The complexity of Neanderthal technology

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A fundamental irony of Paleolithic (or "Old Stone" Age) archaeology is that it concerns a period of human history when most artifacts probably were made from wood. This is suggested by the heavy use of wood as raw material among recent or ethnographic hunter-gatherers (1) and supported by the repeated discovery of microscopic traces of wood-working on the edges of Paleolithic stone tools (2, 3). The technological significance of wood is further amplified in the Lower and Middle Paleolithic by limited use of bone, antler, and ivory (relative to the Upper Paleolithic and recent hunter-gatherers).

Aranguren et al. (4) report a set of wooden artifacts from a 170,000-y-old Middle Paleolithic occupation in central Italy. The artifacts, which were preserved in calcareous mudstone deposited along a lake margin, include roughly 40 pieces of modified boxwood (*Buxus sempervirens*), interpreted as "digging sticks." They are associated with some unmodified pieces of wood, about 200 stone artifacts, and the remains of large mammals, primarily an extinct elephant. No human remains were found at the site (Poggetti Vecchi), but it is confidently attributed to the Neanderthals based on the dating (electron spin resonance and U-series minimum dates).

Until the 1990s, wooden artifacts recovered from Lower and Middle Paleolithic sites were so rare that they existed more as curiosities than objects of study. The most widely known examples were sharpened pieces of *Taxus* or yew from Clacton-on-Sea in southeast England and Lehringen in northern Germany, both interpreted as spears (5, 6), and several objects, including a possible digging stick, from Kalambo Falls in Zambia (7). In 1992, traces or "pseudomorphs" of wood fragments, including some possible modified pieces, were reported from a late Middle Paleolithic context at Abric Romani near Barcelona (8).

Three years later, several remarkably well-preserved wooden spears were found at the Schöningen coal mine (Germany) (9). A total of nine spears and three other artifacts (all but one made from *Picea* or spruce) eventually were recovered from anoxic lakeshore sediments, now dated at roughly 300,000 y ago (10). Once again, human remains are absent, but the site may be attributed to an early Neanderthal based on combined age and location (i.e., Europe). A detailed operational sequence or *chaîne opératoire* was reconstructed by Haidle (11), who identified multiple necessary (or likely) steps in acquiring the raw material and shaping the artifact, including the preproduction steps required to make the stone tools for working the wood.

A similar operational sequence for making the wooden artifacts from Poggetti Vecchi has been reconstructed by Aranguren et al. (4), beginning with nonrandom selection of the boxwood. The production steps include cutting the selected branch from the plant and shaping the "handle" with a heavy chipped stone tool, stripping off smaller branches with sharp stone flakes and planning the residual knots (also with stone flakes), application of fire to facilitate removal of bark, and sharpening of the pointed end (with an abrasive stone) and rounding of the opposite end or "handle," also with an abrasive stone.

While the Schöningen spears are confidently classified as such based on their size and shape, the intended function of the Poggetti Vecchi artifacts is somewhat ambiguous. Their interpretation as "digging sticks" is based on comparison with both ethnographic data (1) and the classification of similar wooden artifacts from more recent sites occupied by modern humans (4). Because they are typically multipurpose implements (in an ethnographic context) used, for example, for grinding plant materials and hunting small game, as well as for digging roots and tubers, digging sticks do not necessarily exhibit a consistent pattern of surface wear (4).

Together, discovery and analysis of the wooden artifacts from Schöningen and Poggetti Vecchi represent a major contribution to Neanderthal technology. They establish two new classes of artifacts, previously represented by isolated and often ambiguous specimens. Although modest in comparison with stone artifacts, the sample sizes for wooden spears and

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Author contributions: J.F.H. wrote the paper.

The author declares no conflict of interest.

See companion article on page 2054.

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Published online February 12, 2018.

Table 1. Computational technic of the Paleolithic

Grammar type	Grammar/language	Automata class	Archaeology	Human fossils
Type 0	Unrestricted or recursively enumerable	Turing Machine	Later Middle Stone Age (<75 ka)/Upper Paleolithic: artifact design exhibits properties of natural language	*Homo sapiens*
Type 1	Context sensitive	Linear-bounded nondeterministic Turing Machine	?	?
Type 2	Phrase structure or "context free"	Pushdown automaton or finite-state machine with memory storage	Later Lower Paleolithic (<500 ka)/Middle Paleolithic: composite artifacts (hierarchically organized strings)	Neanderthals Denisovans *Homo heidelbergensis*
Type 3	Finite state or "regular"	Finite-state machine	Lower Paleolithic (>500 ka): core tools, flake tools, handaxes, single-component wooden artifacts	*Homo erectus* *Homo ergaster* early *Homo*

Application of the Chomsky Hierarchy of formal models of grammar/language (16–18) to the Paleolithic archaeological record suggests that generation of the full range of Neanderthal artifacts requires the equivalent of a type 2 grammar/language.

digging sticks open new avenues for research pertaining to the formal attributes of these artifact types and the potential range of variation within the defined attributes. They expand the set of raw materials used by the Neanderthals and underscore the selective use of high-quality wood, analogous to the selective use of high-quality stone. They provide new operational sequences (or "technological algorithms") for making artifacts. Both the Schöningen spears and Poggetti Vecchi digging sticks required application of several types of stone tools—applied at different points during the sequence—to complete the production process (4, 11). Especially important is the technological application of fire—previously suspected (5, 6) and now seemingly confirmed—in a Neanderthal context, as part of the algorithm for wooden digging sticks.

In terms of production steps, the reconstructed operational sequence for the Poggetti Vecchi digging sticks is comparable to that of the Schöningen spears, as reconstructed by Haidle (11). In both cases, the number of components ($n = 1$), often employed as a complexity measure for hunter-gatherer artifacts (1), masks the complexity of the technology, as measured by the number and variety of production steps. The operational sequence for the digging sticks reinforces a conclusion reached by Haidle (11) concerning the complexity of the underlying algorithm for the Schöningen spear (". . . a far more complicated process than previously assumed"), with implications for the cognitive faculties of their makers (12).

The analysis of Neanderthal wood artifacts complements the two other existing areas of Middle Paleolithic technology, which are lithic technology and hafted or composite artifacts. Preservation and recovery of even the smallest pieces—and traces of surface treatment and percussion—allows complete or nearly complete reconstruction of stone core and tool reduction with reference to experimental lithic technology. Since the early 20th century, it has been understood that the Neanderthals, as well as some of their relatives, were creating stone blanks of specific size and shape through a multistage process of core preparation and flake or blade production known as Levallois (13). Many of the blanks were then subject to edge retouching in accordance with additional production steps.

The discovery that some blanks were attached to wooden handles or shafts with a binding agent to render hafted or composite artifacts (as early as ~500,000 y ago) is a more recent development (2, 14). In this case, none of the wooden components has been identified (let alone complete composite artifacts) but their production is reliably inferred from traces of hafting wear and adhesives on the stone blanks. Neanderthals made both stone-tipped wooden spears and hafted cutting or scraping tools, and they employed a variety of adhesives (15), which fleshes out the complexity of Neanderthal technology by documenting the presence of at least two additional classes of artifacts, each comprising at least three components. By this measure of complexity, the Neanderthals were making food-getting artifacts more complex than those of some recent hunter-gatherers (1).

A general measure of Neanderthal technological complexity may be obtained by application of formal models in computational theory. Originally proposed in the 1950s by Chomsky (16) for grammar/language, the models have been incorporated into Automata theory and general computational theory (17, 18). In each field, they address the question: can a given "string" (such as a specific phrase or sentence) be generated or accepted by a given "grammar" or computational model? For example, can the English sentence "the woman who is carrying the basket walked to the river" be generated by the simplest grammar (i.e., "finite-state grammar")? The answer is no; the sentence is hierarchically structured and a finite-state grammar cannot process hierarchically organized strings. A more complex grammar (i.e., context-free or phrase-structure) is required to generate such a sentence (16–18). Each grammar generates or accepts a subset of the strings generated by more complex models and the complexity scale is known as the "Chomsky Hierarchy" (Table 1).

Computational models can be applied to Paleolithic technology by conceptualizing artifacts as "strings" produced by specific algorithms, such as the wooden digging sticks from Poggetti Vecchi or a hafted scraping tool. The question to be addressed is: What level of computational complexity or grammar is required to produce all of the known artifact types of the Lower and Middle Paleolithic? For the Lower Paleolithic (or until ~500,000 y ago), the types include stone core tools, choppers, large bifaces, and a variety of retouched flake tools, and at least some single-component wooden implements (19). All of the known types fall within the set of strings or artifacts that may be generated by a finite-state grammar or technology. Each artifact is based on an operational sequence comprising a linear Markov chain of production steps, each of which constrains the step that follows, and none of which requires a working memory (16–18).

For the Middle Paleolithic, which is broadly correlated with the technology of the Neanderthals (13), a finite-state grammar may suffice for the known stone and wooden artifact types, but not for

the composite artifacts, which require the processing of hierarchically organized strings. Each component of the composite artifact is generated by a separate operational sequence or technological algorithm that nests within the overall design. Because all three component parts cannot be produced simultaneously, the artifact maker must store information about the other strings in the brain during production (i.e., working memory) (12, 18). As already noted, the latter demands—at a minimum—a context-free or phrase-structure grammar. One of the insights offered by computational theory is that, while nondeterminism (i.e., random variations introduced by the individual artifact maker) does not affect the set of strings that may be generated by a finite-state grammar, it expands the potential set of strings generated by a context-free grammar (17, 18).

For the later African Middle (and Later) Stone Age and the Upper Paleolithic, the computations underlying the artifacts are of comparable complexity to those of recent hunter-gatherers (1, 20). The artifacts, which include mechanical instruments and facilities, such as spear-throwers and even self-acting mechanical facilities or automata (e.g., snares/traps), require the computational complexity (and working memory capacity) of an unrestricted grammar or natural language (12, 18, 20).

1 Oswalt WH (1976) *An Anthropological Analysis of Food-Getting Technology* (John Wiley & Sons, New York).
2 Anderson-Gerfaud P (1990) Aspects of behaviour in the Middle Palaeolithic: Functional analysis of stone tools from southwest France. *The Emergence of Modern Humans*, ed Mellars P (Edinburgh Univ Press, Edinburgh), pp 389–418.
3 Keeley LH (1993) The utilization of lithic artifacts. *The Lower Paleolithic Site at Hoxne, England*, eds Singer R, Gladfelter BG, Wymer JJ (Univ of Chicago Press, Chicago), pp 129–149.
4 Aranguren B, et al. (2018) Wooden tools and fire technology in the early Neanderthal site of Poggetti Vecchi (Italy). *Proc Natl Acad Sci USA* 115:2054–2059.
5 Allington-Jones L (2015) The Clacton spear: The last one hundred years. *Archaeol J* 172:273–296.
6 Movius HL (1950) A wooden spear of third interglacial age from Lower Saxony. *SW J Anthropol* 6:139–142.
7 Clark JD (1969) *Kalambo Falls Prehistoric Site* (Cambridge Univ Press, Cambridge, UK), Vol 1.
8 Castro-Curel Z, Carbonell E (1995) Wood pseudomorphs from Level I at Abric Romani, Barcelona, Spain. *J Field Archaeol* 22:376–384.
9 Thieme H (1997) Lower Palaeolithic hunting spears from Germany. *Nature* 385:807–810.
10 Schoch WH, Bigga G, Böhner U, Richter P, Terberger T (2015) New insights on the wooden weapons from the Paleolithic site of Schöningen. *J Hum Evol* 89:214–225.
11 Haidle MN (2009) How to think a simple spear. *Cognitive Archaeology and Human Evolution*, eds de Beaune SA, Coolidge FL, Wynn T (Cambridge Univ Press, Cambridge, UK), pp 57–73.
12 Wynn T, Coolidge FL (2016) Archeological insights into hominin cognitive evolution. *Evol Anthropol* 25:200–213.
13 Mellars P (1996) *The Neanderthal Legacy: An Archaeological Perspective from Western Europe* (Princeton Univ Press, Princeton, NJ).
14 Wilkins J, Schoville BJ, Brown KS, Chazan M (2012) Evidence for early hafted hunting technology. *Science* 338:942–946.
15 Kozowyk PRB, Soressi M, Pomstra D, Langejans GHJ (2017) Experimental methods for the Palaeolithic dry distillation of birch bark: implications for the origin and development of Neandertal adhesive technology. *Sci Rep* 7:8033.
16 Chomsky N (1957) *Syntactic Structures* (Mouton, The Hague).
17 Lewis HR, Papadimitriou CH (1998) *Elements of the Theory of Computation* (Prentice Hall, Upper Saddle River, NJ).
18 Balari S, Lorenzo G (2013) *Computational Phenotypes: Towards an Evolutionary Developmental Biolinguistics* (Oxford Univ Press, Oxford).
19 Schick KD, Toth N (1993) *Making Silent Stones Speak: Human Evolution and the Dawn of Technology* (Simon & Schuster, New York).
20 Hoffecker JF (2017) *Modern Humans: Their African Origin and Global Dispersal* (Columbia Univ Press, New York).