Chapter 1

Tools as optimal solutions

Robin Torrence

Tool-using is a fundamental attribute of human behavior and as such deserves to be studied in its own right rather than simply as a reflection of other activities. In order to accomplish this task, archaeologists should conceive of technology as one way in which people solve problems posed both by external, environmental factors and by internal social needs. The papers in this volume attempt to achieve this goal by using insights from evolutionary theory to propose how technology can be optimized. Although there are disagreements among the authors about which currency is most appropriate and whether emphasis should be placed on the initial design of tools or how technology adapts to other aspects of behavior, the detailed case studies, which range extensively in time and space, demonstrate the enormous potential of building theory around the concept that tools are optimal solutions.

Theory of lithic studies

Tool-using has often been cited as one of the major distinctions in behavior between what is quintessentially human as opposed to animal: in other words, as one of the fundamental traits in what sets culture apart from nature. Certainly, there can be no doubt that in the contemporary world technology plays an increasingly dominant role in everyday social life. But what can be said about the function and importance of tool-using in prehistoric and pre-modern societies? Unfortunately, anthropology has had little to offer in finding answers to these questions, since it has long ignored technology and material culture except so far as descriptions have been made for their own sake and items collected to enrich museum basements. The current lack of interest has been well portrayed by Oswalt (1976, pp. 214–15) who notes that introductory texts in anthropology rarely devote more than one or two pages to the whole area of tool use. Part of the explanation for this oversight is obvious: indigenous technologies are one of the first components to change with contact. Ethnographers may feel there is little value in studying modern material culture when other traits such as social and ritual behavior appear to survive more intact.

Sadly, one potential consequence of this neglect is the further widening of the gap between the sub-disciplines of archaeology and ethnology, since for the majority of human prehistory by far the largest class of data available in the archaeological record is comprised of stone artifacts. On the other hand, archaeologists have been notoriously poor at producing their own theories for behavior and have depended largely on borrowing from anthropology and ecology, with, it must be admitted, mixed results. As a result, prehistorians are presently either simply ignoring the bulk of their evidence in an attempt to mimic ethnographic studies of subsistence, settlement, and exchange systems or worse yet are conducting their research in a theoretical vacuum. For example, most recent achievements in lithics studies involve the creation of ever more sophisticated methods for studying stone tools (e.g. use–wear and residue analysis, fracture mechanics, spatial patterning), but the results of analyses using this battery of techniques rarely contribute to our understanding of human behavior because the work is not specifically guided by questions significant to the field as a whole. In the end, both archaeology and anthropology have failed to develop a theoretical basis capable of accounting for the wide range of tool-using observed among past and present societies and have therefore failed to address one of the most important aspects of human evolution.

Tools obviously play a part in the way people adapt to their surroundings but they operate alongside and in conjunction with a number of strategies to ensure the continuity of the social group as a whole. How do tools contribute to social reproduction in societies with varying degrees of complexity and how do they relate to other forms of behavior such as exchange, ritual, or symbolic systems? How can we explain variability in the way people manufacture and use tools as well as differences in the tools themselves? Since they are fundamental for the understanding of human behavior and the origin and development of culture, such issues should be central to anthropology and archaeology. A primary aim of this book, therefore, is to refocus the interest of archaeologists and anthropologists on the study of tool-using by illustrating that theory for explaining human strategies of tool manufacture and use can and is being developed. Although none of the authors of the papers that follow would claim to have a completely satisfactory and comprehensive theory about tool-using, all have at least recognized the current need for *theoretical* approaches and have each suggested innovative ways to look at the factors conditioning tool production and use and/or the role tools play in human adaptive strategies.

What, then, are the sources of variability in prehistoric tools? When the book was first conceived, the idea which we set out to explore was in what ways and to what degree are principles derived from evolutionary theory relevant for understanding tool production, use, maintenance, and discard. In particular, the assumption that initially oriented most of these studies was that tool-using, as for many other forms of behavior, was carried out in such a way as to optimize the expenditure of time and energy. Since tools are created and employed to satisfy a perceived need and to accomplish tasks which would themselves be susceptible to selective pressures, then an optimal technology would be favored and would persist. These concepts are operationalized by means of the relationship between the costs of adopting a form of behavior and the resulting benefits which accrue from it. The strategy which produces the most favorable ratio of benefits to costs, calculated in terms of the chosen currency (e.g. time, energy), is then the one which is defined as "optimal."

It is important to note that by adopting optimization theory, the authors do not also assume that "progress" in technology is inevitable. Hayden, Boydston and Torrence make it very clear that earlier notions in which tools somehow evolved apart from their users and that the change from primitive to sophisticated, inefficient to efficient, or simple to complex, for example, is unproblematic are completely unacceptable. In contrast the position clearly taken by the contributors is that technology must be understood as a particular adaptation created by the operation of general principles of optimizing which were working within specific local conditions.

As pointed out by Jochim in the concluding chapter, there are both advantages and limitations associated with the acceptance of optimization theory. On the positive side, the approach allows a large number of different forms of behavior to be conceived of and treated in the same way. Technology, then, can be incorporated into a broader view of behavior and studied alongside and in the same way as subsistence, settlement, or social organization. We can therefore begin to understand how various human strategies operate with respect to each other to achieve desired goals rather than seeing them as totally separate entities. As a result, stone tools have the potential to make a significant contribution to the study of human behavior. This is very good news for the archaeologist and ultimately for all students of human behavior.

On the other hand, optimal behavior in one sphere may be clearly defined, but for various reasons, such as incompatibility between the goals of different forms of behavior, it may never occur. Lack of fit between predictions and reality, therefore, is not unexpected (cf. Foley 1985). Consequently, optimal models can never be tested, but are most profitably used to compare and contrast different forms of behavior, e.g. to evaluate changes in behavior through time or in different environments.

A further limitation is that evolutionary theory strictly applies only to types of behavior which have an effect on reproductive success. In other cases there is no reason to expect that selection will produce an optimal outcome. Most authors here have therefore concentrated their attention on technology used in activities which can be directly linked to reproductive success, as for example in the procurement and processing of food. Despite this limitation, Gero's study of Peruvian stone tools demonstrates that, as in economic studies in general, the basic concepts of cost/benefit maximization have proved to be applicable to an even wider set of behavior. Her work demonstrates that when compared to other forms of material culture, the investment of energy required to carry desired quantities of information does not pay off in certain circumstances. The issue of whether one should restrict optimization solely to evolutionary theory or alternatively adopt the assumption of economic choice theory – that people will always maximize some commodity (i.e. "utility") – is raised here but has not been adequately dealt with. It will certainly require greater consideration if further work along these lines is undertaken.

Although the very basic concepts underlying optimization theory in ecology are generally shared by all the contributors, it is interesting to see how many different directions in theory building and in the associated case studies have been taken by the authors. Beyond the very basic agreement that tools represent some form of optimal solution, there are major disagreements about both the choice of currency (i.e. what problems are being addressed by or otherwise influence technological behavior) and whether the function of the tool or the way technology adapts itself to external constraints should have primacy in constructing an optimal model. It is worth exploring these differences in approach and emphasis since they highlight the issues raised by the volume as a whole and also represent areas where increased attention to theory building is needed. Not surprisingly, many of the controversies raised by

Cambridge University Press
978-0-521-11528-5 - Time, Energy and Stone Tools
Edited by Robin Torrence
Excerpt
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comparing the various articles are also considered to be problematical in optimization studies in general and therefore reinforce the potential contribution of stone tool studies for the wider study of human behavior.

Currencies

Most ecological studies of human behavior have utilized energy as the currency to be optimized, although calories, time, protein, vitamins, trace elements, uncertainty, risk, and security have also been suggested as at least as important, if not more so, particularly in certain circumstances (e.g. Foley 1985, p. 229, p. 233; Winterhalder and Smith 1981; Jochim 1983; Smith 1986; Winterhalder 1986). Not surprisingly, energy is also most commonly utilized here; however, many studies do not explicitly describe their currency because, as noted below, technology is viewed more as responsive to other forms of behavior, rather than as the focus for optimizing.

Energy forms the basic currency in the studies by Camilli, Morrow and Jefferies, Jeske, and Lurie, although Camilli and Jeske mention time as also important. For all these authors technological behavior is envisaged as the outcome of adjustments made because the overall energy budget in the society is assumed to be limited. Since this is the case, if there are additional requirements placed on one aspect of behavior, such as a high demand for processing material (Hayden) or increased difficulty in gaining access to raw materials for various reasons (Morrow and Jefferies, Jeske, Lurie), then tool production, use, maintenance, and discard has to alter in order to help process the smaller amount of energy more efficiently. Efficiency in energy processing is assumed by these authors not so much because it confers advantages by increasing reproductive fitness, but because people have no other choice. Accordingly, emphasis is placed on the constraints imposed on behavior rather than on how the currency can be optimized.

The major criticism that can be directed at using energy as a currency, not only for modelling optimal technologies but for other types of behavior as well, is whether energy is sufficiently scarce in most environments as to impose selective pressures (Foley, 1985, p. 229). I also raise energy scarcity in my paper as one of the reasons for questioning its utility; in addition, I question the ability of most simple technology to process energy efficiently in the first place. In response, Torrence (1983), Myers (1986) and Boydston in this volume have suggested that time is more likely to be a limiting factor and therefore is a more appropriate currency for studying technology.

At this point it is worth considering the role of raw materials in optimization models. For Morrow and Jefferies and for Jeske, who deal specifically with the procurement of raw materials, it is the energy involved in obtaining the stone that affects the subsequent production and consumption rather than the quantity of raw material itself. Lurie also considers the "availability of raw material" to be important but her phrase implies more about the energy required in gaining access to it than simply the abundance of the stones. Only Hayden can be described as using raw material rather than energy as a currency (cf. Bamforth 1986), although his argument could easily be recast in terms of optimization of the energy invested in lithic provisioning as the limiting factor. He himself argues that technologies are devised in order to minimize expenditure of raw material because like food, stone is a rare resource in the environment. The generality of Hayden's assumption is questioned in the final summing up by Jochim and the role of raw material is considered at length in my own paper where, taking an opposing view, I prefer to see it as one of the constraining factors on behavior rather than as a currency which is itself optimized for its own sake. Whether raw material should take precedence over other currencies or should be recast in terms of energy is an unresolved issue which deserves further discussion and debate since many archaeologists share Hayden's emphasis on raw material conservation (e.g. see discussion in Edmonds 1987; Johnson and Morrow 1987).

A third currency is introduced by Gero. She stresses the importance of information, although she does not explicitly assume that all groups will necessarily optimize the amount of information processed. Instead, she focuses on the ability of stone tools to carry meaningful messages which take an active part in the process by which social relationships are negotiated, created, and maintained. Following on from perceptive observations by Wobst (1977) about the role of "style" and from Hodder's (1982) proposals that material culture plays a dynamic, causative role in social strategies, Gero examines the way lithic artifacts were used during the development of social complexity in Peru. What is especially fascinating about her article is not so much her clear demonstration of a decline in the degree of style observed on stone tools as complexity increases, but rather her hypothesis that lithic artifacts can only take a limited part in this behavior because the nature of stone tool production, a substractive technique, severely limits the complexity of forms that can be created and, by definition, the amount of information that can be encoded. In contrast, the potential of pottery for carrying complex messages is greatly enhanced because it is a plastic medium. Here we have the germ of a theory predicting not only the degree of style which we would expect to be expressed on material items, but also the optimum medium for achieving this goal. Certainly, it would be worth pursuing the relationship between information processing and stone tool technology along the lines illustrated by Gero's Peruvian study.

One approach to information which is not considered within this book concerns "uncertainty", or simply lack of information about the environment defined in both physical and social terms. Part of the reason why behavior designed to minimize uncertainty has been neglected may be that stone tools play only a minor role in this regard, although other forms of material culture can be instrumental, such as many types of facility (Torrence 1983) or special purpose tools like calendrical devices for monitoring seasonality. Nevertheless, the potential of stone tools for participating within an optimal solution to problems posed by uncertainty should ultimately be specifically considered.

A final issue that can be subsumed under the discussion of appropriate currency forms the basis of my own paper and is further illustrated by Myer's study of British Mesolithic assemblages. In general, until recently, scholars using optimization theory have assumed that selection would lead to the most efficient forms of behavior. As noted by Boydston and Jeske, for example, efficiency is defined as the ratio of inputs to outputs of time or energy. Nearly all the authors conform to established procedure and have therefore designed their predictions for optimal behavior on the types of procurement, production, etc. that would lead to the most efficient outcome, regardless of whether time or energy was the chosen currency.

Ecologists and some anthropologists have begun to question the validity of focusing solely on efficiency (e.g. Stephens and Charnov 1982; Stephens and Krebs 1986; Smith 1986; Winterhalder 1986). An alternative view expressed by myself and Myers (also cf. Edmonds 1987) and referred to by Boydston, is that forms of behavior which deal with the management of risk will be more sensitive to selective pressures and are therefore more likely to approach optimality. It is argued that risk is especially relevant when considering optimal forms of technology because simple tools have only limited ability to increase the overall efficiency of energy capture but they are essential and can operate effectively in *gaining access* to resources. Instead, I have proposed that tool-using, procurement, production, and maintenance are better understood as being one of the primary means used by humans to reduce the potential effects of risk. Furthermore, in contrast to other types of behavior, such as mobility or exchange (e.g. Weissner 1977; 1982a; 1982b; Cashdan 1985), tool-using is most effective at reducing risk which occurs because resources are only available for short periods of time. For this reason time becomes not a currency to be optimized for its own sake, but the most relevant attribute of the type of risk to which technology provides an optimal response.

There can be no doubt that all the currencies used within the context of these papers are relevant for understanding human technology because energy, time, information, uncertainty and risk comprise basic and critical components of the environment to which human behavior must adapt. As in ecology at present, the relative importance of the likely currencies is still unknown and requires detailed research. For archaeology what is unresolved at this stage is the relevance of each of these currencies for modelling variability in stone tools. Do we need to take all factors into account equally or, as some authors have argued, are some currencies simply more appropriate to modelling technology than others? Alternately, do particular environments pose unique types of potential for optimization or do different forms of selection operate in each case? Not only do we need to know more about the relationships between technology and currencies, but also the nature and role of selection within the process of evolution is still unclear. Hopefully, additional research by archaeologists along the lines initiated by these studies will contribute to these wider concerns.

A problem-solving approach

Beyond the choice of currency, there is a further fundamental disagreement among the contributors concerning how to define the "problems" that are relevant for modelling for stone tools and associated technology as optimal solutions. By technology I am referring to all the activities involved in the acquisition of raw materials as well as the manufacture, distribution or exchange, maintenance, consumption, and re-use and recycling of stone tools. Two basic approaches are represented here, but they can most profitably be seen as two ends of the same process of model-building, rather than as opposing points of view. When they are fully incorporated, I think they will satisfy Jochim's criticism that stones should not be "isolated from the evidence of prehistoric human behavior" and should be "embedded" within "simultaneous analyses of other classes of behavior." Nevertheless, I do not feel that all stages of modelling should necessarily occur "simultaneously," but rather that some should take preference over others. Until we are fully satisfied that our basic principles are correct, we will not make further progress in understanding how and why humans design, create, and use stone tools.

A fundamental principle that must not be overlooked is the fact that tools are not ends in themselves and do not dictate the behavior of their makers and consumers. On the contrary, they are employed by humans to accomplish some function. In modelling the outcome of decisions, we must therefore assume that people choose the technology that will best suit their needs. Consequently, the first step in building an optimal model of stone tool technology must be to identify which among the problems faced by the social group in question can be solved by adopting some form of technology. Such problems may be generated from external causes such as environmental factors (e.g. the abundance of resources or the risk and uncertainty associated with their distribution in space and time) or internal social variables such as competition for prestige or the need for communication.

Having isolated the ways in which tools can be solutions, the next task is to predict the optimal technology. This stage of modelling is considered in detail in the papers in the latter half of the book, i.e. Torrence, Boydston, Myers and Gero. It is not as easy as it sounds. Since people pursue a wide range of goals simultaneously but are ultimately limited in the degree to which all can be achieved, priorities must be established and compromises reached between all the various aims. The result is a complex set of strategies in which the importance of technology will be established by the degree to which goals conflict and the resulting level of priority assigned to the problem which technology plays a part in solving. In other words, the more serious or "important" the problem, the more technology will be used and emphasized. Nevertheless, regardless of their potential to achieve a goal, tools will not be used unless their function is considered necessary. Optimal solutions are therefore not equivalent to the simple maximization of a currency.

The complex juggling of priorities which goes on in every cultural setting means that we should not isolate technology from the wider behavioral setting in which it operates. Jochim stresses this point when he suggests that stone tools be "embedded" in other studies of subsistence, settlement, etc. Although he is undoubtedly correct to refocus the attention of lithics specialists away from tools as the center of all behavior and place them alongside other strategies, I do not think we should then assume that all goals pursued by individuals can be treated as equivalent or that all problems faced are equally serious. In some cases technology will be essential to the successful completion of desired strategies and in others it will play a minor role. For example, it may be crucial to acquire certain raw materials in order to produce particular critical tools or to invest much time and energy in making and maintaining tools which are deemed to be important. As a result, other forms of behavior will have to adapt to technological needs. For instance, as I have suggested in my paper, Eskimos live off stored food at certain times of the year in order to "gear up" equipment which is absolutely essential for their survival. In many other settings, however, technology will have to adapt to other needs. The outcome will always be complex, but in order to understand variability in technology, we need to find ways to predict its relative importance in relation to other activities for each particular setting.

All these complex decisions are carried out within a physical and social environment which obviously determines the costs of certain behavior and may set limits on the time and energy budgets. Technology like other forms of behavior, will therefore be further adjusted to fit the specific constraints of each particular situation. For example, in some environments raw materials are scarce, whereas in others they are not. Groups with high mobility can more easily embed procurement of raw materials in other activities than sedentary groups. All these factors combined with the initial tool requirements will shape the eventual outcome in terms of the means used to minimize the expenditure of raw materials within all stages from production through to discard and reuse. The papers in the first part of the book focus on the ways technology must respond to external constraints posed by the distribution of raw materials or limits in the energy budget and make predictions based on this aspect of the decision making process. These are the papers by Hayden, Camilli, Morrow and Jefferies, Jeske, Lurie.

Obviously, the technology utilized by a group is the outcome of decisions concerning firstly the initial design of the tools and secondly the way technology must fit in and adapt to the overall goals set by people and the constraints under which they inevitably operate. Both aspects are important to the construction of a final optimal model for a technology. Future attempts at constructing predictions should attack both aspects rather than focus on one or the other as is presently the case, possibly because the task is so large and difficult. The papers in this volume indicate that already we have many of the appropriate concepts at hand. In order to counter Jochim's criticism that we have an incomplete understanding of stone tools, we simply need to incorporate all these approaches into a wider view of the total process of problem-solving.

Priorities for future research

Regardless of the importance of examining both the role of technology within the entire range of problem-solving undertaken by past individuals and the ultimate constraints on behavior, the former approach must initially take precedence in making models. After all, it is ultimately the needs that define what aspects of the physical and social environment will be relevant. For example, it may be the case that the demand for tools is so low or that the requirement for raw materials is so flexible that the local scarcity of stone resources is irrelevant to the way technology operates. One would not be able to judge the importance of raw material before knowing the technological requirements in the first place.

Rather than begin with the ultimate limits and then work backward to what might be a range of adaptations, surely it would make more sense to begin with identifying the problems faced, suggest a range of plausible solutions, then choose the optimal technology from among these, on the basis of what is possible given both internal constraints due to tasks with higher priorities and the external, ultimate limits. Another way to think of this is that one should move from general concepts of the role of technology within adaptive strategies to the specific, local conditions within which the basic principles are operationalized. Although theory building should inevitably proceed along all these lines, as is the case in this volume, the most urgent need at the moment is for a better understanding of how technology can be designed to solve problems rather than how it fits into wider behavior or how it adapts to external constraints.

These latter approaches have already received a great deal of attention by archaeologists and perhaps are now in danger of leading us astray and obscuring the importance of studying human technology for its own sake as one of the key elements of social and cultural behavior. The assumption that lies behind most current thinking seems to be that stone tools are completely adaptable and therefore reflect all sorts of behavior, except their function. Certainly contributing to this view are the methodological difficulties faced when attempting to reconstruct past tool uses, but archaeologists appear to be ignoring the fact that tools were made to be used (not necessarily just for utilitarian purposes). Another factor that has also clouded the issue is the emphasis placed on reconstructing the mobility patterns of hunter-gatherers. Since this has become such an important aim in archaeology, lithics experts have focused on the aspects of technology that could adapt to the need for various patterns of mobility (cf. Camilli, Lurie). Yet, one can question the importance of mobility in creating the design of tools relative to the function of the implement or even to third or fourth factors with even higher orders of priority. Mobility patterns will contribute to the context in which tools must be acquired and used, but we should be more specific about its direct effects on the choice of tools in the first case.

Once again it is the desire to develop better methodologies for making inferences about past behavior that has dominated research on stone tools. Tools are currently being studied largely in order to be used to answer questions about other aspects of behavior. Obviously, the need for theory linking artifacts to behavioral strategies is especially crucial to archaeology since all studies of dynamic phenomena are necessarily dependent on inference, which is based on just this type of theory. The significance of these attempts for what Binford (1983) has called middle range theory has not been lost on the contributors. Most of the papers here, and in particular the extremely insightful study by Camilli, make very important contributions to the methodology by pointing to new directions where stone tools can be used to infer about other types of behavior.

Methods are undoubtedly important to archaeology, but I feel that in emphasizing them to the degree that is fashionable at present, we may lose sight of the potential of stone tool studies for contributing to the development of general theories about human behavior. For this reason, it becomes all that much more important for further research to direct more attention to the wider issues raised by the studies represented here. What are the roles which technology plays in human adaptive strategies? How and why do these vary in specific settings? Under what conditions does technology take precedence over other strategies and when does it play a lesser role? What is the relevant currency for modelling technology and does this differ for other aspects of behavior? To what extent do external constraints limit technological behavior? By taking up the challenge of these very general and difficult questions, the study of lithics could play a much more fundamental part in the general debates about the nature of human behavior than has traditionally been the case. It is hoped that the attempts represented here will stimulate a wider audience of archaeologists to direct their efforts to the *understanding* rather than simply to the description, of one of the more neglected facets of human evolution.

Applications

Theories rarely develop in isolation from concrete facts and such is the case with the work presented here. All the authors have analysed their ideas in the context of specific archaeological cases. One of the real strengths of this collection must be the wide variety of the settings represented. The broad range in the spatial and temporal scales of the analyses serves to highlight the generality of using optimality as a way to approach stone tools. Beginning with Hayden who applies his ideas on a world-wide scale and who also considers the entire history of stone tool-using, the temporal but not the spatial scale is decreased in Torrence's paper which focuses on a universal phenomenon, but one that occurs during a much smaller length of time. We then move gradually down in scale to the regional studies of Boydston, Myers, and Jochim and then finally to the site as the major focus of study in the work by Camilli, Morrow and Jefferies, Jeske, and Lurie. Like lithic studies in general, however, the majority concentrate on hunter-gatherer adaptations, although the papers by Hayden, Camilli, and Torrence address the changes that occur with the adoption of agriculture and Gero provides a valuable insight into the changing roles of stone tools with the development of social complexity.

To conclude the volume, Michael Jochim was asked to provide an evaluation of the potential of stone tools studies in light of the work presented here. Since he is not a lithics expert himself, but does have an interest in using evolutionary theory to understand the development of human behavior (e.g. Jochim 1981; 1983), his insights about the general relevance of this work are especially valuable. Although Jochim has pinpointed some real difficulties with the concepts as they stand at present and especially with operationalizing them, he shares the view of the authors that general theory relevant to understanding human behavior is essential for the study of stone tools. Much more hard thinking, carefully controlled experimental work, and detailed archaeological applications are certainly required to fully implement the insights of these studies. Before proceeding further, however, I must stress that we need not limit ourselves to considering only how stone tools can inform us about aspects of behavior. We could also significantly increase our knowledge about human behavior if we also recognized and attempted to understand the active role that tools and technology play in human strategies.

Chapter 2

From chopper to celt: the evolution of resharpening techniques

Brian Hayden

Among hunter-gatherers important constraints exist on the procurement of lithic materials. When changes in one sector of the lithic system increase procurement costs beyond acceptable limits, compensatory change in other aspects of the system become necessary. The two most variable parts of the system in this regard involve (1) the quantity of materials processed and (2) the use-lives of tools as determined by resharpening techniques. Largely because cutting requirements increased over time and also because of advances in wood, hunting, and shelter technology, the resharpening mode changed from hard-hammer percussion, to soft-hammer percussion, to the secondary resharpening of flakes, to pressure resharpening, and finally to edge-grinding. This model posits that as the conservation of lithic raw material becomes an increasingly important consideration, reduction and resharpening techniques capable of conserving material to greater degrees will be adopted despite higher energy costs in obtaining and preparing special raw materials and in the manufacturing of tools.

Introduction

The identification of resharpening techniques has been used for well over a century as an important criterion in the classification of major stages in cultural evolution. By "resharpening technique" I refer to the rejuvenation of dulled edges to prolong the use-life of the tool, rather than the production of the original edge except where manufacturing of that edge is intended to "set it up" for future resharpenings. In the classic European Stone Age sequence, billet techniques were added to hard-hammer percussion resharpening of core tools. This was followed by an emphasis on resharpening flake tools, then by the introduction of pressure flaking for resharpening tools, and finally by edge-grinding. In many areas of the world, changes over time in resharpening techniques continue to be extremely useful for situating assemblages in broad developmental schemes. For instance, if an assemblage contains pressure-flaking or edge-grinding, it is unlikely to be more than 20,000 years old no matter where it is found. Similarly, a1ssemblages with billet worked bifaces are unlikely to be more than a million years old.

Surprisingly, even after almost two decades of processual archaeology, no one has attempted to explain why major changes in resharpening techniques should take place. It seems to have been largely assumed, tacitly or otherwise, that the various resharpening modes changed as a natural effect of "progress" or in the same manner as stylistic elements. For instance, the Acheulian biface is sometimes viewed in terms of its aesthetic superiority to the Oldowan chopper (Childe 1942, p. 29; Clark 1967, p. 35). However, I would argue that there are few aspects of lithic assemblages which can be as directly tied to considerations of energy expenditure and selection mechansims as resharpening techniques. Viewing them in terms of stylistic variation or general notions of progress are probably the least useful explanatory approaches.

The mere fact that changes in resharpening techniques took place over widespread areas, that they persisted for great lengths of time, and that they became increasingly labor intensive in most areas, should be a strong indication that they reflected adaptive responses to powerful material constraints. In this paper I propose an explanation for major shifts that have occurred in resharpening modes over the past two million years. Resharpening modes can be categorized into five strategies, which I will argue are adaptive under different conditions: (1) hard-hammer percussion of core tools; (2) soft-hammer or billet resharpening of core tools; (3) use of resharpened flake and blade tools; (4) use of pressure-flaking; and (5) edge-grinding. A sixth strategy might consist of not sharpening an original edge at all. While the following model can certainly accommodate this strategy, it will not be the main focus of this article.

In some respects, the resharpening strategies that I will be dealing with resemble the "organization" of assemblages that lithic analysts have begun to investigate in recent years (Goodyear 1982; Torrence 1983; Shott 1986; Johnson and Morrow 1987). However, I prefer the term, "strategy" because it more directly implies a unifying principle that is not static but responds to changes in conditions, and is more intuitively explanatory in nature. I do not purport to deal with overall assemblage organization in this study, but only those factors that most directly affect resharpening choices.

Because the material constraints varied from group to group and from time to time, and because several options were often available for dealing with particular problems, there was probably no universal, rigid pattern of succession in the strategies to be discussed. Yet there are some very broad similarities. To a large extent, the following discussions will deal with long-term trends and general evolution – those behaviors which finally emerge as being most adaptive after the vagaries of tradition, poorly-considered short-term solutions, deceptive environmental conditions, and options with poor future potentials have been eliminated. On the other hand, it is also possible that some of the relationships to be discussed may also operate in a strong manner in the context of very specific, short-term adaptations. It should be emphasized that particularly in the latter strategies, several different resharpening modes could be combined in a single assemblage to deal with the differing characteristics of resource exploitation. In the following discussion, I will only discuss tools which were modified to rejuvenate their cutting edges. I will not deal with objects which were pressure-flaked or ground merely to achieve desired shapes, such as ritual or status items or perhaps some arrow points. I do not pretend to provide a model for all classes of stone tools.

The model

Before outlining the details of an explanatory model, it is worth emphasizing that in contrast to traditional interpretations, I view *most* (but not all) tool morphologies as the result of resharpening rather than any manufacturing process in which an artisan had a preconceived form in mind, sat down to make a biface, or a scraper, and then tucked it away for vague future uses. I have rejected this latter point of view largely as a result of my own and other archaeologists' work with contemporary lithic-using groups such as the Australian Aboriginals, the New Guinea Highlanders, and the Maya (Hayden 1979a; Hayden and Nelson 1981; White 1968, p. 513; 1969). Individuals who continue to make stone tools in traditional ways simply do not have normative ideas of morphology when they make most tools. Whether expedient or curated, tools are manufactured largely because individuals are faced both with a task to perform and with the necessity of creating an edge which will accomplish it. The problem, then, is simply to determine what kind of raw material and edge modification will achieve this aim.

In this interactive situation, the details of the resharpening strategy are the major determinants of ultimate tool morphology. This is not to say that morphological patterning is lacking from these assemblages, only that explaining these patterns is a much more complicated affair than the normative view of culture leads archaeologists to believe. I must also emphasize that while the manufacture of pressure-flaked and edge-ground tools or other hafted tools does, to some extent, require the existence of "mental templates" related to the "finished" object, these templates are geared not to the form of an object *per se*, but to the need for solid hafting or for successive resharpenings. That is, such objects are only shaped initially in order to make them serviceable for hafting and initial use *and* to set them up for further resharpenings. In this sense they are not really "finished" at all until they are discarded. Such tools *may* only appear toward the end of the Pleistocene and in environments where it is adaptive to "gear up" for an entire season's work, as among the Inuit (Binford 1979; 1980). However, Acheulian and Mousterian bifaces probably represent early examples of such artifacts. Some aspects of the following model of changes in resharpening strategies have been presented at least in part elsewhere (Hayden 1977a; 1981, p. 520).

Effort and lithic resource procurement

Concisely stated, the model I employ posits that as the conservation of lithic raw material becomes an increasingly important consideration, reduction and resharpening techniques capable of conserving material to greater degrees will be adopted despite higher energy costs in obtaining and preparing special raw materials and in the manufacturing of tools. Because suitable raw materials for making stone tools are not ubiquitous in the environment, there is a definite and usually substantial cost associated with their systematic procurement. In many respects, prehistorians can treat lithic resources like plant food resources (Winterhalder and Smith 1981) since they are necessary for existence, occur in localized patches, and involve (1) search costs, (2) procurement costs, and (3) processing costs. Absolute limits on the amount of lithic material that individuals can carry with them (probably not more than one to two kilograms per family), combined with steady consumption, means that stone materials have to be replenished at regular intervals and are in regular demand.

Although lithic resources may occur in a few areas where food is also found in quantity, in most areas the reliable sources of useful raw material are probably rare enough so that travel to these limited places presents a substantial cost in terms of time, effort, and scheduling. From my experience, I would be surprised if

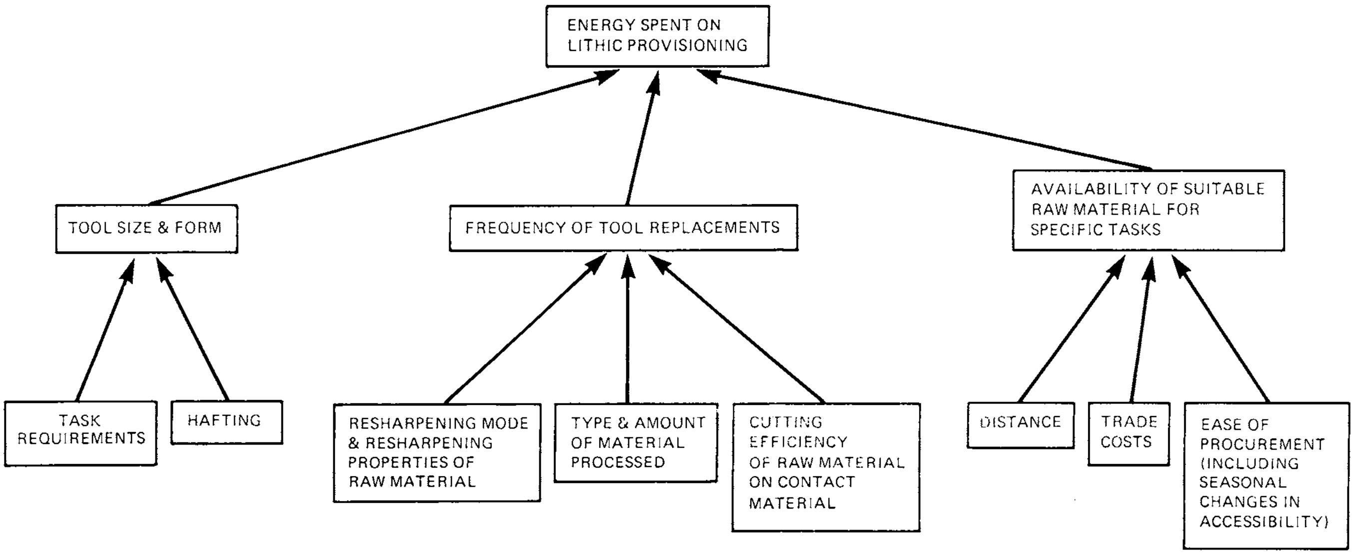

Fig. 2.1. Factors affecting the amount of energy spent on lithic provisioning

the area normally utilized by most hunter-gatherers included more than two or three sources of abundant, high quality lithic material, although other high quality sources with limited quantities and involving high search and procurement costs might occur. Optimal exploitation of food and lithic resources at specific sites might co-occur a few times during the year; however, this could not be expected to be the case for the majority of sites. For most locations, if individuals or groups were to run out of raw material, replenishing lithic resources would involve a significant extra expenditure in time and effort and would create scheduling conflicts. As Lee (1969, p. 60) has emphasized, hunter-gatherers view unnecessary subsistence travel as undesirable, and for good reason. One way of minimizing the effort incurred by inconvenient procurement trips would be to store or cache raw materials at regularly used campsites. This corresponds to Binford's (1979; 1980) logistically organized resource strategy. However, this is only a partial solution to the problem and is primarily useful in emergencies. If this strategy constituted the major way of coping with the risk of running short of lithic material, individuals with significantly increased cutting requirements would find they were spending inordinate amounts of time and energy replenishing their caches.

Because procurement of lithic rescources constitutes a major cost in terms of time and effort during most of the year, there are strong reasons to expect that individuals and groups would have attempted to minimize unnecessary procurement costs. Groups which did not do so might well find that their diet suffered accordingly when they needed to make special trips to replenish stone materials; in famine years they might find that the resulting scheduling conflicts and extra energy expenditure of such trips could have disastrous results. Groups following such non-optimal strategies would have strong natural selection pressures brought upon them to change their behavior. Thus, there are important reasons for assuming that lithic procurement costs were kept relatively low among hunter-gatherers.

There are three factors which directly determine how much effort must be expended in the yearly provisioning of lithic resources: (1) the size and shape of tools; (2) the availability of suitable raw materials for specific tasks; and (3) the frequency of tool replacements (fig. 2.1).

Tool size and shape

Variation in tool size can affect the frequency with which lithic material must be procured. The smaller the tools and the more blade-like they are, the more economically a given quantity of raw material can be used (Sheets and Muto 1972; Byrne 1980). However, the nature of most tasks usually imposes relatively narrow ranges on size. These limits can be overcome to a considerable extent by the use of blade forms and/or hafting. With hafting, for example, a small chipped stone adze can perform many of the tasks of a core chopping implement. Reduction in tool size and the use of blades or hafting might help decrease raw material procurement costs, but such strategies are relatively limited in their capacity to offset increasing consumption of stone when compared to other factors, such as resharpening techniques.

Availability of suitable raw material

The availability of suitable raw material for specific uses is affected by a number of factors (fig. 2.1) which will be discussed here only in summary fashion since my main concern is with resharpening strategies. It must be emphasized from the outset, however, that raw material availability may vary according to the specific task. For instance, vein quartz pebbles which may be perfectly suitable for butchering small or moderate-sized game, are often found widely dispersed over landscapes used by hunter-gatherers and are therefore easily accessible. On the other hand, such material would be of little use in heavy woodworking and in the butchering of very large animals. Suitable material for these tasks might only be found in a single location in the same landscape. Thus, each task may be associated with a separate strategy for minimizing the effort involved in lithic provisioning, and several different strategies might be represented in a single assemblage. Of course, in the case of generalized industries with only a few multi-functional tools, the number of strategies used would be minimal.

The most obvious factor influencing the availability of suitable raw material for a given task would be the distance to the source. Distance is a measure of the time and effort costs of acquiring raw material. In cases where barriers prevent direct procurement by users, raw materials would have to be obtained via exchange or trade. In such cases, availability would be measured in terms of trade costs. Substantial barriers to raw material access are probably more typical of sedentary communities since they have reduced foraging ranges and more limited movements away from residences (Rolland 1981, p. 31, p. 34).

A factor which is often overlooked in assessing the availability of suitable raw materials is difficulty of procurement. Although suitable material might have been found in a number of different locations, the very sporadic occurrence at these locations of acceptable quality and appropriately sized pieces probably resulted in excessive search or even excavation costs. Thus, as with food resources, it was probably more efficient only to exploit sources where suitable quality *and quantity* of raw material could be obtained rapidly and easily on a regular basis. This does not imply that individuals would have ignored good pieces of raw material if encountered by chance, or that less desirable sources would be ignored when need and opportunity dictated. Similarly, most foragers do not ignore unexpected encounters with game, and they shift to less cost-efficient foods when necessary. The main point is that for the regular, systematic, dependable lithic requirements of hunter-gatherers, sub-optimal lithic sources would not be efficient or reliable. Consequently, heavy use or dependence on sub-optimal sources would increase lithic procurement costs above acceptable limits.

One other factor affecting procurement costs in temperate areas, which is often overlooked by prehistorians, is the seasonal variation of ground conditions and water levels. In areas with significant snow cover, for instance, procurement of raw materials may become prohibitively expensive during the winter months, thereby requiring stock-piling or careful conservation of raw materials for much of the year (Rolland 1981). Similarly, seasonal flooding may render cobble beds in streams inaccessible, as among metate makers in Guatemala (Hayden and Nelson 1981). Thus seasonal availability probably influences the strategies used for minimizing effort spent on lithic provisioning during each season.

Tool replacement

There are several factors which strongly affect the frequency of tool replacement (fig. 2.1). The edge efficiency and rate of edge dulling of lithic materials used in specific contact situations is one of the most obvious factors. For example flint edges last far longer in meat cutting or woodworking than calcareous chert edges. Another extremely important factor in determining the frequency of tool replacement is the frequency and amount of work required, that is, the types and amounts of materials being processed for making tools, facilities, and as food. This is far too often overlooked by prehistorians who tend to assume that the quantity of material processed by hunter-gatherers has changed relatively little during the Pleistocene and Holocene. In fact, there is ample evidence to indicate that the quantity of organic materials processed has changed over time by many orders of magnitude with substantial consequences for the lithic provisioning system (Hayden 1981).

Finally, and most importantly, the type of resharpening used on tools has a dramatic effect on the frequency of tool replacement. Depending on the technique employed, a tool may last a few minutes, or several generations. Not all lithic raw materials can be satisfactorily resharpened using the same techniques. Consequently, the resharpening properties of the available raw materials also affect the frequencies of tool replacements. In most areas, materials suitable for the full range of resharpening techniques could probably be procured either directly, or indirectly by trade, if the advantage of doing so was perceived as great enough.

Variable interactions

In the above model, factors affecting the effort expended on lithic provisioning have been presented separately. However, there are several additional important features of the model: (1) it is interactive, or systemic, and (2) the ranges of values for many of the factors differ considerably. When I refer to the interactive nature of the model, I mean that changes in one aspect resulting in unacceptable increases in energy spent on lithic provisioning must be offset by changes in other aspects which will return energy expenditures to acceptable levels. Failure to accomplish this can have severe survival consequences in times of resource stress. Thus, where there is insufficient raw material for whatever reason, and assuming a minimal number of cutting/processing operations are necessary for survival, the energy spent on lithic provisioning can be kept within reasonable limits by either (1) reducing the size of stone tools, (2) obtaining more cutting edge from raw material, (3) decreasing the frequency of tool replacements (e.g. Walker 1978), (4) using a combination of techniques, or (5) using non-lithic substitutes such as bone, shell, or bamboo. These will not be pursued here. Similarly, where the amount of organic material processed increases the consumption of tools and thus the energy spent on lithic provisioning, such increases can be offset by augmenting availability through trade, by decreasing tool size, by using more efficient resharpening strategies, or by using raw materials with more efficient cutting properties. However, if a particular resharpening technique becomes more efficient, only certain raw materials might be suitable, and this in turn affects the availability of appropriate raw materials. Thus, the interactive characteristics of the model can be relatively complex and a number of alternate solutions to given cost increases can be envisioned (fig. 2.1).

In reality, however, it appears that some of the factors considered have relatively limited ranges of acceptable values. For instance, the difference between the minimal and maximal cutting efficiency of lithic materials likely to be used in a given task is probably not great. When the efficiency of lithic materials drops below a certain point, they cease to be used and efforts are directed toward procuring more acceptable raw materials. Alternatively, the task might simply be dropped from the cultural repertory if it