# COPYING ERROR AND THE CULTURAL EVOLUTION OF "ADDITIVE" VS. "REDUCTIVE" MATERIAL TRADITIONS: AN EXPERIMENTAL ASSESSMENT

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*Copying errors that occur during the manufacture of artifactual traditions are potentially a major source of variation. It has been proposed that material items produced via "additive" processes (e.g., pottery) will possess less variation than traditions produced via "reductive" processes (e.g., stone knapping). The logic of this premise is that "additive" production methods more readily allow for the reversal of copying errors compared to strictly "reductive-only" processes. Here, we tested this hypothesis in shape data using an experimental framework in which we generated and statistically analyzed morphometric (size-adjusted) shape data under controlled and replicable conditions. Participants engaged in one of two alternative conditions: an irreversible ("reductive-only") manufacturing process or a reversible ("additive-reductive") process. With a number of factors held constant, participants were required to copy the shape of a "target form" as accurately as possible using a standardized block of plasticine and a steel table knife. Results demonstrated statistically greater levels of shape-copying errors in the replicas produced in the reductive-only condition. This indicates that "mutation rates" in the shape attributes of artifactual traditions produced via reductive processes are inherently greater than those produced via alternative means. Several implications for the study of variation in artifactual traditions are discussed.*

*Los errores de copiado que ocurren durante tradiciones de la manufactura de artefactos constituyen potencialmente una fuente importante de variación. Se ha sugerido que los objetos producidos mediante procesos "aditivos" (p.ej. cerámica) variarían menos que aquéllos producidos mediante procesos "reductivos" (p.ej. tallado de piedra) debido a que, a diferencia de los procesos estrictamente reductivos, los métodos aditivos de producción facilitarían la correción de errores de copiado. Aquí pusimos a prueba esta hipótesis en un marco experimental en el que generamos y analizamos estadísticamente datos morfométricos (ajustados al tamaño) en condiciones controladas y reproducibles. Los participantes tomaron parte en una de dos situaciones: en un proceso de manufactura irreversible ("sólo reductivo") o en un proceso reversible ("aditivo-reductivo"). Se pidió a los participantes copiar la forma de un "objeto modelo" con la mayor precisión posible utilizando un bloque estandarizado de plastilina y un cuchillo metálico. Los resultados demostraron estadísticamente un mayor número de errores de copiado en las réplicas producidas en la situación "sólo reductiva". Esto indica que la "tasa de mutación" en artefactos producidos mediante procesos reductivos es inherentemente mayor que en aquéllos producidos mediante otros procesos. Se discuten algunas implicaciones para el estudio de variaciones en artefactos tradiciones.*

In recent years, there has been a growing recognition that spatial and temporal change in material culture traditions can be modeled analytically, according to principles analogous to those seen in biological evolution (e.g., Eerkens and Lipo 2007; Henrich 2004; Jordan and Shennan 2003; Kuhn 2004; Lipo et al. 2006; Lycett 2011; Lyman and O'Brien 2000; Mesoudi et al. 2004, 2006; Mesoudi 2011; O'Brien and Lyman 2000, 2003; Perreault 2012; Premo 2012; Shennan 2011). As O'Brien and Lyman (2000) have noted, to some extent these approaches build on earlier attempts to model cultural change according to evolutionary principles (e.g., Boyd and Richerson 1985; Cavalli-Sforza and Feldman 1981; Clarke 1968; Evans 1875; Platnick and Cameron 1977). Studies of material culture traditions from this perspective have actively drawn on formal analytical methods from evolutionary biology, such as phylogenetics (e.g., Buchanan and Collard 2007;

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Lycett 2009; Marwick 2012; O'Brien et al. 2001; Tehrani and Collard 2002) and population genetics models (Bentley et al. 2004; Eerkens and Lipo 2005; Hamilton and Buchanan 2009; Lycett and von Cramon-Taubadel 2008; Neiman 1995; Rogers et al. 2009; Shennan 2001; Shennan and Wilkinson 2001). Such approaches have also benefitted from the application of quantitative experiments (e.g., Caldwell and Millen 2008; Kempe et al. 2012; Mesoudi and O'Brien 2008a).

The conceptual basis for such work is Darwin's (1859:459) recognition that any genuine evolutionary system is fundamentally a process of "descent with modification," characterized by three essential properties: (1) a mechanism of inheritance; (2) the existence of variation in inherited properties; and (3) the differential representation of inherited variants through time (Mesoudi et al. 2004). In the case of culture, the mechanism of inheritance is the process of social transmission, which is comprised of several different potential learning mechanisms, such as stimulus enhancement, emulation, imitation, and teaching (Byrne and Russon 1998; Whiten et al. 2004). Likewise, several different mechanisms of "sorting" may influence whether particular variants are passed to subsequent generations in lesser or greater numbers in cultural evolution, just as they are in biological evolution (i.e., drift, natural selection, artificial selection). For example, the influence of transmission biases on change and variation, such as preferentially copying prestigious or successful individuals (indirect bias), has been demonstrated using explicit archaeological examples such as Great Basin projectile points (Bettinger and Eerkens 1999; Mesoudi and O'Brien 2008a, 2008b). In addition, researchers have adapted genetic drift models to material cultural evolution, illustrating that, in the absence of transmission biases or other selection mechanisms, drift alone can create cultural macroscale changes and historical patterns through incremental small-scale modifications over the repeated course of cultural transmission (Bentley et al. 2004; Kohler et al. 2004; Neiman 1995; Shennan 2011; Shennan and Wilkinson 2001).

The additional key element in any genuine system of descent with modification, however, is the existence and generation of *variation*. In the absence of variation, neither drift nor selection can operate. As Eerkens and Lipo (2005:317) put it, "Variation is the raw material upon which selection operates to cause changes in the frequency of cultural traits through time." In the context of artifactual variation, therefore, the study of variation generation at a microevolutionary level is the equivalent of studying genetic mutation in biology (Cavalli-Sforza and Feldman 1981; Eerkens and Lipo 2005). In principle, a number of potential mechanisms (e.g., deliberate embellishment) might lead to the generation of new cultural variants, and it is important to note that the deliberate, intentional introduction of variation does not invalidate an evolutionary theory of cultural change (Mesoudi 2008). However, it is also recognized that unintentional copying errors (i.e., imperfect replication) during the manufacture of artifacts can lead to the introduction of novel variation in material traditions (Clarke 1968:161; Eerkens and Lipo 2005; Hamilton and Buchanan 2009).

To date, the majority of studies examining microscale copying errors have focused on physiological limits in the accuracy of human perception, specifically in terms of our ability to perceive differences in the sizes of objects (Eerkens 2000). The perceptual threshold below which humans fail to discriminate variation in the size of different objects is termed the *Weber fraction* and is now established at a level of ~3 percent difference for a dimensional variable such as "length" (Eerkens 2000; Kempe et al. 2012). In other words, if a person is presented with two objects and the difference in their length is less than 3 percent, they will generally fail to perceive this difference. Such insights provide a basis for comparing patterns of size variation in artifactual assemblages (Eerkens 2000; Eerkens and Bettinger 2001; Kempe et al. 2012).

Eerkens and Lipo (2005) used the Weber fraction to formulate what Hamilton and Buchanan (2009) later dubbed the "accumulated copying error" (or ACE) model. Using computer simulation, Eerkens and Lipo (2005) modeled change in a continuous trait value as it was transmitted over successive generations of individuals in 10 independently evolving transmission-chains with a pre-set random error rate of 3 percent. This simulation demonstrated divergence in the different transmission chains through successive generations, as some chains became progressively larger while others became increasingly smaller. They also found that while between-chain variation increased through time, the random character of the error did not lead to a change in the overall mean size through time. Using the output of this simulation as a comparative (null) model, they then demonstrated that the thickness of Rose Springs projectile points from Owens Valley (USA) varied in accordance with the predictions of the random accumulated copying error model. However, the basal width of these projectile points exhibited less variation than expected, suggesting that some non-mutation process (i.e., some form of stabilizing selection such as conformity) was operating on this particular variable. Kempe et al. (2012) recently tested the predictions of the ACE model experimentally by transmitting two-dimensional images of an artifact along chains of participants, with each generation instructed to copy the previous generation's artifact as best they could. The results of this experiment supported the prediction that accumulated copying error leads to an exponential increase in artifact size variation through time. However, the experiment also found that mean size may increase through time if the initial size of the image that the participants were asked to resize was larger than the size of the artifact image they were copying.

It must be noted that all of this previously undertaken work has focused exclusively on the size (i.e., scale) of artifactual attributes and the patterns of variation that may be produced via copying error rates due to limits in size perception. However, variation in the overall *shape* of artifacts is also evidently important, given that aspects of shape may have specific functional or aesthetic properties. Moreover, historically, variation in the shape of artifacts has been used as a key variable in archaeological classification schemes (Trigger 1989:200–203). Although size and shape are often conflated ("form" = size + shape), both conceptually and empirically, size and shape are fundamentally distinct (Bookstein 1989; Jungers et al. 1995). While the size of an object is a univariate property and can therefore be described by a single measure of scale such as volume, shape is inherently a multivariate property. A quantitative concept of shape, therefore, relies not on the appreciation of a single variable such as "length," but on the relative relationships between multiple aspects of morphometric variation in a given object. To date, no studies have specifically examined copying error in shape in these terms.

The potential importance of shape-copying errors in the role of cultural evolution is particularly emphasized when differing methods of artifact manufacture are considered. Some time ago, Deetz (1967) contended that fundamentally distinct processes of artifact manufacture might have different effects on the generation of copying errors and, in turn, resultant patterns of variation. Specifically, Deetz (1967:48–49) noted that, in the case of a "reductive" process of manufacture, such as the knapping of stone artifacts, errors are not easily reversed. Indeed, as Baumler (1995:11) noted more recently, the production of stone tools is an inherently subtractive process "characterized by the removal of raw material." Hence, once a piece of material is removed it cannot be replaced in order to correct an error. Conversely, Deetz (1967:48–58) contended that in the case of more readily reversible (or "additive") processes of manufacture, such as pottery or basketry, such errors are readily reversed by the replacement of material. According to Deetz, differences between such alternative manufacturing processes would lead inevitably to greater levels of variation in non-reversible manufacturing traditions.

Testing these predictions via the archaeological record is potentially fraught with difficulty given the differing conditions under which alternative sets of artifacts might be made. Moreover, comparing variation in artifacts made of differing raw materials (e.g., stone vs. clay) is problematic in this case given that the medium of manufacture itself might influence variation patterns. What is needed is an approach that can control such factors, such that the key contrasts between the two alternative manufacturing conditions are emphasized. Here, therefore, we adopted an experimental approach to this issue. We implemented an experimental procedure that consisted of a simple copying task. Two alternative conditions were implemented, one representing an irreversible ("reductive-only") manufacturing process, the other representing a reversible ("additive-reductive") manufacturing process. Participants were asked to copy the shape of a "target form" as accurately as possible utilizing a standardized block of plasticine and a stainless steel table knife. Following Deetz (1967), the central prediction that we tested is that reductive

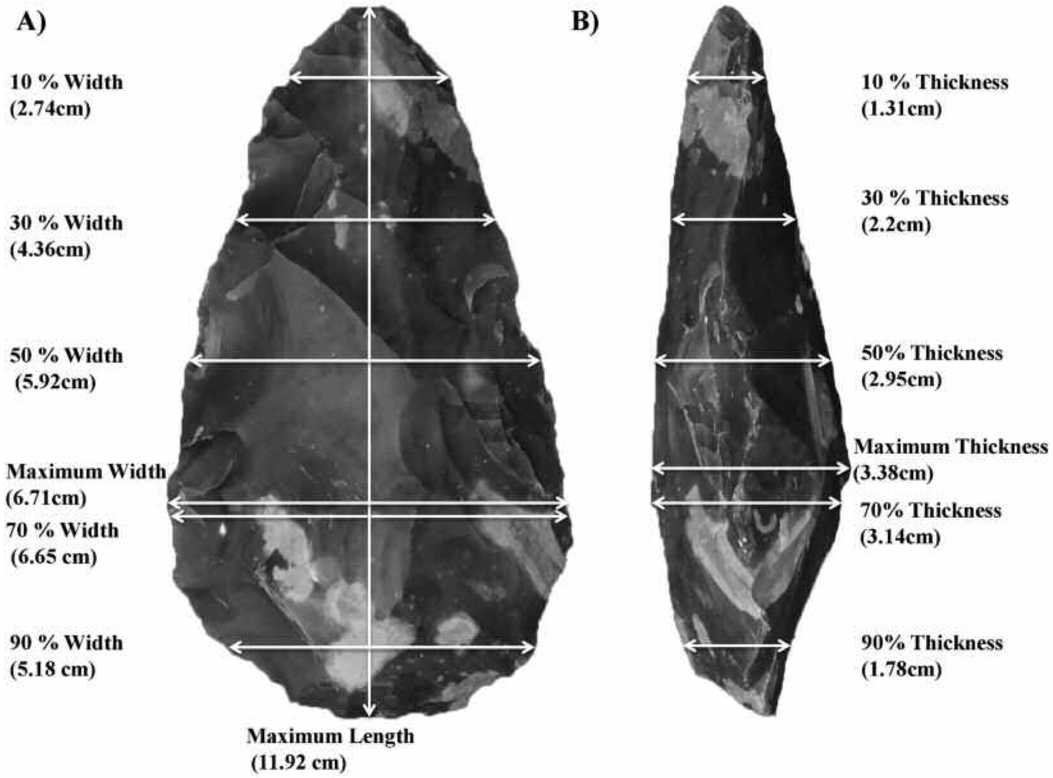


**Figure 1. Flint handaxe replica used as the "target" model during the experiment. Major dimensions are shown at various percentage points in (a) plan-view along the length (by orientation) line and (b) profile-view.**



manufacturing processes, where material can be removed but not added, automatically lead to an overall higher rate in copying error for shape than reversible manufacturing conditions. We specifically targeted the statistical effects on shape attributes, using a dataset of size-adjusted morphometric variables. It should be noted, therefore, that in contrast to the majority of previous work examining the phenomenon of copying error, this experiment is not so much aimed at the issue of perceptual bias (in terms of establishing a baseline error rate) as *procedural bias*—additive vs. reductive manufacturing processes—and establishing whether one procedure has intrinsically greater error rates than the other.

## Materials and Methods

### *Handaxe Form as a "Model Organism" for Studying the Evolution of Material Traditions*

The "target form" chosen for this experiment was a replica of a flint Acheulean handaxe (Figure 1). The goal of reproducing a "handaxe" form in plasticine was chosen for a variety of reasons. Firstly, the application of real stone knapping was deemed unsuitable for multiple reasons concerning safety and feasibility, especially given the need to recruit numbers of participants large enough to facilitate statistical testing of resultant data. The manufacture of handaxe forms requires levels of skill and experience that are built over months, if not years, of intense practice (Edwards 2001; Stout 2002). Also, it is possible to inflict severe injury during knapping (Whittaker 1994). Conversely, plasticine "handaxes" are easily manufactured, thus facilitating the immediate recruitment of multiple participants who could engage in the type of physical manufacturing task required. Importantly, this experimental design also enabled the implementation of both reversible ("additive-reductive") and non-reversible ("reductive-only") manufacturing processes using identical apparatus, with only subtle modification of the experimental procedure in each case (see below).

The final justification for using handaxe shape as a target form during these experiments is perhaps less intuitive. Evolutionary biologists have long recognized the value of using so-called "model organisms" to study fundamental evolutionary processes such as genetic transmission and mutation in experimental settings (Mesoudi 2011:136–138). Commonly used model organisms, such as fruit flies (*Drosophila spp*.), tend to have a variety of characteristics that make them particularly suitable for such experiments, including economy, speed of replication, and controllability (e.g., Allen 1978; Ashburner et al. 2005; Ashburner and Novitski 1976; Greenspan 2004; Roberts 1986). The most suitable model organisms thus display some of the complexities of the phenomenon of interest, yet are generally not so complex that they are unwieldy in experimental settings.

We suggest that the characteristic shape of Acheulean handaxes can serve as an experimental model akin to model organisms in biology. Archaeologically, Acheulean handaxes are defined by the imposition of a long axis on artifact form by means of invasive bifacial knapping around the edge of a stone nodule or large (i.e., generally > 10cm in length) flake blank (Gowlett 2006; Isaac 1977; Roe 1976; Schick and Toth 1993). Handaxes thus have a "bilateral" organization around their long axis that may in some instances tend toward symmetry, although the extent of "symmetry" in Acheulean handaxes varies widely in space and time, and within individual assemblages (Clark 1994; Lycett 2008; Wynn 2002). Such artifacts first appear in the archaeological record of Africa 1.75–1.5 MYA (Beyene et al. 2013; Lepre et al. 2011), but they subsequently appear in Western Europe and large parts of Asia (Clark 1994; Gowlett 2011). Evidence from experiments, residue analysis, usewear, design theory, and archaeological context has led many to contend that the form of such artifacts was driven, at least in part, by functional requirements relating to their use as cutting and/or chopping tools (e.g., Bello et al. 2009; Domínguez-Rodrigo et al. 2001; Gowlett 2006; Jones 1980; Keeley 1980; Roberts and Partfitt 1999; Simão 2002; Yravedra et al. 2010). As Gowlett (2006) has noted, the deliberate manufacture of handaxe form requires—minimally—the interrelated manipulation of the relative length variable(s), width(s), and aspects of thickness variability on the part of their manufacturer. Such was the case in our experiment, as participants attempted to copy the various integrated shape components of the target form. Hence, although the replication of "handaxe" form in our experiments does not necessarily approach the most complex manipulation of form variables required in alternative instances of artifact production via reductive or additive processes, it certainly required the manipulation of a multiplicity of integrated aspects of shape. Given our stated goals, handaxe form thus provided a suitable experimental model for many similar reasons to those that lead to the selection of "model organisms" in alternative experimental contexts.

### *Participants*

A total of 60 participants were recruited to take part in this experiment. Most of these were postgraduate and undergraduate students recruited from the campuses of Queen Mary, University of London, and the University of Kent. Of the participants, 30 were female (mean age = 26; $s = 5.4$; age range = 18–44 years) and 30 were male (mean age = 28; $s = 9.8$; age range = 18–64 years). Equal numbers of males and females were employed deliberately in order to control for any potential confound in terms of sex differences (see below). Each volunteer was compensated with £4 for their participation.

### *Materials*

All participants began the manufacturing process from identical, standardized plasticine blocks in order to control for confounding effects resulting from any heterogeneity in starting conditions. In order to produce these standardized blocks, plasticine was molded into a plastic container measuring 13.5 cm in length, 8.7 cm in width, and 4.5 cm in depth. The container was filled with plasticine until level with the edge of the box opening, and the upper surface of the block was molded flat. Placement of a clear sheet of thin (~12.5 $\mu$m) plastic (i.e., food wrap) into the box prior to loading with plasticine enabled easy removal of the block.

The stone handaxe replica used as the target form during these experiments was knapped by

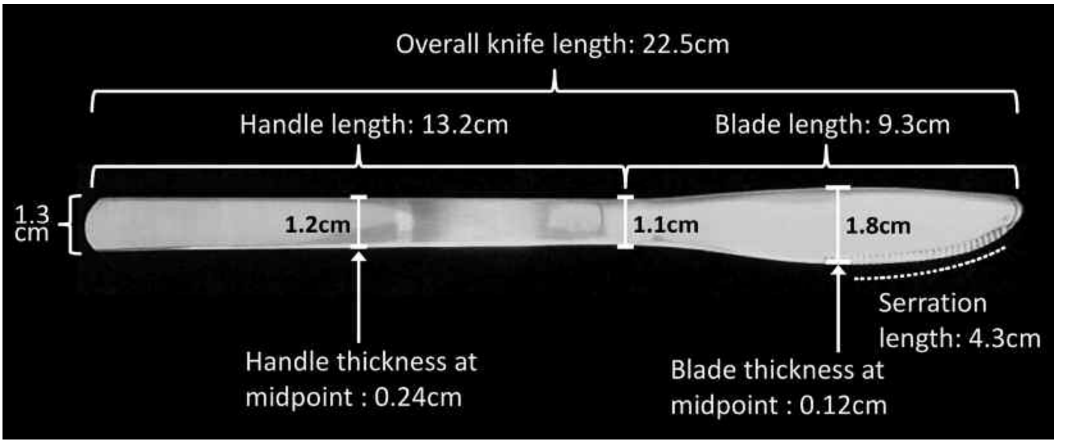


**Figure 2. The stainless steel knife used by participants during the experiment in order to either remove or add material to their plasticine block.**



one of us (SJL) using flint procured from the Kent coast, United Kingdom. Major dimensions of this replica handaxe are shown in Figure 1. It should be noted that it is (in principle) possible to produce an exact isometrically scaled copy of this target from the plasticine block provided.

Participants were required to manipulate the plasticine block using a standard table knife (Figure 2). This knife was comprised of a single piece of stainless steel and had a total mass of 40.93g. Metric attributes of this knife are described in Figure 2.

### *Experimental Conditions and Procedure*

The experiment was divided into two alternative conditions. Condition 1 was termed the *additive-reductive condition*. This experimental task simulated more readily reversible manufacturing processes. That is, in this condition, participants were instructed that they were free to both remove *and* add plasticine during the manufacture of their plasticine replica.

Condition 2 was termed the *reductive-only condition*, and it simulated reductive manufacturing processes as found in stone-tool knapping. Under this condition, participants were permitted only to remove material from the plasticine block as desired; they were instructed that they could not add plasticine onto their plasticine replica once material had been removed. Participants were observed throughout the experiment in order to ensure that this condition was implemented faithfully.

The 60 participants were divided equally between each condition (i.e., 30 for each condition). Statistically significant differences in laboratory tests of spatial perception and mental rotation have been observed in human males and females, whereby males tend to outperform females (e.g., Halpern 2000; Linn and Peterson 1986; Voyer et al. 1995). This potentially has implications for the production of material items, including stone tool forms (Wynn et al. 1996), although it should be noted that such sex differences are reduced substantially in some tasks when real 3D objects are involved rather than 2D representations (Robert and Chevrier 2003). However, in order to control for any potential confound in this regard, male and female participants were distributed evenly between the two experimental task groups (i.e., 15 females and 15 males per condition). Upon arrival, participants were assigned to each group/condition alternatively, until the desired number of males and females was reached in each case. All participants took part in the experiment only once, and were not permitted to repeat their participation in the alternate condition.

Prior to each experiment, participants in both conditions were provided with one minute to handle and examine the target handaxe from all sides. Participants were instructed to pay attention to the overall form and shape properties of the flint replica, but they were specifically instructed to prioritize copying *shape*. Once the minute was over they were handed a standardized plasticine block

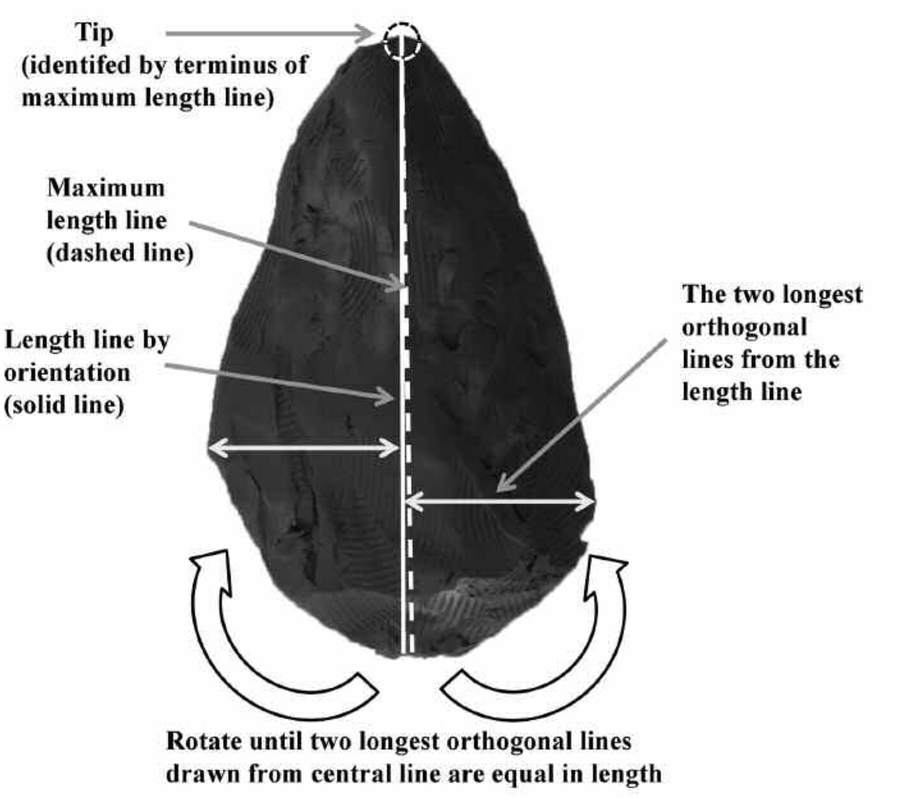


**Figure 3. The orientation protocol used to orient all specimens in a standardized manner.**



and table knife and given a time limit of 30 minutes to complete the copying task. Only one attempt was given, although all participants completed the task within this time limit. The flint replica remained with the participants throughout the experiment and they were permitted to compare the flint replica with their own plasticine replica from any side or angle and at any desired point during the experimental task (hence controlling for memory effects). Any participants requiring vision-corrective spectacles or contact lenses for close tasks were permitted to wear these during the experiment, thus controlling for major discrepancies in visual acuity. However, participants were not permitted to make use of any additional external aids (e.g., scaled rules) that could improve their perceptual accuracy.

### *Morphometric Procedures and Compilation of the Data Set*

Measurements were obtained digitally for 42 variables (28 plan-view and 14 profile-view) for each plasticine handaxe (plus the "target" form) using the freely available morphometrics software tpsDig v2.16 (Rohlf 2010). Photographs of each "handaxe" were taken using a copy-stand fitted with a Fujifilm DSLR camera (30× zoom lens: 24–720mm). During photography, each plasticine handaxe was placed on a light box in order to clearly emphasize outline form.

A standardized orientation protocol was applied in order to obtain homologous measurements from each plasticine replica (Figure 3). The orientation protocol used is a variant of that originally designed by Callow (1976) and subsequently adopted by Costa (2010). We implemented the orientation protocol as follows. The maximum length line of each handaxe was identified in plan-view, and the terminus of this line at the more pointed end of the handaxe defined the "tip." Thereafter, each handaxe model was oriented through the tip such that the two longest orthogonal lines diverging from a second length line (i.e., "length by orientation") were both equal in length

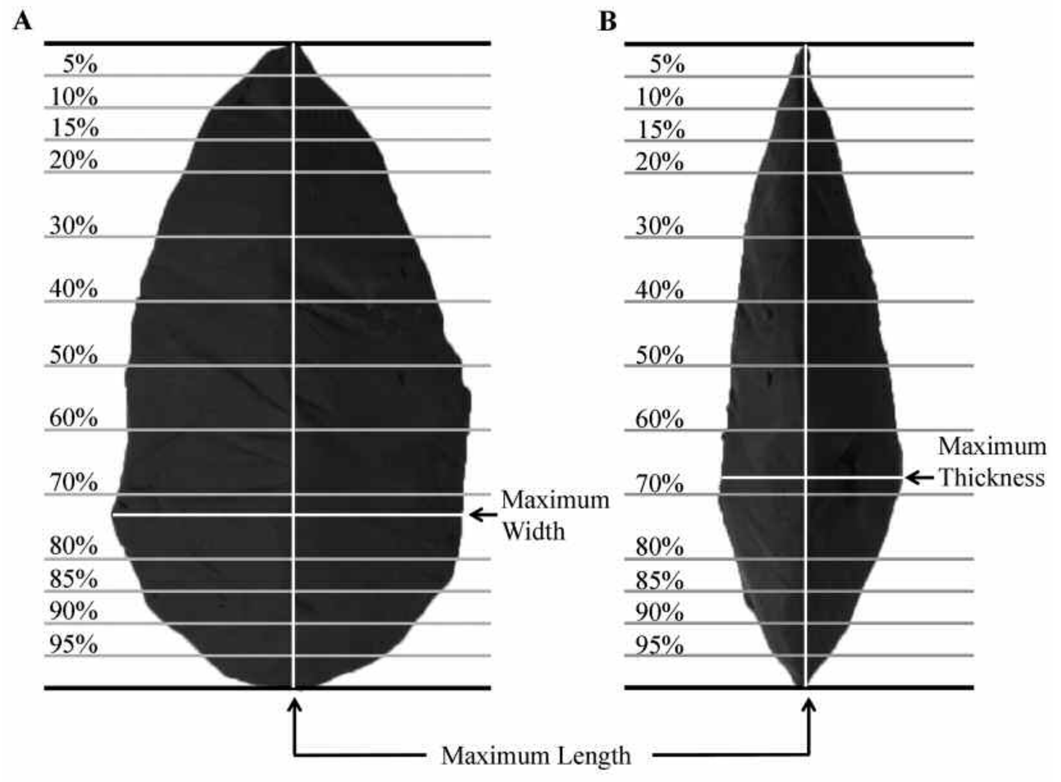


**Figure 4. The position of gridlines along the length axis in both (a) plan-view and (b) profile-view. A total of 42 measurements were obtained using this protocol. Bilateral measurements were obtained from the center line to the extremity of the outline at each percentage point plus the maximum width and length in (a) plan-view, providing 28 plan-view measurements. Thickness measurements were obtained at each percentage point plus maximum thickness in (b) profile-view, providing a total of 14 profile-view measurements.**



(Figure 3). Profile views were obtained by turning the oriented replica through an axis of 90 degrees such that all thickness measurements were taken orthogonal to the plan view measurements.

A digital grid was placed onto each of the photographic representations in order to obtain an array of lateral and bilateral measurements from the plan-view and profile-view perspectives (Figure 4). Similar versions of this measurement framework, sometimes referred to as “comb” configurations, have been applied previously by Buchanan and Collard (2010a) and Monnier and McNulty (2010). For both the plan- and profile-views, the measurement grid was superimposed onto the digital image of the replica so that the grid’s central line was placed above the maximum length line by orientation. The upper and lower boundaries of the grid were adjusted to the maximum length margins of the replica’s area (Figure 4a). The grid’s horizontal lines were placed at equally-spaced incremental distances of 10 percent along the length of the orientation line. Additional gridlines were placed at 5 percent, 15 percent, 85 percent, and 95 percent of length. These latter measurements thus captured additional variation around the “tip” and “base” of each handaxe replica. For the profile-views, the grid boundaries were equivalently placed onto the maximum length margins of each replica (Figure 4b). Thereafter, each image was imported into tpsDig v2.16 (Rohlf 2010), and bilateral measurements from the center line to the edge of each handaxe were recorded in the plan-view. In profile-view, thickness measurements were recorded laterally from one side of the “handaxe” outline to the other. Maximum width (in plan-view) and maximum thickness (in profile-view) were also obtained.

### *Size-Adjustment and Computation of Shape Error Rates*

We applied an analysis that extrapolated shape data from confounding size variation, since we were specifically focused on monitoring shape-related changes in the designs of the experimentally generated replicas. The data were size-adjusted via use of the geometric mean method (Jungers et al. 1995; Lycett et al. 2006). This method of size-adjustment effectively removes isometric size (scaling) variation between specimens, yet retains their relevant shape data (Falsetti et al. 1993; Jungers et al. 1995). The geometric mean of a series of *n* variables ($a_1, a_2, a_3 \ldots a_n$) is equivalent to $(a_1 \times a_2 \times a_3 \times \ldots \times a_n)^{1/n}$. Simply, the geometric mean is the *n*th root of the product of all *n* variables (Jungers et al. 1995; Sokal and Rohlf 1995: 43). The method proceeds on a specimen-by-specimen basis, dividing each variable in turn by the geometric mean of the variables to be size-adjusted. Hence, to implement the method, the geometric mean of each handaxe replica was calculated separately and, thereafter, each of the 42 morphometric variables for each specimen were divided by the geometric mean for that particular specimen.

In order to investigate changes in shape morphology that arose during the copying task, copying error rates were extracted from the size-adjusted data set using a straightforward two-step procedure. Firstly, the size-adjusted values of the 42 morphometric variables from each replica were subtracted from the equivalent 42 size-adjusted variables of the target flint replica in turn. Thereafter, mean shape error rates were computed for each of the 42 morphometric variables across the 30 replicas obtained in each experimental condition. It is these 42 mean error rates that were used in the subsequent statistical analyses.

### *Statistical Analyses*

In order to visualize patterns of overall shape-copying error across the two alternative conditions, box plots of the error rates were produced for each condition. Two sets of inferential statistical analyses were additionally undertaken. In the first analysis, copying error rates in the additive-reductive condition vs. the reductive-only condition were assessed for statistical difference. Since the shape-error data were found not to be normally distributed, a conservative non-parametric Mann-Whitney *U* test was implemented. Both asymptotic and Monte Carlo (10,000 random assignments) *p*-values were recorded ($\alpha = .05$). These analyses were undertaken using PAST v2.17 (Hammer et al. 2001).

In the second analysis, the geometric means of all "handaxe" replicas in the additive-reductive condition and the reductive-only condition were assessed for statistical difference. The purpose of this analysis was to ascertain whether participants in either condition were systematically producing either smaller or larger replicas than in the alternative condition. This could potentially provide insight as to whether any underlying directional size trends were being employed systematically by the participants (e.g., potentially removing greater amounts of material in the reductive-only condition in order to "correct" shape-copying errors). Since geometric mean data in the two alternative conditions were found to be normally distributed, a two-tailed *t*-test (independent samples) was undertaken ($\alpha = .05$). However, for more direct comparability with the previous analysis, a Mann-Whitney *U* test was also again applied. These analyses were also undertaken using PAST v2.17 (Hammer et al. 2001).

## Results

The first analysis compared shape-copying error rates in the reductive-only condition vs. the additive-reductive condition. Figure 5 illustrates that overall shape-copying error was greater and contains more variation in the reductive-only condition, when compared to the additive-reductive condition. Mean shape-error rates for each of the 42 variables can be viewed for both conditions in Figure 6 and Figure 7. The additive-reductive condition had an overall mean copying error rate of .115 ($s = .040$). The reductive-only condition had a mean of .134 ($s = .053$). The results of the Mann-Whitney *U* test demonstrated that copying error in the reductive-only condition was statistically greater than in the additive-reductive condition ($U = 621.5$; asymptotic $p = .0191$; Monte Carlo $p = .0199$). Hence, the results of this first analysis confirmed that shape-copying rates were statistically higher in the reductive-only condition compared to the additive-reductive experimental condition.

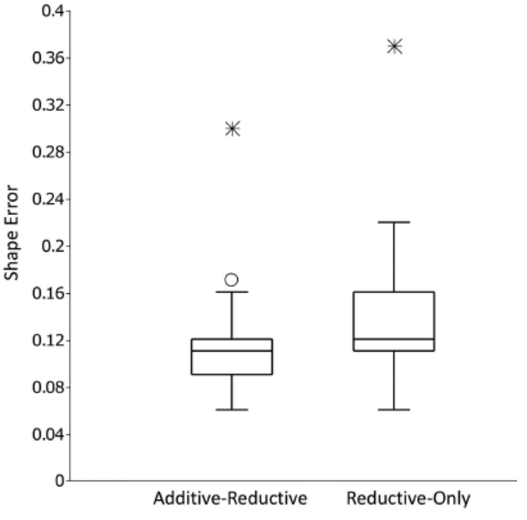


**Figure 5. Box plots of overall shape-error data in the experimental replicas for each of the two alternative conditions. Medians are indicated in both cases by the horizontal lines across each 25–75 percentile box. Whiskers mark largest data point ≤ 1.5 times box range. Outliers (circle) and extreme cases (star) indicated.**

A second statistical analysis compared the sizes of the plasticine handaxe forms in the two alternative experimental conditions. The average geometric mean in the additive-reductive condition was 2.305 ($s$ = .162), and the mean for the reductive-only condition was 2.350 ($s$ = .265). Results indicated no significant difference in the sizes of the plasticine handaxes produced in the two alternative conditions in either the $t$-test ($t$ = .793; $df$ = 58; $p$ = .432) or the Mann-Whitney $U$ test ($U$ = 410; asymptotic $p$ = .559; Monte Carlo $p$ = .552). Since the geometric mean values were not significantly different, this analysis demonstrated that the sizes of the replicas were not systematically smaller or larger in one experimental condition vs. the other.

## Discussion and Conclusions

In an explicitly cultural evolutionary framework, the study of variation generation mechanisms is a vital endeavor (Eerkens and Lipo 2005). Baumler (1995:12) noted that in the case of stone tool manufacture via knapping, "each removal is irrevocable and its consequences are permanent." Indeed, Deetz (1967:48–49) had earlier argued that this factor would lead inevitably to greater levels of variation in artifacts produced via non-reversible manufacturing traditions, compared to instances (such as pottery production) where copying errors may be reversed by the reapplication of material.

Here, we tested this proposition for shape data using a controlled experimental framework, morphometric (size-adjusted) shape data, and inferential statistical analysis. Participants engaged in one of two alternative conditions: one representing an irreversible ("reductive-only") manufacturing process, the other representing a reversible ("additive-reductive") manufacturing process. Participants in each condition were asked to copy the shape of a target form (a flint replica handaxe) as accurately as possible utilizing a standardized block of plasticine and a stainless steel table knife. Two sets of statistical analysis were undertaken. The first analysis found that replicas produced in the reductive-only condition displayed statistically greater levels of shape-copying error than those produced in the additive-reductive condition. Our second statistical analysis indicated that participants in each condition were not systematically producing either smaller or larger replicas than in the alternative condition, which demonstrates that statistically significant differences in shape-copying errors were present even in the absence of significant size differences between the two sets of experimentally produced copies. Overall, the results of our analyses are consistent with the proposition of Deetz (1967) that copying errors, at least in terms of shape, will be higher in artifacts produced via processes of irreversible reduction than in artifacts produced via reversible processes of manufacture. In other words, "mutation" rates in the shape properties of material traditions produced under irreversible "reductive" conditions (such as stone knapping or carving) are intrinsically greater than those produced via alternative means. Hence, shape mutation rates are process dependent.

Several implications for the study of material traditions arise from these results. In two traditions of equal duration, all else being equal, the potential for evolutionary diversification of shape attributes would have been higher in the case of those items of material culture produced via reductive processes than those produced by additive processes. In biology, such a phenomenon is referred to as "evolvability" (Ridley 2004:587). This

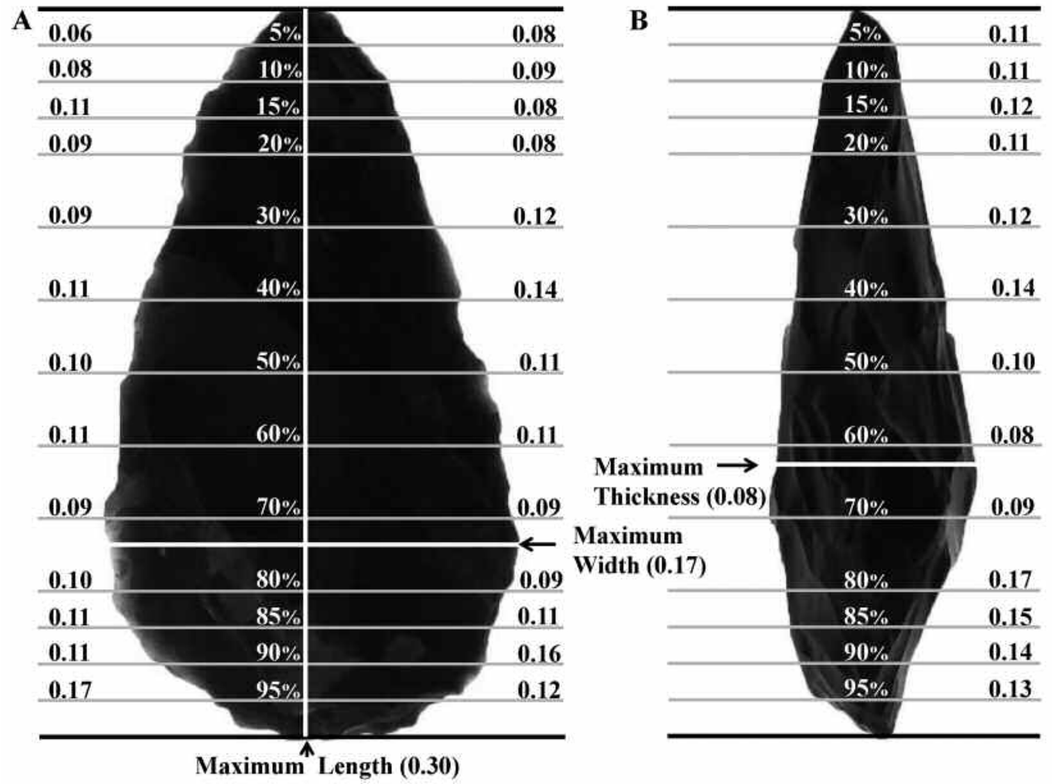


**Figure 6. Mean shape-copying error levels in the additive-reductive condition for each of the 42 variables.**



factor will need to be taken into account in future discussions of material cultural traditions that have evolved in equivalent spatiotemporal milieu, yet are produced via contrasting processes. This may be important given that "behavioral variability" has been proposed as a means by which key events in hominin behavioral evolution might be recognized (Shea 2011).

A second implication is that, due to their high mutation rates, artifactual shape traditions produced via reductive processes will be inherently unstable, tending always toward variation and diversification in the absence of any stabilizing mechanism. In our experiments, each of the morphological design attributes was equal in fitness (i.e., the importance of copying each component of shape was equal). However, in cases where particular shape attributes of archaeological artifacts were considered important by their manufacturers, either due to functional or aesthetic reasons, this would provide particular motivation for the instigation of what Patten (2005:54–56, 2012) refers to as "process controls." That is, the imposition of deliberate stabilizing strategies that led to specific outcomes having a greater predictability. The introduction of Acheulean handaxe manufacture in certain hominin populations from ~1.7 mya is often considered to be a switch from the situation in the preceding Oldowan, where core forms of particular shapes were not necessarily specifically desired (Toth 1985), to one where the shape attributes of handaxes were deliberately imposed (e.g., Roche 2005). As noted above, there is evidence from experiments, residue analysis, usewear, design theory, and archaeological context to suggest that the form of such artifacts was driven by functional requirements relating to their use as cutting and/or chopping tools (e.g., Bello et al. 2009; Domínguez-Rodrigo et al. 2001; Gowlett 2006; Jones 1980; Keeley 1980; Roberts and Partfitt 1999; Simão 2002; Yravedra et al. 2010). If concepts pertaining to handaxe shape were in any way culturally mediated, this would place particular importance on the potential introduction of

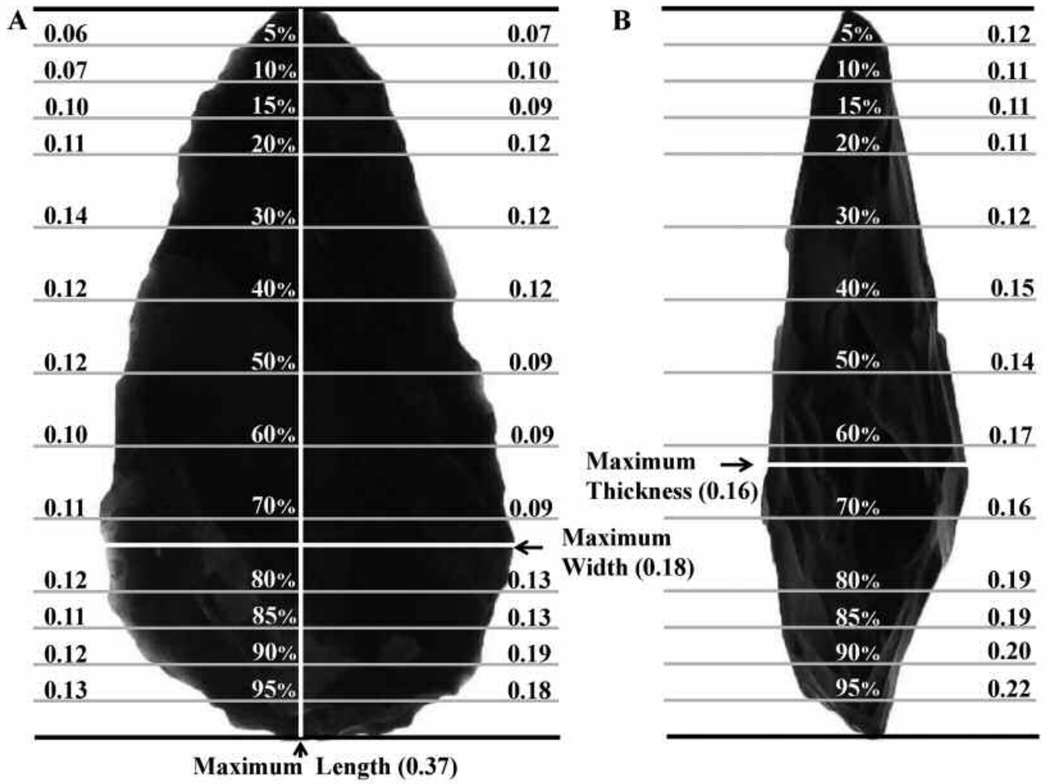


**Figure 7. Mean shape-copying error levels in the reductive-only condition for each of the 42 variables.**



process controls in the transition from Oldowan to Acheulean industries. In some instances of stone projectile point traditions from later periods of prehistory (e.g., Buchanan and Collard 2010a, 2010b), it has been suggested that specific shape trajectories were not merely targeted, but were maintained even in the face of resharpening bouts. If this is correct, then process controls must have been particularly well established in these circumstances, as Patten (2005) suggests.

A further, related implication arising from our results is that, in the case of items of material culture produced via reductive processes, the risk of error is greater for each production step than for equivalent steps in artifacts produced via alternative (reversible) processes. As Baumler (1995:12) notes, the only option available to a stone knapper to obtain a desired shape result is to remove more material. In other words, as a knapper strives to correct any shape errors by increasing the number of production steps, there is an increased level of risk of creating yet a further error that accompanies that step. Moreover, although sacrificing size may be an option in order to obtain a desired shape, this is potentially detrimental wherever size parameters (independently of shape) may have their own associated fitness values, as may be the case for certain stone tools such as Acheulean handaxes (Gowlett 2006, 2009; Kempe et al. 2012). Hence, this would put a premium on the economization of the number of task steps in reductive technologies, further motivating the instigation of process controls under such conditions.

Finally, our analyses emphasize the importance of experimental work in the evolutionary analysis of material culture. Although experimental psychologists have sometimes used the production of material items to study social learning processes and their outcomes, this has generally not specifically concerned the ultimate effects of these processes on the cultural evolution of material artifacts themselves (e.g., Caldwell and Millen 2008; Caldwell et al. 2012). So far, only a limited amount of experimental work has been specifically undertaken with the artifactual components of cultural evolution and their physical attributes of variation as the specific research goal (e.g., Eerkens 2000; Kempe et al. 2012; Mesoudi and O'Brien 2008a). Our results emphasize the importance of an experimental approach to understanding the evolution of material culture, specifically investigating the outcomes of certain cultural processes on artifactual attributes and patterns of variation in those attributes.

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