoad 2002) can be determined analytically to occur at

$$q_c = A^{-\frac{1}{N}}, \qquad (1)$$

where N is the sequence length and A is the relative reproductive advantage (fitness) of the master sequence (the fitness peak) with non-master sequences having unit fitness.

But if we instead fix q we can solve for

$$N_c = -\frac{\ln A}{\ln q}; \qquad (2)$$

i.e., the critical sequence length. If q remains fixed and selection pressures push for longer sequences, then this means that it must be expected that there will be an equilibrium sequence length. Above N_c the sequences fall prey to the error catastrophe and below they are out-competed by longer sequences, e.g., by more complex adaptations (more on this later).

AN EXPANDED MODEL

In the expanded model we want to investigate how the system behaves if q changes and: 1) the knowers are not constrained by any cognitive inability to invent longer sequences; and, 2) fitness increases indefinitely with sequence length. The idea is to have a simple model system where observed evolutionary stasis faces the same "Darwinian challenge" as do the preserved traces of our deep ancestry (see Poorly Explained Evolutionary Patterns above). Apart from making sequence length variable and subject to selection, this expanded model is otherwise identical to the original model.

The model has a population T of binary sequences $\tau_i \in T$ abstractly representing short-term storage of knowledge. Each update cycle, a subset of these are selected, based on their fitness $f(\tau_i)$, to replicate and produce offspring. Population size is conserved by an unbiased removal of the same number of sequences. There are two selection pressures: 1) favoring master sequences (i.e., homogenous sequences of 0's); and, 2) favoring longer master sequences over shorter ones[8]. A sequence τ_i has fitness $f(\tau_i) = AN(\tau_i)$ if it belongs to the master sequence, otherwise $f(\tau_i) = 1$. $N(\tau_i)$ is the length of τ_i. The parameter A, originally the height of the fitness peak, here also becomes a parameter controlling the strength of the selection pressure for longer sequences.

Sequences in the population are selected at a rate that is proportional to their fitness over the sum of all fitness values in the population. Upon being selected, an offspring is replicated from the parent subject to the per-bit fidelity q. Also, with probability r, a bit is either added or removed. Added bits are always adaptive 0's—i.e., inventions are maximally intelligent, they are rational. Each update cycle, individual sequences furthermore undergo a cycle of replication and innovation with a certain probability d regardless of fitness to ensure that short-term memory carriers do not linger in the population.

Let us first discuss numerical results, then the analytical interpretation. With parameter values fixed, the sequence lengths soon reach a steady-state. In Figure 1 and Figure 2 we observe statistics of the lengths of the sequences in the population; $q = 1$ leads to an indefinite increase in N as selection pressures for longer master sequences are then unconstrained. In Figure 2 we reproduce a punctuated equilibrium pattern of sequence lengths with rapid transitions triggered by the introduction of higher values of q. This tells us that the Glass Ceiling effect will cap evolutionary adaptation (when effected through KTKK expansion) also when no classical Darwinian reasons to expect such a cap obtain. Note here that during stasis in Figure 2, there is nothing that prevents longer master sequences from arising (and they do the whole time) and selection operates indefinitely in their favor. The efficacy of the selection pressure reveals itself in the punctuation events when increases in q promptly bring about expansion up to the new Glass Ceiling level.

Using a smoother fitness landscape does not affect the qualitative behavior of the model—if departures from the master sequence give only small fitness effect (or that there is even a neutral plateau)[9], this does not change the fact that we get a Glass Ceiling effect. What we then see is only a change in equilibrium N (whose numerical value is here in any case entirely fictive).

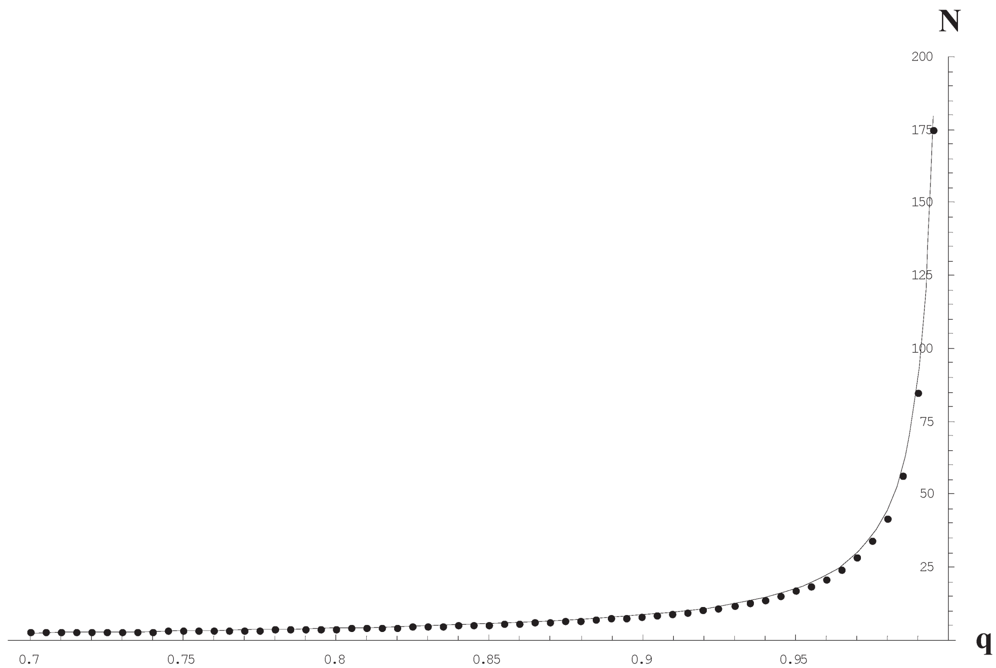

*Figure 1. A comparison between the analytical prediction of the relationship between N and **q** and numerical results from the simulation model. The simulated data was produced using a simulation model using the following settings: population size of 10,000 sequences out of which 2,000 were updated each round of selection; d=0.05, A=5, r=0.1. Initial sequence length was N=5. The data points show average N of master sequences in the population averaged over 5,000 selection cycles after equilibrium was determined to have been reached.*

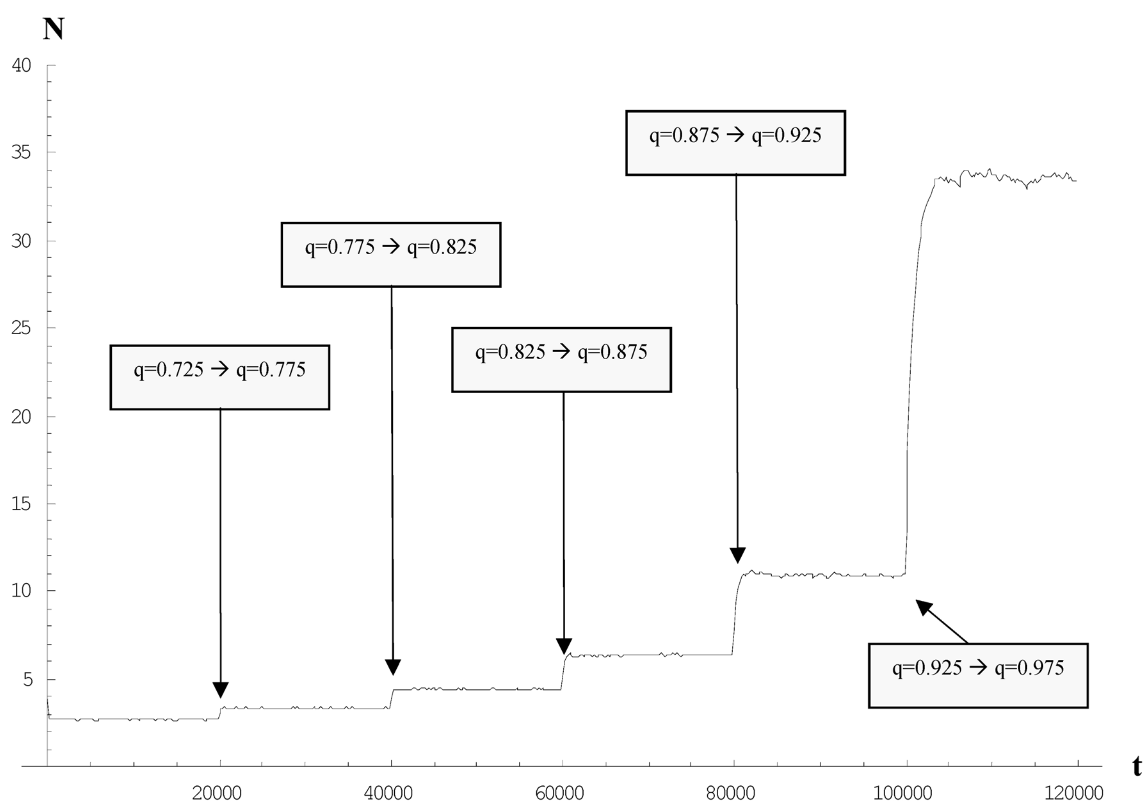

*Figure 2. The response of sequence length N to imposed bumps in replication fidelity **q** is shown, the x axis represents number of update cycles. All aspects of the model are otherwise constant throughout the run. The response to changes in replication fidelity is rapid and results in transitions in the long-term memory capacity of the system. Settings and parameters used were the same as for Figure 1, but here showing a single simulation run over 120,000 update cycles where **q** was increased by 0.05 every 20,000 updates.*

We now turn to the analytical model to clarify certain relations. As opposed to in the original model, fitness is here a function of sequence length and this means that equilibrium sequence length (long-term memory capacity) is here a function of itself. Let us say we have a linear dependence between maximum fitness and sequence length[10], $A(N)=N$. Recalling Equation (2) above, we then have

$$N_c = -\frac{\ln N}{\ln q}, \qquad (3)$$

$$\frac{dN_c}{dN} = -\frac{1}{NLn(q)}. \qquad (4)$$

For a given value of q the system will dynamically approach an attractor sequence length given by solving Equation (4) for N at the point where we have

$$\frac{dN_c}{dN} = 1 \,,$$

which gives us,

$$N_c^{'} = -\frac{1}{Ln(q)}. \qquad (5)$$

$N_c^{'}$ should then give us the location of the Glass Ceiling in the model. Just like Equaton (2), Equation (5) is a function of q but not of r; it is shown in Figure 1 that simulated equilibrium sequence lengths conform well to this analytical prediction. Furthermore, it is notable that Equation (5), contrary to Equation (2), is not a function of A. This means that the level of the Glass Ceiling is insensitive to the strength of the selection pressure on technology[11].

Below the Glass Ceiling, sequences freely adapt while above it they evaporate. The inventiveness parameter r can furthermore do nothing to budge this Glass Ceiling—we see in Figure 1 that simulated sequence lengths are predicted analytically by Equation (5) independent of r. Varying r in the simulation model produces no equilibrium effect beyond the trivial effect at $r=0$ where longer sequences never appear. Intelligence is not a parameter here, but higher intelligence (which would be the relevant investigation here) is not possible since innovations are rational and the likelihood of further invention remains constant regardless of N.

STRATEGIES FOR A LONG-TERM TECHNOLOGICAL MEMORY

But while there is much that can be said on the abstract levels of fitness and fidelity, and that is said with the greatest parsimony and clarity on such a level, there also is much that will evade us completely until we go into the details of the underlying dynamics. There is not much room here for doing so, so we will have to limit ourselves to one big question—what evolutionary avenues on the level of hominids and groups of hominids were available for adapting a toolbox under the Glass Ceiling?

So how would the Glass Ceiling Effect constrain the possible strategies for adaptation of technology? It would certainly not be a constraint on technological sophistication directly. In fact, it would not be a constraint on the quality or power of KTKK either, but on the "volume of KTKK," which we said (see Knowledge and Information Dynamics above) corresponds approximately to the number of things that must be remembered to achieve a certain ability. That is, it would constrain something that otherwise would be a highly attractive avenue for increasing sophistication—the addition of more things (steps, criteria, relations, etc.) to remember.

With this in mind we may begin our inquiry quite analytically by suggesting three ways of maintaining (and increasing) technological sophistication in the presence of the Glass Ceiling constraint:

1. Maintaining high fidelity in KTKK transfer to new generations of knowers; i.e., controlling the Glass Ceiling itself;
2. More elegant descriptions; i.e., making room under a given Glass Ceiling level by reducing the space occupied by what is already there; and,
3. Using non-KTKK memory carriers with superior intrinsic persistence, such as stone; i.e., making room for more KTKK under the Glass Ceiling by moving other knowledge out from under it.

Strategies can, of course, combine these three categories and if they have been pursued this must be expected to have left traces behind. So we must ask whether the fossil and archaeological records are consistent with such strategies.

MAINTAINING HIGH FIDELITY IN KTKK TRANSFER

A higher Glass Ceiling can be accomplished in only one way—by increasing the fidelity of KTKK transfer between generations. Once achieved, and once technological reliance on a certain KTKK volume has developed, this fidelity must then be maintained. High fidelity, in turn, can be realized in a large number of ways. Both social and biological factors that affect the fidelity of knowledge transfer can be identified; many of these have obvious parallel benefits (which, as we will shortly discuss, is important) that could have driven their evolution[12].

Among factors with a strong biological component we find *language capability*, which allows exactness, the ability to use narratives for structuring processes, and the ability to recount knowledge also in the absence of the objects that are involved (Donald 1991). Language with its classifications, relations, and metaphors also has a tremendous structuring effect on the world as experienced by humans (e.g., Lévi-Strauss 1968; Lakoff 1987). Increased *ability to conceptualize* is important both for fidelity and descriptional elegance and will shortly be discussed in more detail under the latter rubric. Here we note that the ability to conceptualize is, in a powerful way, not only important for inventing new types of technology, but also for efficient learning from all sorts of sources. Learners capable of quickly and correctly "getting the point" open the door for the formulation and use of more abstract, effective, and robust descriptions; ability to reason recursively and to construct higher-order concepts out of lower-order concepts is an example of this (see Read et al. 2009). The integrity of details over time in the knower's *neural memory* (i.e., memories stored in the brain, available for cognitive recall and use) also is important because a more error-prone neural memory will demand more social error correction (Henrich and Boyd 2002). A well-honed long-term memory of individuals is often reported from primitive cultures who lack writing as an aid (see, e.g., Lévi-Strauss 1968). Finally, as Mead (1999) argues, the ability to *teach* is much less widespread among animal species than the ability to learn, and the practice of simulational playing is highly developed in humans in contrast to other species (Donald 2001).

Predominantly cultural factors affecting fidelity include as their most obvious factor the *amount of time and effort* dedicated to teaching and learning. This variable is bounded by the requirement of time and effort for all the other tasks that need to be performed in the group. Of additional interest is the time allocation dilemma between learning more knowledge less carefully or learning less knowledge more carefully. If more knowledge causes lower fidelity (diluted attention), but at the same time demands *more* fidelity in order to survive long-term, then the emphasis must be expected to lie firmly on careful learning. Among cultural factors we also find *conservatism* as an attitude towards tampering with existing knowledge. Conservatism is often reported from modern primitive cultures (see, e.g., Mead 1999) and the technological conservatism of ancient Paleolithic cultures is clearly visible in the archaeological record. Bar-Yosef (2006), for example, brings to attention the remarkability of how even minute details in Middle Paleolithic *châines opératoires* have survived for time periods in excess of 40–50,000 years. The mechanisms behind conservatism have been studied by, for example, Ghirlanda et al. (2006) and Acerbi et al. (2009), who note that social conservatism may be self-perpetuating for the simplest of reasons—the conservative can be expected to be conservative also regarding its conservatism. Palmer (2010) describes how metatraditions, serving as a strong cultural inhibition against change, are common or even universal. We here add an external adaptive motivation for conservatism. Mechanisms of *error correction* also have been discussed and studied by Boyd and Richerson (e.g., conformist transmission [Boyd and Richerson 1985, 2005]). *Larger social groups* including trade networks and confederations of groups would have the effect of dispersing knowledge more widely. This could greatly diminish the likelihood of adaptive technology being lost. This importance of the size of communicating populations in this role has been stressed also by, e.g., Henrich (2004) and Powell et al. (2009) (but for an opposing view, see also Read [2009]), but with a different causal role; this will be discussed later in some detail. *Division of labor* and a higher degree of specialization also could improve fidelity because it would increase the amount of time available to single individuals learning, practicing, and teaching a narrower spectrum of knowledge. In other words, it would allow experts. Experts in combination with improved social organization also would allow *more formalized teacher roles* with multiple students. Further research is, however, needed to understand what the actual effects of such a development could be. On the one hand, fidelity would seem to increase if knowledge passes through a more narrow channel with a single version being spread to many students. On the other hand, redundancy would be reduced, counteracting another fidelity-increasing factor discussed above. As discussed already by Durkheim (e.g., in Durkheim 1984), the development of experts also could lead to an increasing sense of responsibility and identification with a body of knowledge, the possession of which would make the person more unique within the group. However, increasing individuation at the same time brings the need for new means for social cohesion to avoid fragmentation of groups due to internal tension (Read 2003), which, as argued above, could lead to decreased fidelity. As a final example, *sublimation* of knowledge by associating it with religious beliefs and their imperatives can be a major proximate mechanism for conservatism and the Glass Ceiling *could* be an ultimate reason for its emergence and persistence.

MORE ELEGANT DESCRIPTIONS

More elegant descriptions could reduce the volume of KTKK needed for carrying some technological capability. Reducing the number of things that we must keep in memory is something that we do cognitively the whole time to keep the world manageable and amenable to reasoning. We would be utterly unable to keep a sufficient number of relevant features of the world around us in our Short-Term Working Memory (STWM), where we can manipulate it mentally (see, e.g., Coolidge and Wynn 2005), if we were not able to move up and down hierarchically between higher and lower levels of conceptualization.

Read and van der Leeuw (van der Leeuw 2000; Read and van der Leeuw 2008) make an interesting connection between the development of STWM that has taken place over the course of human evolution (Read 2008b) and technological capabilities. Chimpanzees (*Pan paniscus/troglodytes*) are taken as marking an upper bound on the STWM of the earliest common ancestor shared with *Homo sapiens* and it is concluded that a development of STWM from 2±1 in chimpanzees to a STWM of 7±2 in *Homo sapiens* has taken place over the past approximately six million years.

Of particular interest here is the proposed (Read and van der Leeuw 2008) connection between STWM evolution and work by Pigeot (1991). Pigeot attempted to determine what sort of conceptual machinery is minimally needed to conceive of artifacts characteristic of major technological stages and noted that there is an increase in dimensionality over time—Early Oldowan flaking can be accomplished with the concepts of a point and an angle, later we move to an edge (late Oldowan), to a surface (late Acheulean), and finally to a volume (prismatic blades, Upper Paleolithic). What Read and van der Leeuw argue is that the ability to juggle these conceptualizations in memory depends critically on STWM size. But apart from representing an increasing scale of sophistication of thought, this also represents a corresponding sophistication of *description*.

As biology teaches us, a lack of conceptualization ability itself does not explain why something or the other failed to evolve or why all detectable expansion of knowledge halted at a certain point. For example, we do not ask at which point the molecular basis of genes got the cognitive capability to conceive of vertebrates. We could in principle envision robot-like instructions for how to make a surface based only on points. Rather than saying "remove flakes to make a surface that looks like this," we would have to say "remove flakes here, here, here, here...," and so on. Such an extensive and low-dimensional instruction would challenge our memory and patience more than it would our wits. But would it fit into the long-term cultural memory?

The results here indicate that at some point it would not. The former description is not only much more flexible and robust, it is also shorter and easier to remember—it has a smaller KTKK footprint and is more adapted to survive long-term in a noisy transmission environment. In other words, by the exact same merits that moving from low- to high-level conceptualization simplifies thinking (to the point of making at all possible), it also would have another and at least as important effect—a *dramatic* effect on the economy of descriptions, and thereby on the potential for technological complexity.

USING NON-KTKK MEMORY CARRIERS

The king of non-KTKK memory carriers is, of course, writing, which commits language—the most human of all knowledge vectors—to an external existence where it does not require the presence of (and can outlive) its originator. Writing, of course, emerged long after the time period that we are considering here, but there are other external knowledge carriers that were used earlier and that are likely to have pulled a heavy load. In fact, it has been proposed that the external world is so essential to the mind that it makes sense to conceptualize it as an "extended mind;" i.e., as something that fundamentally comprises the environment *and* the brain (Clark and Chalmers 1998; Menary 2010; but also Polanyi 1967). Maintaining artifacts as models would, for example, be a realistic external knowledge storage method. Even if the old tools could not convey *how* they were made directly, they could at least provide an example of what the end-result should look like. It also is possible to imagine more finely grained schemes where tools on different points during their manufacture were stored as models so that the sequence of steps involved could be even more firmly supported (see, e.g., Read 2008a). A cheap version of this could simply be the maintenance of manufacturing sites over long periods of time. However, without the capacity to carry language (or for that matter gestures, sensory information, and so on), external knowledge carriers in the Paleolithic were still limited in scope and powerful only as a scaffolding component together with other forms of knowledge within a knowledge system.

THE EVOLUTION OF FIDELITY

In this study we concentrate of the *effects* of fidelity rather than on the evolution of fidelity, which is an interesting question in itself and in need of further research. But in order to understand better what fidelity means here, we should still briefly discuss its evolution and in particular how it could plausibly be suspected to often remain quite constant. Let us begin with the question of why selection would not just favor fidelity by proxy of its technological effects. Let us consider the related case of the evolution of human cognition. The fact that cognitive capabilities must precede any technological fruits that they open the door for, and that cognition evolution is thereby not easily driven by selection for its technological effects, has been discussed by e.g., Alvard (2003). Cognitive powers, however, have many social and societal uses (e.g., "Machiavellian" intelligence, see de Waal 1982) where their fitness effects are much more immediate. The situation is analogous in the case of technology driving adaptations leading to increased fidelity. Lifting the Glass Ceiling will no doubt be highly adaptive in terms of the technology that is thereby made possible. But, a potential benefit is not yet a benefit—the fitness of technology materializes only once such technology has actually had time to develop. Note that Figure 2 does not provide any hints into this dynamic. Fidelity in the present model is just a parameter. When we raise it we simply postulate that it is raised, and Figure 2 shows the effect on sequence length of doing so.

To make matters worse, many of the factors (see above) that could affect fidelity would carry a substantial cost (demanding time, attention, resources, and so on) that their effects first must offset. So, because no immediate technological benefit can be expected, whatever lifts the Glass Ceiling must first survive on other merits. Then, once a more complex technology (dependent on this higher fidelity) has established itself and is spread widely, the benefit of this technology would guard against the loss of the new factor maintaining fidelity. Preliminary simulations confirm this (essentially letting q in the model undergo variation and assigning a fitness effect directly to it)—with no cost related to q, technological selection can act and rapidly maximizes q and N with it. But even at very low costs, q is minimized despite strong selection pressures for technology. The system is then indeed altogether insensitive to the pressure for technology since it never gets the chance to kick in in the first place.

THE GLASS CEILING FROM THE HOMINID PERSPECTIVE

Another pressing question is that of how the Glass Ceiling can be expected to have been experienced by those living under it. The short answer is that various cultural and physiological adaptations to its presence would affect daily life greatly but that the Glass Ceiling effect itself would be a long-term phenomenon far outside of the realm of the comprehensible.

With technology constrained by the Glass Ceiling before and differently than cognitive capability would constrain it, hominids would have the cognitive potential for technology of higher complexity (possibly considerably higher) than what they could stably maintain a long-term cultural memory of. This would not just be an idle capability however, and it would be an excess only relative to technology. It would be used to the ends that had driven its evolution; perhaps most importantly, the multitude of social interactions of complex hominid societies, which would have tremendous and very direct ordinary Darwinian fitness consequences.

If hominids constantly invented new things (which there is evidence that they did; see Hovers and Kuhn [2006]), these inventions would tend not to "stick;" meaning they would not fit in under the Glass Ceiling. As soon as anything did stick, congestion under the Glass Ceiling would increase the likelihood of something else being lost, and a long-term equilibrium would ensue. This is, however, something that happens over the long term and that may have been anything but obvious from the point of view of individual hominids with a reliable historical memory of specific events and facts of a few generations at the most. They may have existed in a persistent cloud of inventions with a transient content, possibly under a perpetual illusion of progress since they would not know that their inventions had been invented uncountable times in the past (hence the metaphor of a Glass Ceiling). Things in the cultural analog of the Vygotskian zone of proximal development (Vygotsky 1978) of their repertoire might have been repeatedly re-invented as needed in a quite persistent way. Indeed, a core technology conducive to *ad hoc* adaptation for short-term needs may have been favored because it would in this way emulate a more complex technology. If the environment changed, or if a group migrated to other areas, this innovation cloud (and the excess intelligence that made it possible) would be the variational fodder for quickly adjusting the makeup of their repertoire to meet new needs. This would also mean that the technological transitions that seem so dramatic from our coarse-grained vantage point might not even have been noticeable on the ground—the particles of the ever-present innovation cloud just began to stick for a while until the new equilibrium level was reached; possibly many generations later and beyond the reach of first-hand witness reports.

RELATED MODELS

Even if the question of knowledge retention has not been raised in its own right, the question of what circumstances may bring about technological refinement and decline, and what may cause refinement to be bounded, has been addressed in a series of models, beginning with Shennan (2001), with some affinities to the model used here. These models (Shennan 2001; Henrich 2004; Powell et al. 2009) have in common that they identify population density as the important causal factor; something that is also one of the factors that are here argued to affect fidelity and thereby technological refinement. Let us briefly discuss how these models differ from the present model by considering Henrich's (2004) model; the other models cited above differ in very similar ways.

Henrich's model examines the dynamics of technological skill with the proximate purpose of explaining the loss of technology in Tasmania after its geographical separation from Australia around 10,000 years ago, and the ultimate purpose of much wider applicability. In Henrich's model, it is the evolution of a continuous quantification of technological skill that is observed: "This [z_i, i.e. the skill of an individual i] could be a quantitative measure of a skill like how straight an arrow shaft is, or it could measure the possession of several discrete skills." Using Price's equation (Price 1970, 1972), the equation expressing change in skill under selection is rendered:

$$\Delta\vec{z} = -\alpha + \beta(\varepsilon + \ln(N)),$$

where α and β roughly correspond respectively to how hard something is to learn and the variability in learning performance among the population. N here denotes population size. Knowledge degradation from factors that in the present paper are treated as affecting fidelity is simply summed up in the α parameter—something that is hard to learn is assumed (quite reasonably) to degrade more quickly than something that is easy to learn.

It is interesting to consider briefly how the models map onto each other. The parameter α in Henrich's model combines features of fidelity and the volume of KTKK, and an α value for a whole group would be akin to sequence length in our model. However, KTKK and sequence length would partially have to do also with z since this inclusive parameter lumps together both the width and the depth of technological repertoires. The amount of knowledge is hence not quantified separately in Henrich's model, and, as a consequence, phenomena concerning knowledge volume cannot be studied. While β has affinities with the fidelity parameter q in our model, the similarity does not go all the way as it only captures a limited aspect of fidelity. Degradation of knowledge is in Henrich's model assumed to be a smooth process—it is the quality of technological systems that can vary. But the disappearance of, say, fishing nets means that the very idea of such a thing disappears. From such a state of non-existence, its quality clearly cannot be adjusted upwards. In Henrich's model, technologies would drop out of repertoires because they could not evolve (negative $\Delta\vec{z}$)—they would decline to a state where, presumably (since it is not internalized in the model), they would be eliminated because they were no longer of any use.

Henrich's model thereby hides the Glass Ceiling effect studied here, which in terms of Henrich's model would be best viewed as an upper bound on z due to limitations to the KTKK it is based on. Indeed, in the problem formulation used in the present paper, Henrich's model would predict that technology tokens for which conditions were ripe (see Figure 2 of Henrich 2004) would increase in quality indefinitely[13]. There is no limitation to the potential for increasing z for those technologies that make this quality cut (positive $\Delta\vec{z}$) and there is no addressing of the question of how many technology tokens can be maintained—the model is applied only to the tokens individually. To explain prolonged periods of stasis in Henrich's model, we would have to explain how z-value would first be positive to generate the technological equilibrium level and then how they suddenly all changed to close to 0 and remained there over very long periods of time and over large geographical areas. Rather than implying an infinite cultural memory, the question of memory that is raised in the present paper is simply not represented in Henrich's model.

The results of Henrich's model and the other cited models demonstrate a type of mechanism that affects the speed and direction of evolutionary refinement of function. The present model calls into question the validity of assuming that increasing z (in its spectrum of meanings) is uncomplicated. To the extent that an increasing z implies a need for more KTKK memory, as it would eventually have to (even if not at all times and in every specific case, see Strategies for a Long-Term Technological Memory above), then z would be bounded upwards by the Glass Ceiling. This bound would not be expressible within these models. The present model predicts that for the Tasmanian case (assuming Henrich's account of it to be correct; see Read 2006, 2009) it would indeed be the population size drop that caused the technological decline, but, by lowering the Glass Ceiling such that the original repertoire was too large to fit under its new level and with this an elimination of the technologies that were least critically needed would likely happen.

CONCLUSIONS, PROPOSITIONS AND FUTURE DIRECTIONS

Items A-D are results that follow quite directly from the abstract models. Items E-J offer new takes on some of the recalcitrant empirical observations briefly reviewed (as stylized facts) in Poorly Explained Evolutionary Patterns (above). Finally, items K-M are miscellaneous predictions with varying degree of support at the present but that are still of interest. We are here concerned primarily with what the present model has to say about these problems and space does not allow any deeper and wider review of alternative explanations that have been proposed.

- **A:** *Strong dependency between fidelity and the amount of knowledge that can be maintained long-term.* This is the central point of this paper and it is argued throughout.
- **B:** *Temporally stable fidelity: the Glass Ceiling.* If, as argued in Strategies for a Long-Term Technological Memory (above), fidelity either comes as a result of physiological changes or as a result of costly cultural novelty, and that it is not easily selected for on the basis of its technology effects, then fidelity could have been rather constant over long periods of time, see The Evolution of Fidelity (above). If fidelity remains constant, then, as long as the selection pressure for better technology is reasonably strong, the expressed technological complexity should be expected to be pushed upwards against this Glass Ceiling.
- **C:** *Higher fidelity causes rapid increase in expressed technology complexity: punctuations.* If the selection pressure for more complex technology is reasonably strong, then an increase in fidelity would have a rapid (on the order of tens or hundreds, rather than thousands, of generations) effect on the amount of technological knowledge held by the culture in question. That this phenomenon is sufficient on its own to bring about punctuations is demonstrated in Figure 2, where the only thing that changes along the run is the fidelity—the ability and propensity to invent, as well as the adaptive value of doing so, remains the same.
- **D:** *The Glass Ceiling does not affect the ability to adapt as long as net KTKK volume is conserved.* Fidelity concerns only how faithfully knowledge is reproduced and the amount of KTKK that can thereby be maintained long-term. This involves no assumptions about the content of this knowledge and its internal composition should be open for change as long as KTKK volume is conserved. Hence, there is no reason to believe that adaptation, as long as the total amount of knowledge does not increase, would be precluded by this constraint.
- **E:** *Hominid technology complexity generally lower than cognitive potential to invent.* If intelligence was driven by social factors and the complexity of expressed technology was bounded well before being limited by some cognitive potential maximum sophistication, then hominids would generally have been smarter than what their technological traces lead us to believe. We know this is the case today and that it is the case with chimpanzees (Belfer-Cohen and Hovers 2010).
- **F:** *Going-nowhere-fast and local adaptation while overall technological complexity static.* Importantly, conclusion D means that the present model is in no way inconsistent with innovation during periods of overall stasis or with the ability of hominids to adapt to new environments encountered as a result of migration or ecological change. In this view, inventiveness and adaptation under a stable Glass Ceiling is expected to yield adaptive and KTKK-volume-neutral change but not more complex repertoires. An "excess intelligence" would in this respect indeed likely be highly adaptive—it is easier to adapt a toolbox that many users can easily master than to adapt a toolbox that is beyond everybody except exceptionally gifted and highly trained individuals.
- **G:** *Mechanisms for strong technological conservatism*

The Glass Ceiling provides an explanation for why strong technological conservatism would have been adaptive. One may also infer that the more basic a technological operation was, the more heavily it would have been guarded from alteration. As they undergo adaptation, early and fundamental stages in technological or organical systems undergo what Wimsatt (1999) calls "generative entrenchment." This means that as more and more derived structures of adaptive value become dependent on the specifics of the basic structures (e.g., later stages being dependent on earlier stages in *châines opératoires*), the harder it will be to alter the basic structures—change in a basic structure cascades to more derived structures but not the other way around.

- **H:** *Recursive technology elements characteristic of later industries.* As briefly reviewed in Poorly Explained Evolutionary Patterns (above), the early appearance of sophistication is theoretically troublesome because this should be strictly impossible if cognition were the main constraint on technology. Under the view proposed here this is no longer the case and there are at least two distinct mechanisms that could give rise to such premature sophistication: 1) locally narrow specialization; and, 2) technological forays during a small number of generations that were doomed over the long run but nevertheless made their mark on history. As for mechanism 1, local conditions must be expected to vary temporally and geographically and this means that in some times and places, the environment could offer a rich but more narrow range of resources (such as, say, dependence on large fish suitable for spearing). Adaptation to such an environment with a conserved overall KTKK volume would mean that more space would be available to a narrow range of technology. Trade could moreover produce the same effect if over-production of narrow technology could be traded for complementing technological imports. Technologies could then develop into a sophistication that under more typical circumstances would not be possible; the MSA holds possible examples of this, see Poorly Explained Evolutionary Patterns (above). Later, with a larger technological memory, the same level of sophistication could consequently appear at a lower degree of adaptive importance. This also explains why it is characteristic for such occurrences to be isolated in space and time. Space: neighboring groups in areas where the technology had a lower utility could not "afford" the technology as its adoption would mean that they would have to get rid of other technologies to make room for it. Time: when the local environment changed, the utility of this technology may have diminished and the atypical level of sophistication would no longer be possible. As for mechanism 2, within the course of one or a small number of generations, glimpses of an "excess intelligence" may have been reflected directly in transient technology. For example, given result E, a seafaring *H. erectus* (Bednarik 2003) might have been possible even if no technology even remotely approaching that level of complexity had any hopes of being retained over time. The technology itself might be archaeologically undetectable and would leave traces only insofar as it caused something of lasting merit, such as the settlement of previously uninhabited parts of the world.
- **I:** *"Transitional cultures": primitives adopting bits and pieces of more modern culture.* The fateful encounter between modern *H. sapiens* and *H. neanderthalensis* easily conjures up the image of conquest, dominance, and enslavement where Moderns invaded Europe with superior weaponry and social organization. In reality the process took several millennia and the above imagery is probably too inspired by later eras with entirely other resources and levels of social coordination (such as the return of the Europeans to Africa much later). Finding out what really happened in these encounters is a question that attracts a lot of attention and perhaps the most suggestive lead is provided by the so-called "transitional cultures" of Europe and Western Asia where superficial Aurignacian elements were patched onto fundamentally Mousterian toolboxes. This, and not least reports of personal ornamentation (White 2000), is also troublesome from the traditional point of view on technological evolution. If both species did not exploit their full cognitive capability for technology, the encounter between *H. sapiens* and *H. neanderthalensis* (and possibly yet other hominid species, Krause et al. [2010]) might have been little different than encounters between *H. sapiens* groups with different social and technological characteristics[14]. For the MSA/MP this is suggested by studies of settlements in the Levant (Bar-Yosef 2000) and later on the rate of spread of UP technology is remarkably similar on both sides of the Mediterranean converging on the Gibraltar Strait (Bar-Yosef and Pilbeam 2000). Telling the difference between peaceful assimilation of the new technology and its spread by displacement is not easy unless the identities of the groups in interaction can be kept track of, such as through skeletal differences. Under the present thesis, it is quite possible that both Neanderthals and Moderns operated technologically well under their capability[15]—we do know for certain that the latter did, but we seem to assume without further qualification that the former did not. So it could be that Neanderthals (and for that matter culturally archaic *H. sapiens*) managed to adopt bits and pieces but were still unable to copy the bulk of the technology of the invaders—not because they were more stu-

pid (they may or may not have been) but because they lacked some cultural or physiological fidelity-boosting feature.

- **J:** *Time lags between physiological and technological transitions.* The poor synchronization between new hominid species and new technological regimes is mysterious under the assumption that technology was the main driver of cognitive evolution. We are slightly better off if social interactions are viewed as the driver of cognition evolution, but even then we must wonder why new cognitive capabilities were not promptly put to use in technology. The view that becomes possible by taking the Glass Ceiling effect into account is that, in order to bring about a transition, a fidelity boost also was needed, and that such a boost would neither follow automatically with new cognitive capabilities nor could be easily driven by selection for technology. That is, the needed fidelity boost would have to arise as a by-effect of something completely different; something that could pay up front in the currency of fitness. This means that we could search in vain for direct causes for technological revolutions that would explain why they happened there and then rather than elsewhere at other points in time—the cause could be culturally endogenous and have nothing to do with technology or the need thereof. Hidden adaptations, such as proposed by Klein and Edgar (2002), are in no way ruled out, but neither are they required in every and all transitions. This is an advance since there are other serious problems, see Poorly Explained Evolutionary Patterns (above), with such an explanation for transitions.
- **K:** *Small populations should tend to be less technologically complex than large populations.* We here reach this conclusion in a different way than the models reviewed in Related Models (above). As discussed in Maintaining High Fidelity in KTKK Transfer (above), it can be expected that redundant short-term storage should make effective fidelity higher. That is, if one person or group fails to properly learn to reproduce a technology, then a larger population means that there is a higher chance that the knowledge survived elsewhere and may be re-introduced. The ability to tie together large populations could change drastically, if, for example, a qualitatively new cultural mechanism for amicable group interaction suddenly arose, or more prosaically with varying carrying capacity of the environment.
- **L:** *Times of plenty should be more likely to trigger technological revolutions than times of dearth.* It was discussed in The Model (above), in particular Equation 5, that the strength of the selection pressure for technology is relatively unimportant as long as it is reasonably high. Hence, if social boosts of fidelity tend to come at a cost, then periods where the margins for survival are small would be less likely to see the emergence of new institutions that only much later would provide a technological benefit. Periods of more abundant resources would likely relax the selection pressure for better technology (but hardly eliminate it), but, on the other hand, it could also provide a honeymoon both for new social mechanisms with a chance of increasing fidelity and for experimentation with novel artifacts. Since selection for technology probably in any case was a poor driver for fidelity (see The Evolution of Fidelity above), and since the Glass Ceiling level is relatively insensitive to selection pressure (see An Expanded Model above)[16], the latter can be predicted to be more important than the former. Besides, in historical times, development has emerged from expansive cities and city systems rather than out of impoverished and backward areas with great immediate needs (see, e.g., Jacobs 1969, 1984).
- **M:** *Economy of description/design and the use of external knowledge storage were highly evolved.* Although not all types of knowledge could be stored externally, and although sophistication of representation is possible only to a point, one must expect that the evolutionary incentive to use these avenues would be great under an inflexible Glass Ceiling. KTKK would be a scarce and needed resource and it would likely come to be used as wisely as possible, including using parts of it for precisely the meta-purpose of enabling sophistication of description and use of external knowledge storage to still yield a net KTKK memory gain. A simple example can be found already in the development of abstract technology, such as prepared cores and blanks. These are not tools themselves but useful because they can be specialized into wide ranges of tools. It follows that many steps of the operational sequence do not bring us closer to any particular tool at all, but to such abstract way-points. This does have a distinct effect of storing technological knowledge hierarchically rather than linearly; technically the memory storage complexity would go from N to $Log(N)$ (Figure 3).

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ENDNOTES

1. Although bifaces are not strictly lacking east of the Movius Line, they are considerably more rare in East Asia than elsewhere in the Old World and are moreover morphologically different from their counterparts west of the Movius Line (see Norton et al. 2006).
2. Meaning that they emerge only to be lost at a later time without leading to further development; not to be confused with recursive as in recursive thinking. Recurrent technology widely separated in time and space clearly suggest separate re-invention rather than retention,

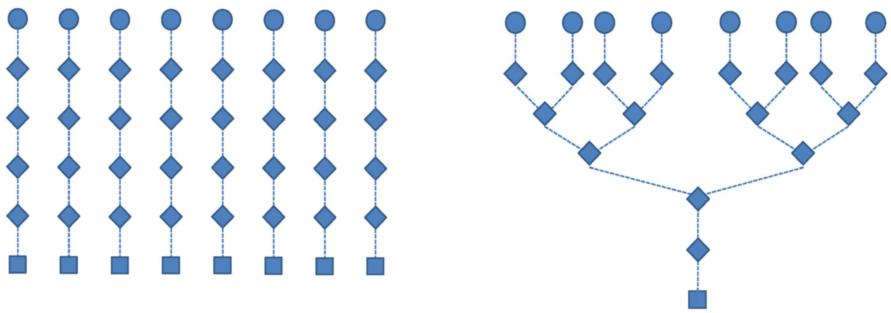

Figure 3. A schematic illustration of the information saving effects of hierarhically structured operational sequences. In both figures, eight tools (circles) result from four intermediate steps. In the left figure the operational sequences are separate and knowledge of 32 unique intermediate steps is needed, whereas in the right figure sequences are coordinated hierarchically with abstract way-points and now only 16 unique intermediate steps are needed.

not least if retaining knowledge is to be seen as costly and problematic.

3. In fact, the present work stems from an argument that it is *not* a good general model (Andersson 2008).
4. The reverse engineering of ancient *châines opératoires* engaged in by modern archaeologists is sophisticated, methodological, and hardly likely to have been practiced widely by Paleolithic tool makers.
5. As an illustrating example, consider how physicists with the highest level of understanding of mathematics and physics still in the 1950›s thought that it would one day be possible to compute virtually indefinite weather forecasts. This was far from true—even the tiniest inexactness in measurement would rapidly come to dominate the whole dynamics of the models, rendering them useless. In dynamical systems theory, instability of this kind is often quantified using Lyapunov exponents (see Cvitanovic et al. 2005).
6. A much more complex model where groups compete for regrowing finite resources and interact in numerous quasi-realistic ways (knowledge exchange, conflict, migration) has been developed and despite the large number of confounding mechanisms, the outcome is qualitatively identical and differs numerically only by a scale factor.
7. Meaning that the population is dominated by the master sequence due to selection in its favor.
8. We do not imply that more complex technology *is more adaptive* but rather that it opens up combinatorial space within which more adaptive solutions can be found.
9. Representing the case when minor deviations have minor or no effects on functionality.
10. It can be readily verified that replacing the linear function with other functions yields similar results as long as they grow slower than an exponential function.
11. In the simulation model *A* affects the time it takes to reach equilibrium but not the ultimate location of the equilibrium. The reason is that *any* selection pressure will strive, but fail, to increase *N* beyond the Glass Ceiling.
12. We should also acknowledge the possibility that fidelity also could be affected on higher levels of organization. The most salient example, as discussed in this paper, would be redundancy between communicating groups. But Premo and Kuhn (2010) furthermore investigate whether cultural stability can be affected by a factor unrelated to what we might call "micro level fidelity," namely the rate of group extinctions.
13. This is not so for the model of Shennan (2001), whose fitness function has a maximum.
14. For one thing, there is certainly no shortage of historical examples of *H. sapiens* displacing other *H. sapiens* groups quite without the benefit of cognitive superiority.
15. It is indeed even fully possible that *H. neanderthalensis* were cognitively superior to *H. sapiens* although nothing of course suggests that this was the case.
16. It is easy to experiment with replacing the linear fitness function used for different functional forms and verify that the sensitivity is low.

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