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Introduction

Archaeology is the study of human culture and behavior through its material evidence. Although archaeology sometimes works with the material evidence of contemporary societies (ethnoarchaeology) or historical societies (historical archaeology and classical archaeology), for most of our past, the archaeological record is the only source of information. What we can learn about that past must come from surviving artifacts and modifications of the earth's surface produced by human activity. Fortunately, people tend to be messy.

Our basic sources of evidence consist of artifacts, waste products produced during the manufacture of artifacts or their use, food waste, ground disturbances including pits and mounds, constructions that enclose spaces such as buildings and walls, and the physical remains of people themselves. Study of this evidence includes identification of the raw materials used, what modifications occurred to make the object useful, and the physical shape and dimensions of the final product. Wear and breakage of the object and its repair are also examined.

In addition to its life history, each object has a context. It was discovered in a particular part of a site, in a particular site in a region, occupied by humans at a particular time. Together these make up the three dimensions that Albert Spaulding referred to as the "dimensions of archaeology" (Spaulding 1960).

Our discovery and analysis of archaeological evidence is directed toward the broad goal of understanding our past. The range of questions archaeologists are attempting to answer about the past is substantial. Broadly they could be grouped into a number of big questions:

1. How did our ancestors come to develop a radically new way of living that involved changes in locomotion (bipedalism), increasing use of tools, the formation of social groups unlike any other living primate, and increases in cranial capacity? Quantitative methods are used to identify sources of raw material

for stone tools to determine how far they were transported. They are also used to classify stone tools, to compare the kinds of tools and the kinds of animals found at different sites, and to look for correlations between the distributions of stone tools and animal bones.

2. Human culture involves the transmission of information across generations without depending on genetic inheritance. Part of that transmission involves the use of a flexible communication system and language, but culture includes the use of other symbolic forms of communication embedded in objects and artwork. Culture also includes the construction of different kinds of social groups and networks. How did culture emerge initially and how did its role in our survival increase? How did culture facilitate the migrations of our ancestors across the globe? Quantitative methods are used to study the distribution of artifact types, their composition, and the sources of the raw materials used to construct them. They are also used on plant and animal remains to identify changes in diet. The spatial distribution of artifacts, structures, and hearths can provide information on how societies subdivided space for various purposes.
3. How did cultures around the world begin to depend on domesticated resources after the end of the last Ice Age? How did this require the construction of new kinds of social groups and networks? What role did artifacts, art, and structures play in communicating those new social arrangements? Quantitative methods are used to trace dietary changes, including the introduction of domesticated plants and animals. Stable isotopes in human bone provide evidence of diet and to determine how much people moved from their birthplace during their lifetime. Differences in ceramic design and house construction can help to identify the sizes and geographic range of social groups.
4. Changes in social complexity and the division of labor emerge in many parts of the world after the establishment of farming communities. How does differential access to resources in some farming communities allow the development of power differentials that result in social stratification? How are power differences communicated though artifacts, art, and structures? Quantitative methods allow for the comparison of site sizes and locations to identify hierarchical settlement patterns and to document differences in wealth and social rank through comparisons of domestic house size and complexity, mortuary customs, and the construction of public spaces and buildings. Shifts toward craft specialization often reflect the production of standardized artifact forms with less variation and the production of objects produced from non-local materials and exhibiting a high degree of craftsmanship.

5. Beginning about 2,500 years ago, transcultural ideologies (Buddhism, Christianity, Islam) began to spread outside their areas of origin, creating networks of people who share a common religion, but not a common culture or language. The last 500 years has seen the emergence of capitalist economies and colonial empires that extended power differentials across cultural and geographic boundaries. In the last 250 years, the Industrial Revolution has transformed artifact production, agriculture, and transportation. While historical records provide many details, archaeology can contribute by focusing on the local impacts of these changes. Most of the approaches mentioned above are relevant here as well. Standardization of artifact types continues and evidence of trade networks such as ships, port facilities, and roads reflects greater transportation and human migration.

The big questions involve major transformations in the ways our ancestors lived, but they were gradual and our understanding of the changes will necessarily involve looking at quantitative differences as well as qualitative ones.

Quantifying archaeological materials is as old as archaeology itself. While archaeologists have developed a few of their own quantitative methods (e.g., seriation), they have also actively borrowed methods from related disciplines, especially ecology and geography. The present volume attempts to provide archaeologists with some of the tools they need in order to make some headway toward answering the big questions.

Archaeological data consist of measurements of objects, pits, and structures. Usually there are multiple measurements and they are made on different scales. Dichotomies measure the presence or absence of a characteristic. Categorical (or nominal) measures increase the number of categories beyond two to include a variety of qualitative differences such as cord-marked, incised, or plain. Rank (or ordinal) measures allow comparison between two objects to indicate that one is more or less than the other for some characteristic (e.g. older or younger), but the exact amount of the difference cannot be expressed. Numeric measures express the amount of the difference. Important distinctions for numeric measures include interval versus ratio and discrete versus continuous. Interval measures lack an absolute zero (Fahrenheit, Celsius, BCE/CE dates, and years BP). Ratio measures have an absolute zero (Kelvin, length, weight, volume). Discrete measures can only take positive integer values (e.g., the number of sites, flakes, or tools) while continuous measures can take any real value (e.g., length, width, thickness). Some quantitative methods are appropriate only for certain kinds of measurements. For example, if the raw material of stone tools is measured as rhyolite, flint, or quartz, then average raw material is a meaningless concept (but the mode is not).

Quantitative archaeological data can be divided into four broad classes: shape, composition, age, and location. Compositional data can be further divided between object composition (e.g., elemental or isotopic composition) and assemblage composition (counts of particular types of artifacts from a site, grave, level, or grid square). Quantitative methods that are applicable to these classes of data fall into four broad areas:

1. Descriptive statistics include ways of visualizing data using simple numeric summaries, tables, or graph including many methods described as exploratory data analysis.
2. Classical inferential statistics (aka frequentist inference) involves confidence interval estimation and statistical hypothesis testing. The data consist of a sample of a larger population (e.g., measurements of 25 passage graves thought to be representative of all of the passage graves in England). Classical inferential statistics provide methods to estimate the dimensions of the population (all passage graves) using the sample and to place confidence intervals around that estimate. Classical inferential statistics also provides a method for testing the hypothesis that two samples were drawn from a population with the same parameters (e.g., that the dimensions of passage graves from England are identical to those from Ireland). These estimates can be made assuming that the underlying population has a normal distribution (parametric statistics), or not (non-parametric statistics).
3. Bayesian inference incorporates prior knowledge into the inferential process whereas the classical approach does not. In archaeology, Bayesian statistics has had its greatest impact in radiocarbon dating where stratigraphic relationships and closed depositional contexts provide some prior knowledge about the ages. Bayesian statistics has become more important since the widespread availability of computing since the models quickly become too complex to compute by hand.
4. Statistical learning (aka data mining or data science) is a relatively new approach to quantitative methods that has been stimulated by the availability of massive computing power and massive data sets although most of the methods were developed in the first half of the twentieth century. Statistical learning involves efforts to make a prediction about something based on a large number of variables. Supervised methods use a sample of data with known characteristics. Using discriminant analysis on samples of obsidian flakes from known sources to predict the source of obsidian artifacts found in site is an example. Unsupervised methods attempt to find groups in the data using only the data

itself. Using cluster analysis to divide graves into groups based on their contents would be an example.

All of these approaches are used in archaeology. Basic descriptions of data form an important part of the research process and the reporting of results. Those descriptions consist of tables of statistical summaries as well as graphs and charts depicting the distribution of the data. If we can treat the data as a sample (or a set of samples), statistical hypothesis testing may let us identify differences between samples or construct a confidence interval for a particular estimate. Finally, we may need ways to simplify the mass of data to identify patterns that provide insight into past culture and behavior.

One barrier to the wider use of quantitative methods in archaeology has been the availability of computer programs that provide the access to traditional and more recent methods. Spreadsheet programs such as Microsoft Excel® and LibreOffice Calc® provide basic data handling and graphics functionalities, with the ability to add an increasing number of statistical methods. Commercial software such as SPSS®, SAS®, Systat®, Stata®, Statgraphics®, and JMP®, each provide most of the necessary functionality, but can be expensive to license. Further, these comprehensive packages can be slow to add new methods, especially those for a narrow market such as archaeology.

No single text can hope to cover every method of interest to archaeologists. The goal of this book is to provide a resource that provides more hands-on guidance than is currently available. One way to provide that guidance is to standardize on software that is readily available and that provides access to all of the quantitative methods typically used by archaeologists. That software is The R Project for Statistical Computing, which has emerged over the last 20 years.

The R Project for Statistical Computing is the only comprehensive statistical analysis system that is open-source and freely available worldwide without licensing fees. It is available for Windows®, Apple®, and Linux operating systems (R Core Team 2016). R provides the same functionality as commercial programs and it includes a powerful programming language for manipulating data and coding new methods. New procedures for specialized purposes are readily added. The basic R package provides a great deal of functionality that can be extended by the availability of over 8,890 packages of specialized functions on the Comprehensive R Archive Network (CRAN) and 1,211 packages specialized for bioinformatics on Bioconductor (August 2016).

Quantitative methods in archaeology are not something that happens briefly toward the end of the long process of archaeological research from location to excavation to analysis and finally publication of the results. Just as excavation can involve long periods of tedium interrupted by discovery, so do quantitative analyses. There are blind alleys and methods that seem to provide no useful insights for a particular data set. We should not be just hunting for the occasional significant hypothesis test in order to publish and move on to the next project. Quantitative methods are a way of interacting with the data that is less tangible than handling the artifacts, but just as valuable. Our overall guide should be that a good quantitative analysis tells us something new and useful about the data, a bad one tells us something we already know, and an ugly one sends us in the wrong direction (with apologies to D. H. Thomas, 1978).

1.1 ORGANIZATION OF THE BOOK

This book consists of three parts. Part I introduces the R statistical system, reviews basic descriptive statistics (both numeric and graphical summaries), confidence intervals, and hypothesis testing. Part II expands to include multivariate methods for pattern recognition that have proven useful in archaeology. Finally, Part III provides examples of specific methods often used by archaeologists. You will learn more if you work through the book interactively, running the commands as they are listed in the book. The figures in the book show you what to expect, but they are black and white where the figures you produce may include color. Also figure titles have sometimes been eliminated from the published versions to save space.

Part I, R and Basic Statistics, provides a basic introduction to R. R allows you to create data sets, transform variables, and conduct a dizzying number of statistical analyses, but it has its own way of doing things that can be intimidating at first. Chapter 2 is a basic introduction to installing and using R. Chapters 3–9 each include a brief introduction of an important topic in R and then show how to use R to compute descriptive statistics, tabulate data, and produce charts and graphs. Often it is necessary to transform data distributions or deal with missing data and these topics are addressed next. From there, we move on to constructing confidence intervals and comparing two or more groups and to methods for measuring the association between two or more variables.

Part II, Multivariate Methods, explores statistical methods that operate on many variables simultaneously. Broadly they fall into two categories depending on the nature of the variables we are using. In Chapters 10 and 11 multiple regression and discriminant analysis assume that the variables can be divided into two groups. Explanatory (or independent) variables are used to make a prediction

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about the values of the response (or dependent) variable (or variables). These methods use some of the variables to predict the value of another variable or variables. Unsupervised multivariate techniques do not divide the variables into groups. The variables may be ways of measuring the size and shape of an artifact or the composition of an assemblage. These techniques try to find ways of displaying the data to reveal interesting patterns that we would not have seen otherwise or to combine artifacts or assemblages into groups. Principal components analysis (Chapter 12), correspondence analysis (Chapter 13), multidimensional scaling (Chapter 14), and cluster analysis (Chapter 15) are examples.

Part III, Archaeological Approaches to Data, provides introductions to specialized topics in quantitative methods as they are used in archaeology. Chapter 16 describes ways of using R to analyze the spatial distribution of sites, features, or artifacts. Chapter 17 illustrates quantitative approaches to the seriation of archaeological data, and Chapter 18 describes approaches to assemblage diversity.