Reaching the Point of No Return: The Computational Revolution in Archaeology

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Abstract

Archaeologists generally agree that high-power computer technology constitutes the most efficient venue for addressing many issues in archaeological research. Digital techniques have become indispensable components of archaeological surveys, fieldwork, lab work, and communication between researchers. One of the greatest advantages of the digital approach is its ability to examine large assemblages of items using advanced statistical methods. Digital documentation has reached the point of no return in archaeological research, and reverting to traditional methods is highly improbable. However, digital data may also contain additional information that has yet to be extracted by computer analysis. In this arena, new computer algorithms can be triggered by research questions that cannot be addressed without digital models.

INTRODUCTION

The computational revolution is undoubtedly the most influential and far-reaching step taken by humanity in our time. Not only has it transformed our daily routines, but it has also permeated the way we perceive and interact with the world around us. In particular, it has had a major effect on science by providing radically new methods to gather, store, and retrieve data and by enabling entirely new approaches to analyze and interpret them.

Computer applications made a relatively late appearance in archaeology (Chenhall 1968). However, once launched, they grew exponentially so that only four years after their introduction, the number and variety of computer applications in archaeology were far too numerous to count (Whallon 1972). Today, high-power computer technology provides the most efficient venue for addressing many issues in archaeological research: It enables precise and complete recording and documentation of sites and finds and can also unravel properties and patterns of archaeological data that could not otherwise be explored.

Many groups worldwide almost simultaneously recognized the immense potentialities of computer technology for archaeological research, and this multiplicity of efforts resulted in a confusing multiplicity of terms to describe it. For instance, "cyber archaeology" (Levy et al. 2012, p. 5) was put forth as a new pragmatic approach that "integrates the latest advances in computer science, engineering and the hard sciences to address anthropological, archaeological and historical questions." Similarly, "digital archaeology" was defined as the way to explore the relationship between archaeology and information and communication technology (Evans & Daly 2006). "Virtual archaeology" (for the history of virtual reality and virtual archaeology, see Frischer & Dakouri-Hild 2008, Frischer et al. 2002, Kirchner & Jablonka 2001, Reilly 1991) was adapted from anthropology (Weber 2014) and is defined as "the introduction of fundamentally changed working methods in archaeology with the aid of the most modern technologies, not only in the area of primary data acquisition but also in data processing and editing for scientific purposes and for the presentation of archaeological knowledge to a broad general public" (Kirchner & Jablonka 2001, p. 235).

Despite the multiplicity of terms, all these activities have many ideas and aims in common. This review summarizes the main research directions and objectives. Before doing so, however, I note that these research efforts were closely associated with a similar growth in publications, many (but definitely not all) of which appeared in the proceedings of the Computer Applications and Quantitative Methods in Archaeology (CAA) conferences.

The first step in any project where computer technology is applied is the mapping of the real, tangible world of sites and finds to the digital world. This work is done by adapting existing technological innovations for specific archaeological purposes. This step involves mostly immense computational tasks (provided as "black boxes" by equipment manufacturers), which integrate the many views of the recorded object into a complete digital model. These basic data then need to be further processed to address the requirements of the archaeological project. At this juncture, processing can take two different directions that vary in purpose and hence in scope and methodology. This division is not necessarily sharp, and many features overlap in applications. Yet, this dichotomy is helpful to distinguish between documentation and analysis applications.

Documentation projects make use of the vast capabilities of digital technology to store (digital preservation and reconstruction) and visualize data (in two or three dimensions) and for display (printing as well as virtual reality). For this use, computer technology and applications are considered to be an additional set of tools that assist the archaeologist at work and that provide new techniques for obtaining easy and accurate documentation of the archaeological finds. Digital technology was adapted by archaeology in the same way as other important innovative tools such as absolute dating and stable isotope analysis, among others. Digital techniques have become crucial to archaeological surveys, fieldwork, and lab work as well as for communication between researchers. New technologies (developing commercially at a high rate) are harnessed to provide more efficient, low-cost, and accurate documentation that generates immense advantages in terms of quantity, quality, and detail.

Analysis projects extract archaeological information that requires further computations and analysis. A striking example is the determination of the center of mass of lithic tools. Obtaining this parameter can be accomplished only by using the digital data, and it is critical to understanding the possible uses of these artifacts. There are many other such examples where archaeological issues can be approached from entirely new angles. Another important class of projects within this approach takes advantage of the computer's ability to examine large assemblages of items using advanced and sophisticated statistical methods. Here, quantity (large numbers) is directly responsible for quality (reduction of statistical uncertainty) and may have a significant impact on classification and correlation projects. Computerized analysis certainly creates new opportunities in archaeological research that necessitate innovative interactions between qualitative- and quantitative-oriented minds. Will digital innovations determine the scope of archaeological theory (Zubrow 2006)? Have we reached a point of no return in this area of computerized archaeology?

The present review investigates this issue. Because I am active in two interlaced fields of research—prehistoric archaeology and computerized archaeology—this review highlights new developments primarily in the interface of these two domains. I provide some key examples to show that digital documentation has reached a point of no return in archaeological research and that reverting to traditional methods is highly improbable. This is followed by a discussion of the analysis mode, in which the development of new computer algorithms is triggered by research questions that cannot be addressed without the availability of digital models. Finally, I discuss current unresolved issues that may orient future goals in this evolving subdiscipline. These issues have been neglected for too long and could be resolved in the near future by applying new research strategies.

VISUALIZATION AND DOCUMENTATION

Ten years ago, digital cameras were comparatively rare and obtaining three-dimensional (3D) data required highly prized laser and structured light scanners. The current market offers a whole range of sophisticated digital imaging devices that are economical, portable, and flexible.

Within the archaeological community there has been a process of in-house developments, as seen in the recent advances in reflectance transformation imaging (RTI) technologies (Beale & Reilly 2014). This change has led to successful application of various 3D scanning devices with different qualities and data output. There have been numerous studies in this area on photogrammetry (Lerma et al. 2014), laser structure light (Niven et al. 2009), airborne LiDAR (light detection and ranging; Chase et al. 2011), a hybrid sensor of laser and photogrammetry (Lambers et al. 2007), X-ray computed tomography (Zhang et al. 2012), and RTI (Diaz-Guardamino & Wheatley 2013). The high resolution of 3D models enables different and informative perspectives on landscape (Chase et al. 2011, Rajani et al. 2009), caves (Lerma et al. 2010), desert palaces (Al-kheder et al. 2009), and archaeological findings such as wood (Lobb et al. 2010), stone artifacts (Abel et al. 2011), and fauna remains (Niven et al. 2009). These cutting-edge documentation studies are summarized below as they relate to three selected archaeological settings: sites, art, and portable artifacts.

Sites

Three-dimensional information has proven its value primarily in excavation recordings and has had considerable impact on the workflow of the excavation process and postexcavation studies (De Reu et al. 2014 and references therein). Use of 3D modeling during excavation produces two-dimensional (2D) accurate recording (e.g., Olson et al. 2013) and also 3D reconstruction by-products (Forte 2014).

In fact, the 3D approach as developed, for example, in Roosevelt et al. (2015) suggests that the old archaeological sawhorse of "excavation is destruction" should be revised to "excavation is digitization." For instance, while excavating Kaymakc in Western Turkey, investigators utilized a system that captures the 3D environment dynamically during each excavation stage and spatial context (Roosevelt et al. 2015). A similar technique that integrates digital methods for site documentation was developed at Faynan, the ancient copper mining and metal production region, and was named the cyber-archaeology research environment (Levy et al. 2012). The *REVEAL* database environment was developed for acquiring and presenting archaeological data that integrate both 2D and 3D data (Gay et al. 2010), which allows for interactive tools and real-time 3D searching and the rebuilding of the excavation process from the initial stages. These new tools for on-site documentation have replaced traditional excavation tools altogether and have led to greater accuracy, efficiency, and data sharing at low costs.

Digital mapping by areal techniques (drones) of the archaeological landscape has also increased exponentially, and many technologies have been developed to document excavations better and in more detail (Hill et al. 2014, Verhoeven 2009). LiDAR remote sensing technology has been utilized in several archaeological projects. This technology measures the time-of-light distance by illuminating a target with a laser and analyzing the reflected light on the surface at high accuracy. Aerial LiDAR is most frequently used for landscape studies that detect features and sites. One of its first successful applications was during the survey conducted at Stonehenge, which led to the discovery of new sites (Bewley et al. 2005). Investigators also used LiDAR to scan a large area covering the settlement of Caracol, a Mayan long-term occupation site in Belize, where the scans "saw" through gaps in the rain forest canopy. The images portrayed the topography of the landscape, structures, causeways, and agricultural terraces (Chase et al. 2011, 2013). These examples and many more have made this technology the prime method for site documentation and reconstruction (e.g., Corns & Shaw 2009), and its workflow is being upgraded constantly to better serve archaeologists' needs as shown with the "bonemapping" method used at Mesoamerican archaeological sites (Pingel et al. 2015). Unfortunately, only a few studies have used the LiDAR technique beyond visualization (e.g., García Puchol et al. 2013, Romero & Bray 2014). Romero & Bray (2014) developed methods for extracting features related to water manipulation at the imperial Inca site of Caranqui in northern Ecuador.

Art

Digital documentation of prehistoric art has gained momentum in the past ten years and has revolutionized the objectivity, accuracy, and drawings of rock documentation (Bourdier et al. 2015 and references therein). Noninvasive documentation of rock art sites harnessing a wide range of equipment and software is capturing the geometry of engraved motifs and the color of painted images (e.g., Bourdier et al. 2015; Clogg et al. 2000; Díaz-Andreu et al. 2006; Diaz-Guardamino & Wheatley 2013; Domingo et al. 2013; Lerma et al. 2013, 2014; Robson Brown et al. 2001). Photogrammetry and laser scanners can obtain precise 3D models of rock surfaces with further manipulation for automatic positioning of these models to extract and match specific features in complex rock art (Lerma et al. 2013). The combined method of 2D and 3D documentation has recently made it possible to overcome conservation problems and produce highly precise volumetric reproductions when faded motif and complex superimpositions cannot always be identified (Domingo et al. 2013). Researchers have attempted to develop analytical tools for shape identification that have greatly enhanced the interpretation of rock art features at Magdalenian sites in France (Bourdier et al. 2015). Nevertheless, there remain problems to be addressed such as the subjectivity of the 3D model extraction and its degree of resolution, the segmentation of features, etc.

Artifacts

Computerized processing of 3D models to obtain a precise image of the artifact's surface has been developed to position and draw artifacts at a rate and reliability far exceeding traditional manual methods (Grosman et al. 2008, 2014a; Jungblut et al. 2013; Karasik & Smilansky 2008; Magnani 2014). Several algorithms have been developed that produce print-ready drawings from 3D models that meet traditional standards while integrating additional tools that are easy to implement and versatile and provide additional views and metric information. Using scanning equipment, several groups have produced, with high precision and at low cost, accurate drawings of ceramic sherds that are comparable to traditional drawings in the archaeological literature (Kampel et al. 2005, Karasik & Smilansky 2008, Mara & Sablatnig 2005).

The Pottery 3-D software was developed to automatically find the axis of rotation of scanned potsherds (Karasik & Smilansky 2008). This user-friendly software enables quality control of the drawing, can add or remove details on demand, and can print potsherd plates to scale. It also provides additional information beyond that of traditional documentation such as snapshots of the object from specific directions and the volume of the vessel (Grosman et al. 2014a).

Artifact3-D software was developed for the documentation of artifacts that do not have simple shape or surface features (scars, ridges, engravings, etc.). The program's documentation procedures enable the automatic positioning of nonsymmetric objects such as lithic artifacts, bones, and stone vessels. The traditional drawing of lithic artifacts depends on how artifacts are positioned, and the result may vary substantially depending on who composes the drawing. Moreover, differences in artifact positioning by the researcher lead to differences in the extraction of even the simplest metric information. The program positions the artifact by deducing its intrinsic geometric properties and generates views, dimensions, and sections that have been selected algorithmically without concomitant interpretation (Grosman et al. 2008). The program also enables a large repertory of measurements, the production of sections, or the addition of visual aids. The software calculates quantities that are not accessible without this 3D information such as the location of the center of mass and its inertia moments (**Figure 1**).

An algorithm has been developed for the automatic, objective, and precise segmentation of the artifact surface into scars and ridges, which is essential to its complete documentation (Richardson et al. 2013). This functionality makes documentation of the object possible; the tool can automatically draw lines that represent the scars on the surface. The surfaces of many objects are also decorated with 3D features that convey highly important archaeological information. In many cases, the reliefs lose their original acuity over time, thus impeding reconstruction and comprehension of their content. To that end, additional software has been developed for processing and improving the visibility of the relief of the artifact's surface based on 3D scanning (Gilboa et al. 2013, Kolomenkin et al. 2009). The program uses an algorithm that records changes in the degree of curvature, the troughs, as the deepest lines on the surface and displays them as black lines.

These programs are now available as user-friendly applications and have been applied successfully on thousands of pottery sherds and lithic artifacts (at a rate of five per hour for full documentation) and many other archaeological finds from more than 200 expeditions

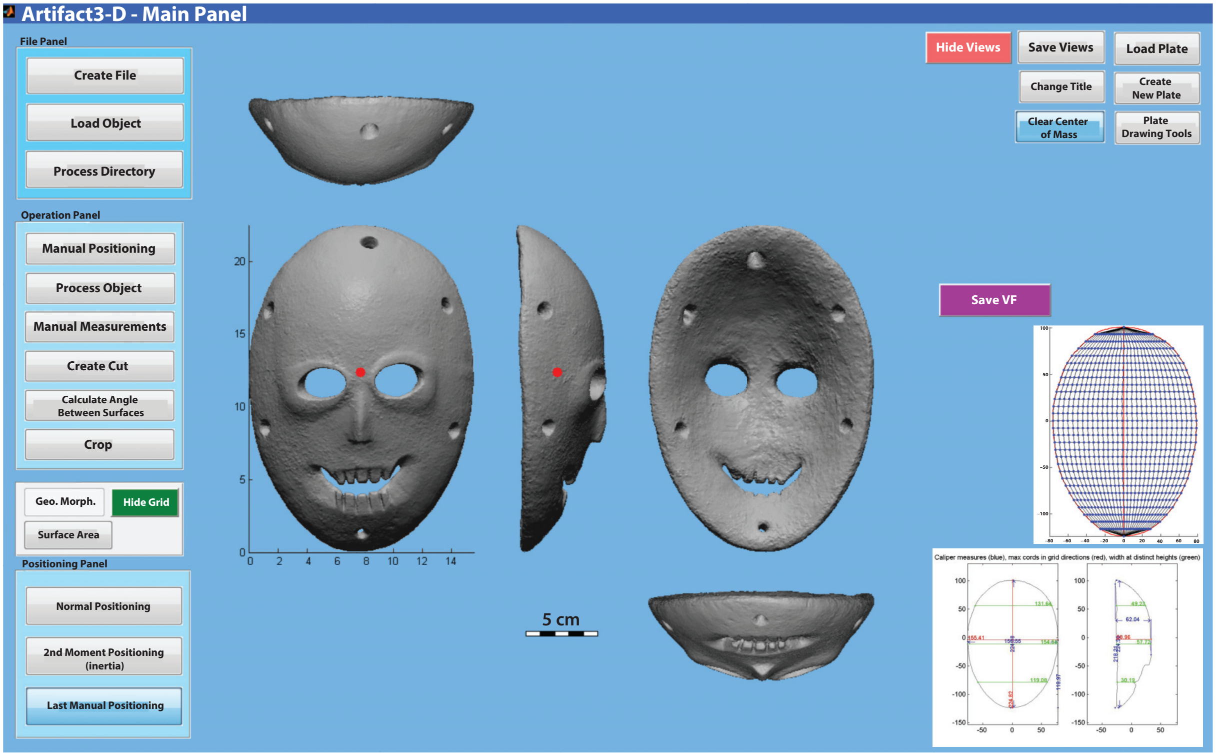

Figure 1

The Artifact3-D program for artifact documentation and analysis. Note the range of functions included in the program such as "Calculating the Angle Between Surfaces," "Surface Area," and "Center of Mass." After positioning the three-dimensional (3D) image, the artifact is presented in five views. Basic measurements are presented in sketch form (*lower right*, *bottom image*), which include standard measurements. The grid pattern marking semi-landmarks is presented (*lower right*, *top image*). The Neolithic mask is from the Israel Museum Collection, exhibited at the Israel Museum, Jerusalem.

(Grosman et al. 2014a). We recently documented the up-to-date life cycle of archaeological objects, from their first sighting at the excavation to their final resting place in the storehouse at the Israel Antiquity Authority, where a complete set of digitation and computerized methods were implemented: (*a*) high-precision 3D scan, (*b*) automatic positioning and drawing of the object, (*c*) sophisticated visualization and modeling techniques, (*d*) automatic classification and typology, and finally (*e*) integration into the database for long-term digital conservation and accessibility (Karasik et al. 2014).

Digitization and 3D documentation clearly provide new data and new venues for the dissemination of information to both the professional community and the general public. These methods are increasingly integral and fundamental to the practice of archaeology.

ANALYSIS: BEYOND VISUALIZING DATA

Several research groups have attempted to integrate digital data with cutting-edge archaeological research to better investigate current research topics analytically. One of the most substantial efforts involves advances in comparative analysis, one of the building blocks of archaeological research. In archaeology, comparison analysis is the only way to understand an object never found before, follow variations in time and space, and identify changes over time between cultural units. Comparison makes it possible to trace human behavior and spot unique features (Smith & Peregrine 2011).

The new digital technologies allow investigators to utilize metric, quantitative rather than descriptive language to characterize the shape of an artifact. In the digital era, archaeological material is transformed into the virtual domain of 2D or 3D models on a computer, thus making shape analysis essential. Study of the geometric shape of a digital model can supply simplified versions that incorporate important information for further comparison, which can then be linked to important archaeological investigations. The simplified representations are usually easier to use for further comparison than the complete digital object.

The most frequent type of shape is a representation of the contour of an object. The simplest way to model contour is by extracting a set of traditional discrete metric measures (length, width, etc.) of an artifact from the triangulated point cloud of the 3D model after automatic positioning based on its geometry. The result characterizes an assemblage of artifacts accurately and objectively in terms of the distribution of their metric measures (Grosman et al. 2008). For example, this quantification successfully established the degree of similarity between lower Paleolithic handaxe assemblages in the southernmost location in the Levant (Zihor Paleolake) (Grosman et al. 2011a). The most striking result from this study was that it strengthened the claim that the Dead Sea Rift 1.6 Ma was one of the main routes out of Africa (Goren-Inbar et al. 2000).

The 3D study of the handaxe assemblages from the Southern Levant revealed that the metric measure of the thickness of the tool's butt was homogenous over time, despite substantial differences in size (Grosman et al. 2011a). Thus, the base dimension discloses a functional constraint on size in favor of a comfort grip regardless of temporal, style, or cultural changes, as evident in the other dimensions (**Figure 2**). These results reinforce previous observations that only minor changes occurred in the power grip during the Paleolithic, thus indicating modest evolutionary changes in the human hand (Susman 1994).

There are many other novel ways to simplify digital artifacts for further shape analysis. Global attribute analysis has generated promising results when harnessed for archaeological investigations, as demonstrated in the following examples.

Symmetry and Roughness

One of the key advances in contour analysis is the quantification of the shape properties by the description of the symmetry and roughness of the shape (Saragusti et al. 2005). After dividing the contour by a line (symmetry axis) into two parts, the value of the minimum difference between one side and the reflection of the other is measured, yielding the degree of asymmetry. This measure has been applied to Lower Paleolithic handaxe assemblages from the Southern Levant. The results showed that the asymmetry values generally tend to decrease over time; i.e., handaxes generally become more symmetric (Saragusti et al. 2005).

The measurement of the variations in the artifact's contour was calculated as the roughness of the edge. The degree of roughness was based on the degree of concavity of the contour because the smoothest closed curves are convex. Roughness can be determined by the frequency and amplitude of the transitions between convex and concave sections along the curve (Saragusti et al. 2005).

These measures and the volume of artifacts extracted from the 3D models serve to track the wearing history as recorded in the shape parameters of experimental and prehistoric handaxes (Grosman et al. 2011b). Variations in these parameters can be used as markers of the extent of postdepositional damage affecting artifacts originating from a similar chronological unit. Many Lower Paleolithic sites are disturbed, and a comparative analysis shows how important it is to

Figure 2

Handaxe. Artistic illustration by Ami Drach and Dov Ganchrow (blade #9 from the BC–AD Contemporary Flint Tool Design Series, 2011, flint and elastomer). Photographed by Moti Fishbain.

take into account the effects of postdepositional processes before assigning an assemblage to a chronological or cultural unit.

Center of Mass

Above all, the most important advantage of 3D model analysis is the ability to extract global attributes that are not accessible without 3D information, such as the location of the center of mass (CM) and its inertia moments. For example, the assumption that hafting was not utilized during the Lower Paleolithic allows us to consider the stone artifact as the complete tool. In many cases, the original function of prehistoric artifacts and the mode in which they were used are unknown. However, the location of the artifact's CM is essential for an optimal design of the tool's shape to perform most efficiently. Thus, the location can provide information on whether the artifact was used as a projectile, a precursor, or a cutting tool. In large hammering tools, the CM should be located at the distal end/tip of the tool, which adjusts the force for percussion precision. In projectiles, the CM needs to be at the center of the artifact to avoid tumbling. As a result, 3D analysis can help reconstruct the basic use of an artifact. Our preliminary results show differences in the location of the CM as it relates to the center of the minimum enclosing cube between different tool categories (e.g., handaxes and large scrapers) and subcategories (e.g., handaxes and cleavers). Future analyses will further establish these trends.

Another study that used the CM attribute was conducted on Neolithic masks (Hershman 2014) to explore whether the Neolithic people wore these masks on their faces. After the automatic positioning of the masks, the results were clear-cut, demonstrating that the CM was not in the center of the mask but rather between the two eyes (**Figure 1**). This location is not surprising because it enables a more comfortable apportioning of the mass when the mask is placed on the face: Most of the mass is at the widest part of the skull, in the area of the mask's CM, and enables secure attachment to the face. Thus the frequent assumption that these masks were not worn but rather displayed on pillars or placed on the skulls of the deceased should perhaps be revised. Our study showed that most of the masks were made in such a way that they could be worn on the face: The eye holes allow for a wide field of vision, and the comfortable apportioning of the mass is suited to human facial contours (Grosman et al. 2014b) (**Figure 1**).

Geometric Morphometric Analysis

The geometric morphometric (GM) analysis of archaeological artifacts has attracted many researchers, and a growing number of publications have integrated this type of shape analysis. The analysis is based on distance measurements of the relative shape change by the use of homologous landmarks placed on specific locations on the artifacts. The shapes are expressed as a cloud of points in Cartesian space that takes into consideration a substantially larger degree of shape complexity, which thus enables a much more realistic representation of the artifacts. GM makes it possible to conduct powerful statistical analyses of an assemblage such as cluster and discriminant analysis. GM analysis has been applied on 2D digitized data of artifact contours to identify shape differences regardless of size (e.g., Buchanan & Collard 2010, Cardillo 2010, Charlin & González-José 2012, Lovita & McPherron 2011, Lycett & von Cramon-Taubadel 2013, Thulman 2012).

Landmark coordinate extraction is a difficult task. In some early cases, it was done manually by a caliper (e.g., Clarkson et al. 2006, Lycett et al. 2006) or by semiautomatic procedures with computer programs (e.g., Costa 2010) that may have introduced inaccuracies in the data.

Despite challenges, this quantitative analysis has prompted innovative discussions and opened up new avenues for understanding prehistoric technology. For example, the use of GM analysis of flake assemblages reinforced the hypothesis that two technologies, the discoid and the Levallois recurrent centripetal methods, have the same techno-morphological features (Picin et al. 2014). In one study, the interrelationship between properties of the core and those of its margin were examined by GM analysis and provided further evidence for the claim that Levallois core technology was directly developed from the strategies used for producing earlier handaxes (Lycett & von Cramon-Taubadel 2013).

There are currently only a few instances (Archer & Braun 2010, Sholts et al. 2012) in which GM analysis of artifacts has been applied to 3D information where the landmarks have been manually extracted. The main challenge in 3D analysis is defining homologous measuring points on the artifact (Weber 2014). These artifacts do not have intrinsically identical points by contrast to natural objects, e.g., bones, and in many cases, the extremities are missing in the archaeological context (Lycett et al. 2006). A grid pattern marking semi-landmarks was recently developed (G. Herzlinger & L. Grosman, manuscript in preparation) (**Figure 1**) on a 3D model to obtain a data set that was sensitive to the surface properties and enabled a 3D comparison between artifacts as a function of small changes in the shape pattern. This method has been applied to experimental and archaeological assemblages. The results confirmed the success of this method in identifying prehistoric knappers' levels of expertise (Herzlinger 2014).

Complete 3D Data Analysis

Only a few studies have utilized the methods developed for manipulating the complete 3D data beyond extracting landmarks (Shott 2014). These have been developed mainly for ceramic sherd refitting (Filippas & Georgopoulos 2014), morphological classification of ceramic sherds (Karasik & Smilansky 2011) and fossil bones (Terhune et al. 2007), and lithic analyses (Grosman et al. 2011b, 2014a; Riddle & Chazan 2014).

As shown in the examples above, lithic studies use shape analyses of artifacts to obtain insights into the lithic evolution and particularly the stages of lithic *chaînes opératoires* or the "operational sequences." These stages include (*a*) the procurement of raw materials (i.e., cortex coverage; see Lin et al. 2010) and tool production (i.e., technological aspects; e.g., Bretzke & Conard 2012, Clarkson & Hiscock 2011), followed by (*b*) their utilization (i.e., typological features; e.g., Grosman et al. 2011a) and resharpening of the tools (Zaidner & Grosman 2015), and ending with (*c*) the final abandonment of the object, frequently accompanied by various postdepositional processes (Grosman et al. 2011b). These studies trace variations over the use history of tools ranging from the early handaxe to late projectile points in archaeological contexts around the world (North and South Africa, North America, Southern Levant, etc.). For example, a new core reduction index was recently presented that calculates the ratio of number of flake scars to the 3D surface area. This new analysis confirmed that cores from the later Howieson's Poort and Middle Stone Age III stages are more heavily reduced and that local and exotic raw materials and different types of cores were all more heavily reduced during these periods (Clarkson 2013).

Ongoing studies aim to decipher the reduction process of lithic production, which can be identified by the network of scars left on the artifacts because the arrangement and patterning of these scars can be used for identifying methods of core preparation and flaking. One step in this direction has been the development of a method for automatic detection of the scars and ridges on 3D-scanned lithic artifacts and the extraction of quantitative complete shape and scar-related features (**Figure 3**) (Richardson et al. 2013). By introducing new concepts taken from the theory

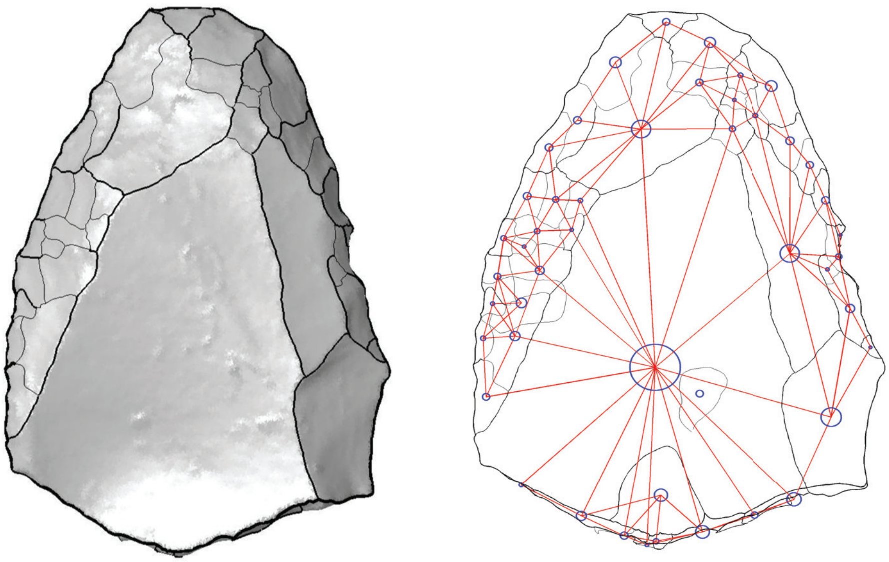

Figure 3

Lithic artifact represented as a graph of the scars (*left*). The scar graph diagram is superimposed on the drawing of the object (*right*). Each node scar contains several attributes such as area of the scar, mean normal direction curvature values, and edges that connect to adjacent scars (after Richardson et al. 2013).

of networks, such as the connectivity of the ridge network, this 3D method has made hitherto inaccessible data readable: for instance, the distribution of scar counts, their areas, shapes, and mean concavity. These parameters have paved the way for a more precise description and analysis of the lithic artifact surface and the underlying production technology. This segmentation also enables a quantitative analysis of the scar and ridge networks, including the number of scars, their surface area, and their depth and mean curvature (L. Grosman, E. Richardson, and U. Smilansky, manuscript in preparation).

A pilot case study manipulated the data by applying machine learning techniques developed in computer science to determine the degree of similarity between flakes from various Middle Paleolithic assemblages in the Southern Levant. The preliminary results are promising because the methodology successfully distinguished between assemblages without relying on the traditional technotypological criteria (L. Grosman, E. Richardson, U. Smilansky, manuscript in preparation; Richardson & Werman 2014). This study may lead to a novel method for clustering and separating prehistoric assemblages and a new way to control the validity of the traditional classification. Thus although not yet widely employed, computer analysis can be harnessed to explore archaeological research questions that cannot be addressed without the availability of digital models and therefore has wide-reaching implications for archaeological research.

FUTURE CHALLENGES

We are part of a new age in science across all domains in which digital technology has initiated significant changes. Progress in digital analysis in archaeology cannot replace the role of conventional archaeological study in reconstructing the historical narrative, providing meaning beyond the objects, or incorporating information from a variety of evidence to summarize the history of humanity. Only archaeological thinking can generate the important questions that will set the stage for further study.

Yet, the digital era poses challenges and creates opportunities in every school of thought, even those that traditionally have had little to do with computers and computing. One of our biggest challenges is determining how to respond to this new era of data-intensive science (Hey et al. 2009). Clearly, this is true for archaeological research as well.

Are We Looking At or Are We Seeing the Data?

> The historian of science may be tempted to claim that when paradigms change, the world itself changes with them. Led by a new paradigm, scientists adopt new instruments and look in new places. Even more important, during revolutions, scientists **see new** and different things when **looking** with familiar instruments in places they have looked before. It is rather as if the professional community had been suddenly transported to another planet where **familiar objects are seen in a different light and are joined by unfamiliar ones as well**. (Kuhn 1962, pp. 35–36, emphasis added)

Advances in digital technology are comparable to the paradigm shift in the development from photographs depicting moments frozen in time to the invention of motion picture cameras and the rise of film production companies. Rather than looking at the findings by thumbing through a photo album and noticing differences from picture to picture as end results without being able to obtain a real sense of the material, the digital era allows us to look at our findings from numerous dimensions. This overview has shown that we have new ways of looking at archaeological information and that a data-intensive science paradigm (Hey et al. 2009) is emerging. But are we seeing the data?

Archaeological research should not restrict computer power to digital archiving and documentation. The computer revolution in archaeology should be geared toward providing novel forms of interpretation. It should aim to link computerized methods with traditional archaeological efforts to recognize and compare patterns, spotting outliers and identifying relationships. We should target issues that cannot be resolved using traditional approaches and benefit from data that are accessible only by applying digital methodologies. There have been several attempts to go beyond illustration and discover tools and recover data (see also Frischer & Dakouri-Hild 2008 and references therein).

Although this overview should encourage archaeologists to pursue this line of research and even though digitization and documentation have clearly advanced considerably, a direct correspondence with archaeological research questions lags behind and has not yet reached the point of no return. Llobera (2011, p. 217) recently challenged the archaeological community: "We have the capacity to process and visualize information in novel ways but are we actually doing this?" We should be cautious not to accumulate huge amounts of digital data without clearly defined scientific goals.

New Modes of Thought?

Archaeological observations in the past were descriptive and dependent on the acumen of the researcher. Yet, the mind tends to be too narrow and dynamically deficient, omitting data and enabling comparison only to a limited extent. The power of the computerized digitation era is that it can enable us to overcome some of these obstacles and engender more complex modes of thought. Doing so will provide valuable insights into areas where archaeology has reached an impasse. The power of the digital world can take over where the old methods have failed.

For example, global theoretical models accounting for archaeological change during important transitions have been presented but have not been successful because they were archaeologically invisible; they failed to provide high-resolution evidence. The patchy nature of the retrieved archaeological data resulted in an incomplete view of a global phenomenon and made empirical verification impossible. Studies were forced to rely on local archaeological reconstructions in which the general pattern was played out. Efficient, high-resolution, and easily transported digital data can help us reexamine global phenomena and look for general trajectories. We can now compare patterns on a global scale and monitor processes that were not possible to evaluate before the computerized age.

What Can Archaeologists Do With the Growing Amounts of Data?

We are collecting enormous amounts of archaeological data from sites and from the material remains retrieved, and soon there will be no easy way to manage or analyze this influx. Mitigating the "data avalanche" (Levy et al. 2012) in archaeology needs a solution because the volume of data is growing exponentially. The next step should be oriented toward developing data management tools for archaeological communities worldwide and toward establishing a virtual environment for all documented data for comparative analysis, similar to the Digital Archaeological Record (United States) and the Archaeology Data Service (United Kingdom) (Kintigh et al. 2014). Several question-oriented databases are being developed, such as the ongoing ROAD database project for querying, analyzing, and modeling the expansion of early humans (at the Heidelberg Academy Research Center in Germany; see Haidle et al. 2010, Kandel et al. 2016). The ROAD project incorporates text data and geodata from many fields, including paleoanthropology, archaeology, paleontology, geology, geography, geomorphology, and paleobotany. Another example is the mapping of human settlements at large scales and the establishment of a large archaeological database for landscapes in Mesopotamia (14,000 sites have been mapped over 23,000 km^2; Menze & Ur 2012).

Although databases are an active research topic in archaeological research groups, large-scale databases with applications for query optimization and analysis should be developed. This type of mega database should incorporate an analytical tool for comparison at a large scale, namely a Google-like algorithm for an archaeological search engine that incorporates both 2D and 3D digital forms.

Applied or Integrated Science?

We should aim to go beyond the basic applications of computer technology and develop a new array of scientific methods. This review of the key literature pertaining to the digital era shows that the advances in this field in many cases have been carried out by scientists from other domains, primarily from the field of computer science. Unfortunately, some archaeologists observe the digital revolution from the sidelines, believing these techniques to be beyond them and yet something that they can neither ignore nor escape. For archaeology to take utmost advantage of the digital era, there must be an interaction between archaeological researchers and technology-oriented researchers to promote these new directions. The way to achieve this goal is by educating new scientists who are familiar with both orientations rather than being specialized in one or the other. We need approaches that integrate the archaeology and computer aspects of each field to generate fruitful and innovative discourse and produce new methods, which will in turn trigger other new challenges in archaeological lines of thought.

This overview is not exhaustive and could present only a small selection of the growing number of studies carried out in the field of computerized archaeology. It takes time to adjust to the shift in archaeological practices, particularly when certain forms of traditional technical expertise may become extinct (e.g., the draftsperson). But in most cases, this technical revolution is taking place gradually by incorporating changes in ways of thinking that will, in fact, lead to a point of no return.

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