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The Structural and Functional Complexity of Hunter-Gatherer Technology

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Abstract The complexity of hunter-gatherer technology has been measured by counting artifact parts or production steps. There are a variety of alternative approaches to the measurement of artifact or system complexity. If technological complexity is assumed to reflect the complexity of the problem (or amount of entropy reduction) that the artifact is designed to address, the most appropriate measure of technological complexity is *functional design complexity*, which entails application of the entropy formula from information theory to the making and using of an artifact and the results obtained by its use. Functional complexity is related to structural or *hierarchical complexity*, because the entropy formula can be represented as a hierarchy (or step-by-step reduction of entropy) and the functional differentiation is related to the structural differentiation of an artifact. Another approach to hunter-gatherer technological complexity entails definition of a class of "complex artifacts" on the basis of general design characteristics (*e.g.*, incorporation of moving parts). The most structurally and functionally complex artifacts are those that possess multiple states, either through changes in the physical relationship between parts (or sub-parts) during use or through structural differentiation. Although functional complexity is difficult to measure, structural or hierarchical complexity may be measured—and *multiple-state artifacts* may be counted—with adequate ethnographic and archaeological data on hunter-gatherer technology.

Keywords Technological complexity · Hunter-gatherers · Information theory

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Introduction: The Complexity of Hunter-Gatherer Technology

In a survey of food-getting technology ("subsistants") among non-industrial peoples, Wendell H. Oswalt (1976) found considerable variation in the complexity of technology in hunter-gatherers. Complexity was measured by counting (1) the number of subsistants and (2) the number of parts ("technounits") contained in each subsistant (Oswalt 1976, 33–44). Among the 20 recent hunter-gatherer groups included in his survey, the range of variation extended from the *Tiwi* (north Australia), who made a total of 11 subsistants, each composed of an average 1.3 technounits, to the *Deg Hit'an* (interior Alaska), who made a total of 55 subsistants, each composed of an average 5.4 technounits (Oswalt 1976, 245–285). Other hunter-gatherers in the survey, such as the *Owens Valley Paiute* (California) and *Tlingit* (Pacific Northwest), fell between these extremes (Oswalt 1976, 238–267).

Oswalt (1976, 230) believed that the study of variation in their technology not only would improve understanding of hunter-gatherers but also would shed light on the role of technology in human evolution. He explained the variation in the complexity of subsistants as a function of the types of foods obtained by the various hunter-gatherer groups in his sample (Oswalt 1976, 181–195). At one extreme, the *Tiwi* depended heavily on immobile plant foods that were acquired with simple instruments or without any technology, while at the other extreme, the *Deg Hit'an* (and other high-latitude groups) subsisted almost entirely on various mobile animals, including fish, birds, and small mammals, acquired with a variety of specialized, multi-component instruments and facilities.

Oswalt's (1976) explanation of hunter-gatherer technology was discussed by other researchers (see Kelly 2013, 120–124), beginning with Torrence (1983), who found a significant correlation between subsistant and technounit totals and latitude. Subsistant and technounit totals also yield a strong inverse correlation with "effective temperature" (Hoffecker 2002, 10; Collard *et al.* 2005, 11–12).[1] Torrence (1983) concluded that the increased complexity of technology among high-latitude hunter-gatherers reflected the constraints of time available for obtaining foods ("time stress"), but subsequently argued that minimizing the risk of resource failure accounted best for hunter-gatherer technological complexity (Torrence 2001, 79–82; see also Collard *et al.* 2005).[2] Shott (1986) proposed that the lower carrying costs of reduced residential mobility would allow more complex tools. Read (2008) concluded that both risk minimization and residential mobility contributed to technological complexity.[3]

Here, we adopt a different approach to the problem of technological complexity among hunter-gatherers. Instead of devising a measurement of complexity and then seeking to explain the pattern of variation revealed by its application to a sample of

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[1] The algorithm for *effective temperature* (ET), which reflects the duration and intensity of the growing season, was developed by Bailey (1960, 4): $ET = 8\ T + 14\ AR\ /\ AR + 8$, where T is average annual temperature and AR is the average annual range of temperature.

[2] Torrence (2001, 79) concluded that "the level of risk increase(s) toward the poles because the availability of food decreases with longer winters and there are fewer alternative resources because species diversity has an inverse relationship with latitude. Latitude is therefore a useful proxy measure for severity of risk."

[3] Read (2008, 606) measured complexity in hunter-gatherer technology by applying Oswalt's (1973, 37) distinction between "simple" and "complex" (*i.e.*, mechanical) to artifacts, rather than subsistant/technounit counts.

hunter-gatherers, we begin with an assumption or proposition—that the complexity of technology is a function of the complexity of the problem that it is designed to solve. Given this proposition, we ask: what is the most appropriate measure of complexity?

The answer depends on how the complexity of the problem is measured. We apply *information theory* to the measurement of problem complexity, defining complexity in terms of the amount of uncertainty (or *entropy*) that must be reduced to solve the problem. In the context of hunter-gatherer subsistence, collecting food from abundant plant species requires less reduction of uncertainty, for example, than catching a mobile animal (*e.g.*, Oswalt 1976; Winterhalder 2001). The complexity of the technology designed to solve the problem is therefore measured in terms of the amount of uncertainty or entropy that it reduces, which is defined as *functional complexity*, and is a function of the artifact's probability of fulfilling its functional requirements, as measured in *bits* of information (Braha and Maimon 1998, 530–534).

Functional complexity is difficult or impossible to measure with any precision among recent hunter-gatherers, however, let alone the archaeological record of ancient hunter-gatherers. It is possible nevertheless to identify a category of artifacts made by hunter-gatherers that exhibit a high degree of functional complexity (especially in comparison to artifacts outside this category used for similar functions): *multiple-state artifacts*, which include self-acting devices such as snares and traps, as well as other artifacts that contain moving parts, such as a bow and arrow. Functional complexity, moreover, is closely related to *structural complexity*, as defined by Simon (1962), because living systems evolve solutions to complex problems by decomposing a problem into a set of smaller sub-problems, each of which is solved independently of the others; functional differentiation requires structural differentiation (Heylighen 1999, 30–32). With adequate ethnographic (and archaeological) data, the types and numbers of multiple-state artifacts can be inventoried and counted, and the structural or hierarchical complexity of individual artifacts can be measured, among recent and ancient hunter-gatherers.

Below, we review several measures of complexity and their application to hunter-gatherer technology. We argue that functional complexity is the most appropriate measure of technological complexity—given our definition of problem complexity—and that hierarchical structure is so closely related to function that it is a proxy measure for functional complexity. We follow this with a discussion of the most functionally and structurally complex forms of hunter-gatherer technology (*i.e.*, *multiple-state artifacts*). We then examine variations in the occurrence of multiple-state artifacts among a sample of recent hunter-gatherers in relation to several general environmental variables (*e.g.*, effective temperature) and compare the results with those based on the measurement of subsistant and technounit counts (*e.g.*, Torrence 1983; Read 2008). Following Oswalt (1976) and others, we confine the discussion to food-getting technology, but note that it is applicable to other categories of technology (*e.g.*, clothing and shelter).

Measuring Technological Complexity in Hunter-Gatherers

Most discussion of hunter-gatherer technological complexity has been based on the measure of complexity proposed by Oswalt (1973, 1976). The only notable exception of which we are aware is Perreault *et al.* (2013), who proposed counting "procedural units" or production steps rather than technounits or parts. There are, in fact, a variety of ways to measure complexity (see Lloyd 2001; Mitchell 2009, 94–111), and a number of them are potentially applicable to technology. In this section, we describe some of these complexity measures—beginning with Oswalt—and discuss the advantages and disadvantages of applying them to hunter-gatherer technology.

Quantity of Parts (Technounits)

Oswalt (1973, 1976) subdivided instruments (*e.g.*, bow and arrow) and facilities (*e.g.*, deadfall trap) into their irreducible component parts ("technounits") and calculated the number of parts for each artifact or feature. Parts not functionally differentiated from each other (*e.g.*, such as the multiple and more or less identical wooden stakes used to construct a fish weir) were not counted as separate technounits (Oswalt 1973, 33–34) and parts "having only ornamental or supernatural impact" were not counted at all (Oswalt 1976, 53). The *technological complexity* of each instrument and facility was determined on the basis of the total number of its technounits.

Oswalt (1976) counted technounits for food-getting technology (subsistants) among 36 hunter-gatherer and horticulturalist groups, drawing on earlier ethnographic publications for detailed descriptions of specific instruments and facilities (Marlowe (2010) applied the method to the technology of the *Hadza* in Africa). For example, a spear made by the *Aranda* (Australia) was broken down as follows (Oswalt 1976, 237):

> spear, used with throwing-board: wood point + wood barb + sinew, point-barb binder + wood foreshaft + wood shaft + sinew, point-foreshaft binder + resin, point-foreshaft binder + sinew, foreshaft-shaft binder + resin, foreshaft-shaft binder = 9 technounits

The Aranda spear was determined more complex than, for example, a fish trap (technounits = 6) made by the *Klamath* (Northwest coast), but less complex than a salmon drag gill net (technounits = 12) made by the *Deg Hit'an* (Alaska) (Oswalt 1976, 264–283). In addition to counting technounits for each instrument and facility, Oswalt calculated the average and total number of parts for subsistants among each group in his sample. Oswalt (1987) later applied his measure of complexity to the full spectrum of technology (including clothing and shelter) in two high-latitude hunter-gatherer groups.

Oswalt (1976, 218–227) discussed some of the limitations of counting parts as a measure of technological complexity. For example, he recognized that the modification of an individual part might increase the functional complexity of an artifact without adding to—or even subtracting from—its technounit total:

> The Klamath made certain arrows that appear to have been designed to skip across water to kill waterfowl. Typically the arrow point was made from wood with a pitch and sinew binder near the tip. However a bulge sometimes was carved as a collar beneath the point, and this served as an alternative to the sinew and pitch combination… The wood bulge may represent an integrative design principle resulting in a reduction of technounits (1976, 225).

More generally, some artifacts comprising a low number of parts (*e.g.*, *Paiute* two-component rabbit snare) are characterized by higher functional and/or structural complexity than artifacts (*e.g.*, *Aranda* spear described above) composed of a higher number of parts (Oswalt 1976, 236). In cases where parts—including moving parts—are not discrete components, such as the knot in a noose, they are not distinguished as separate technounits (Oswalt 1976, 51). Nevertheless, it is apparent that the average and total number of technounits (which correlate with the total number of subsistants) provide a rough or general measure of complexity for the food-getting technology of hunter-gatherers (*i.e.*, yields results broadly similar to those obtained by application of other measures described below).

Quantity of Production Steps (Procedural Units)

Perreault *et al.* (2013) reconstructed the number of procedural units required to make stone artifacts from several Paleolithic sites in Africa and the Levant (and noted that a similar approach might be applied to non-stone technologies). The approach is grounded in the *chaîne opératoire* method developed decades ago and often applied to lithic technology in the form of reconstructed core and tool reduction sequences (*e.g.*, Boëda 1995). Haidle (2009) reconstructed the many steps (illustrated with a "cognigram") required to make and use a 400,000–300,000-year-old wooden spear from the archaeological site of *Schöningen* (Germany). Lombard and Haidle (2012) employed the same approach to the manufacture and use of a bow and arrow (in a southern African setting).

The counting of production steps has some advantages over the counting of parts as a measure of complexity. The often complex sequence of steps required to make an individual part is not reduced to the same quantity as a much simpler set of steps required to make another type of part. A *Schöningen* spear, for example, required many more production steps (as reconstructed by Haidle (2009)) than an *Deg Hit'an* grinding stone (Osgood 1940, 104), but equals the same number of technounits as the latter ($n = 1$). As in the case of technounits, however, production steps represent a cost in terms of time and energy. Furthermore, we see no logical relationship between the quantity of production steps and the structural or hierarchical complexity of an artifact.

Functional Complexity

Many formal definitions of complexity entail application of the mathematical concept of information (see Mitchell 2009, 94–111), defined by Claude E. Shannon (1916–2001), who created the basis for "information theory" (*e.g.*, Pierce 1980, 19–44). Shannon (1948) defined *information* as the reduction of uncertainty or "entropy" (Shannon and Weaver 1963, 8–16), quantified in "bits" of information received according to the general entropy formula:

$$H = \log_2 N \tag{1}$$

where N is the number of possible states or values that a variable can assume. For example, if the variable has two possible states or values, it has $\log_2(2) = 1$ bit of information.

The "functional design complexity of an artifact" has been defined as the uncertainty of fulfilling its functional requirements (*i.e.*, a measure of its *information content*) in the context of the problem that it is designed to solve (Braha and Maimon 1998, 533–534). We can construct a model problem/technology system with well-defined functional requirements to obtain an exact quantification of functional complexity. If the problem, for example, is acquiring an individual prey animal that may be in any one of n patches at a given time, the system can take on one of n different possible states in a set $Q = \{s_1, s_2, \ldots s_n\}$, *i.e.*, one for each possible location of the prey animal. Without prior knowledge of the animal's location, a random search of one of the patches for the animal has a probability of success of $1/n$. The $p(x_i) = \frac{1}{n}p(x_i) = 1/n$ average entropy of the system is computed by

$$H = -\sum_{i=1}^{n} p(s_i)\log_2(p(s_i)) \tag{2}$$

where $p(s_i) = 1/n$ is the probability or frequency of a state s_i. If $n = 1$ (*i.e.*, there is only one patch to search) the system has 0 entropy or no uncertainty. Systems containing $n = 4$ and $n = 100$ patches have $\mathrm{H} \approx 2$ and 6.64 bits of entropy, respectively (the average number of binary digits required to specify a particular state in each system). In this context, entropy is a measure of the complexity of the problem. Entropy reduction may be described as a hierarchy of simplifying steps, where an increased number of required steps corresponds to a more complex problem.

If an artifact designed to snare or trap the prey animal is randomly deployed on one of the patches (*i.e.*, if a technological solution is applied to the problem), the prey animal—moving randomly from patch to patch—increases its chances of encountering the artifact each time. The artifact or facility is effectively sampling the animal's spatial probability distribution over time, and ensuring that once snared or trapped, the prey can no longer move from patch to patch. As the probability of successfully locating the animal within a single search event approaches 1, the corresponding entropy of the problem is reduced from its initial value toward 0, and this information difference is a measure the artifact's computational contribution to the problem or its "functional design complexity" (Braha and Maimon 1998).

The functional complexity of an artifact should be considered within the larger system addressing the problem that the technology is designed to help solve (*i.e.*, the person or persons making and using the artifact). Solving a problem, e.g., fulfilling the functional requirements of a technology, like other forms of information processing, involves the expenditure of energy. And it follows that the more complex the problem, i.e., more hierarchical steps, the greater the relative energetic costs. The cost associated with making and using the artifact (*i.e.*, expenditure of energy) must be factored into the equation (*e.g.*, Bettinger 2009, 59–80). The functional complexity of an automaton such as the snare/trap in the above example is high compared to a solution to the same problem that incurs the high energy costs and uncertainties of searching and capturing/killing the prey with a net or bow and arrow.

The predictable actions of the animal also contribute to the reduction of uncertainty and the functional design complexity of the artifact. Both the design of the snare/trap and its deployment in space and time reflect knowledge of the behavior and functional anatomy of the prey animal. The animal not only moves to the artifact but also either triggers the snare/trap or entangles itself in the device as a result of its (predictable) body movements (*e.g.*, Osgood 1937, 94). A similar observation applies to fish weirs and associated traps. Because it amounts to obtaining—either by artificial design, by construction of a predictive model system, or by inference on the basis of empirical data—a detailed mechanistic understanding of a particular problem, including environmental, biological, and interactive variables, functional complexity is an important quantity in the study of hunter-gatherers and their technology.

An advantage of measuring functional complexity, rather than quantities of parts or production steps, is that it excludes aspects of the artifact that do not contribute to solving the problem it was designed to address. Although Oswalt (1976, 53) excluded ornamental parts from technounit totals of subsistants, he counted them in other categories of hunter-gatherer technology, such as clothing (*e.g.*, Oswalt 1987, 89).[4] One of the steps in making a *Ju/'hoansi* wooden club (total production time = 5 h) is sanding and polishing, which apparently does not contribute to its effectiveness as a subsistant, but rather to the social status of its maker (Lee 1979, 141).[5]

The principal drawback of functional complexity is that—in the context of recent or ancient hunter-gatherer technology—it is impossible to measure with any precision. The information required to make a quantitative comparison between the functional complexity of a *Ju/'hoansi* club and a *Tanaina* rabbit snare is not available.[6] The value of functional complexity is primarily heuristic. There is a significant relationship between functional and structural complexity, however, that has a practical application to the problem of measuring technological complexity among hunter-gatherers.

Structural Complexity

In a classic 1962 paper, Herbert A. Simon (1916–2001) argued that hierarchical structure represented the most appropriate measure of artifact or system complexity (see also Simon 1996). From this perspective, the complexity of an artifact is measured in terms of the number of hierarchical levels that it contains and increased structural complexity may be equated with a greater number of organizational levels. Although Simon (1962, 478) used a two-dimensional matrix to describe a hierarchically

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[4] In counting technounits for clothing in two *Inuit* groups, Oswalt (1987, 89) notes that "garments often had numerous tus (technounits) unrelated to the protective needs because of the attention paid to design amplification, meaning tu elaborations beyond basic structural requirements."

[5] Lee (1979, 141) observes that "great care is lavished on sanding and polishing them to an ultrasmooth finish that is admired by other men."

[6] Time and energetic costs have been measured in some cases, however. Winterhalder (1981, 81–83) estimated net acquisition rate in kilocalorie per hour for various categories of prey (*e.g.*, stalking moose versus snaring hares) among the *Cree* (eastern Canada), while Lee (1979, 274–275) estimated time (in minutes) invested in making various types of subsistants among the *Ju/'hoansi* (southern Africa).

organized system, structural complexity can be described equally well with a linear string of symbols:

$$(a + b) + c + d$$

where a and b are sub-parts of a component on the same organizational level as c and d, or with a tree diagram, as in linguistics (*e.g.*, Jackendoff 2002, 3–18).

In contrast to functional complexity, the hierarchical complexity of hunter-gatherer technology is easily measured, if adequate ethnographic data are available, and may be applied in an archaeological context if the total organization of the artifact can be reconstructed. Measurements of structural complexity build on counts of parts or production steps, because the hierarchical organization of an artifact or its *chaîne opératoire* is deduced from the relationships among individual parts or production steps. Comparisons can be made between individual artifacts or between specific hunter-gatherer groups. For example, the *Tiwi* did not make any food-getting instruments or facilities that exhibit three or more organizational levels (*i.e.*, sub-parts with sub-parts), whereas the *Deg Hit'an* made many hierarchically organized forms of technology (Oswalt 1976, 245–285) (see example below).

The accessibility of data on the hierarchical organization of hunter-gatherer technology is important to the problem of measuring functional complexity, because there is a relationship between the structural and functional complexity of an artifact. As noted in the preceding section, the reduction of entropy may be characterized as a hierarchy of simplifying steps, and the required number of steps corresponds to the complexity of the problem (*i.e.*, the amount of entropy that must be reduced to solve the problem). The entropy formula (see above) can be represented as a hierarchy, as illustrated in Fig. 1. Structural complexity appears to be a proxy measure for functional complexity.

More generally, adaptive systems solve complex problems by *decomposing* them into a set of smaller sub-problems, each of which can be solved independently (Simon 1962, 472–481; Heylighen 1999, 30–32). A fox, for example, solves the complex problem of obtaining food by executing a sequence of hierarchically organized functions that involve searching an area, locating a specific prey animal, pursuing the prey, capturing, killing, and consuming the prey—each of which successively reduces the entropy of the problem.

In the context of hunter-gatherer economy, an example of a complex problem that may be solved with technology is the harvesting of substantial quantities of fish from a stream. Various hunter-gatherer groups have solved this problem by installing a combination of weirs and traps at selected times/places designed to divert fish into the traps (*e.g.*, Osgood 1940, 226–237; Nelson 1973, 57–59). Beginning with its strategic placement in a stream channel at a specific time in the annual cycle, the weir-trap complex "performs" a sequence of functions that redirect the fish toward and into the traps, from which they cannot escape. The functional differentiation of the facility is reflected in its hierarchical organization (*i.e.*, component weirs and traps composed of sub-components), which

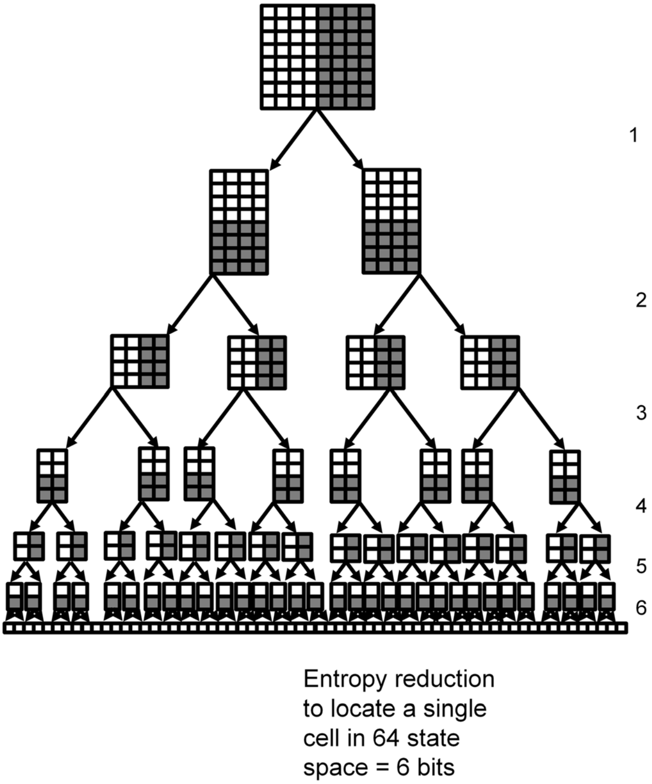

Fig. 1 The relationship between functional and structural complexity, illustrated by the step-by-step reduction of entropy required to locate 1 cell in a 64-cell space, which is equal to 6 bits of information, and entails 6 hierarchically organized steps or levels

ensures high probability of success (and corresponding step-by-step reduction of uncertainty) (see Fig. 2).

Kolmogorov Complexity

The mathematician A. N. Kolmogorov (1903–1987) proposed that the complexity of an object or system should be measured by the shortest possible description of it (Kolmogorov 1963). For example, although the expression 10 × 10 × 10 × 10 contains more symbols than 10^4, the two expressions are equally complex and contain the same amount of information. Kolmogorov complexity (sometimes referred to as "algorithmic entropy") may be applied to technology, including hunter-gatherer technology, by describing multiple, functionally undifferentiated parts (such as the multiple posts of a fish weir) as one part, multiplied by the number of times that the same part is added to the artifact.[7] "Kolmogorov

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[7] As already noted, Oswalt (1973, 33–34) did not count non-functional parts or multiple, functionally undifferentiated parts as separate technounits (and did not count non-functional parts, at least in the context of food-getting technology).

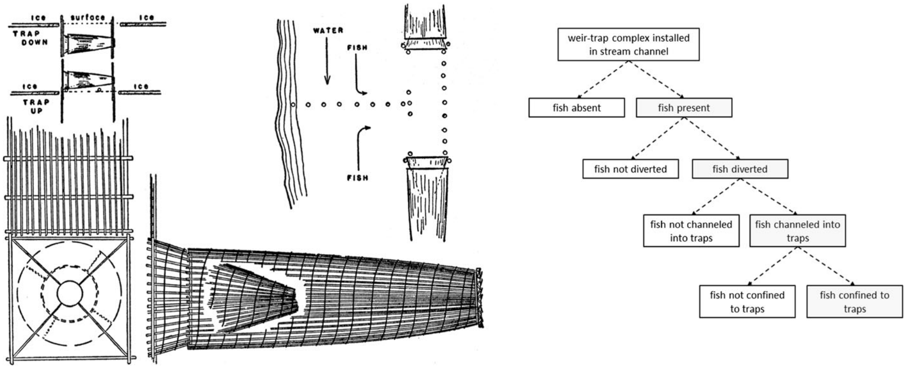

Fig. 2 Deg Hit'an fish weir-trap complex used in winter (from Osgood 1940, 229–230), which contains multiple identical parts (both weir posts and trap units) Courtesy of Yale University Publications in Anthropology. (*left*), and "decision tree" for a weir-trap complex, illustrating how it solves the decomposed problem of fish capture by solving a series of smaller sub-problems with multiple "functions" (although it lacks moving parts) (*right*). The functional complexity of the artifact is reflected in its structural complexity.

complexity" is important in the context of the preceding discussions of functional and structural complexity, because it underscores the observation that an increase in the total number of parts or production steps does not necessarily increase the structural/functional complexity of an artifact or facility.

Network Complexity

The technology of any animal may be viewed as a *network* comprising materials and operations in the form of "nodes" and "edges," respectively (*e.g.*, Newman 2003). As such, a technological network is subject to standard measures of network complexity or graph theory (Bonchev and Buck 2005). In general, network complexity increases with the number of nodes and degree of connectedness (connections or edges between nodes).

The measurement of technological network complexity in hunter-gatherers can be demonstrated by mapping a small portion of the very complex network of materials and artifacts made by the *Deg Hit'an* (and described in detail by Osgood (1940)). As shown in Fig. 3, a few materials (spruce root and wood, caribou bone and hide, and beaver incisor) and artifacts (nodes) made by the *Deg Hit'an* (bone skin scraper, babiche line, man's awl, and beaver tooth wood chisel) exhibit a complex web of inter-relationships (edges). All of the materials and artifacts included in Fig. 3 have many other connections within the larger network of *Deg Hit'an* technology.

Like the structural complexity of individual artifacts, network complexity can be measured in the context of hunter-gatherer technology if the ethnographic data are available (and conceivably in an archaeological context, if the materials and artifacts can be reconstructed). It represents an alternative quantifiable measure of technological complexity in this context. Network complexity is not the most appropriate measure of problem complexity, because it provides a less direct measure of the latter than functional complexity. It does, however,

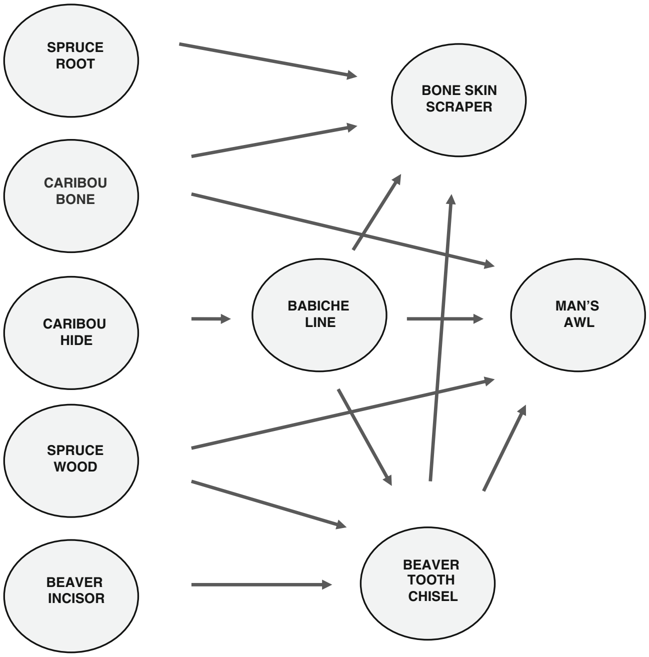

Fig. 3 A network diagram, comprising nodes and edges, of a small portion of the technological network of the Deg Hit'an (based on data in Osgood 1940, pp. 65–105), illustrating inter-connections among several materials and artifacts. The babiche line node is both artifact and material, and the chisel node is an artifact used to make other artifact nodes. Although the unidirectional inter-connecting edges represent various operations, they are simplified as generic arrows

represent a suitable measure of overall technological complexity among hunter-gatherers, as well as other societies and economies (and other species).[8]

The Complex Technology of Hunter-Gatherers: Multiple-State Artifacts

In addition to breaking down hunter-gatherer subsistants into their constituent parts or technounits, Oswalt (1973, 36) classified items as "complex" (or *mechanical*) if they contained parts that "change their relationship with one another when the form is used" (Oswalt 1976, 50), regardless of the number of technounits.[9] In his survey of hunter-gatherer and horticulturalist food-getting technology, he subdivided all instruments and facilities into simple and complex, but did not analyze the overall pattern of variation in mechanical artifacts (Oswalt 1976, 171–195). With the exception of Read (2008), others followed

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[8] Chimpanzees exhibit a simple technological network of materials and artifacts; for example, a small branch or twig is used for both termite-fishing and ant-fishing (McGrew 2004, 111–114).

[9] In his survey, Oswalt (1976, 135) noted that "simple untended snares never included more than six parts, exclusive of guide fences," and Wadley (2010, 179) described the technology of snares and traps as "relatively simple."

his lead by emphasizing variations in subsistant and technounit counts (*e.g.*, Torrence 1983; Shott 1986; Collard *et al.* 2005).

The definition of a class of complex artifacts on the basis of general design characteristics represents another approach to the complexity of hunter-gatherer technology. We believe that it is a potentially useful approach, but only if the class of complex artifacts is defined with reference to Automata Theory (*e.g.*, Minsky 1956). In our view, Oswalt's (1973, 1976) definition of "complex artifacts" was flawed both in conception and in application. The definition is too narrow and excludes a number of functionally and structurally complex artifact types that lack parts that "change their relationship with one another" such as a noose snare (which contains a single moving part) or a fish weir/trap complex (*e.g.*, Oswalt 1976, 286). The conceptual limitations were compounded by arbitrary decisions on classification (*e.g.*, arrows were counted as separate complex artifacts [*e.g.*, Oswalt 1976, 281]).

We propose a class of complex artifacts that includes all types of instruments and facilities that exhibit multiple states during use. *Multiple-state artifacts* not only include all facilities that fit the formal definition of a finite-state machine or *automaton* (*i.e.*, transition from one state to another without the intervention of one or more humans) but also include facilities that do not contain moving parts, but nevertheless perform a sequence of functions as a result of their structural differentiation (*e.g.*, the weir-trap complex illustrated above). In the case of these facilities, the "multiple states" are simultaneous rather than sequential (*i.e.*, each successive function is performed by a sub-system of the facility). They also include instruments that exhibit multiple states, but only as a result of human anatomical function ("semi-automata").

Automata

Many recent hunter-gatherers made self-acting facilities in the form of snares and traps designed to obtain small mammals, birds, and sometimes large mammals (*e.g.*, Oswalt 1976, 131–143; Wadley 2010, 180–181; Kelly 2013, 126–128). There is some archaeological evidence (based on the analysis of faunal remains) for this technology in southern Africa as early as 65,000–62,000 years ago (Klein 1981; Wadley 2010). Traps and snares meet the formal definition of *automata* or machines (*e.g.*, Rich 2008, 56–60). They exhibit a high degree of functional complexity (or "information content") based on a twofold reduction of entropy: they reduce the uncertainty associated with finding and catching mobile prey (usually small and highly mobile prey) and conserve the energy that would be lost by an organism performing their functions without them. Snares and traps, once deployed on the landscape, function as specialized, stationary robots, analogous to an organism.

As with the computer, automata theory has its roots in the early nineteenth century with Charles Babbage (1791–1871), who devised a system of "mechanical notation" to describe the multiple states of a machine (Babbage 1826). A more widely used system of "kinetic notation" was developed in the late nineteenth century (Reuleaux 1963 [1875]). The modern theory of automata arose in concert with the programmable digital computer in the 1950s (*e.g.*, Mealy 1955; Moore 1956), along with a new form of graphic notation for machines ("state diagram") (*e.g.*, Minsky 1967, 21–25).

The simplest form of automaton is a deterministic *finite-state machine* (*e.g.*, Jackson 1985, 45) where:

Q	is a finite set of states (S_1, S_2 … S_n)
X	is the input
Y	is the output
$\delta: Q \times X \rightarrow Q$	the next state function
$\lambda: Q \times X \rightarrow Y$	the next output function.

The distinguishing features of a finite-state machine (as opposed to other forms of technology) are that it contains both multiple states (S_1, S_2 … S_n) and the means to transition from one state to another (δ, λ), including a state that will yield the output (Y).

An example of a hunter-gatherer finite-state machine is a rabbit snare designed by the *Tanaina* (southwestern Alaska) and illustrated—with a machine state diagram—in Fig. 4 (Osgood 1937, 92–95). The Tanaina rabbit snare may be classified as a "two-state machine" that is either unsprung (S_1) or sprung (S_2) with its captured prey (Y). The input (X) is represented by the rabbit before it enters the snare. The operation of the machine is described by the combined "transition functions" (δ, λ). It performs a deterministic computation with materials (rather than information), lacks memory storage, and does not require a program—the functions of the computation are built into the structure of the automaton.

Both its placement in space and time and modifications to the immediate environment may contribute to the functional complexity (*i.e.*, reduction of uncertainty) of a trap or snare. Snares typically are placed on a game trail, where the probability that a prey animal will occur within some period of time is high. They are often placed during a specific season, such as winter, when the value of the prey animal is high (*e.g.*, high fat content). Obstructions may be placed around the snare in order to decrease the probability that the animal will wander away from it (*e.g.*, Osgood 1940, 241). Conversely, some form of bait may be placed in or near the snare or trap to increase the probability that the animal will enter it (*e.g.*, Nelson 1899, 122).

Pseudo-Automata

Some recent hunter-gatherers made a class of "untended facilities" that do not technically meet the definition of a machine, but nevertheless play a role similar to that of automata in a foraging economy—and also exhibit a high degree of functional complexity (or information content). These facilities include fish weirs and associated traps, made and used by northern interior hunter-gatherers who consumed a substantial quantity of fish, and which we have classified as "pseudo-automata." As in the case of snares and traps, their use may have considerable time depth in the archaeological record.[10]

An example of a pseudo-automaton in the form of a fish weir-trap complex made by the *Deg Hit'an* (see Osgood 1940, 229–230). As illustrated in Fig. 2, the weir-trap

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[10] The use of fish weirs and traps may be tentatively inferred from the high ^{15}N values—suggesting high consumption of freshwater aquatic foods—found in human bone from Europe and Siberia dating as early as 45,000–35,000 cal BP (Richards et al. 2001; Fu et al. 2014).

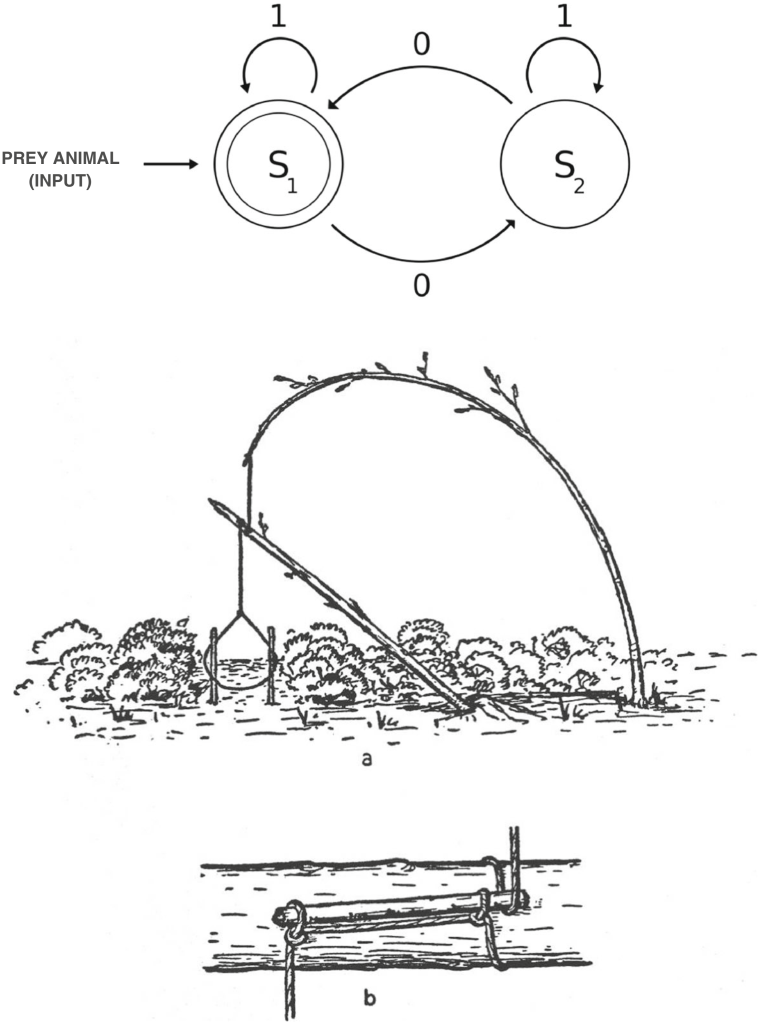

Fig. 4 Multiple-state artifact: self-acting facility or automaton in the form of a Tanaina rabbit snare (**a**), showing detail of mechanical trigger pin (**b**) (from Osgood 1937, p. 93, Fig. 20). Courtesy of Yale University Publications in Anthropology. Simple model of a two-state machine with no memory storage (*above*): state one (S_1) represents the unsprung snare, and state two (S_2) represents the sprung snare with captured prey (modified from https://commons.wikimedia.org/wiki/ File:DFAexample. svg)

complex is installed in a narrow stream channel and diverts fish from both directions into a partial enclosure, from which they are likely to swim into one or two traps. The functional complexity (and corresponding structural complexity) is reflected in the sequential reduction of uncertainty as the fish accumulate in the trap(s). As untended or minimally tended facilities, they conserve energy (*i.e.*, reduce entropy), although they often require significant time, energy, and materials for construction.[11] They do not

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[11] For example, Osgood (1940, 227) reported that at least 5 days were required to make an *Deg Hit'an* dog salmon trap ("three or more days to split enough fish trap sticks for the trap, another day to make the trap, and still another to make the fence which blocks the fish from passing").

meet the formal definition of a machine because—while they possess multiple states, input, and output—they lack a transition function.

Another group of untended facilities in this category are snares and traps that are powered (rather than simply triggered) by the prey animal. They include, for example, an *Deg Hit'an* ptarmigan/grouse tether snare, which functions without a trigger and spring—the prey is guided into the snare and becomes entangled in a noose (Osgood 1940, 240–241). In this case, the transition function is present, but is not part of the artifact.

Semi-Automata

Many hunter-gatherer groups made instruments and facilities with moving components that did not function independently of the human body (*e.g.*, fire drill, bow, and arrow) (see Oswalt 1976, 233–294). These artifacts lack most of the defining elements of a machine, but they do exhibit multiple states (S_1, S_2 … S_n) and we classify them as semi-automata. The multiple states increase their functional complexity or reduced uncertainty relative to artifacts without moving parts or with fewer moving parts used for the same function (*e.g.*, bow-operated versus hand-operated fire drill). If automata and pseudo-automata are analogous to a functioning organism, semi-automata are analogous to the functioning part of an organism, such as a limb (which cannot function without the organism). The earliest known mechanical artifacts (other than automata and pseudo-automata) now are dated to 44,000–42,000 years ago in southern Africa (Villa *et al.* 2014).

Explaining Technological Complexity in Hunter-Gatherers

Following Read (2008), we applied our own definition of complex artifacts (*i.e.*, multiple-state artifacts) to a sample of recent hunter-gatherers to examine variations in complex food-getting technology. We simply counted multiple-state artifacts for each group in the sample and correlated the results with several general environmental variables. The sample included 19 of the 20 groups in Oswalt's (1976) survey (the Tasmanians were excluded due to concerns about the completeness of their artifact inventory; see Oswalt 1976, 175). Two African groups were added for which detailed descriptions of food-getting technology were available, including the *Ju/'hoansi* (Lee 1979) and *Hadza* (Marlowe 2010).

Multiple-state artifacts were inventoried from the ethnographic data for all 21 of these groups, and the results are shown in Table 1. Significant variation was observed in the sample, ranging from the *Tiwi* (Australia), who did not make any multiple-state artifacts, to the *Deg Hit'an* (Alaska), who made 21 different types of multiple-state artifacts, including automata, pseudo-automata, and semi-automata, as defined above. The two extremes are the same as those identified in the Oswalt (1976) sample.

The counts for multiple-state artifacts were correlated with three environmental variables, (1) latitude, (2) effective temperature, and (3) plant productivity (or net primary production), and the results are shown in Fig. 5. There is a moderately strong correlation between the use of multiple-state artifacts and latitude (r^2 = 0.638) and somewhat less strong (inverse) correlation between multiple-state artifacts and effective

Table 1 Technological complexity among selected hunter-gatherer groups: *multiple-state subsistants* (based on Oswalt 1976; Lee 1979; Marlowe 2010)

Group	Number of subsistants	Technounit average	Multiple-state artifacts	% Multiple-state artifacts
Andamanese (Bay of Bengal)	11	4.6	2	18
Angmagsalik (Greenland)	33	6.1	14	42
Aranda (western Australia)	16	2.6	2	12.5
Caribou Inuit (northern Canada)	34	3.5	10	29
Chenchu (southern India)	20	2.8	4	20
Copper Inuit (NW Canada)	27	4.5	5	18.5
Hadza (East Africa)	22		3	14
Iglulik (eastern Arctic)	42	5.4	15	36
Deg Hit'an (Interior Alaska)	55	5.4	21	38
Ingura (northern Australia)	13	2.5	4	31
Ju/‘hoansi (southern Africa)	11		3	27
Klamath (NW Pacific coast)	43	3.5	5	12
Nabesna (Interior Alaska)	25	4.2	13	52
Naron Bushmen (southern Africa)	12	3.3	4	33
Owens Valley Paiute (California)	28	3.8	9	32
Surprise Valley Paiute (California)	39	2.5	8	20.5
Tanaina (southern Alaska)	40	5.6	19	47.5
Tareumiut (Arctic Alaska)	35	5.9	16	46
Tiwi (northern Australia)	11	1.3	0	0
Tlingit (NW Pacific coast)	28	4.3	9	32
Twana (NW Pacific coast)	48	4.9	12	25

temperature (r^2 = 0.575). There is a weak (inverse) correlation between the use of multiple-state artifacts and plant productivity (r^2 = 0.276). The results are similar to those found by Torrence (1983, 18–19) for latitude and Hoffecker (2002, 10) and Collard *et al.* (2005, 12) for effective temperature. In contrast to Collard *et al.* (2005, 12), we did not find that plant productivity had a significant influence on technological complexity.

Following our assumption that the complexity of technology reflects the complexity of the problems that the technology is designed to solve, we conclude that the results indicate that high-latitude hunter-gatherers confront the highest level of problem complexity among most or all recent hunter-gatherers. This presumably reflects the fact that—in addition to generally scarce resources—high latitude hunter-gatherers face the combined challenge of virtually no digestible plant foods and the high caloric demands of a cold-climate setting. They must obtain as much as ~48% more calories than their equatorial counterparts—almost entirely from mobile animal foods (*e.g.*, Harrison *et al.* 1988, 479–497; Kelly 2013, 41–43).

Northern interior hunter-gatherers such as the *Deg Hit'an* and *Tanaina* developed a diverse array of complex multiple-state artifacts to harvest various species of birds, fish,

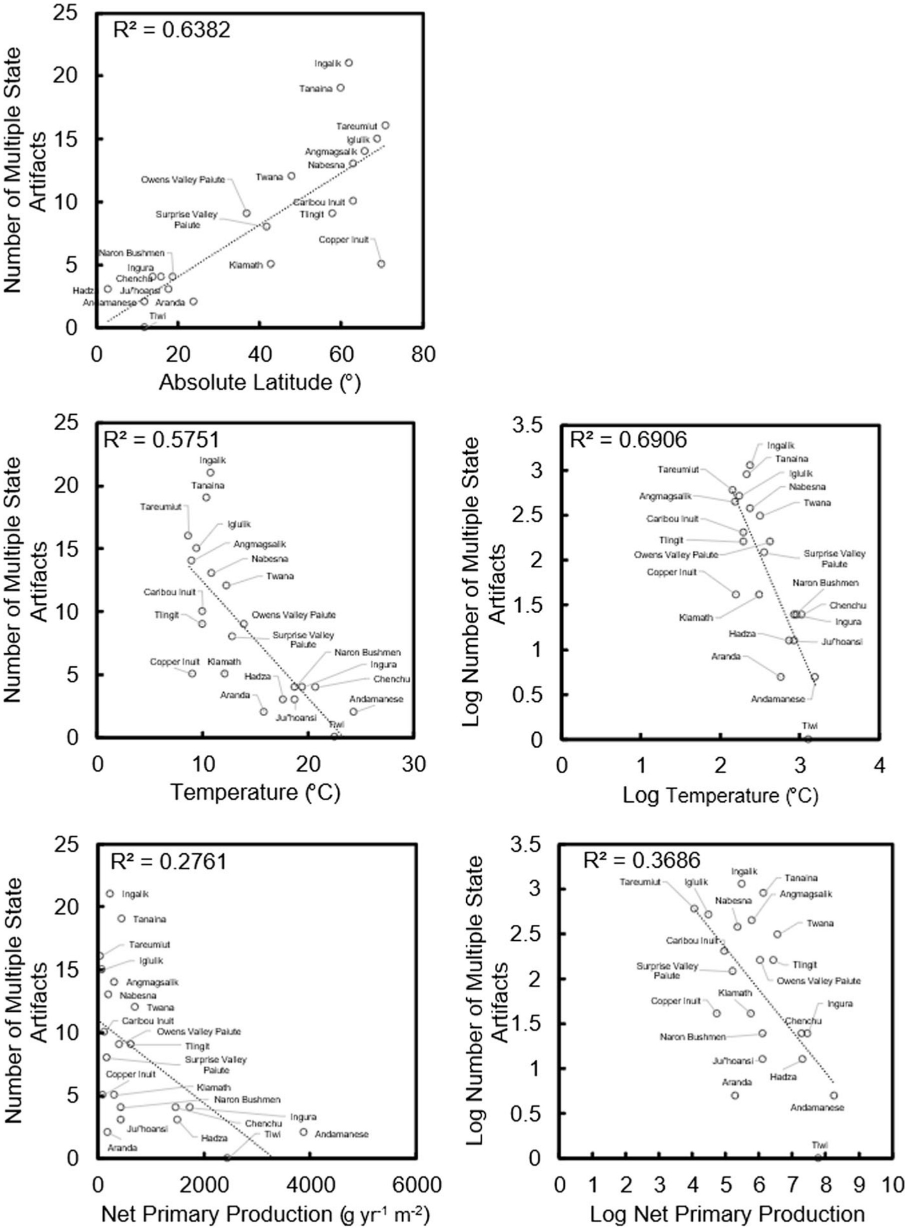

Fig. 5 Correlation of multiple-state artifacts with latitude, temperature (measured as "effective temperature" [Bailey 1960]), and plant productivity (or net primary production)

and small mammals—all of them small and elusive prey—in large numbers with minimal energy costs (Osgood 1937, 1940). Coastal groups such as the *Tareumiut* and *Angmagsalik* developed a comparable array of multiple-state artifacts to exploit abundant—but even more elusive—marine mammals, which required technological solutions to a different set of complex problems (*i.e.*, searching for, killing, and retrieving mobile animal prey in Arctic seas or beneath sea ice) (Murdoch 1892;

Thalbitzer 1914). Their complex food-getting technology was integrated with equally (or more) complex technology for transportation, clothing, and shelter (Oswalt 1987).

Why is not the correlation between multiple-state artifacts and latitude (and effective temperature) stronger? A review of the ethnographic data suggests that at least some hunter-gatherers in low latitude and/or high effective-temperature settings did not need to use multiple-state artifacts in order to sustain a long-term viable population, but they made them anyway. In some cases, the use of multiple-state artifacts probably contributes to unusually high densities for a hunter-gatherer population. An example is the *Andamanese*, who adapted the bow and arrow to fishing (Radcliffe-Brown 1922, 417–441) and enjoyed an unusually high population density for a hunter-gatherer group (Kelly 2013, 178–184, Table 7-3).

The weak correlation between multiple-state artifact frequency and plant productivity (NPP) apparently reflects a pattern of organizational and dietary responses to resource scarcity among hunter-gatherers at lower latitudes. In low-latitude settings, *per capita* caloric demands are minimal and the proportion of digestible plant foods on the landscape is relatively high (*e.g.*, Harrison *et al*. 1988, 479–497; Kelly 2013, 41–43, Table 3-1). In arid regions where NPP was low despite high effective temperature, groups such as the *Ju/'hoansi* and *Aranda* foraged over wide areas (with an extensive network of alliances and information exchange) (Lee 1979; McDonald and Veth 2011; Kelly 2013, 78–96). While the technological demands of plant collecting were comparatively low, high mobility discouraged transport of numerous and complex artifacts (*e.g.*, Gould 1980, 68–72).

In some respects, Simon's (1962) proposed measure of hierarchical levels represents the ideal approach to hunter-gatherer technological complexity. Structural complexity is one of the most striking and significant features of highly evolved living systems, and may be the most appropriate general measure of system or artifact complexity. Furthermore, structural complexity is related to functional complexity, and appears to represent a proxy measure of the latter.

Unlike the rather esoteric "functional complexity" defined by Braha and Maimon (1998), hierarchical complexity is easily and objectively measured with the artifacts of hunter-gatherers.

The principal limitation of hierarchical complexity in this context is the uneven level of detail in the available ethnographic data. Graphic illustration of specific artifacts is often necessary to measure their hierarchical structure, and there is insufficient data for many of the groups in the hunter-gatherer sample listed in Table 1.[12] Instead, we assessed the hierarchical complexity of food-getting technology for two representative groups in the sample for which sufficient data are available. The results for the *Hadza*, who occupy a rich tropical habitat in East Africa, are listed in Table 2 (based on Marlowe 2010), while the results for the *Deg Hit'an*, who occupied northern interior habitat in Alaska, are listed in Table 3 (based on Osgood 1940). We found that 71% of *Deg Hit'an* subsistants, but only 14% of *Hadza* subsistants, were composed of three or more hierarchically organized levels. Most—but not all—of the structurally complex artifacts met our definition of functionally complex multiple-state artifacts.

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[12] Contrast for example, the extensive illustration (and supporting detailed written description) of *Deg Hit'an* material culture in Osgood (1940) with the account of *Upper Tanana* material culture in McKennan (1959), who did not include a single illustration of a snare, trap, or weir-trap system.

Table 2 Food-getting technology of the Hadza (based on Marlowe 2010, pp. 77–78, Table 4.4)

Subsistant	Materials	Technounits	Organization	Multiple-state artifact
Twig	1	1	Single component	No
Wooden stake	1	1	Single component	No
Stick (often cut)	1	1	Single component	No
Stick (whittled)	1	1	Single component	No
Torch	2	2	Composite (2 parts)	No
Wooden club	1	1	Single component	No
Stick (cut)	1	1	Single component	No
Digging stick	1	1	Single component	No
Digging stick (iron)	1	1	Single component	No
Throwing stone	1	1	Single component	No
Hammerstone and anvil	1	2	Composite (2 parts)	No[a]
Porcupine quill	1	1	Single component	No
Knife	2	2	Composite (2 parts)	No
Scabbard (for knife)	2	2	Composite (2 parts)	No
Ax	2	2	Composite (2 parts)	No
Bark twine	1	1	Single component	No
Basket	1	3	Composite (3 parts)	No
Wood carrying pole	1	1	Single component	No
Gourd (with twine)	2	2	Composite (2 parts)	No
Hunting blind	4	4	Composite (4 parts)	No
Bow	5	5	Hierarchical (3 levels)	Yes
Arrows (5 types)	3–9	3–9[b]	Hierarchical (3 levels)	(Yes)[c]
Quiver (for arrows)	?	5	Hierarchical (3 levels)?	No

[a] As in the case of chimpanzee nut-cracking with stone and anvil, this hammerstone and anvil could be considered a multiple-state artifact without a fixed link between the components

[b] Materials and parts include three types of poison (and one mixture of two types of poison)

[c] Arrows are used with bows and are therefore part of a multiple-state artifact. Marlowe (2010, 97) notes that "men spend much of their time in camp working on arrows"

Summary and Conclusions

Since Oswalt's (1976) ground-breaking study, most discussion of hunter-gatherer technological complexity has been focused on the explanation of increased complexity (*e.g.*, Torrence 1983; Collard *et al*. 2005; Read 2008). Here, our primary concern has been the *measurement* of technological complexity among hunter-gatherers. Drawing on concepts from complexity theory—and more generally information theory—we suggested some new ways that the complexity of hunter-gatherer technology (specifically, food-getting technology) might be measured (*e.g.*, Pierce 1980; Mitchell 2009; Floridi 2010).

In a departure from the approach taken by others, we simply assumed that the complexity of technology reflects the complexity of the problems that it is designed to solve. We defined problem complexity in classic information-theory terms as the reduction of uncertainty or entropy: the complexity of technology should be a function of the

Table 3 Food-getting technology of the Deg Hit'an (based on Osgood 1940, pp. 194–252; Oswalt 1976, pp. 281–285)

Subsistant	Materials	Technounits	Organization	Multiple-state artifact
Wooden stick	1	1	Single component	No
Wood club	1	1	Single component	No
Fish impaler	2	2	Composite (2 parts)	No
Ice pick	3	3	Composite (3 parts)	No
Bone club	4	4	Hierarchical (3 levels)	No
Spear	3	3	Composite (3 parts)	No
Leister	3	3	Composite (3 parts)	No
Knife	3	3	Composite (3 parts)	No
Bird dart and board	3	7	Hierarchical (3 levels)	Yes
Fish harpoon dart	4	5	Hierarchical (3 levels)	Yes
Toggle-head harpoon	5	7	Hierarchical (3 levels)	Yes
Self bow	3	3	Composite (3 parts)	Yes
Arrow (4 types)	6–7	6–7	Composite (6–8 parts)	(Yes)[a]
Arrow (big mammal)	7	8	Hierarchical (3 levels)	(Yes)[a]
Pole and line	2	2	Composite (2 parts)	No
Bear lure	3	3	Composite (3 parts)	No
Lamprey stick	2	3	Composite (3 parts)	No
Beaver net	4	4	Hierarchical (3 levels)	No
Caribou snare fence	3	5	Hierarchical (3 levels)	Yes
Fish-hook and pole	5	5	Hierarchical (3 levels)	No
Blackfish dip net	2	7	Hierarchical (3 levels)	No
Salmon dip net	3	9	Hierarchical (3 levels)	No
Salmon drag gill net	6	12	Hierarchical (4 levels)	Yes
Tree squirrel snare	5	5	Hierarchical (3 levels)	Yes
Ground squirrel snare	3	6	Hierarchical (3 levels)	Yes
Ptarmigan snare	4	7	Hierarchical (3 levels)	Yes
Waterfowl snare	4	8	Hierarchical (3 levels)	Yes
Blackfish trap and fence	5	8	Hierarchical (3 levels)	Yes
Whitefish trap	2	12	Hierarchical (3 levels)	Yes
Salmon trap	2	12	Hierarchical (3 levels)	Yes
Winter fish trap	3	12	Hierarchical (3 levels)	Yes
Bear snare	3	10	Hierarchical (3 levels)	Yes
Tossing pole snare	4	10	Hierarchical (3 levels)	Yes
Beaver deadfall trap	4	10	Hierarchical (3 levels)	Yes
Lynx tether snare	4	11	Hierarchical (3 levels)	Yes
Toppling trigger deadfall trap	1	11	Hierarchical (3 levels)	Yes
Friction trigger deadfall trap	2	12	Hierarchical (3 levels)	Yes

[a] Arrows are used with bows and are therefore part of a multiple-state artifact

amount of uncertainty or entropy that it reduces in the context of the problem. From this perspective, technology is analogous to *Maxwell's Demon* (*e.g.*, Floridi 2010, 64–66).

Accordingly, the most appropriate measure of hunter-gatherer technological complexity is *functional design complexity* (or information content) defined as "the probability of successfully achieving the functional requirements" or simply "the probability of success" (Braha and Maimon 1998, 533). We used a rabbit snare as an example of a subsistant that exhibits high functional complexity in comparison to alternative technologies for obtaining a rabbit (*e.g.*, hand-held net). Like Maxwell's Demon, the increased entropy associated with the information cost of the technology (in this case, the energy expended making the snare) must be factored into the equation. We noted that snares often are composed of few parts and require few production steps (*i.e.*, they often register low on the complexity scale, based on these widely used measures of complexity).

Regardless of its suitability from a theoretical perspective, functional design complexity cannot be measured with any precision in the context of hunter-gatherer technology (let alone the archaeological record). Its value is primarily heuristic. We proposed two alternative approaches to assessing the functional complexity of hunter-gatherer technology. Noting the relationship between structural and functional complexity—both are hierarchically organized—we suggested that structural or *hierarchical complexity*, proposed by Simon (1962) as an appropriate measure of artifact or system complexity, might be considered a proxy measure of functional complexity. Structural complexity is easily and objectively measured with adequate ethnographic and archaeological data.

A second alternative is to define a class of structurally and functionally complex artifacts and simply count the number of such artifacts among a sample of hunter-gatherers. Although Oswalt (1973, 1976) defined a class of complex artifacts on the basis of the presence or absence of moving parts, both this definition and his application of this definition fall short of describing the structurally and functionally complex technology of hunter-gatherers. We redefined the latter with reference to automata theory as *multiple-state artifacts*: artifacts that possess at least one or more of the elements in the formal definition of a machine (*e.g.*, Rich 2008, 56–60). They include artifacts, such as weir-trap complex, that lack moving parts but nevertheless perform multiple functions (*i.e.*, achieve multiple states) through their structurally complex design. The number of multiple-state artifacts made by a hunter-gatherer group should reflect the amount of entropy reduced by the technology (minus the increased entropy of making it), which should reflect the amount of problem complexity.

Measuring the correlations between the frequency of multiple-state subsistants among a sample of 21 hunter-gatherer groups and several general environmental variables, we found a good correlation between the former and latitude, as well as effective temperature. And, although the uneven quality of the ethnographic data on the groups in the sample prevented a similar analysis between the frequency of hierarchically complex artifacts and the same environmental variables, we found a significant difference between a representative group from a low latitude/high effective temperature setting and a high latitude/low effective temperature setting.

The results are similar to those obtained with the use of technounit (or part) counts proposed by Oswalt (1973, 1976) and used by others attempting to explain variations in the complexity of food-getting technology among hunter-gatherers (*e.g.*, Torrence 1983; Collard *et al.* 2005). Of what use, then, are the alternative measures of complexity proposed here? Our response to this question is that the application of functional and structural complexity measures provides a firmer basis for the analysis of hunter-gatherer technological complexity—one that is closely tied to the problems that the technology is designed to solve.

Oswalt (1976) believed that the measurement of technological complexity among hunter-gatherers (and horticulturalists) would shed light not only on pre-industrial people but also more broadly on the evolution of human technology. Along similar lines, we suggest that the class of artifacts we defined as multiple-state may have applications in paleoanthropology. To date, multiple-state artifacts are confined to anatomically modern humans (*Homo sapiens*), which may be related to the cognitive demands of designing functionally and structurally complex artifacts.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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