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Measuring the Evolution of Toolmaking Complexity: Indices of Operational Complexity

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ABSTRACT

Archaeologists and animal behaviorists have provided increasingly sophisticated descriptions of how hominids and animals construct operational sequences. The ability to translate these detailed descriptions into a measureable, comparative format of relative complexity would provide a useful tool for describing patterns of evolutionary change. Cyclomatic Complexity, *k*-paths, and *k*-cycles are three metrics from computer science and graph theory that can index the Operational Complexity of an operational sequence. These methods are applied to the production of an Acheulean handaxe and five nonhuman animal operation sequences.

INTRODUCTION

Claims of increasing cognitive complexity are common in the study human cognitive evolution. Such claims are usually framed in qualitative terms. This presents difficulty in comparing change through time. Some behaviors seem to be more cognitively demanding than others. However, the nature and relative magnitude of these demands is rarely explored in a precise and comparable way. In Cognitive Archaeology, "complexity" is not well defined and there are no available methods with which measure "more" or "less" of it. Presumably, objective measures of the complexity of different cognitive phenomena should be applicable across hominid taxa as well as hominids and non-hominid animals.

Closely related disciplines are also attempting to come to terms with this problem. In the area of comparative primate cognition, Rumbaugh (1969) introduced a simple quantitative method of indexing the cognitive flexibility of different species, the transfer index. Following Rumbaugh's example, this paper explores the use of simple complexity measures from graph theory and computer science for the measurement of the operational complexity of tool making and similar forms of object manipulation.

Tool-use was once believed to be a unique and defining trait of hominids. It was hypothesized that tool use may have may have been catalytic in the evolution of the human body, mind, and culture (Oakely 1950; Washburn 1960, 1959). Over the past sixty years, evidence of tool-use in diverse taxa from the great apes to birds has steadily accumulated (Seed and Byrne 2010). The analyses of human and animal tool production and use have also become increasingly sophisticated (i.e. Byrne and Stokes 2002; Byrne and Russon 1998, Pelegrin 2005; Lemmonier 1992; Moore 2011). To describe toolmaking and use processes, or *operational sequences*, archaeologists and other researchers studying stone toolmaking and tool use have produced detailed flowcharts describing sequences of inter-related technical actions. Chimpanzee nut cracking (Carvalho *et al.* 2008), Oldowan tool manufacture and use (Haidle and Bauer 2011), Magdalenian blade production (Karlin and Joulien 1995), or wooden spear production (Haidle 2009) all have been graphically described this way. Byrne and collaborators have produced extraordinarily detailed program-level descriptions of the actions and decisions involved in the techniques chimpanzees use to roll thorny "defended" leaves (Stokes and Byrne 2003) or those that gorillas use to eat similarly defended foods like nettles and gallium (Byrne and Russon 1998).

These graphical descriptions of operational sequences contain valuable information regarding the technologies and techniques that they depict, but as detailed qualitative representations they do not lend themselves to comparative evolutionary analysis beyond presence or absence. These flowcharts often include a mix of ontological categories such as actions, intentions, and knowledge whose interpretation involves potentially idiosyncratic subjective interpretation.

A few quantitative methods proposed. Moore (2011) has proposed an analytical method based on Greenfield's (1991) "action grammar" approach. This approach's comparative scope, between species as well as between research traditions, would be increased by a more direct integration with Chomsky's (1956) hierarchy of formal and natural language.

In this paper I propose a simple alternative method to supplement other approaches to the description and analysis operational complexity. *Graph theory* offers techniques to supplement these analyses by abstracting quantitative information from an operational sequence. A formal graph is very similar to qualitative flowcharts, but when ontologically consistent and empirically valid terms are used formal graphs make quantitative comparison possible.

Graph theory has the advantage of being well-understood, conceptually simple, and widely accepted in disciplines such as chemistry (Balaban 1985; Schultz 1989), physics (Gutman and Trinajstic 1972), social network analysis and ethnography (Alvin 1978; Wasserman and Faust 1994), epidemiology (Christakis and Fowler 2007; Morris 1993) and biology (Bunn *et al.*2000; Mason and Verwoerd 2007). Formal graphs are used to model relational data. Such graphs can be represented mathematically as adjacency matrices. As an adjacency matrix, relational data can be analyzed using a variety of well-established metrics and statistical analyses. Furthermore, these graphs can also be related to Hidden Markov Models, Bayesian Graphs, and other sophisticated modeling techniques.

Rugg (2011) has recently introduced the use of graph theory to archaeological analyses, applying it to explore the depth of the socio-economic activities required for the production Acheulean hand axes, ground stone axes, and copper axes. Following the classical concept of the the *chaine operatoire* (or "operational chain") (Lemmonier 1992), Rugg includes all phases in the use-life of the artifact from the techniques of acquiring raw materials to the final discard and deposition in archaeological contexts. Description as a graph allows Rugg to quantify these differences in "fabricatory depth" in operational chains. An increase in fabricatory depth through time index increases in the temporal and spatial scale of technologies as well the elaboration and accumulation of socially transmitted knowledge (Gibson, 2002).

As with the traditional graphical flowchart approach, Rugg's graphs are useful for come comparisons but not others. His graphs are fundamentally holisitic in that they combine intentions and a variety of social and cognitive processes. This is problematic when attempting to understand the emergence of particular cognitive capacities. In order to grapple with particular problems, such as potential changes in working memory over human evolutionary history (Coolidge and Wynn 2009), we need to break down these holistic complexes into simpler, comparable units consistent across a sample.

The goal of this paper is to explore a few possible avenues of approach to this problem. I compare operational chains across humans producing stone tools as well as nonhuman animals producing tools. To do this, I will include the individual object manipulations involved in each task. In the case of stone toolmaking, aspects of the task before and after tool production will be ignored to make the available descriptions of toolmaking comparable. The further development of these or similar techniques will allow researchers to generate increasingly more complex and compelling models of the ancient hominid mind.

OPERATIONAL COMPLEXITY AND COGNITIVE CAPACITIES
If the differences in early Early Stone Age (ESA) and late ESA technologies are the result of an increase in cognitive capacity, then later technologies should be more complex to produce than earlier ones. This paper assumes that quantitatively complex action sequences are correlated with increased cognitive capacities or "cognitive complexity." However, it is not the purpose of this paper to test the validity of this assumption. There are reasons to be concerned about this proposed correlation. It could be the case that increase in cognitive abilities involved in planning or problem solving might lead to simpler, more efficient solutions to adaptive problems rather than more complex ones. For instance, later ESA 'Kombewa' flake tools or large cutting flakes removed from a boulder core are an elegant but simple solution to the problem of producing a handaxe or cleaver-like tool without the thousands of sequenced actions involved in making a Late Achuelean handaxe described in this paper. Sophisticated insight may lead to simplicity, not

complexity. That said, more complex processes should involve increased planning abilities with changes to memory systems, cognitive control, and other affiliated systems.

This paper will explore methods for assessing the complexity of operational sequences, or "Operational Complexity." Operational Complexity will be operationalized two ways. First, it is operationalized as the number of decisions that have to be made during the performance of the operational sequence. This approach is widely used in computer programming where it is termed "cyclomatic complexity." Second, Operational Complexity is operationalized as the number of potential relationships between the actions or operations that comprise the operational sequence. This combinatorial potential will described in the terms of *k*-paths and *k*-cycles.

As already mentioned, the classic concept of the operational sequence describes the entire use life of an artifact from source to discard (Lemmonier 1992). As such, it is a complex cognitive-behavioral process involving multiple cognitive domains such as manual activity and conceptual knowledge. For the ESA, we lack high enough resolution of hominid conceptual knowledge structures. Instead, we have records of sequenced actions in stone. Similarly, we do not have intersubjective access to the thought processes of nonhuman animals, though they do perform operational sequences of interest to researchers. To render a series of comparable graphs, we will only consider the actions that can be observed visually and ignore, for now, the intentions that inform them. This methodological behaviorism will allow the comparison of a wide range of species including modern people, human ancestors, and nonhuman animals.
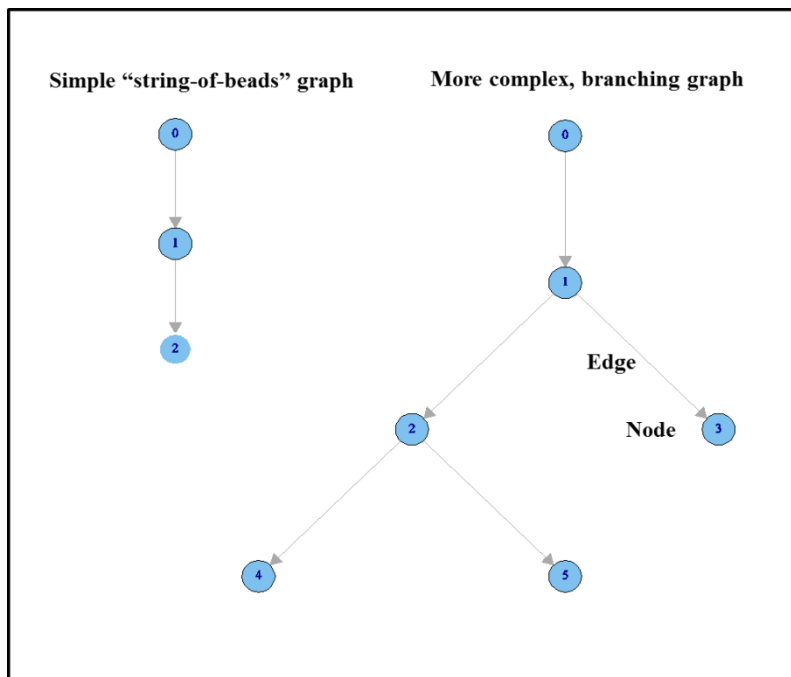

It is assumed here that simple processes involve fewer contingent decisions for the agent performing it. As a result, there are fewer potential combinations of the observed actions. Theoretically, the simplest operational sequences would look like a "string-of-beads" (Wynn 1995) with no branches (Figure 1). Actions tend to be performed in sequences with little or no variation in the order of operations. More complex operational sequences are comprised of branching and looping structures.

Transforming the flowchart of a lithic reduction into a graph is a fairly simple procedure. A graph is comprised of a series of nodes indicating states or events and a series of edges or links that connect these nodes (Figure 1). If the graph has edges (or "arcs") connecting nodes in an assymetric relationship (A → B) then it is referred to as a directed graph or a digraph.

Figure 1: A simple "string-of-beads" graph and a more complicated, branching structure. An edge (or "arc") is a link between two nodes. Branches imply a point at which a decision has to be made, requiring active monitoring and allowing increased flexibility over a simpler process.

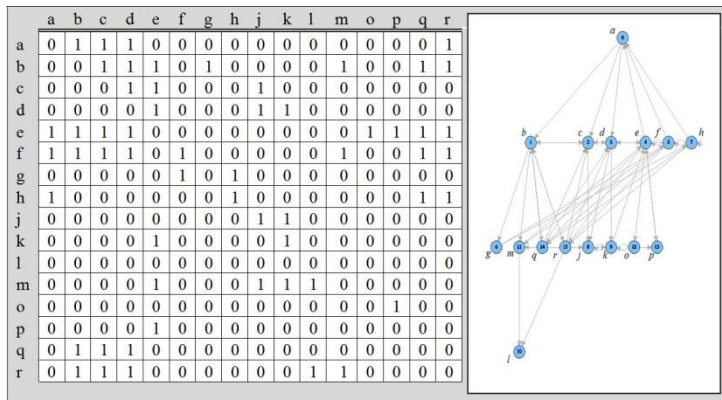|	a	b	c	d	e	f	g	h	j	k	l	m	o	p	q	r
a	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1
b	0	0	1	1	1	0	1	0	0	0	0	1	0	0	1	1
c	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
d	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0
e	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1
f	1	1	1	1	0	1	0	0	0	0	0	1	0	0	1	1
g	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
h	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1
j	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
k	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
l	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
m	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0	0
o	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
p	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
q	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
r	0	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0

Figure 2: An adjacency matrix for the production of a Late Acheulean-type hand axe. In the adjacency matrix the presence of a link from one state to another is represented as a "1" while the absence of such a link is a "0."

Graphs can be described as an adjacency matrix that describes which nodes are adjacent, or linked, to other nodes (Figure 2). In the adjacency matrix the presence of a transition from one state to another is represented as a "1" while the absence of such a transition is a "0." The representation of graphs as adjacency matrices means that they are mathematically and statistically tractable.
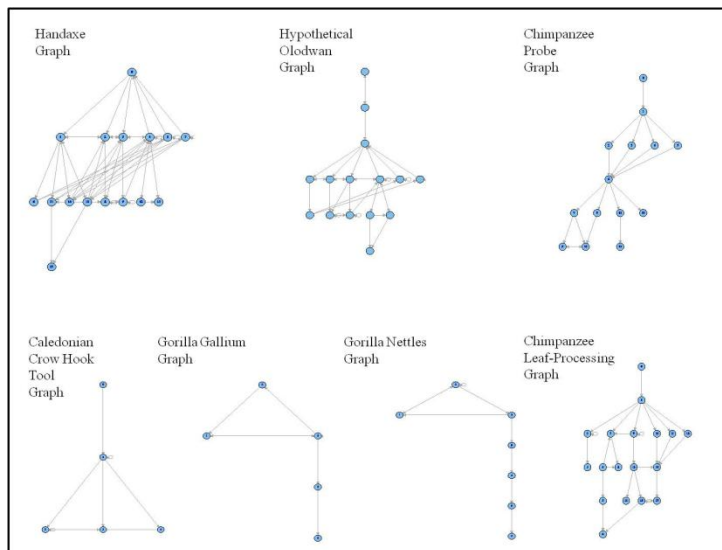
When an operational sequence is presented graphically, each action is represented as a node. The edges between them represent the transitions from one action to another. If there is more than one possible transition, then the branching structure indicates an instance of decision-making. This is the case even if we do not fully know what the criterion for the decision is or what type of mechanism is involved in monitoring and deciding between alternatives.

Descriptions of toolmaking or object manipulation procedures across a wide range of taxa were collected observationally or from the literature for the purposes of the demonstration of the techniques involved in indexing operational complexity (Figure 3).

Figure 3: Graphs produced in R 1.2.1 with the igraph function tkplot.

These included:

1. Caledonian Crows manufacturing hooks tools from twigs to hunt hidden insects (Hunt and Gray 2004)
2. Chimpanzee Leaf Processing of thorny, defended leaves (Stokes and Byrne 2003)
3. Chimpanzee Probe Tools to fish for ants (Nishida and Hiraiwa 1982)
4. Gorilla Nettle Processing (Byrne and Russon 1998)
5. Gorilla Gallium Processing to remove small, hoo*k*-like thorns (Byrne and Russon 1998)
6. The videotaped production of a Late Achulean-like hand axe by an expert stone knapper[1] (Figure 4)

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[1] Nicholas Toth was videotaped for 40 minutes with an AIPTEK HD-DV 1080P high definition digital video camera as he made a late Acheulean Handaxe out of a piece of high quality Texas flint at the Stone Age Institute in Gosport, Indiana in Fall 2010.

Figure 4: The production of a Late Acheulean-type hand axe from initial shaping through thinning. An expert stone knapper (N. Toth) was videotaped for 40 minutes with an AIPTEK HD-DV 1080P high definition digital video camera as he made a late Acheulean Handaxe out of a piece of high quality Texas flint at the Stone Age Institute in Gosport, Indiana in Fall 2010.

7. A "Hypothetical Oldowan" graph was produced by removing actions associated with platform preparation from the Acheulean graph. For the purposes of this methodological paper, it is reasonable to assume that most of the actions involved in examining positioning the core would otherwise be the same in both forms of stone toolmaking.

The video recording of the hand axe production (6 above) was analyzed by coding the component actions into sixteen distinct technical actions (Table 1). While there are many descriptions of animal toolmaking behavior available in the literature, only those that provide detailed descriptions of the

Component Actions of Hand axe Production		
1	*a*	Left Hand. Place blank on thigh
2	*b*	Left Hand. Orients lateral edge horizontally
3	*c*	Left Hand. Orients lateral edge, raises by lowering opposite edge
4	*d*	Left Hand. Orients lateral edge, lowers by raising the opposite edge
5	*e*	Left Hand. Rotates lateral edge up, into view, with blank on thigh
6	*f*	Left Hand. Rotates lateral edge up, into view, after lifting blank
7	*g*	Left Hand. Lifts blank.
8	*h*	Left Hand. Flips blank.
9	*j*	Right Hand. Touches platform with percussor ("aims")
10	*k*	Right Hand. Strikes blank.
11	*l*	Left Hand. Rotates counter-clockwise.Right Hand. "Chisel-like" platform preparation.

Table 1: Component actions performed during the operational sequence for hand axe production.

actual actions used and the sequence of progression through the series of procedures were included.

Graphs are generated and analyses performed in the open-source statistical software R 1.2.1 using the igraph package (Csardi and Nepusz 2006), network, (Butts 2008) and sna packages (Butts 2008) in the statnet package suite (Handcock *et al.* 2003.). Graphs are produced in R using the tkplot( ) function in the igraph package. The open-source statistical software PAST (Hammer *et al.* 2011) is used to generate *k*-path and *k*-census graphs.

First Index: Cyclomatic Complexity

Computer science provides a metric called Cyclomatic Complexity to quantify the amount of branching in a graph description of a program. Cyclomatic Complexity is used by programmers to index the control flow of a program and determine the number of diagnostic tests required to maintain and debug software (McCabe 1976; Capers 2008). For programmers, it is important to remove unnecessary complexity which may create unintended interactions within their code.

   If there is more than one possible path from a node in a graph, the execution of a control flow statement determines which branch will be selected. A cyclomatic number is an index of the number of decisions within a program. It is calculated with the formula:

$$v(G) = e - n + 2$$

where *e* is the number of edges in a graph *(G)*, *n* is the number of nodes, and 2 is a constant. A simple graph with no branches has a *v(G)* of 1:

$$v(G) = 2 - 3 + 2$$
$$= 1$$

A process this simple is paradigmatic of a "string-of-beads action sequence." Alternatively, if there are 5 edges and 3 nodes in a c more complex graph it will have a *v(G)* of 4:

$$v(G) = 5 - 3 + 2$$
$$= 4$$

	Edges	Nodes	Cyclomatic Number
Hands Axe Production	55	16	41
Oldowan (Hypothetical)	38	15	25
Caledonian Crow: Hook	8	5	5
Gorilla: Galliium Processing	5	5	2
Gorilla: Nettle Processing	9	7	4
Chimpanzee: Nutcracking	5	4	3
Chimpanzee: Probe Production	27	15	14
Chimpanzee: Leaf Processing	27	18	11

Table 2: Cumulative counts of edges, nodes, and the cyclomatic number for each operational

Using this formula, we can measure the complexity of the procedures. The higher the cyclomatic number, the more complex the control flow. When applied to the operational collected for this paper, we receive the following results (Table 2). Hand axes have the largest number of edges (55) and nodes (16) as well as the highest Cyclomatic Number, *v(G)* =41. It is followed by Hypothetical Oldowan (*v(G)* = 25), Chimpanzee Probe Tools (*v(G)* = 14), Chimpanzee Leaf Processing (*v(G)* = 11), Crow Hook Tools (*v(G)* = 5), Gorilla Nettle Processing (*v(G)* = 4), and Gorilla Galliium Processing (*v(G)* = 2). In this example, hand axe production has a more complex control flow than similar activities performed by great apes and Caledonian Crows.

Second Index: k-path census and k-cycle census

Another way to measure Operational Complexity is to take a census of the path and cycles in a graph. Paths and cycles are concepts from graph theory and network analysis (Bang-Jensen and Gutin 2010; Wasserman and Faust 1994). Both describe the ways in which it is possible to move through a graph under specified conditions. A path is the route from one node to another node in which intervening nodes and edges are only crossed once. A cycle is a path that begins and ends at the same node. Both paths and cycles represent sets of possible ways of sequencing a series of actions, providing an index of the combinatorial possibilities within each graph of an operational sequence.

Paths k	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Hand axe	50	165	463	1070	2084	3423	4646	4989	4034	2240	749	122	8	0
Hypothetical Oldowan	28	70	144	241	332	372	331	210	79	18	2	0	0	0
Chimpanzee Probe Tool	19	31	39	44	28	12	0	0	0	0	0	0	0	0
Chimpanzee Leaf Processing	24	25	17	10	3	0	0	0	0	0	0	0	0	0
Gorilla Galliium Processing	6	5	2	1	0	0	0	0	0	0	0	0	0	0
Gorilla Nettle Processing	8	7	4	3	2	1	0	0	0	0	0	0	0	0
Caledonian Crow Hook Tool	6	6	3	1	0	0	0	0	0	0	0	0	0	0

Cycles k	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Hand axe	5	14	30	43	58	69	73	59	15	0	0	0	0	0
Hypothetical Oldowan	3	8	12	16	18	17	18	13	3	0	0	0	0	0
Chimpanzee Probe Tool	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Chimpanzee Leaf Processing	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gorilla Galliium Processing	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Gorilla Nettle Processing	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Caledonian Crow Hook Tool	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3: Path and Cycle Censuses. Maximum k darkened.

In describing a path or cycle, the number of participating nodes is k. For instance, the number of 3-paths ($k = 3$) in a graph indicates the number of paths that involve three other nodes. Census statistics developed by Butts (1996) and implemented in the sna package in R (Butts 2008) allow us to measure the Cycle and Path Censuses in a graph. An operational sequence with a large number of nodes and many linkages and loops between nodes will have a higher number of possible paths and cycles at any k and may also have the longest k. A graph with a small number of actions or with a low density of linkages between nodes will tend to have lower values.
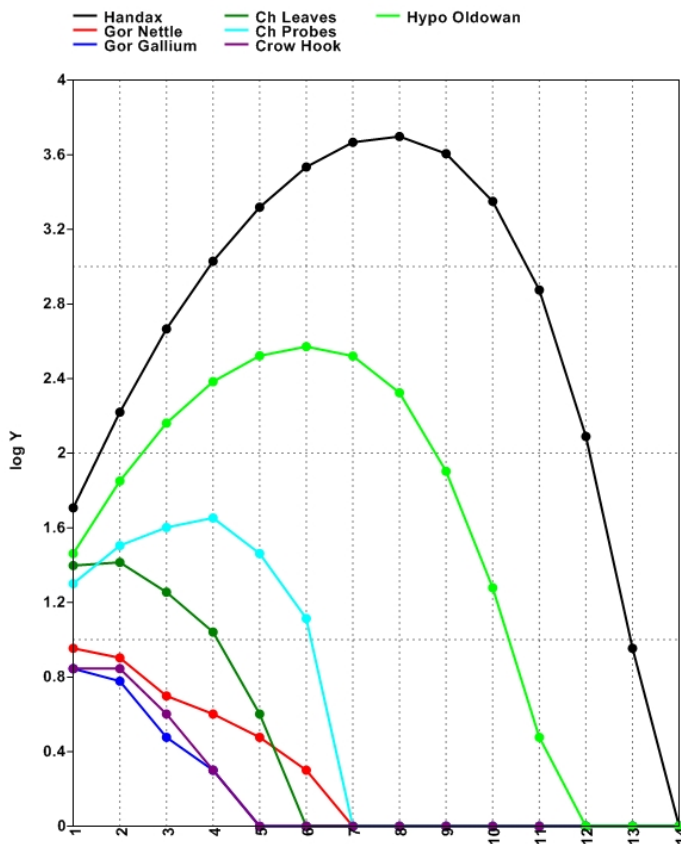

Figure 5: Logged Path Census Ratios. A path is defined as a walk from one node to another through any number of other nodes, but it can only pass over each edge and node once. A k-path census uses an equivalent random graph model process to estimate the number of paths in a graph. More complex processes should have larger path censuses than simpler processes.

When applied to our sample, a number of things stand out (Table 3). Considering k-paths first, it is first apparent that the production of the Hand axe had the largest number of paths of any length at 24043, compared to 1827 for Hypothetical Oldowan, 173 for Chimpanzee Probe Tools, 79 for Chimpanzee Leaf Processing, 25 for Gorilla Nettle Processing, 16 for Crow Hook Tools, and 14 for Gorilla Gallium Processing. The hand axe also had the longest k-paths, with 8 paths with 13 participants. It is followed by Hypothetical Oldowan ($k = 11$, 2 paths), Chimpanzee Probe Tools ($k = 6$, 12 paths), Chimpanzee Leaf Processing ($k = 5$, 3 paths), Gorilla Nettle Processing ($k = 6$, 1 path), Crow Hook Tools ($k = 4$, 1 path), and Gorilla Gallium Processing ($k = 4$, 1 path). Hand axe production has by the far the largest cumulative number of paths and the longest paths.

If we focus on the k value at which each operational sequence had its maximum number of potential paths then Hand axes had the highest number of paths at maximum k ($k = 8$, 4989 paths), followed by Hypothetical Oldowan ($k = 6$, 372 paths), Chimpanzee Probe Tools ($k = 4$, 44 paths), Chimpanzee Leaf Processing ($k = 2$, 25 paths), Gorilla Nettle Processing ($k = 1$, 8 paths), Gorilla Gallium Processing ($k = 1$, 6 paths), and Crow Hook Tools ($k = 1$, 6 paths). When the logged path census ratios are graphed (Figure 5) we can see the maximum k for Hand axes is approximately one order of magnitude larger than maximum k for Hypothetical Oldowan and more than two orders of magnitude greater than the other operational sequences.
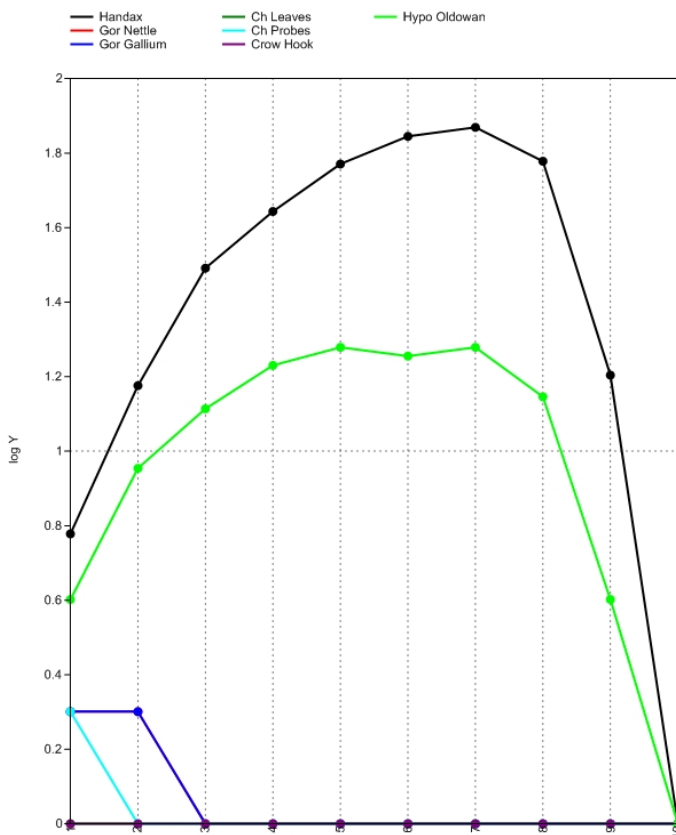
Figure 6: Logged Cycle Census Ratios. A cycle is defined as a walk that begins and ends at the same node, but it can only pass over each edge and node once. A *k*-cycle census uses an equivalent random graph model process to estimate the number of cycles in a graph. More complex processes should have larger cycle censuses than simpler processes.

Moving on to *k*-cycles, it is first apparent that the production of the Hand axe had the largest number of cycles of any length with 366, compared to 188 for Hypothetical Oldowan, 2 for Gorilla Nettle Processing, 2 for Gorilla Gallium Processing, and 1 for Chimpanzee Probe Tools. Chimpanzee Leaf Processing and Crow Hook Tools both were acyclic. Hand axe production and hypothetical Oldowan debitage both had the longest *k*-cycles at 9 participating nodes. It is followed by Gorilla Nettle Processing (*k* = 3, 1 path), Gorilla Gallium Processing (*k* = 3, 1 path), and Chimpanzee Probe Tools (*k* = 2, 1 path). Both hand axe production and the hypothetical Oldowan graph contain a far larger number of cycles and the longest cycles.

When the logged cycle census ratios are graphed (Figure 6) we can see the maximum *k* for Hand axes and Hypothetical Oldowan are approximately oe order of magnitude greater than those for the other operational sequences in the sample.

DISCUSSION

Using graphs in this way reduces complexity to single, formal dimension describing the ways in which actions can be potentially combined. This is operationalized in terms of the number of decisions to be made and the number of sequences that can be generated within a graph. Of course, many of these potential sequences are not realistic given the constraints of a particular toolmaking tradition. The goal of a stone knapper, for instance, is obviously not to string together actions for the sake of creating long sequences. Obviously, they string together actions in order to achieve a pragmatic goal such as solving a problem emerging while shaping a biface such as hinged flake or incongruous mass. That said, this method does index the relative formal complexity of a graphed operational sequence in a consistent, principled manner.

The emergence of Acheluean technologies 1.8 million years ago (Lepre *et al.* 2011) is of particular interest to Paleolithic archaeologists. While the earlier Oldowan flake industry appears to be within the competence of modern nonhuman apes (Wynn *et al.* 2001; Toth and Schick 2009) the production of Acheluean tools may represent the appearance of something different.

The production of Late Acheulean-style hand axes involves that hierarchical integration of long sequences of operations involving an active decision-making process (Stout *et al.* 2008). Measures of formal complexity regarding decision-making and combinatorial potential should be high relative to earlier hominid technology.

None of the human or nonhuman animal operational sequence fit the description of a "string-of-beads," but it is clear that there are vast differences in the complexity between them. If we define a loop as the repetition of a single action (A → A) or the cycle involving two or more actions (A → B → A), then Crow Hook tools and Gorilla Gallium and Nettle Processing appear to involve a single loop and a string of simple actions. It could be the case that these represent to different elements; one requiring monitoring while the preceding or following string is simply elicited. Chimpanzee Leaf Processing and Probe Production are primarily branching structures with few loops within them. Hand axe production, on the other hand, is a much more densely connected graph.

As may be the case in the Crow Hook Tools and Gorilla food processing graphs, it could be the case that the graph for Hand axe production includes multiple, compiled processes. However, the example observed here is best described as involving at least four repetitive phases bracketed by single or multiple flake removals: information collection, processing, the ballistic gesture, and assessment. During information collection, the knapper tended to spend most of his time manipulating the object, presumably actively collecting visual information from different incident angles as well as different sensory modalities, such as proprioception. After placing the blank on the thigh in the desired orientation, the knapper placed the hammerstone on it for a moment, pausing before the strike. Both the orientation and placing of the core indicate a period in which the information is being actively processed, perhaps involving simulation of the anticipated strike (Jeannerod 2001) and its product (Nonaka *et al.* 2008). During assessment, the knapper matches anticipated with actual results. This is not simply visual. As anyone who spends even a small period of time around a stone knapper in action can report, it is possible to tell from the sound of the strike if it was successful. Assessment begins with aural information as soon as the hammer makes contact with the platform.

Most of the actions in the hand axe graph occur during the active collection of information by the knapper. These include the weighing the blank and using a series of repeated rotations to view its facets from multiple angles of incidence. As with the phonemes in a morpheme or the phrases of a sentence, the individual actions occurring during all four phases are meaningless outside of the overall context of the process. To rotate a rock in order to view it from different angles is not the same thing as to rotate it in order to determine the best spot from which to detach a thinning flake which will remove a persistent island of cortex which is restricting your ability to thin the opposite edge. Considering this, including all of these actions into a single graph may be justified.

CONCLUSION
The use of graphs is an important tool in the analysis of trends in the earliest stone tool technologies. They provide a means of quantifying changes in the overall fabricatory depth of the operational chain. Additionally, they can provide a method of measure the formal complexity of a series of operations used in the processing of food or production of tools. Stout (2010) has argued for an increase in cognitive control during the long Early Stone Age. The hierarchical structure present in the production of Late Achuelean hand axes is shared by technologies and techniques skillfully exhibited by the great apes (Byrne 2008). However, the fact that it is present

in a reductive lithic medium is significant given the unique computational demands of the ballistic knapping gesture. Analysis of this trend will require valid comparative measures. Using graphs and the matrices that represent them allow analysts to measure operational complexity across a wide range of technologies and taxa.

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