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THE CHALLENGE OF 'TECHNOLOGICAL CHOICES' FOR MATERIALS SCIENCE APPROACHES IN ARCHAEOLOGY*

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Recently several anthropological and sociological studies have interpreted technologies as cultural choices that are determined as much by local perceptions and the social context as any material constraints or purely functional criteria. Using the example of ceramic technology we consider how materials science studies can contribute to and benefit from this understanding of technology as a social construct. Although we acknowledge some potential difficulties, it is our contention that both materials scientists and archaeologists have gained much and have much to gain by cooperating together to study ancient technologies, and that the concept of 'technological choices' can facilitate a wider consideration of the factors shaping technological developments.

KEYWORDS: ANTHROPOLOGY, ETHNOARCHAEOLOGY, MATERIALS SCIENCE, CERAMICS, KILNS, TECHNOLOGICAL CHOICES, *CHAÎNE OPÉRATOIRE*

What would you choose given the choice, indeed do we have the choice to choose, or can we be choosy about the choice too? (Rowan Atkinson)

INTRODUCTION

One of the most significant changes within the social sciences has been the recognition of the active role that material culture plays in the construction and reproduction of social relations and cultural values (Bourdieu 1977; Appadurai 1986; Hodder 1986; Miller 1987). A king's crown is not just a royal emblem; its production and use is the direct result of royal power and authority and it also provides a major focus for the social recognition and reproduction of that power. Within this approach, several anthropologists (Ingold 1988 and 1990; Lemonnier 1986, 1992 and 1993; Pfaffenberger 1988 and 1992) and sociologists (Bijker *et al.* 1987; Law 1991; Latour 1991 and 1996) have emphasized how technologies can be analysed as cultural choices which depend as much on the social, economic and ideological setting as any functional criteria. Archaeologists have also been involved in this revitalization of technological studies (e.g., Dobres and Hoffman 1994 and 1999; van der Leeuw 1993; Schiffer and Skibo 1987 and 1997; Schiffer 1992; Schlanger and Sinclair 1990; Stark 1998); indeed, the whole approach owes much to the pioneering work of anthropologically-informed archaeologists, such as Leroi-Gourhan (1964 and 1965) and Lechtman (1977, 1979 and 1984). How does this recognition of the social significance of material culture and technology affect materials science approaches to technological studies?

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This introduction and the three papers that follow it (Livingtone-Smith; Sillar; Pool) consider technological choices in ceramic production. The papers were first presented at the World Archaeological Congress 4 in Cape Town, South Africa, within a session on 'Technological choices in ceramic production' organized by Michael Tite and Bill Sillar. This conference session, and the three papers presented here, aimed to discuss how best to integrate the study of functional and cultural factors affecting technological choices. This introduction is intended to provide a general overview to the concept of technological choices, to introduce some of the relevant literature, and to discuss the contribution that materials science analysis has made and can make in the future to the study of technological choice in pottery production. It also attempts to point to further archaeological examples to complement the more ethnographic orientation in the papers by Livingstone Smith and Sillar.

ONE HUNDRED AND ONE WAYS TO SKIN A CAT

'There's more than one way to skin a cat.' This statement, which is still a fairly common way of saying 'there's more than one way of achieving your goal', always seems to beg the question 'Why would you want to skin a cat in the first place?' This is the essence of investigating 'technological choices', questioning what the actor wanted to achieve, the techniques s/he chose to use, and the consequences of these choices. Like a dedicated member of the Royal Society for the Prevention of Cruelty to Animals, we should not only ask why the cat butcher used a cleaver to flail the animal, but what made him want to peel off its skin in the first place, and what were the consequences of this act? Because cat skinning remains (we believe) a relatively unusual activity, it would be reasonably easy for us to identify what decisions were being made and question how these decisions reflect the actor's social, economic, and ideological understanding. This becomes significantly harder when we choose to investigate agricultural production, aeroplane design, or pottery making, because the necessity of these activities seems to us so obvious, and the mechanics of them appear to be largely determined by material constraints. However, the material world enables many forms of interaction, and there is a great degree of creativity and flexibility in how people achieve their material ends. The physical properties of matter provide a vast range of technical possibilities, only a few of which are ever realized. If nothing else, the large number of ethnographic reports on pottery production and firing should allow us to appreciate the near-infinite variety of materials and techniques that can be used in the craft. If we could bring the same astonished innocence as our outraged animal lover to questioning the decisions involved in relatively common technologies, such as pottery making, there would be much to be gained.

IDENTIFYING CHOICES

The production of every pot requires the potter to make a series of 'choices' selecting from a range of possible raw materials, tools, energy sources, and techniques. In this sense every pot is the unique result of a series of choices between alternative techniques. As archaeologists investigating past technologies it is our job both to elucidate how the technology worked and how it fitted into the wider cultural context. One of the best ways to do this is to reconstruct the production process looking at each step in the operational sequence and questioning the choice of the particular techniques and tools used (cf. van der Leeuw 1984). This sequence of steps has been described as a *chaîne opératoire* (Leroi-Gourhan 1964 and 1965; Cresswell 1972) which involves the manipulation of both tools and raw materials within local cultural perceptions about appropriate ways of working the materials. Cresswell (1976 and 1990, 46) defined the *chaîne opératoire* as 'a series of technological operations which transforms a raw material into a usable product'. Nonetheless, this analysis will not be sufficient if it is confined to a linear analysis of how a particular object was made. It is only through a consideration of the overall context that affects the availability of resources as well as the valuation of alternative techniques that we will be able to explain why particular technological choices were made and what material and social effects they had. This overall context spans the environmental and technological constraints, the economic and subsistence base, the social and political organization, and the ideology or belief systems of the people making the choices.

There are five main areas of 'choice' within any technology:
(1) raw materials from which the pottery was made (e.g., clay, temper, pigments, water—these may include the products or by-products of earlier activities such as the choice of grog as a temper or sawdust as a firing fuel);
(2) tools used to shape the raw materials (e.g., picks, spades, settling tanks, scrapers, wheels, workshop structures, kilns, carts—by far the most important tool is the potter's hands);
(3) energy sources used to transform the raw materials and power the tools (e.g., animal or water power to grind clays, sun to dry vessels, fuels to fire them—by far the most important source of power is the potter's body which collects materials, shapes the vessels, powers the wheel, loads the kiln, etc.);
(4) techniques used to orchestrate the raw materials, tools, and energy to achieve a particular goal (e.g., to collect and process the clay, to form the pot, to surface treat, decorate, and fire the vessel—again, note that most of these techniques are enacted through the potter's body and his/her manipulation of the tools);
(5) the sequence (or *chaîne operatoire*) in which these acts are linked together to transform raw materials into consumable products—this includes the order of the techniques, the frequency with which they are repeated, and the locations at which they take place (e.g., is the clay pounded and sieved before adding a temper to it, does the potter do this each day, once a week, or twice a year, and to what extent is the clay processed at source, at the potter's house or at a specialized clay processing area?).

These areas of choice are each influenced both by their associated properties and performance characteristics and by a large range of social, economic, and ideological factors that shape the cultural perception of what options are available. The succeeding three papers all look at choices within ceramic production: Livingstone Smith looks at factors affecting the choice of raw materials and processing techniques in Cameroon, Sillar looks at the choice of fuel in the Andes, and Pool looks at the choice of firing techniques in Mexico. What is clear from each of these papers is that it is impossible to account for any of these choices without combining a consideration of both the material properties and the cultural context.

FACTORS AFFECTING TECHNOLOGICAL CHOICES

Schiffer and Skibo (1997) have proposed a theoretical framework in which variability and change in production technology are explained in terms of the constraints imposed by the performance characteristics required for each activity within the overall life cycle, or behavioural chain, of an artefact (i.e., procurement of raw materials, manufacture, distribution, use, reuse, discard) (cf. Schiffer 1975). The identification of these performance characteristics is achieved by considering how the overall situational context (i.e., environmental, technological, economic, social, political, and ideological) impinges on the relevant activities. Thus, for the choice of raw materials, tools, energy sources, and techniques, we consider, first, how the situational context impinges *directly* on this choice and, second, how it impinges *indirectly* via the context of production, the distribution, and the use. Using these concepts we have prepared a diagram (Fig. 1) that summarizes some of the most important interrelationships that can influence the technological choices made in pottery production. No diagram of this type can ever be 'complete', but our intention is to represent the complex series of factors that influence pottery technology in order to provide a framework within which the different factors can be identified and, thus, considered systematically.

A starting point for this diagram is the production (i.e., procurement and manufacturing) stage of the overall life cycle of the pottery, which includes the raw materials, tools, and energy sources together with the techniques and sequence used in procuring, processing, forming, surface treatment, and firing (Rice 1987; Rye 1981). Also relevant is the context of production, particularly the mode of pottery production (e.g., household, workshop, or factory) and extent of craft specialization (Peacock 1982; Costin 1991; Rice 1981 and 1991; Earle 1981). Although the production process may be the point of entry for our analysis, like the proverbial chicken and egg, pottery making has no single identifiable starting point. In order to make a pot, the potter must have some conception of its practical and social function, or at least a potential market for the vessel, as this provides a focus for choosing the raw materials and techniques to be used. For example, as discussed below, the expected use greatly influences the performance characteristics and properties required of the vessel and is a further crucial factor affecting the technological choices.

In the context of *direct* influences, we start by considering the more material influences, such as the natural environment, technological knowledge, and the economic system. These influence technological choice, first, via the availability of raw materials, tools, energy sources, and techniques, and, second, via the properties and performance characteristics that the options chosen possess in procuring, processing, forming, surface treatment, and firing. For example, the plasticity, and the drying and shrinkage rates, of available clays greatly influences the choice of processing techniques. A very plastic clay prone to substantial shrinkage may require the addition of tempering materials, whereas a less plastic clay may need to be refined or have wet dung added to it to improve its plasticity. However, these choices are co-dependent on the choice of forming and firing methods. Potters forming their vessels on the wheel usually prefer fine plastic pastes, a coarse fabric being both irritating to the potter's hands and less responsive to the forming technique. But, in addition to drying more slowly and shrinking more, finer fabrics tend to be less tolerant of sudden changes in the firing temperature and benefit from the steadier (controlled) firing that a kiln can offer. This is one of the reasons why there is a frequent (but not universal) relationship between the use of the wheel in pottery forming and the use of kilns to fire the pottery. A slow, controlled temperature rise may also be desirable if the pots have an awkward form, such as sculptural pieces that may have great variation in wall thickness and areas of stress such as angles and joins. Kilns also provide the potential for consistent high quality surface colours.

Thus each technological choice is co-dependent on other technological choices which go together to form a particular *chaîne opératoire* that produces a pottery vessel with specific properties and performance characteristics. However, it is important not to draw a hard line between these more material influences and the cultural influences. The two spheres are so

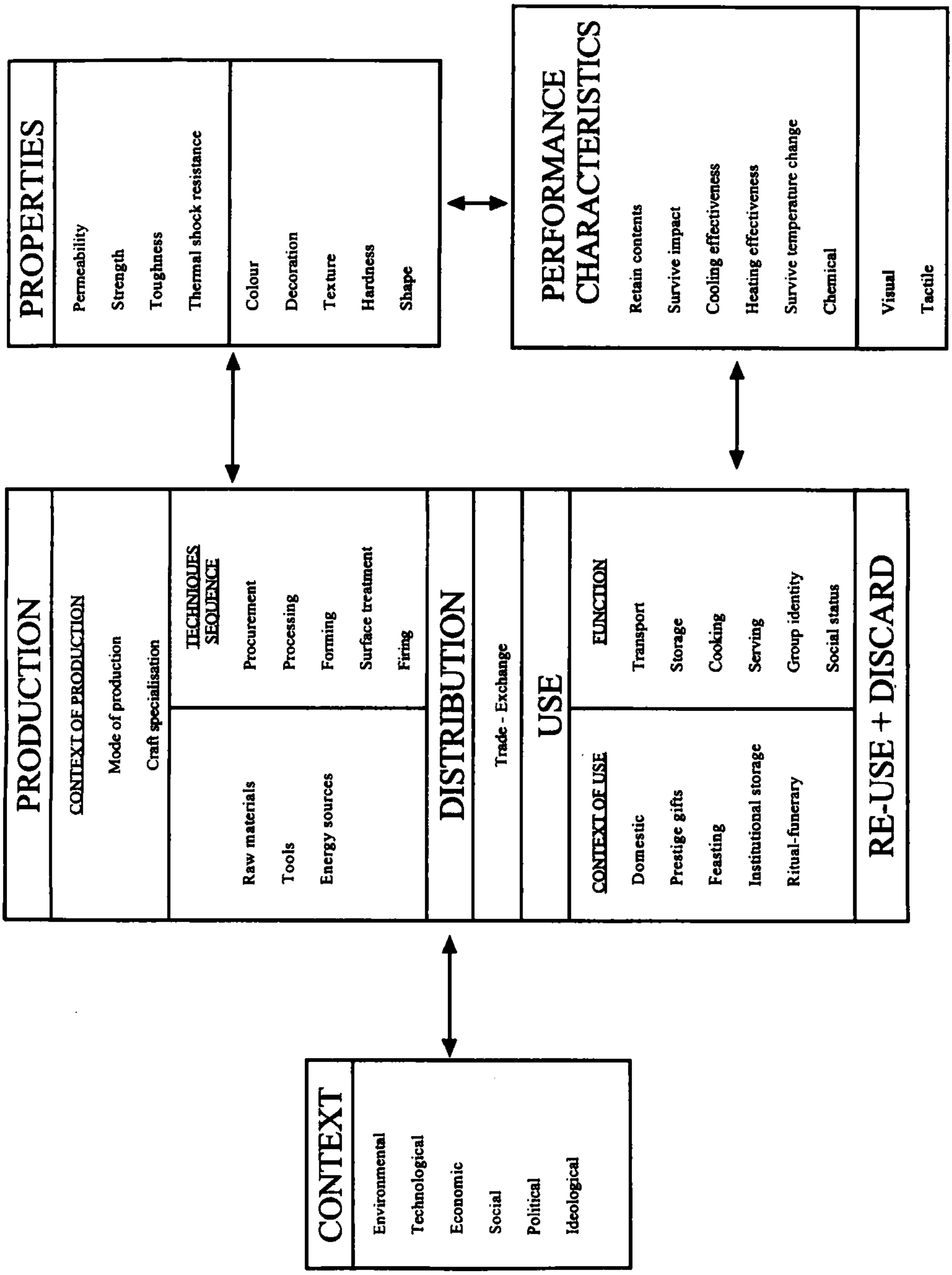

Figure 1 *Diagram summarizing the more important interrelationships affecting the technological choices made in pottery production.*

thoroughly interdependent that it is impossible to consider one without the other (van der Leeuw 1991 and 1993; Schiffer and Skibo 1997). Thus, the availability of raw materials is dependent on the local environment and the technical ability of the potter to collect and process them, but it also depends on the potter's perception of the clay as a suitable material for pottery making and the politics of who controls the resource. Similarly, choice of both temper and forming method may have some cultural significance or express some aspect of group identity or social status. For example, Jones (1997) discusses how the choice of clay and temper in the Orkneys during the Neolithic period could have had ancestral and ideological significance (cf. Sillar 1997). Similarly, in ethnoarchaeological studies in the southern Cameroons, close links have been established between the methods of forming used by the potters and their ethnolinguistic groupings (Gosselain and Livingstone Smith 1995). More generally, as discussed by Livingstone Smith (this issue), other culturally-based situational factors that can influence technological choices include the social status of the potter, the social network within which potters learn their craft, and the settlement pattern (i.e., concentration of population and location of uninhabited zones).

In the context of *indirect* influences, we start by considering the contribution from the mode of pottery production and the extent of craft specialization. Here, multiple material and cultural influences are relevant. Thus, the organization of pottery production may depend partly on raw materials and technical skills but it is at least as dependent on the economic framework and social organization of the society. For example, coil construction, in which the pottery vessel is progressively built up over a period of time, is ideally suited to part-time household production, in that it can be taken up or left off as other demands allow (Arnold 1985). In contrast, throwing on a wheel, if it is to achieve the significantly higher production rate of which it is capable, requires working for substantial and continuous periods. Therefore, wheel throwing is normally associated with workshop or factory production, frequently involving full-time specialists. But, this relationship between techniques and particular forms of economic or socio-political organization is a complex one that cannot be assumed and may be seen as another sphere within which technological choices are made. Who performs the techniques, where, when, and under what relations of production? Roman Samian ware production was ideally suited to factory-type organization (using settling tanks, complex moulds, the wheel, and sophisticated kilns), but Gaulish Samian wares were produced in relatively small workshops probably using free labour, whereas the Arretine wares were produced in large industrial complexes sometimes using up to 60 slave labourers (Peacock 1982). The economic context defines certain parameters, but within this many different ways of organizing production often coexist. Thus, these technological choices are both a product of the economic context and one of the ways in which the socio-economic system is created and reproduced.

Next, in the context of *indirect* influences, we need to consider how the intended method of distribution and use of the pottery influence the technological choices. For instance, the choice of transport and distribution methods may determine some technological choices in the production of the vessels (e.g., the shape and strength of the vessels may be selected to facilitate efficient packing). Similarly, the scale of trade and exchange can also influence technological choice via its own influence on the mode of production, large-scale inter-regional trade typically requiring factory or at least workshop production and, therefore, favouring, for example, wheel throwing.

In considering the use of the pottery, we think that it is helpful to distinguish between the different contexts of use and the intended or actual functions of the pottery within these contexts, both of which are dependent on the overall situational context. In addition to domestic use, the contexts of use may include the distribution of prestige gifts, public feasting, institutional or political storage of commodities, or use in ritual and funerary contexts. Then, within these contexts, the pottery can be used for transport, storage, cooking, and serving, as well as for conveying information on social status and group identity. The corresponding performance characteristics, that affect a pot's suitability for different uses, include the mechanical, thermal, and, sometimes, chemical characteristics together with visual and tactile characteristics.

The mechanical and thermal performance characteristics required for transport, storage, cooking, and serving include the ability of the vessels to retain their contents and to survive impact; heating effectiveness and the ability of cooking pots to survive rapid changes in temperature; and the cooling effectiveness of water storage vessels. The relevant physical properties are permeability, strength, toughness, and thermal shock resistance. Thus, permeability, which greatly affects the heating and cooling effectiveness of the vessel, can be modified through the choice of pottery paste, surface treatment, and firing method, and these choices influence the suitability of the vessel for cooking or water storage. Similarly, thermal shock resistance determines the ability of vessels to survive rapid changes in temperature, and the choice of temper (i.e., the quantity, particle size, and type) for cooking vessels may be influenced by these material constraints.

Visual and tactile performance characteristics are similarly influenced both by the intended context of the pottery use, that is, whether it is intended as a prestige gift or for use in a more mundane domestic context, and by its intended function, that is, for storage, food preparation or serving, or to convey social status. The required visual and tactile characteristics determine the choice of surface colour and decoration, texture and hardness, and vessel shape, all of which can influence technological choice and may have significance and meaning that is understood by those using or observing the use of the vessel. For instance, the Inka state served maize beer from highly characteristic large 'aryballus' forms with a restricted range of geometric designs on the front. The presentation of beer in these pots, used to reward the state work force and to make ritual libations, must have been well understood by the Inka's subjects. Similarly, technological distinctions that at first appear purely 'functional' may also be utilized for socio-political purposes. For instance, it seems highly likely that the distinctive styles of Roman amphora used for different produce (such as wine, olives, and fish sauce, etc.) (Peacock and Williams 1986) must have been recognized by people managing large villas and estates and used to identify and catalogue the contents of their stores.

In considering the social and ideological factors affecting technological choices we have been influenced by the concept of 'technological style' developed by Lechtman (1977). Central to this concept is the idea that 'style' resides in every stage of a technological process, that is, in both production and use. The resulting 'technological style', therefore, reflects the conscious and unconscious elements that together influence the technological choices. In addition, as with morphological and decorative styles, 'technological style' can serve a cultural function by conveying information on, for example, social status and group identity (Stark 1998). Perhaps the most obvious example of this is in the choice of food preparation and cooking techniques where we are all aware that different ways of preparing food express cultural identities that we invest with enormous emotional and sentimental meaning. Thus, the Romanization of Britain is characterized by the production and importation of a wide range of new pottery forms (amphorae, mortaria, wine cups, flat platters, etc.), all of which relate to the preparation and serving of a more 'Mediterranean' style of food and drink consumption. Similarly, as discussed above, the choice of temper and forming method may serve a social or cultural function (Jones

1997; Gosselain and Livingstone Smith 1995). Furthermore, it should be remembered that the choices of materials and techniques are embedded within and, therefore, may be dependent on wider cultural values and ideological concepts that stretch well beyond any single technology (Lechtman 1984; Sillar 1996).

In summary, it is apparent that every technological activity is the result of practical possibilities being reviewed and selected through cultural criteria. Indeed, any attempt on our part to define a hard boundary between the practical and symbolic contents of a technology would largely be an expression of our own representations and cultural values. Ingold (1999) has highlighted the division that we frequently make between technology and art, pointing out that this rather unhelpful opposition is a relatively recent 'enlightenment' distinction between the way objects work to alter the world physically and the role of objects to communicate meaning. 'Technology' tends to be seen as necessary and determined whereas 'art' is represented as a spontaneous expression of personal freedom. But, like the equally unproductive separation of function and style, this split between technology and art effectively denies the creativity and meaning inherent within technology. 'Technology is society made durable' (Latour 1991) and people's 'World Views' are expressed and reproduced through their day-to-day activities in the production, distribution, use, and discard of materials. Material objects and technologies are 'concrete expressions and embodiments of human thoughts and ideas' (Childe 1956, 1).

Therefore, our research will be most successful if we integrate the study of the functional or practical reasons for technological choices with an appreciation of the cultural construction of knowledge that is necessarily at the heart of all human activities. We must remember that the fundamental source of every production process, which should also be the focus of our analysis, is the potters themselves; they are the active agents who make the technological choices and perform the technical acts. It is the potter's previous experience and perception of what is technically possible and socially desirable that shapes the technology, albeit within the potential of the local environment and the cultural context. It must also be emphasized that pottery technology is firmly embedded within the wider environmental, technological, economic, social, political, and ideological contexts and practices. Therefore, in the next two sections, we will consider in more detail, first, who makes the choice and in particular the issue of 'individual' versus 'cultural choice' and, second, the embeddedness of pottery technology within the overall situational context, beyond the immediate production, distribution, and use of the pottery itself.

WHO CHOOSES?

Who makes 'technological choices'? The word choice suggests some agency. Potential alternative techniques were rejected in order to favour the particular techniques that were chosen. But where does the agency lie? In some cases we may be referring to an individual making this selection. But, archaeologists are rarely able to identify a specific individual who is responsible; rather we are looking at how a particular group or even a whole society adopted one technique where others could have been used. It may be possible to show that this was a true 'choice', in that other techniques that were known about and being used in the same area at the same time were rejected in favour of a specific choice. But the term 'technological choice' is frequently used when looking at the social and environmental context of a technological tradition or the long-term development of the material culture in a specific region. Within this framework 'technological choice' usually refers to archaeologists or anthropologists trying to account for the particularities of a localized tradition or variations in the products within that tradition. Although there was the abstract potential of many alternative techniques, few if any of these alternatives may have been actively considered by any one individual potter.

There is a vital dynamic between 'individual choices', the innovative way in which people can alter and extend existing material practices, and 'cultural choices', the underlying technological traditions from which a substantial portion of each individual's experience and knowledge is derived. The longer-term development of 'technological traditions' emerges out of the active interplay between the conservative force of 'cultural choices' and the innovative nature of 'individual choice'. This is similar to Gidden's (1984) discussion of the dynamic relationship between social structures and the active agency of the knowing subject. All technological choices are dependent on wider social and economic practices that affect the availability and knowledge of materials, tools, energy sources, and techniques. There are innumerable ways of achieving almost any end result; for instance, a round-based cooking pot can be made using techniques such as paddle and anvil, coiling, moulding, or throwing, with an enormous potential for variation within each of these gross techniques (van der Leeuw 1993). Yet, the potter making the vessel is rarely aware of all these potential techniques; each artisan uses a limited number, the majority of which will be the techniques 'traditionally' used and learnt from other potters. Van der Leeuw *et al.* (1991) suggest that such traditions of pottery making are shaped by the potter's 'unquestioned assumptions' about what techniques should be used, that is, by the 'technological style' within which the potters are living and working. Where innovation does take place, the innovator frequently draws on materials, tools, and techniques used in one sphere of technical activities in order to adapt them for another purpose (Sillar 1996). This is perhaps most evident within the dynamic force of two distinct traditions meeting; for instance, Vilcabamba, the refuge of the last Inkas who held out against the Spanish, was recognized for the mixture of Inka architecture and Hispanic-style roofing tiles. But, it can be seen equally as the more mundane event of a potter picking up his or her soupspoon and using it to shape a cooking pot. The conservative force of 'cultural choices' can be understood by looking at how a technology is embedded within wider practices—that is, the degree of interdependence between a particular 'technological choice' and related areas of production and consumption as well as the social relations it helps to define and maintain. A consideration of agency in technological developments will help us to think through the process of innovation and the adoption of new technologies (van der Leeuw and Torrence 1989) as well as the social, economic, and political effect of particular technological choices (Dobres and Hoffman 1999). Technological choices are never made in relation to a single isolated technology. All techniques can be understood as choices that are made within the wider context of local perceptions or 'representations' (Lemonnier 1986, 1992, and 1993). We need to consider the cultural background that accounts for technological choices. How and why particular choices were made, how they were maintained and developed, and what repercussions particular choices have on other areas of society.

An extreme argument from this perspective might claim that two people could never come up with the same technology and that there would always be some differences in the selection of raw materials, tools, energy sources, and techniques, as well as the particular construction sequence, that would differentiate them. Indeed this is precisely what allows art historians to differentiate between the work of a particular 'master' and the copy made by a 'forger' (cf. Hill and Gunn 1977). Within archaeology it will not usually be possible, or desirable, to take our analysis to this extreme. But when we state that paddle and anvil pottery is made in many different communities throughout the world, we have overlooked a wide range of differences in the mixing of clays, form of the tools, and performance of the technique in order to categorize all of our examples as being within a single genre (Cort *et al.* 1997). Archaeological pottery typologies frequently highlight precisely these subtle differences in the surface treatment, form, and fabric of pottery vessels in order to differentiate different pottery groups that are most commonly interpreted as different cultural groups or different pottery production centres. What the 'technological choices' perspective provides is a framework through which we can think about what these differences may have meant in terms of the perception and intentions of the potters and the social and political climate that they were working in. One example of this can be seen in the various ways in which the Inka State affected local technologies in the Mantaro valley (Costin *et al.* 1989). Rather than seeing artefact typologies as the fortuitous, but rather arbitrary, markers of cultural difference, we can ask what precisely is the nature of the difference between two artefact groups and how might we account for these differences in terms of behaviour and cultural understanding.

For most artisans, it may seem that their choices of materials and techniques were made in response to functional necessities resulting from environmental, technological, and economic factors. It is often only with the benefit of hindsight or cultural distance that we can recognize where alternative techniques could have been used, and it is always easier to identify different cultural concepts and social influences on past technologies if it can be shown that the technological choice was a social or technical failure (Lemonnier 1992 and 1993). But, one of the benefits of the comparative approach in archaeology and anthropology is precisely that it makes us aware of alternative 'choices'. Without this knowledge of other periods, other regions, and other technologies we might assume (from our own ethnocentric perspective) that there were only one or two functional possibilities available. It is up to us as researchers to develop a wide knowledge of alternative techniques in order to analyse what technological choices were made, discuss what functional, environmental, and cultural factors may have influenced these choices, and consider what the immediate effects and the longer-term consequences of these choices were. There can be no simple formulation for the identification of the particular mixture of environmental, physical, economic, social, and ideological influences that affect technological choices. Each case study will require a careful consideration of 'universals' such as the mechanical properties of clay and cultural specific studies of the particular social context in which materials were understood and manipulated—the embedded nature of the technological choices.

EMBEDDED TECHNOLOGIES

General considerations

In his paper (this issue), Sillar suggests that technological traditions are partly maintained because of the way that specific technologies are embedded within wider technical and social practices—that is, the degree of interdependence between a particular 'technological choice' and the other activities it is related to. Ideally, all technological studies would consider how particular technological choices were reproduced and maintained over the longer term; this will depend on how the particular choices of raw materials, tools, energy sources, and techniques fit into the wider society and how access to these resources was justified and made sustainable. Izumi Shimada (1999) has argued that the importance of metal production within the Sicán culture on the coast of Peru led to such a demand for wood charcoal that the craftpeople involved in the less highly valued production of pottery were forced to look to llama dung as an alternative fuel. Shimada's work helps to demonstrate the importance of cultural values in shaping technological choices that affect a variety of crafts and the environment. Alexander Livingstone Smith's paper (this issue) shows how clay selection and processing is embedded within the social relations and ethnic affiliations of the potters in Cameroon, and highlights how the choice of raw materials and techniques can reflect and reproduce social relations. The recent volume on *The archaeology of social boundaries* edited by Miriam Stark (1998) is a significant advance in this area. In this book the authors investigate variations in the technologies associated with diverse artefacts (pottery, personal ornaments, buildings, site structures, etc.) and consider a wide range of practical, economic, and social processes that may affect the distribution of these technological variations. Similarly, large-scale processes, such as the imposition of state taxes, may have a major effect on people's access to materials, the space where they can work, or the profitability of their activities, all of which may lead to innovations in the technology. François Sigaut (1994) highlights how milling technology in Classical Greece developed rapidly in association with the gradual removal of this activity from the relatively small-scale, conservative, environment of the domestic sphere when it was given to slaves to perform. The result was the development through saddle querns and rotary mills to watermills. The control of resources, techniques, locations, and the timing of production activities can all be used to maintain or transform social relations and mark social differences (e.g., gender, age, kinship, or class). The recent volume on *The social dynamics of technology: practice, politics and world views* edited by Marcia-Anne Dobres and Christopher Hoffman (1999) is particularly significant for its careful consideration of the social and political ramifications of technological choices (cf. Law 1991).

From a European perspective it seems surprising that in the Mesoamerican world the wheel was used in art and on models or toys, but that it was never developed as a central tool of production or transport technology. However, we should be equally inquisitive about why, and in what circumstances, the wheel was developed in Eurasia. In this example it is clear that we are dealing with an issue of different cultural perceptions, the materials and the basic ideas being available in both areas. Therefore, we must look at both the social and the environmental contexts to understand why this technical possibility was or was not developed in each area, possible influences being the presence or absence of draft animals, and different attitudes to the organization of labour. In other situations two very different technological traditions may be maintained together for a long period, as happened with the production of black-burnished pottery during the Roman period in Britain (Peacock 1982). The black-burnished pottery tradition originated in Dorset as a handmade, open fired product of the pre-Roman Iron age; this production expanded during the period of Roman occupation with pots being shipped throughout most of England, Wales, and southern Scotland. Another group of potters working on the north Kentish coast imitated the forms and the black-burnished appearance of this pottery, but these potters used the wheel to make their pottery and fired it in kilns. These two industries coexisted for a long period, and in fact it was the Dorset potters with their relatively 'simple' production technology that lasted longest, maintaining their production to the end of the fourth century AD. The continuity of any industry depends on maintaining access to raw materials, tools, energy sources, and techniques, and, as long as these remain part of the current representations and ideals of both the producers and the consumers, there is no reason why such access should not continue for a long period. Pool (this issue) discusses a similar situation in Veracruz, Mexico, where he considers a range of explanations as to why kiln firings and open firings should continue to coexist in what he calls a 'balanced polymorphism'. Pool uses 'threshold values' to discuss the Mexican potters' choice between these alternative firing technologies. It is significant that these 'threshold values' are defined as much by cultural values as material constraints. For instance, the importance of pottery surface colour may be highly significant in one society, or for one area of pottery production, but only a minimal consideration in another, and it will be this which shapes the development of the pottery technology. One of the important conclusions of Pool's paper is that, although these two firing traditions have coexisted for some 1700 years, he suggests that the social and economic values that maintain these technologies today are very different to the conditions which first saw the development of kilns in the area.

Pottery firing—bonfire of vanities

'Kilns probably were an early response to three needs of potters: more control over product, higher firing temperatures, and more economical use of fuel' (Rice 1987, 153). When discussing technology we frequently end up discussing generalizations rather than specifics. Generalizations are a necessary part of academic discourse, but we must reach these through a consideration of the small-scale variations that are at the heart of technological choices. In fact, most early kilns could not have achieved significantly higher temperatures than open firings (Gosselain 1992, 244); kiln firings, particularly using small kilns, do not necessarily save fuel (Arnold 1991); nor do kilns necessarily result in a higher success rate (Sillar this issue). Like the domestication of toxic yams, one wonders why kilns were ever developed? The end result has been beneficial, but what inspired it? The most frequent answer is that kilns may permit a more steady temperature rise and fall, and a skilful potter can maintain a more homogenous temperature throughout the pottery load (Gosselain 1992). But, the use of a kiln is not just a technical change; it is a difference in perception of the firing process itself, in particular the concept that the pots should be kept separate from the fuel. While this may relate to changing interests in the products of pottery firing (possibly sponsored by elite members of the society), it may also depend on changes in other technologies such as food production (e.g., the use of ovens) or changes in the resources available (e.g., fuel supply). There can be no single explanation for kiln use; the reason for the innovation and its continuing use will be somewhat different in each setting. Neither can the effects of the introduction of kiln firing be predicted. In China the continuing development of kiln technology and ceramic paste led to the development of very high temperature firings and the creation of translucent porcelains, but in Mexico, prior to the Spanish conquest, the focus of pottery production remained with relatively low fired earthenware pottery in complex sculptural forms and with elaborate decoration using oxides. Explanations for these differences in technological developments will not be found by focusing on the capabilities of the potters, but rather by considering the role that pottery played in these different societies.

The degree of permanence of the kiln structure is of great significance for archaeological recovery, but it is also a technological choice of some significance. Kiln structures are put under great strain from the expansion and contraction they experience during firing; this means that potters have to balance the advantages of permanence over the constraints of their materials and their construction methods (with the potential catastrophe of kiln collapse). This may mean that potters can either adopt a momentary/adaptive attitude, re-making the kiln, or parts of the kiln, structure for each firing, or investing the time and energy into acquiring the knowledge and skill necessary to build a more permanent structure that can take this repeated strain. Vivian Swan

(1984) has provided one of the most thorough and thoughtful studies of ancient firing technology in her study of Romano-British kiln structures, where she has documented the location and date of over a thousand kiln structures and created a detailed and locally relevant typology. For instance, Swan (1984, 113–14) suggests that the Romano-British single-chamber and single-flued kilns of Suffolk and Essex, which have no evidence of a raised floor, were derived from the previous pit-clamp firing structures used in the area. Here we see the description of a particular local firing method that reflects the local way in which technology is understood and reproduced. Swan's interpretation was only possible due to a detailed analysis of hundreds of excavation reports and the fact that this allowed her to develop a comparative approach to understanding local and regional developments in kiln structures in relation to major social factors such as the role of the Roman army. If we wish to interpret the firing arrangements used in the past from the material properties of the firing structures (or from pottery sherds) we will need to develop just such good localized understandings of technological variations in the firing structures and their performance characteristics.

Firing technology is related to the availability of fuel; indeed, fuel is frequently the potter's most important recurring cost. For this reason pottery firing must be considered in the context of other activities such as agricultural production and woodland management. For instance, in Romano-British pottery making we know of rudimentary kilns built into the edge of fields (e.g., at Mucking: Jones and Rodwell 1973). These may have been built by itinerant or part-time potters using the hedge cuttings (in late winter/early spring) or wheat and barley stalks (late summer) and firing at a time which avoids the danger of setting fire to the mature crops in the nearby field. The design of a kiln partly depends on the fuel being used and the fuels suitable for one type of kiln (or open firing technique) may not be suitable for another. While chopped wood can be used in open firings, it has particular benefits in ease of loading and predictability when it is used as a fuel for kiln firings. The Romano-British industry at Alice Holt used kiln structures with a small opening to their fire box which probably reflects the use of well-managed coppice woodland to provide straight twigs/poles (Lyne and Jefferies 1979, 12–19). If we remember that browsing animals must be kept out of coppice woodlands, we can appreciate how the management of land and animals implied by this moderately sized, pottery-making industry may have had far reaching repercussions. Thus, as Sillar argues (this issue), the technological choices in firing methods depend on the social and economic context of the potter and are related to many other activities beyond the immediate manufacture and use of the vessels. How else can we investigate the strong interdependence between pottery, bronze, and charcoal production during the British Bronze Age? This interdependence between different activities is a major challenge to the traditional structure of analytical practices within archaeology. If we wish to analyse the embeddedness of past technologies we need overcome the separation caused by different specialists analysing pottery, stone, wood, pollen, geology, and so on, and re-incorporate this information within a more holistic approach that recognizes the essential interaction between different production and consumption activities.

MEASUREMENT AND MEANING: MATERIALS SCIENCES APPROACHES IN ARCHAEOLOGY

It is our belief that a critical consideration of the cultural nature of technological choices will lead to a more exciting phase of technological analysis in archaeology. Indeed, this approach has already been responsible for a renewed interest in technological studies. But, the incorporation of stricter materials science approaches to technological analysis within a cultural approach to the study of technology requires a conscious effort (Tite 1988). Thus, the question that we now want to address is how to ensure that materials science analyses can make the maximum impact within a more cultural approach to the study of technology.

Materials science, together with experimental replication, has already made a major contribution to our understanding of pottery production technology. We now have a very considerable body of data, for a wide range of periods and regions, on what raw materials were used, how they were processed, how the pottery was formed and surface treated, and the firing arrangements. Materials science has also provided more universally applicable information on the properties both of the raw materials, tools, and energy sources used to make the pottery and of the finished vessel, and, hence, on the performance characteristics during manufacture and use.

A significant proportion of such research has been undertaken by physical scientists, including materials scientists, geologists, mineralogists, chemists, and physicists. As a result of a combination of training and funding practices, physical scientists often have only a limited understanding of archaeology and its underlying aims. Therefore, such studies often stop at the reconstruction stage avoiding any interpretation in terms of the cultural reasons for particular technological choices. Indeed, the challenge and satisfaction of the extraction, description, and quantification of such information are often the main driving forces for these researchers who frequently find the more ambivalent and inconclusive interpretations offered by the social sciences frustratingly irresolute and non-quantifiable. Others have searched for the comfort of quantifiable and predictable regularities within the cultural world or they have used the principles of evolutionary biology to account for any social differences. Even so, the data that have been obtained through physical science studies into past pottery technologies are extremely valuable and they provide the basis for future syntheses of technological innovation and change and greatly widen our understanding of ceramic material properties.

In addition, during the past 15–20 years, a significant number of Ph.D. theses, that have included pottery technology studies, have been completed either by people whose primary training was in archaeology but who have acquired considerable expertise in materials science or vice versa. Many of these 'archaeological scientists' have then continued, particularly in the UK and USA, to undertake research into pottery production technology that clearly crosses the boundary between interpretative archaeology and materials science.

A possible criticism of some of the past research undertaken by these 'archaeological scientists' is that the interpretations of the technology have tended to be limited to functional or material explanations. For example, in the USA, considerable emphasis has been given to the investigation of the choice of temper used in cooking vessels and the extent to which shell and limestone tempers were deliberately chosen in order to maximize thermal shock resistance (Steponaitis 1984; Bronitsky and Hamer 1986; Feathers 1989; Hoard *et al.* 1995). However, this research was initiated at a time when processual archaeology was dominant. As a result, the roles of environmental, technological, and economic factors in determining the choice of temper have been emphasized to the almost complete neglect of cultural factors.

Further, the mechanical, thermal, and chemical performance characteristics which are studied by materials science methods involve material-material interactions which are subject to essentially universally applicable laws. In contrast, the 'technological style' or those performance characteristics associated with the cultural framework involve culture-material interactions that are not subject to similarly universal laws and, thus, tend to be culturally specific (Schiffer 1996). Thus, we can measure the mechanical strength of a pottery sherd, predict the thermal properties of using rounded quartz as a temper, or use a Munsell Colour Chart to characterize the surface colour of a decorated pot. But, it is very much more difficult to identify to what extent shell temper was chosen for its physical/chemical performance characteristics and to what extent cultural factors, such as the cultural valuation of shell, influenced the choice. Similarly, it is more difficult to identify the social relations constructed through the use of pottery in food preparation, or the cultural meaning of the decoration on a serving vessel. Materials science data are, therefore, inherently more suited to providing an explanation for technological choice based on material or functional factors. However, these data also provide a baseline against which the role of cultural factors can be considered.

As we have argued above, cultural values play a significant role in determining why one technological choice in pottery production was made rather than another. Therefore, in order to understand fully the technological choices that were made in the past we need to consider the full trajectory of the *chaîne opératoire* for the production of the object within its overall life cycle or behavioural chain. This includes a critical consideration of how the production, use, reuse, discard, and burial of the object will alter its properties (e.g., the colour, mechanical strength, and chemical make-up) and how natural and social formation processes affect the total assemblage. But, there is also a need to go beyond specific artefacts to consider the overall environmental, technological, economic, social, and ideological context within which the technological choices were made.

For the future, therefore, we need to build on the existing achievements of materials science analyses in the study of technological choice in pottery production by trying to encourage more 'archaeological scientists' to give greater consideration to the social and ideological factors that influence technological choice. First, this could be achieved via the 'archaeological science' Ph.D. research that forms a crucial element in materials science studies of pottery production technologies, the recently completed Ph.D. thesis by Jones (1997), referred to above, being an example of this broader based approach. Second, large-scale, long-term research excavations have an important role to play in that they can provide both the funding and the meeting ground for the in-depth collaboration between researchers with the range of different expertise that can help in fully understanding past technological choice.

One case study that illustrates the potential of a collaboration in the context of a research excavation is the investigation of the firing procedures used in the production of Formative period pottery from Batan Grande, in northern Peru, dating from the period 800 BC to AD 400 (Shimada *et al.* 1994). A wide variety of techniques was used to analyse both the kiln structures and the pottery (e.g., petrographic analysis, neutron activation analysis, Mössbauer spectroscopy, radiocarbon dating) to determine the type and source of raw materials, the temperatures and atmospheric conditions of the firing, and to identify the fuels and date the period of kiln use. These data were then interpreted with reference to detailed observation and analysis of Formative period kilns, pottery products, wasters, and ash deposits, together with a consideration of the wider environmental context and in relation to the contemporary archaeological sites in the area. Experimental firings using both reconstructed and original kilns as well as the observation of ethnographic pottery production were used to identify the ancient pottery forming and firing sequence. This work demonstrated the highly sophisticated control of the firing atmosphere and temperature that was possible within these small kilns and demonstrated that the structures had been reused for a succession of different firings. It was also possible to demonstrate a technical division of labour with the most sophisticated firing structures being used for the more complex decorative and sculptural pieces, while somewhat larger structures which did not facilitate such a complete control of the firing conditions were used for larger jars and storage pots. This detailed collaborative research has permitted the investigators to develop further questions about how the ceramic technology relates to wider social and economic practices such as the organization of the fuel supply, the relationship between pottery making and metallurgical technologies, and the longer-term development of these technologies in relation to changing political aspirations (Shimada 1999).

Other examples of large-scale excavations providing the meeting ground for collaborative research include, first, the excavations of the Eighteenth Dynasty capital of Amenophis IV at Amarna in Middle Egypt; this was previously excavated by Flinders Petrie late last century and excavations have continued at the site up to the present day. Recently, Nicholson (1995) initiated the excavation of one of the glass factories at Amarna, originally identified by Petrie (1894). The collaborative research generated by this project has significantly extended our understanding of the interrelationship between glass, faience, and pottery production at Amarna (Nicholson and Jackson 1998; Shortland 1998). A second example is the excavation of the glass and pottery production areas at the Islamic city of Raqqa in Syria (Henderson 1996). In this case, an extensive collaborative programme of post-excavation studies, involving both archaeological and materials science analyses, is about to start.

CONCLUSIONS

In summary, we have emphasized the importance of investigating technological choices and integrating the study of functional or practical reasons with an understanding of the social and ideological context in which these choices are made. Further, it is crucial to consider how the technology under study was embedded within wider environmental, technological, economic, social, and ideological practices. In assessing the various factors influencing technological choices, the input from materials science is clearly of prime importance. First, materials science provides the methodology for reconstructing past technologies. Second, it allows us to assess the extent to which physical and chemical performance characteristics have influenced past technological choices and, thus, provides a baseline against which the role of cultural factors can be considered.

For the future, we believe that the maximum encouragement should be given both to 'archaeological science' research into past technologies and collaborative work within the context of large-scale, long-term research excavations. At the same time 'archaeological scientists' should be encouraged to give greater consideration to the social and ideological factors that influence technological choice. We are hopeful that the current interest in technological choices will provide a suitable framework through which anthropological approaches can be incorporated within materials science analysis, a valuable focus for fruitful collaboration, and, ultimately, an even more rewarding experience for all the researchers involved.

In the quotation at the start of this paper Rowan Atkinson asks '. . .can we be choosy about the choice?' Our answer would be 'No'! As archaeologists interested in past cultures, not merely materials scientists interested in the properties of ancient materials, it is essential that we consider the cultural context of technology. A consideration of 'technological choices' provides a framework for that analysis.

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