Stone Tools and the Evolution of Human Cognition

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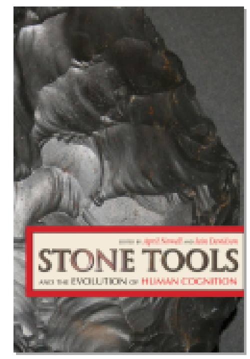

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TWO

"Grammars of Action" and Stone Flaking Design Space

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ABSTRACT

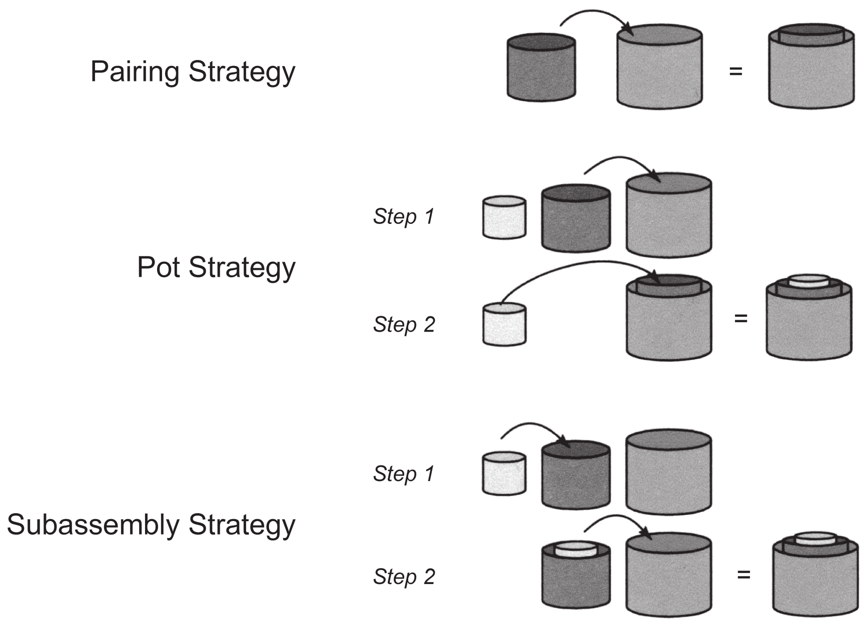
Human infants and primates use similar strategies to organize utterances and motor actions. These strategies, called "grammars of action," are initially similar followed by an ontogenetic divergence in children that leads to a separation of complex linguistic and action grammars. Thus, more complex grammars arose after the emergence of the hominin lineage. Stone tools are by-products of action grammars that track the evolutionary history of hominin cognition, and this study develops a model of the essential motor actions of stoneworking interpretable in action grammar terms. The model shows that controlled flaking is achieved through integral sets of geometrical identifications and motor actions collectively referred to as the "flake unit." The internal structure of the flake unit was elaborated early in technological evolution and later trends involved combining flake units in more complex ways. Application of the model to the archaeological record suggests that the most complex action grammars arose after 270 kya, although significant epistemological issues in stone artifact studies prevent a more nuanced interpretation.

INTRODUCTION

Experiments conducted by psychologist Patricia Greenfield and her colleagues explored the grammatical strategies of various primates, including monkeys, chimpanzees, bonobos, and human infants (Greenfield 1991, 1998; Greenfield and Schneider 1977; Greenfield, Nelson, and Saltzman 1972). The research demonstrated that human children consistently employ three strategies for ordering utterances and motor actions, referred to collectively as "grammars of action." Primate experiments showed that grammars of action applied by chimpanzees and children are initially similar, followed by an ontogenetic divergence by children. The authors concluded that more complex grammars of action evolved after the divergence from a common ancestor. Greenfield emphasized utterances in her research rather than motor actions "because there is no fossil record of behavior" (Greenfield 1991:545).

Greenfield interpreted these changes according to a modular model of brain function, since superseded by a more nuanced paradigm based on distributed neural networks. Nevertheless, many researchers agree with Greenfield's thesis that the evolution of higher cognitive functions, such as cognitive flexibility and syntactical ability, are linked with the evolution of motor control (Lieberman 2006). Greenfield's empirical observations remain robust because they focused on spontaneous motor behaviors (Parker 1990; Parker and Jaffe 2008:156). The enduring value of Greenfield's model for archaeologists is in the way it explicitly links cognitive evolution with motor actions. Since stone tools are physical correlates of motor actions (the ostensibly absent "fossil record of behavior"), Greenfield's model is uniquely suited for an archaeological study that tracks the part of the evolutionary story missing from Greenfield's discussion, from the common chimpanzee/hominin ancestor to modern humans. To do this, a model of the essential motor actions of stoneworking is required that can be translated into "grammars of action." Although the essential actions of stoneworking are well-understood, studies into early stone flaking have traditionally focused on tools and cores as the accumulation of those actions; a practical model suitable for applying Greenfield's model has not been forthcoming.

This study presents a model of the "design space" of knapping—the essential actions of stoneworking—in terms compatible with Greenfield's model. The goal of the study is twofold: first, to use the design space model to theoretically pinpoint some of the key turning points in technological evolution, and second, to identify those areas where our empirical evidence is vague or our epistemology weak.



2.1. Motor action strategies used to combine cups (after Conway and Christiansen 2001).

GRAMMARS OF ACTION

Greenfield’s model links developmental changes in brain anatomy with changes in the hierarchical organization of speech and motor skills (Greenfield 1991). Greenfield’s thesis is that changes in speech and motor skills are reflected ontogenetically in young children. This progression of abilities, when tested against living primates, has phylogenetic implications. The term “grammars of action” reflects the basic similarity between speech structure and motor skills.

Laboratory studies of human children show that there are three strategies for ordering motor actions (Greenfield 1991:532; Greenfield, Nelson, and Saltzman 1972) (Figure 2.1).

1. *Pairing strategy*. A single active object acts on a single static one to create the final structure. This involves one chain-like combination.
2. *Pot strategy*. Multiple active objects act on a single static one to create the final structure. This also involves chain-like combination but results in a longer chain.
3. *Subassembly strategy*. Multiple active objects are combined to form a subassembly, which is in turn combined with a static object or another subassembly to create the final structure. The two-level combination is hierarchical.

The three strategies are reflected in the way children organize nested cups and emerge sequentially between about eight and twenty months (Swann 1998: table 1). A similar progression is seen in the way sounds and words are combined. At about two years, the ways that children combine objects drift away from the ways that they combine sounds and words. Words are combined with increasing hierarchical complexity based on syntactical rules (Greenfield 1991:541–542). Greenfield argued that complex syntactical features have no analogues in grammars of motor action and, conversely, complex grammars of action that emerge at about the same time have no analogues in linguistic grammars (Greenfield 1991:544; see Greenfield and Schneider 1977). The increasing separation of linguistic grammars and action grammars reflects ontological changes in brain circuitry (Greenfield 1991:542–544; however, see Stout 2006:296–297).

Greenfield interpreted the grammatical competence of bonobos in light of this model (1991:545–547; Greenfield and Savage-Rumbaugh 1990) and explored how the ontological patterns of linguistic and action grammars are reflected in phylogeny (Conway and Christiansen 2001; Johnson-Pynn et al. 1999). Greenfield's premise was that brain features in different primates are homologous. Analogous brain features may be responsible for convergent pairing/pot/subassembly motor strategies seen in nonprimate species, such as parrots, but they offer little direct insight into primate evolution (Piñon and Greenfield 1994:362–363). Greenfield's aim was to pinpoint the probable grammatical capacities of the common ancestor of humans and apes.

Primates demonstrate the pairing strategy in laboratory experiments by touching cups together and combining two cups. Chimpanzee nut-cracking demonstrates the pot strategy: "Two active, moving objects (nut and stone) are combined in succession with a single passive object (anvil)" (Greenfield 1991:545). Greenfield described examples of the subassembly strategy among primates as "borderline"; possible examples include sopping water with a leaf, or inducing ants to affix themselves to a stick, and moving the subassembly to the mouth (cf. Byrne 2004, 2005). The pot strategy dominates the complex motor behavior of wild chimpanzees (Greenfield 1991:545), captive chimpanzees and bonobos, and capuchin monkeys (Conway and Christiansen 2001; Johnson-Pynn et al. 1999; Piñon and Greenfield 1994:362–363). Chimpanzees and bonobos seem incapable of constructing subassemblies to act on an object outside their own bodies (Conway and Christiansen 2001; Gibson 1990:98; Johnson-Pynn et al. 1999).

Greenfield concluded that the pairing, pot, and a rudimentary version of the subassembly strategies—and the overlapping neural wiring for both action and linguistic grammar—were shared by the common ancestor of humans and chimpanzees. She argued that language and tool use coevolved because they were controlled by shared brain structures. This resulted in an expansion of the prefrontal cortex, stimulating an increase in hierarchical complexity of combined motor actions (Greenfield 1991:550–551). Following from Greenfield's ontogenetic model, changes in early stone flaking should reflect the evolutionary development of an action grammar through subassemblies and combinations of subassemblies of ever-increasing complexity.

A MODEL OF LITHIC DESIGN SPACE

Stone tool design consists of two aspects. "Engineering" design produces techniques that cope with the latitude offered by the mechanics of stone fracture defining the boundaries of design space; and "formal" design assembles engineering techniques to produce a tool. It is useful to consider engineering techniques separately from formal design choices. Although some formal stone tool designs might be realized only by certain techniques, technique can be divorced from form. For example, the "gull wing" technique (the engineering choice) was used by some Australian Aborigines to produce stone adzes (a formal tool design) (Moore 2004) but stone adzes were also produced using other techniques (e.g., Gould, Koster, and Sontz 1971).

Stone tool replicators discover and verify sequences of engineering techniques in the context of formal types (e.g., Callahan 1985; Wilke and Quintero 1994). In this context the linkage between technique and form seems absolute because creating complex forms required complex, and often form-specific, sequences of techniques. Analyses of individual techniques are typically applied to debates about artifact form (e.g., Bradley and Stanford 2006; Straus, Meltzer, and Goebel 2005). The restrictive boundaries of design space (Van der Leeuw 2000) caused knappers in the past to independently rediscover useful techniques in the context of widely varying formal designs.

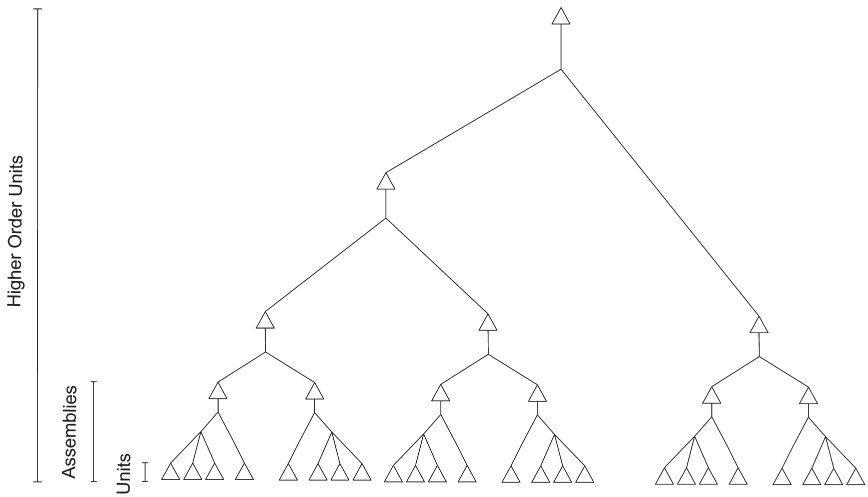
Greenfield's work shows the importance of understanding the structural aspects of how simple motor actions were arranged to produce formal designs. Holloway (1969) was among the first to seriously consider the structure of stone tool making, proposing that linguistic structure is homologous with the structure of the motor actions used in flaking. "Phonemic" motor actions are combined into techniques—low-order organization—and techniques are arranged according to grammatical rules—high-order organization—to produce stone tool forms. Low-order organization techniques are combined, according to Gowlett (1984, 1986, 1990, 1996), by rote actions into a structure called a "flake loop." Pelegrin (1990, 1993, 2005) observed that Gowlett's flake loop requires two types of "know-how": ideational know-how, or visualization, and action know-how, or motor execution. Skill at low-order organization, dismissed by Wynn as "a simple action requiring only minimal organizational ability" (1979:374), is gained through experience (Pelegrin 1993:304). Despite the pertinence of low-order know-how to accomplishing higher-order tasks (Bril, Roux, and Dietrich 2005; Roux and David 2005), research is rarely conducted into low-order know-how. Pelegrin characterized higher-order organization—Holloway's grammatical rules of stoneworking—as "knowledge." Similarly, Gowlett suggested that flake loops are combined according to a static "mental template" identifying the stoneworking goal (Pelegrin's "conceptual knowledge") and a "procedural template" that directs the removal of individual flakes (Pelegrin's "action modalities"). Lithic studies often focus on stoneworking "knowledge," such as the goal-driven concepts expressed in a *chaîne opératoire* (e.g., Boëda 1995; Schlanger 1996; Van Peer 1992; Wynn and Coolidge 2004) or underlying an artifact shape (e.g., Edwards 2001; Pelegrin 1993; Roche 2005).

A consensus seems to have emerged in the theoretical literature that low-order organization of stoneworking gestures is of little analytical interest. However, Greenfield's research emphasizes the importance of studying low-order organization as a means of generating insights into evolution toward high-order complexity. The "design space" model described here explores the basic elements that underpin knapping at two levels of abstraction. The first relates to the elements' lower-order internal structures of ideation and motor action, and the second relates to the way that elements are sequentially combined during lithic reduction.

A tree structure is used to model the organization of motor actions, following Greenfield (1991).[1] The smallest division in the model consists of ideational and motor elements and these are organized into freehand percussion "flake units" (Figure 2.2) of three types: the basic unit, the complex unit, and the elaborated unit.[2] The basic flake unit is the smallest divisible element of stone flaking because the individual motor actions that compose it are not themselves sufficient to produce flakes. Units are combined to create "assemblies," which are in turn combined to create "higher-order units," following Greenfield's terminology. The way that units or assemblies are combined into higher-order units are referred to as the technology's "architecture."

The Basic Flake Unit

Controlled knapping by freehand percussion relies on the organization of certain motor and ideational elements. Multiple actions are carried out sequentially on the static object, Greenfield's "pot" strategy. The resulting structure is



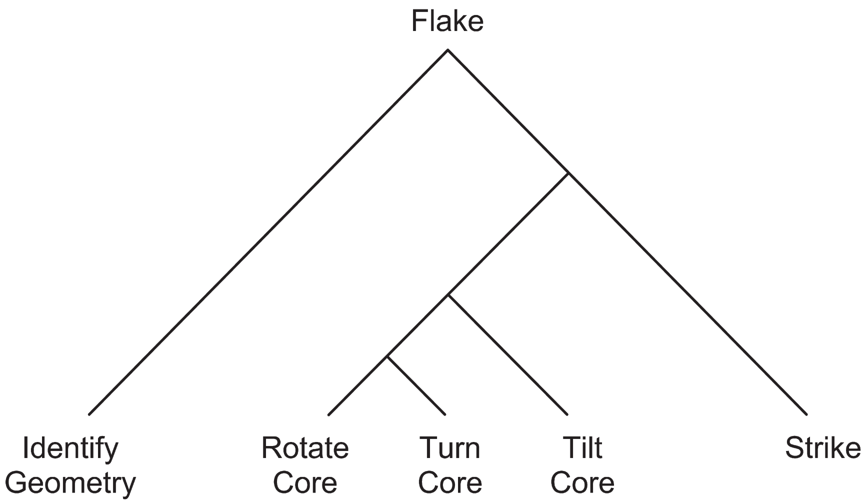
2.2. Terminology used to describe the architecture of stone flaking.

the "basic flake unit" (Figure 2.3). The basic flake unit includes three elements: (1) an ideational element that involves the identification of crucial geometric variables on the core; (2) three action elements done in response to the identification and resulting in the correct positioning of the core; and (3) a fourth action element involving the articulation of two hands to remove the flake.

The ideational element involves the recognition of an essential geometrical relationship with three attributes:

1. An area of high mass on a face of the stone;
2. A suitable platform surface located on a different face of the stone from the high mass but adjoining the high mass; and
3. Features matching 1 and 2 positioned at an acute angle (less than 90°) to one another.

Acting upon the geometrical relationship requires three actions. First, the core must be rotated until the platform surface is positioned for striking (Pelegrin 2005). This will, in many cases, require rotation of the stone between faces to get the geometrical orientations correct. Second, the core must be turned from left to right or right to left (Toth 1985a). This action positions the core relative to the arc followed by the indentor so that the impact point is behind the high mass and the force will propagate through the mass. And third, the core must be tilted in relation to the indentor arc so that the downward and outward forces (Crabtree 1968) are delivered in the correct ratio to one another. The actions



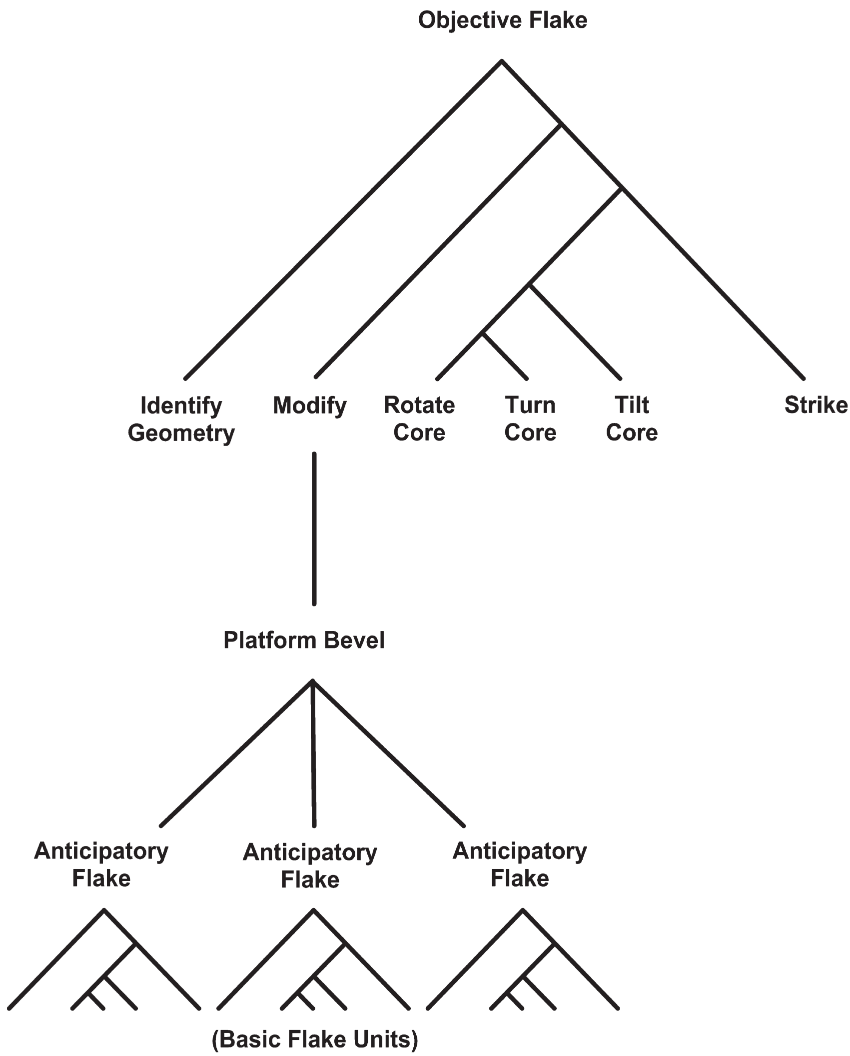
2.3. Model of the basic flake unit. The modified tree structure follows Greenfield (1991).

of geometrical adjustment involve the non-dominant hand in modern humans. Striking the flake requires the articulation of both hands, itself a complex motor task (Dapena, Anderst, and Toth 2006).

Complex and Elaborated Flake Units

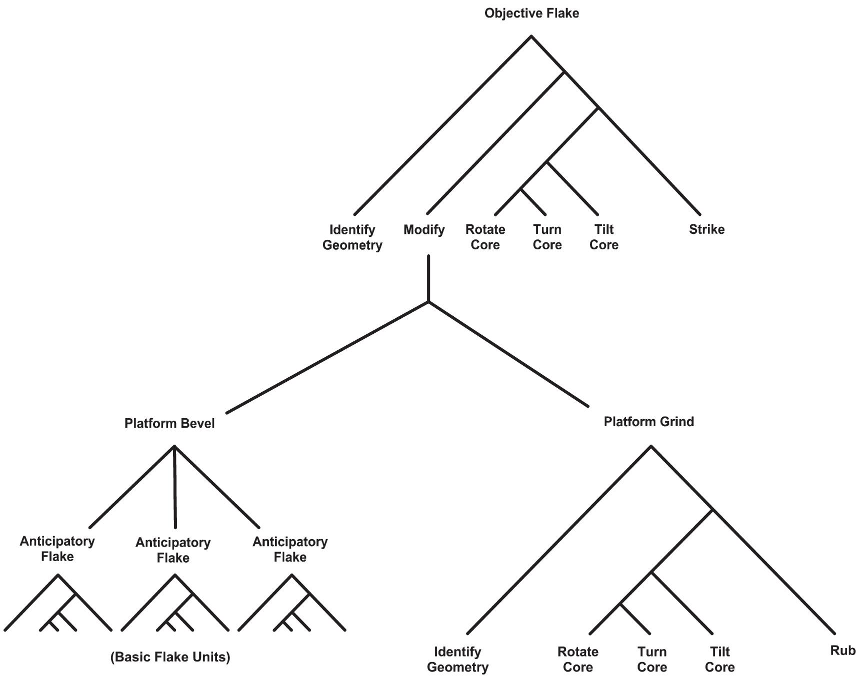
The basic flake unit is applied to zones of exploitable high mass as they are identified on the core. An increase in knapping complexity entails removing flakes to adjust the platform angle to enable the removal of otherwise unexploitable high mass, or more effective removal of high mass. Removing flakes to adjust or bevel the platform—these are "anticipatory" flakes in the sense that they anticipate "objective" removals—involves repeatedly applying the basic flake unit within a structure subordinated to the process of removing the objective flake (Figure 2.4). These are referred to as objective and anticipatory "tiers" and the resulting subassembly is the "complex flake unit."

The stimulus resulting in the complex unit's complex structure is a realization that geometrical relations can be created or improved by flaking. The knapper must recognize that platform preparation is necessary at the objective tier to trigger the actions necessary to prepare the platform in the anticipatory tier. Once this upper-tier identification is made, a series of lower-tier identifications are triggered that drive the flake removals (themselves basic flake units) that modify the platform angle.



2.4. Model of the complex flake unit.

The "elaborated flake unit" is a complex flake unit with the addition of platform grinding, shown as a branch of the subassembly to the right of platform beveling (Figure 2.5). There are a number of features of platform grinding that structurally differentiate it from platform beveling. First, the hominin must assess platform angularity, or "sharpness," as a proxy of platform "strength" or something roughly equivalent. This identification process is different from the one necessary for identifying high-mass/platform/platform-angle relationships.



2.5. Model of the elaborated flake unit.

Second, a different set of actions—distinct from the basic flake unit—are necessary to enact platform grinding. Young and Bonnichsen (1984) have shown that platform grinding involves two "behavior variables": "rub" and "shear." Third, the action of the dominant hand does not involve an "indentor arc" or similar action. A side-to-side rubbing motion, for example, is a unique one with no precedent in the gestures necessary to strike a core to produce a flake. Finally, platform grinding may have required the use of an abrasive stone distinct from the indentor and, in this case, the set of knapping tools was differentiated to form a "meta-kit." After platform beveling and grinding is completed, the upper-tier identification and actions kick in, culminating in striking the objective flake.

Combining Flake Units

The structure of flake units does not dictate the way a reduction sequence is assembled. For instance, the choice of pressure and indirect percussion involves changes in core orientation and indentor action. This has implications for tool design but it does not involve a substantial change to the structure of the underlying flake units. Similarly, the way flake units are combined into assemblies and higher-order units is independent from the complexity of a flake unit's internal structure.

The simplest building process, analogous to Greenfield's pot strategy, involves combining flake units in chain-like series rather than hierarchically. An individual flake is removed in a two-step algorithm:

> identify high mass → apply the flake unit.

A series of flake removals organized by the pot strategy looks like this:

> (identify high mass → apply the flake unit) → (identify high mass → apply the flake unit) → (identify high mass → apply the flake unit) . . . etc.

The knapping process begins anew each time the algorithm is applied, and the "identify high mass" part of the algorithm guides the progressive reduction of the stone.[3] The algorithm is inevitably applied to a novel situation because the removal of a flake always reorganizes the distribution of high mass on the core. There is presently no archaeological method for differentiating an intention to produce a particular core form by deliberately chaining together flake units from the creation of the same core form by "mindlessly" chaining together flake units. Since the removal of a flake consistently modifies the distribution of mass in the same way—the high mass is offset laterally and sometimes distally (Figure 2.6)—the result of mindless flake unit chains can look like deliberate patterning (Figure 2.7). Thus, certain core forms may be "spandrels" (after Gould and Lewontin 1979): patterns created inevitably without prior hominin intention beyond that inherent to the flake unit. This is exacerbated by the fact that many of the geometrical changes that occur inevitably in flaking are precisely those that are intentionally manipulated by modern knappers to produce effects (Moore 2005).

"Higher-order architecture" results from hierarchically combining flake units into "assemblies" and then hierarchically combining the assemblies (cf. Miller, Galanter, and Pribram 1960). In this case, flake units are arranged in complex interlocking tiers. In Greenfield's terminology, this is a "subassembly" strategy of combining motor actions. The creation of complex tool forms requires the manipulation of high-mass zones on core faces through higher-order architecture. Deliberate shaping of high-mass zones requires two things. First, during the identification process, the knapper must visualize the sort of high mass that, once removed, will create the effect. Second, the knapper must visualize how the high mass might be "constructed" (by deconstructing the existing stone) through sequential application of flake units (Figure 2.8). The internal complexity of a

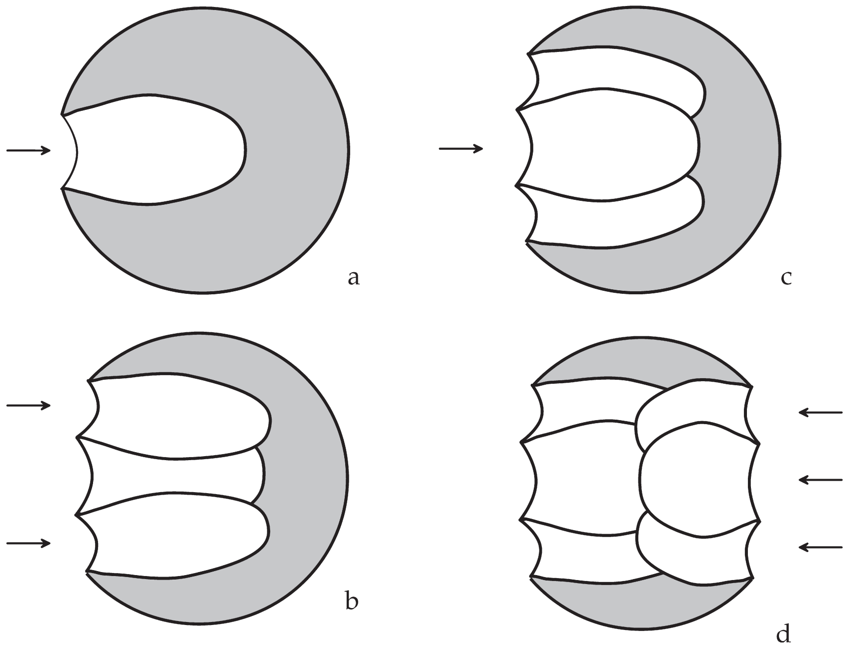
2.6. Platform view of a conjoined core-reduction sequence showing how mass relationships change in predictable ways as flakes are removed. Core reduction was by a simple chain of basic flake units. Flake 1 was struck from a natural ridge on the face of the stone, offsetting high mass to 2 and 3. Removal of 2 offset mass to 6 and 7. Removal of 3 and 4 offset mass to 5. Removal of 6, 7, and 8 offset mass to the unflaked areas marked by white Xs. The mass-offset phenomenon is a predictable effect of striking flakes from stone, but since the effect is also an inevitable one, hominin knappers did not necessarily have to make this prediction to produce cores with patterned morphologies. This is one example of the "spandrel" phenomenon in stone flaking.

flake unit is not necessarily recapitulated in the architectural strategy used to combine flake units. Basic flake units were combined hierarchically by past stoneworkers (see, e.g., Moore 2003) and complex/elaborated flake units might, in theory, be combined serially.

EARLY STONE TOOLS AND THE DESIGN SPACE MODEL

Greenfield (1991) showed that complexity in motor actions progressively evolved in hominin evolution through the pairing, pot, and subassembly strategies. The subassembly strategy dominates in human children older than twenty months, and, beginning at two years, action grammars diverge from linguistic grammars in structural complexity. Greenfield assessed that captive and wild chimpanzees and bonobos frequently used pairing and pot strategies but were only marginally capable of the subassembly strategy. Greenfield concluded that the pairing, pot, and a rudimentary version of the subassembly strategies—and the overlapping neural wiring for both action and linguistic grammars—were shared by the common ancestor of humans and chimpanzees. Subsequent hominin evolution saw a differentiation in neural wiring and increases in motor action complexity.

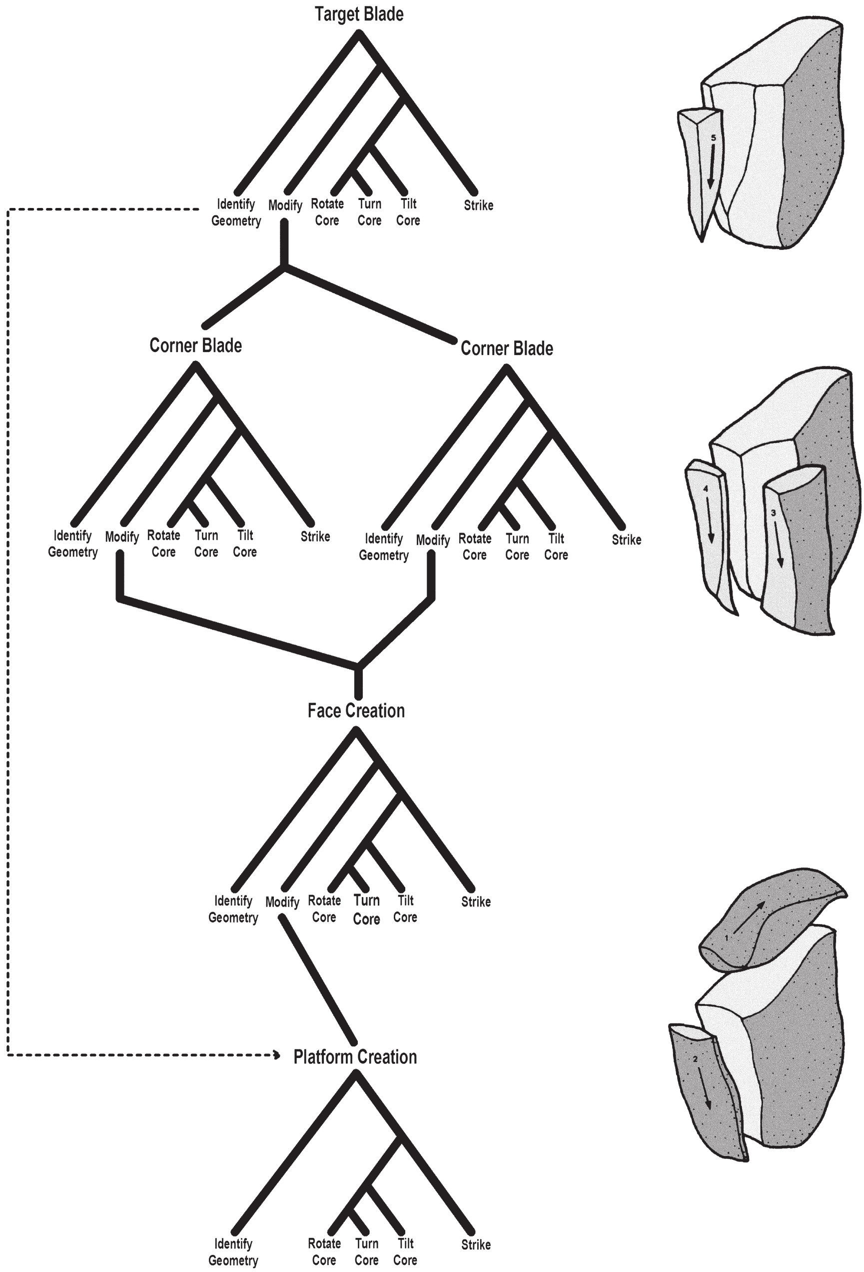
The basic and bipolar flake units, in Greenfield's terminology, reflect a pot strategy because multiple actions are applied to a static object. The earliest stone artifacts are well-struck flakes, and hominins by that stage had mastered the basic flake unit (see, e.g., Delagnes and Roche 2005; Semaw 2006). This does not



2.7. Schematic model showing how the "mindless" process of identifying and targeting zones of high mass can create symmetrical cores. A flake is struck from a natural high-mass configuration on a circular stone, laterally offsetting the zones of high mass (a). Next, the offset zones of high mass on either side of the first flake scar are removed (b). This raises the mass between the two flake scars, which is then removed (c). Flakes are relatively thicker at the proximal ends, so flaking on the core's left margin offset mass toward the right margin. This is removed by a similar series of flakes from the opposite edge (d). This inevitable mass-offsetting phenomenon combined with removing flakes in "mindless" chains can result in a patterned core that appears to reflect hominin intent.

indicate an increase in organizational skills because chimpanzees (and presumably our common ancestor with chimpanzees) are capable of the pot strategy (Byrne 2004, 2005; Greenfield 1991).

Sustained efforts to teach Kanzi, a captive bonobo, the basic flake unit proved unsuccessful (Toth et al. 1993). Kanzi instead invented a thrown-core anvil technique where the core was thrown onto the indentor to initiate fracture (Savage-Rumbaugh and Fields 2006; Schick et al. 1999). This is a pairing strategy where one active object (the core) acts on one static one (the anvil indentor). It would appear that bonobos have sufficiently organized motor action plans to achieve stone flaking (although the precise motor actions inherent to flake



2.8. Core reduction at Camooweal, Queensland, Australia (after Moore 2003). Basic flake units were organized hierarchically to produce an effect.

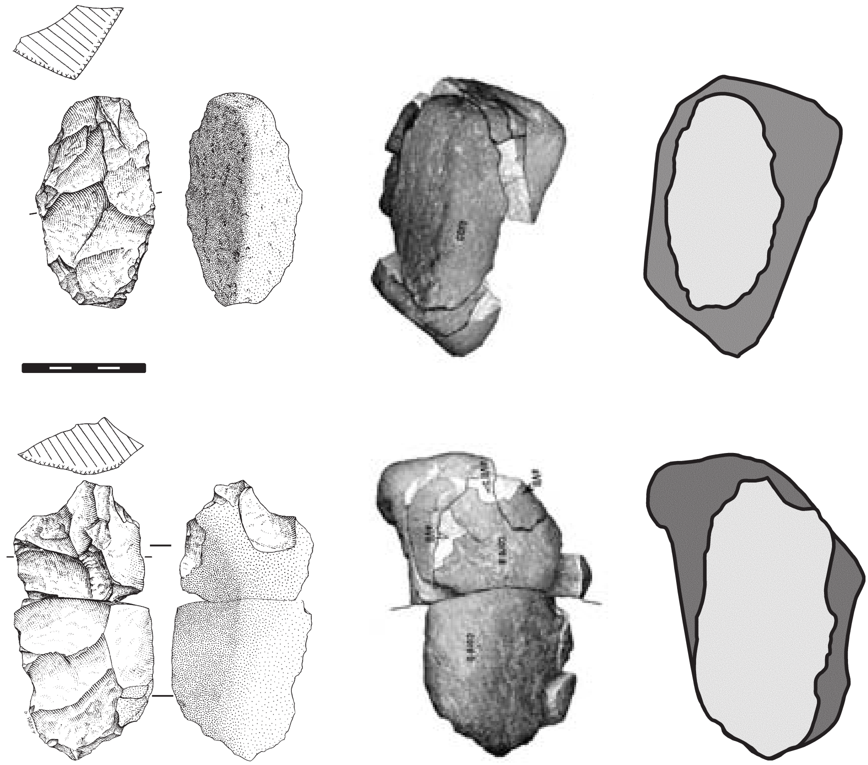
units may be restricted by anatomy [Byrne 2005:166–167; Corbetta 2005; Marzke 2005; Savage-Rumbaugh and Fields 2006:227–228]), but Kanzi was unable to recognize the geometrical relationships underpinning the basic flake unit (Schick et al. 1999; Toth et al. 1993). This geometrical identification may require different skills from those tracked by the evolution of action grammar. An ideational component like this is absent from Greenfield's model (Connolly and Manoel 1991). Since Kanzi appears to be unable to recognize and identify the essential ingredients of controlled flaking—platform angles, outward and downward force relationships, areas of high mass—we can infer, following Greenfield's logic, that our common ancestor could not either. The evolutionary precursors to stone flaking (see, e.g., de Beaune 2004; Joulian 1996, Marchant and McGrew 2005; Panger et al. 2002) are most likely to be found in the way hominins developed their ideational abilities rather than in the way that they organized motor actions (Pelegrin 2005:31; cf. Bushnell, Sidman, and Brugger 2005).

Greenfield suggested that brain differentiation that occurs after two years in human children leads to the phenomenon of "automaticity." Automatic processes are unconscious and routinized (Givon 1998; see Byrne 2005:164). As Greenfield (1998: 160) notes, "as skill increased, the lower levels of [hierarchical] organization became automatic and conscious attention came to be addressed to the higher levels." This is the phenomenon seen where students learning touch-typing first focus their attention on individual letters; then, as letters become automatic, the focus of conscious attention shifts to words; and as words become automatic, the focus shifts to sentences or thoughts (Greenfield 1998:159–160). The unconscious way skilled modern knappers apply basic, complex, and elaborated flake units is an example of automaticity; once flake units are routinized, conscious attention is focused on higher-order problems of combining units to achieve a goal. Automaticity may partly explain why researchers have devalued research into flake units, yet it is difficult to infer when automaticity first emerged in the history of stone flaking. Automaticity in applying flake units is necessary before higher-order architecture can be achieved (cf. Bril, Roux, and Dietrich 2005; Roux and David 2005).

Although the basic flake unit is built by Greenfield's pot strategy, the complex flake unit is a two-level combination (flaking to first one face, then the opposite face) reflecting a subassembly strategy. Clear evidence for a complex flake unit is seen in platform preparation to detach "predetermined" flakes in the classic Levallois method (e.g., Boëda 1995; Van Peer 1992), but complex flake units may have emerged by 285 kya in assemblages from the Kapthurin formation in Kenya (McBrearty and Brooks 2000:495–496). Complex flake units seem to be common in "bladey" technologies in the Near East after ca. 270 kya (Meignen 2007).

The elaborated flake unit is an even more complicated subassembly consisting of a complex flake unit with the addition of platform grinding. Elaborated flake units occur in modern human assemblages from the Late Pleistocene onward. Modern human knappers often use elaborated flake units combined with soft indentors to replicate Middle Pleistocene handaxes (see, e.g., Bradley and Sampson 1986; Edwards 2001; Pitts and Roberts 2000:215–222; Stout, Toth, and Schick 2006:324–325). Although the use of soft-hammer indentors has long been claimed for handaxes after ca. 900 kya (Roche 2005), few studies have documented flake unit types through detailed examination of early archaeological debitage assemblages.[4] In theory, soft indentors might be used with basic, complex, or elaborated flake units because indentor type varies independently from flake unit structure—the key attribute of the elaborated flake unit is the platform grinding. The issue is important because, based solely on organizational complexity, one might predict that complex flake units emerged before elaborated flake units.

Archaeologists traditionally track advances in cognitive evolution through stone tool morphology. Relative cognitive capacity has been inferred from tool shapes by assessing the extent to which hominins impose morphological rules on unpatterned stones (Mellars 1996). An early example of imposed form may be Acheulian handaxes because the symmetries reflected in these tools are considered the result of purposeful goal-driven reduction (e.g., Gowlett 2006; Lycett 2008; McNabb, Binyon, and Hazelwood 2004; Wynn 2002). According to this view, knappers created the characteristic symmetries of handaxes by deliberately reducing certain parts of the core more intensely than other parts. This differentially focused attention is inferred to be cognitively relevant (however, see Davidson 2002). In the model proposed here, objects like handaxes were made by chaining flake units together in a continual process of attrition rather than stacking them hierarchically. Yet the vagaries of reduction intensity and raw material shape (Andrefsky 2009; Chase 1991; Dibble 1984, 1989, 1995; McPherron 2000, 2006; Toth 1985b; White 1998) mean that both "mindless" and goal-directed flake unit chaining can create morphological patterning (Figure 2.9). Further, the "spandrel" effect in stone flaking, described previously, could be an important and presently unknown variable in pattern creation. At present there are no reliable means for inferring intent from tools shaped by flake unit chaining (cf. Monnier 2006; e.g., Moore et al. 2009). Many critics recognize that advanced cognitive processes can be reflected in tool shapes made by flake unit chains—early examples include backed microliths from South Africa, ca. 77–35 kya (Davidson and Noble 1993; Wadley and Mohapi 2008; Wurz 1999), and perhaps bifacial foliate points from various regions across Africa after ca.



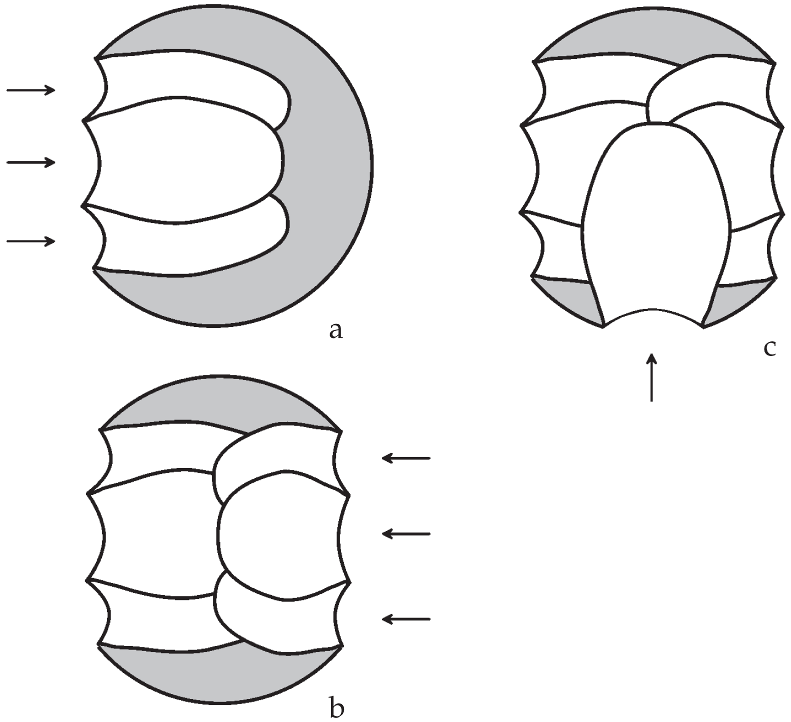
2.9. Conjoined sets of two unifacially reduced cores from the 2.34 myr site of Lokalalei 2C, Kenya (after Delagnes and Roche 2005). The conjoin sets are shown in the middle, and the image at right indicates the amount of cobble attrition caused by repeated flake removals. Core reduction at Lokalalei 2C "is unarguably geared towards the production of flakes" and "cores clearly fall into the category of waste" (Delagnes and Roche 2005:466). If so, this demonstrates that symmetrical core shapes can result from a process of chaining basic flake units together rather than from hominin intent. Scale 50 mm.

230 kya (Brooks et al. 2006; McBrearty and Brooks 2000; Shea 2006; Villa et al. 2009)—but pinpointing the emergence of this remains problematic.

Advanced cognitive abilities have also been inferred for stone reduction processes that reflect higher-order architecture. Higher-order architecture is inferred when effects generated later in a reduction sequence are contingent on effects generated earlier in the sequence by quite different configurations of flake units. Archaeologists infer intent when the contingent relationship is expressed in the same way across multiple core reduction events (cf. Pelegrin 2005). The Levallois method sensu stricto is thought to be an early example of higher-order architecture because detaching the relatively large, specially shaped "predetermined" Levallois flakes (the inferred intended product of the technique) was contingent on prior bifacial flaking to establish a specifically shaped zone of high mass on the core face (Boëda 1995; Schlanger 1996; Van Peer 1992).

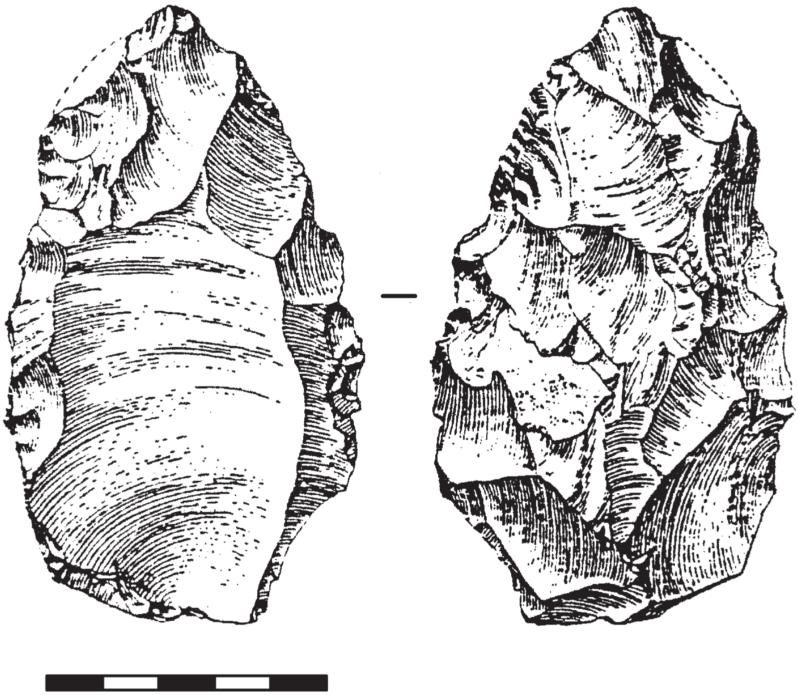
Efforts to identify earlier examples of higher-order stoneworking processes have focused on the historical antecedents of the Levallois method. In various parts of the Old World, large flakes similar or identical to "predetermined" Levallois flakes were removed from handaxes (see, e.g., DeBono and Goren-Inbar 2001; Rolland 1995; Tuffreau 1995; White and Ashton 2003). In Africa, Acheulian cleavers and handaxes were themselves made from "predetermined" flakes struck from very large bifacial cores (see, e.g., Clark 2001; Lycett 2009; Madsen and Goren-Inbar 2004; McNabb 2001; Sharon 2009; Sharon and Beaumont 2006; Tryon, McBrearty, and Texier 2006). Although the "predetermined" flake is morphologically among the largest struck from the cores in each of these cases, it is unclear how it differs in a technical sense from the flakes struck prior to it (cf. Copeland 1995). This undermines the criterion of contingent relationships among different flake unit configurations. Simple flake unit chains might produce similar results. For instance, a large-sized final flake can be a "spandrel" effect of flaking that isolates zones of high mass in a biface's center (Moore 2005; cf. Sandgathe 2004) (Figures 2.10 and 2.11). This occurs without prior intent because a flake's proximal end is usually thinner than its distal end, and hence the flake takes away relatively more mass from the bifacial core's margin than its center. When this central zone of high mass is targeted—and the mindless chain-linking flake unit algorithm predicts that it will be—a relatively large "predetermined" flake can be produced. End thinning like this occurred in biface reduction technologies throughout prehistory, and the fact that an end-thinning flake was further retouched is not itself evidence that hominin knappers specifically intended to produce flakes of this morphology (e.g., Goren-Inbar et al. 2008).[5] Bar-Yosef and Van Peer (2009) suggest that intent like that implied by "predetermination" is often assumed a priori in studies of stone reduction processes. This epistemological issue complicates the identification of the Levallois method sensu lato as an example of higher-order architecture (Davidson and Noble 1993).

Higher-order architecture has also been inferred from the presence of blade making in early assemblages. Blades are flakes that are twice as long as they are wide, and they can be produced by mindless flake unit chaining if the knapper targets elongated zones of high mass (Moore 2007; Moore et al. 2009). Nevertheless, higher-order architecture was clearly employed from the Late Pleistocene onward to carefully maintain elongated zones throughout the



*2.10. Schematic model showing how the "mindless" process of identifying and targeting zones of high mass can create end-thinned cores. Flakes are first removed from one edge (*a*), offsetting mass to the opposite edge, which is removed (*b*). Mass offset from series* B *is concentrated near the centerline of the core face, which is removed from the end of the core (*c*). In this scenario, the creation of a central high-mass zone was a consequence of reduction from opposite core margins and was not necessarily a result of "intent."*

reduction history of the core. Bar-Yosef and Kuhn (1999:329) observed that the proportion of flakes identified as "blades" increases in many assemblages by 300 kya, but it is less clear whether higher-order architecture was used to produce them. The best early evidence may be blade cores from the Near East. These assemblages, dating after about 270 kya, include cores where two core faces were knapped differently from opposed platforms oriented at an angle to one another ("twisted" or "off-axis" platforms) (Meignen 2007:135). Knapping to establish these platforms required different configurations of flake units than used subsequently to remove the elongated flakes, suggesting higher-order architecture. Blade cores recovered from the Kapthurin formation may be an African version of a similar technology (McBrearty and Brooks 2000:495–496), although this is



2.11. End-thinned handaxe (after Tuffreau 1995:418). Scale 50 mm.

not clear from the published descriptions. Complexity in higher-order architecture reached an apogee in the Neolithic period (e.g., Callahan 2006; Kelterborn 1984; Pelegrin 2006; Stafford 2003).

To summarize, knapping began in prehistory with the serial combination of basic flake units. The key breakthrough that led to early flaking was probably ideational rather than based solely on combinations of motor actions. The simple algorithm "identify high mass → apply flake unit" was applied in long chains. A serial architectural organization like this most closely matches Greenfield's pot strategy of motor action. The application of flake unit chains to create specific shapes may have emerged quite early, but this is difficult to resolve. A subsequent evolutionary step involved adding a second tier to the basic flake unit, creating the complex flake unit. The complex flake unit reflects the recognition that platform arrangements could be modified by anticipatory flaking on the obverse core face prior to removing the objective flake from the reverse face. Core faces were now hierarchically organized within the flake unit. The complex flake unit was significantly elaborated by the addition of another branch to grind platform edges. Complex flake units were in place by the late Middle Pleistocene and elaborated flake units by the Late Pleistocene, but it is possible that both were used to produce Acheulian handaxes. Up to this point in evolutionary history we see the elaboration of the internal structure of flake units, but they were linked together in simple chains. Automaticity in applying flake units likely arose early in technological evolution and was a necessary antecedent to higher-order assemblies created by stacking flake units hierarchically. Reduction sequence architecture became hierarchical in response to efforts to alter the size, shape, and location of the high mass removed by an objective flake. Blade making in east Africa and the Near East may indicate this step by ca. 280 kya. Subsequent innovations in lithic technology stem from the development of ever-more complex hierarchical arrangements of flake units, culminating in the complex stone-flaking processes seen in certain Neolithic contexts.

CONCLUSION

This study was an attempt to model the design space of stone knapping by conceptualizing the process in terms of Greenfield's "grammars of action." The form-creation process was deconstructed in line with Greenfield's findings and the model was applied to current understanding about stone tools in early hominin evolution. A trajectory of possible stages in the development of complexity was outlined. However, although Greenfield's work demonstrates that complex motor action grammars emerged among early hominins as cognition evolved, it is important to note that stone tool manufacture did not necessarily reflect maximum abilities of our human, and perhaps hominin, ancestors (Wynn and McGrew 1989). Recent research in Australasian prehistory has shown that cognitively modern *Homo sapiens* sometimes knapped stones in ways that were very similar to non-modern hominins (Moore 2007; Moore and Brumm 2007; Moore et al. 2009). Also, a historical trajectory of increasing complexity similar to the one proposed here occurred in Australia *after* the continent's colonization by cognitively modern humans. In this case, the complexity that emerged in Late Pleistocene and Holocene stone flaking was driven by social and/or environmental pressures, not by cognitive evolution (Brumm and Moore 2005). Comparing the Australasian pattern to the Old World is crucially important for identifying the various stimuli that led to complexity in stone tool manufacture.

Applying the model to the early archaeological record has reframed debates about epistemology in lithic studies, particularly about how archaeologists infer "intent" from stone tools. Deconstructing the stoneworking process has shown where aspects of our knowledge are poorly documented, particularly in relation to the specifics of platform manipulation in early assemblages. Perhaps most significantly, characterizing the reduction event in terms of combinations of flake units has raised the possibility that "mindless" flaking can lead to repetitions of seemingly complex tool forms. This is referred to as the "spandrel" effect. Isaac (1986) proposed a "method of residuals" where archaeological assemblages are compared to baseline patterns and the residual variation is interpreted in cultural or cognitive terms. Archaeology currently has no empirical baseline against which to measure the "spandrel" effect.

The mental and physical aspects of stone tool manufacture likely played a significant role in the evolution of hominin cognition, but sorting the unique aspects of this behavior from that of our hominid relatives remains a challenge (Haslam et al. 2009). This is further complicated by the theoretical and empirical issues emerging from this study. Despite the difficulties, stone tools and flaking debris are the most complete behavioral record across this crucial aspect of hominin evolution, and refining our models linking cognition and stone flaking remains an important goal of evolutionary research.

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NOTES

1. Stone knapping sits somewhat uncomfortably with the terminology used in Greenfield's model because stone flaking is subtractive whereas Greenfield's studies involved additive behaviors. Thus, a stone core is a "structure" in Greenfield's terminology. It is assumed here that the inversion of the relationship is not cognitively significant.

2. Bipolar percussion—smashing a stone on an anvil—requires a different flake unit from those applied in freehand percussion (Moore 2005). However, the simpler ideational and motor action elements of the bipolar flake unit are unrelated to freehand percussion and are less relevant for tracking cognitive evolution (see Moore 2005; Pelegrin 2005).

3. Envisioned in this way, the "plan/schema" (sensu Roux and Bril 2005) or hominin "intention" is the removal of a single flake, not the removal of multiple flakes in series. The empirical evidence of successfully produced flakes in early hominin assemblages supports the notion that actions inherent to the flake unit were coordinated specifically to achieve this effect (e.g., Delagnes and Roche 2005; Semaw 2006). However, concluding a priori that non-modern hominins also removed multiple flakes according to "plans" is

circular reasoning because it projects an approach to skilled tasks that is quintessentially modern (and the "end point" we are studying [cf. Ingold 2001]) onto our hominin ancestors (Bar-Yosef and Van Peer 2009).

4. Mewhinney (1964) traced inferences about soft-hammer flaking to the early experiments of Coutier (1929). Later experimenters reiterated aspects of Coutier's findings (e.g., Bordes 1968; Edwards 2001; Hayden and Hutchings 1989; Knowles 1953; Leakey 1934; Newcomer 1971; Ohnuma and Bergman 1982; Wenban-Smith 1989). Although these studies may indicate the use of soft indentors in biface manufacture, they do not sufficiently describe platform preparation on the archaeological specimens to confirm that early hominins applied elaborated flake units.

5. Similarly, ostensibly predetermined "Kombewa" flakes (Texier and Roche 1995) can result whenever a flake is struck from the ventral surface of another flake (Dag and Goren-Inbar 2001; Dibble and McPherron 2006; Moore et al. 2009). Ostensibly predetermined "cobble-opening flakes" ("*entame*" flakes) (Sharon 2009:339–342) can result whenever large cortical flakes are removed from a cobble.

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