13. Archaeology, GIS, and the time dimension: an overview

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13.1 Introduction

Geographic information systems (GIS) have considerable potential for extending the study of spatial processes in archaeology. However, the present structure of GIS is currently atemporal and consequently only able to deal with spatial phenomena in a single instant of time. If past events and processes cannot be linked to each other, or to the present, we cannot hope effectively to model trends in the past, nor understand fully the nature of dynamic process. This is a problem which has been recognised within the GIS community and a considerable degree of research is currently being directed toward the operational development of a temporal dimension in GIS (cf. Langran 1989a, 1989b, forthcoming; Barrera & Al-Taha 1990; Barerra *et al.* 1990). Because archaeologists are beginning to make considerable use of GIS (cf. Kvamme 1986a, 1986b, 1989; Peregrine 1988; Wansleeben 1988; Allen *et al.* 1990), and because archaeologists have a significant interest in cultural change over time, the search for a temporal GIS is of considerable importance.

In this paper I introduce some aspects of time, archaeology and GIS, beginning with a consideration of the concept of time in general [13.2]. I then survey the role of time as a paradigm in archaeology and geography [13.3], and then go on to examine some of the issues involved in establishing an operational temporal GIS [13.4].

13.2 The concept of time

In order to integrate a temporal dimension in an operational GIS setting, it is first necessary to consider the nature of time and the relationship it has with space. Time is a difficult concept which has exercised philosophers, scientists and others for millennia (Whitrow 1980; Flood & Lockwood 1988; Newton-Smith 1988). Several centuries ago, St. Augustine said that he knew what time was, provided that no-one asked him. If anyone asked, he did not know, and had to pray for enlightenment. Earlier, Aristotle had offered a somewhat circular definition of time when he suggested that it was the number of motion, and that motion was defined by changes of location in space over time. An equally tautological definition survives in the Concise Oxford Dictionary; time is 'duration', and 'duration' is a continuance of time.

Like St. Augustine, we have an intuitive knowledge of time, but it is difficult to specify exactly what this is. As Newton-Smith (1988:23) observes, ostension is no help: we cannot point to time and space, because within our experience they do not have a discernible physical existence independent of temporal entities or spatial objects.

There are two fundamental philosophical positions on the question of time and space. Leibnitz (1646–1716), one of the last universal scholars, contributed much of the foundation on which much current temporal research is being undertaken. He believed that time was a set of temporal items, seen as instants or moments, and that space was a set of spatial items, i.e. locations. Time and space were therefore similar in that each were ordered systems, one of events and processes in time, the other of bodies and their locational relationships in space.

Leibnitz' view is a reductionist one; whatever their ultimate origins, we can arrive at an understanding of time and space by restricting our attention to events and bodies. Thus time can be recognised by the occurrence of change, because time is a collection of events. Similarly, motion in time can only be ascertained by reference to the motion of bodies in relation to other bodies. Time and space are therefore reduced to the things that occupy time and space.

Subsequent views of time and space came to consider that this reductionist view was too narrow, and that time and space could have an existence independent of their spatial and temporal features. This is an absolutist view: time and space can be known by contemplating the *a priori* theoretical nature of space and time, rather than spatial and temporal manifestations. The view that time and space are containers for temporal and spatial entities originates with Newton, and has been extended by Einstein, Minkowski, Russell and others (Newton-Smith 1988). The current view is that time is relative to space. Because the speed of light is finite, information indicating the occurrence of an event takes time to travel from the event to an observer. For example, if the sun were to explode, it would be 8½ minutes before we became aware of it. Time is therefore space-specific.

However, the realm of theoretical physics differs from that of the human world. In most realms of human experience the question of empty time and empty space do not arise; a realistic meaning of time and space can only be apprehended by actual events in time and real entities in space. A pragmatic approach, therefore, may have to ignore the ultimate nature of time and space: it is the representation of temporal and spatial entities which is of primary concern.

13.2a. Temporal perspectives in humanity

These have been considered in some detail by Whitrow (1972, 1980, 1988). We all have innermost feelings about time, but our perception of time as a concept is abstract, and any reflection on time requires a conceptual framework. So although we experience time in our everyday lives, our concepts of time and temporal duration can only be derived from reflection on our experience (Whitrow 1988:5,6). It appears that the conceptual awareness of time is solely a human trait. According to research into animal psychology, there are no conclusive empirical data to support the view that animals have memory or foresight (Walker 1983:190). Consequently we cannot attribute to animals the concept of time. So if a notion of temporality is exclusively a human characteristic, this raises the interesting question of when it first occurs.

We know from the Shanidar burials in Iraq that Neanderthals were burying their dead, and covering them with flowers at least 50,000 years ago (Solecki 1971). This is some of the first known definitive evidence for religious concepts, presumably related to notions of an afterlife and a concept of the future and therefore temporality. If Neanderthals had a concept of time 50,000 years ago, it is also likely that anatomically modern humans, (*Homo sapiens sapiens*), had a concept of time from the outset.

Young children only begin to develop a sense of time between about 2 and 3 years of age, but once established, a temporal framework develops according to specific cultural rules (Flood & Lockwood 1988; Whitrow 1988; Aveni forthcoming). Spans and intervals of time are very much subjective and symbolic. Our 'sense of time' varies according to our cultural norms. Cultures who do not utilise formal numerate or literate calendrical systems are obviously not able automatically to conceive of intervals of time in the same way that we do.

Studies of circadian or bio-rhythms have shown that, deprived of all external sensory indicators, the inner 'clock' of humans varies considerably from individual to individual. Without some external referent, it is exceedingly difficult to estimate the passage of time. How intervals are measured varies from culture to culture, and any cross-cultural survey will show a wide range of variation in methods used to delineate time. In some cultures of southern and southeast Asia, for example, the minimum unit of time is the interval taken to boil rice or tea. In general, though, use will often be made of regular markers in nature, such as day or night, the lunar month or the seasons, or human generations. Most industrialised societies have a synchronised system based on clocks and calendars which mark mechanically agreed intervals of time. However, individuals may have specific interests in extremes of disparate ranges of time. In our own society, some people deal with minute quantities of time — for example, millionths of a second for physicists and computer engineers, and hundredths of a second for sporting figures. At the other end of the spectrum, geologists, archaeologists and palaeontologists deal with vast spans of time. In between we have minutes, hours, days, months, years, generations, centuries, and millennia. Time is a highly variable entity.

Time is not necessarily a unitary concept and two separate notions of time are in evidence. There is the linear notion of time, as in our society, where events have a beginning, a span, and an end. But there are also cyclic concepts of time, such as those associated with the seasons, or the Buddhist cycle of rebirth and incarnation. Not all cultures share the Euro-Western notion of three temporal categories of past, present and future. Linguistic studies are useful indicators of the ways in which different cultures perceive and analyse the world (cf. Whorf 1956). The classic exemplar of this is the tenseless language of the Hopi Indians of the southwestern USA, who distinguish only between those things which are happening and those which have happened. Events in the future are classed together with the subjective world of the spirits, the fanciful, and therefore, in material or secular terms, the non-existent.

Most research into temporal GIS seems to be predicated on the Euro-Western concept of linear time. But as this brief synopsis has attempted to show, the notion of time is not invariant cross-culturally, and it might well prove worthwhile to pursue more intensive cross-cultural studies into notions of time and space.

But, notwithstanding the current state of knowledge about contemporary human perceptions of time and space, for archaeologists the questions of immediate interest relate to what happened in the past, and what frameworks are appropriate for understanding past events.

13.3 Archaeology and time

Because archaeology is all about understanding what humans did in the past, and because the past is one of the dimensions of time, one could be mistaken for thinking that archaeologists have spent a good deal of time thinking about the very concept of time. Unfortunately, on the evidence of the published literature, this does not appear to be the case. A great deal of work has been done on measuring time, developing dating methods and techniques, and establishing chronological frameworks; few archaeologists have addressed the wider issue of time. In this section I provide an overview of the current position, beginning with a brief review of the history of archaeological uses of time.

The first antiquaries had little perception of time depth. Monuments such as Stonehenge and Avebury were known to predate the Christian era, but it was not known by how much. The absence of a definitive temporal framework was obviously a handicap, necessitating some rather strange assertions about the origins of prehistoric artefacts. According to Daniel (1950:26), a seventeenth century antiquary named Tollius believed that flaked stone tools were 'generated in the sky by a fulgurous exhalation conglobed in a cloud by the circumposed humour.' Humour has come on a long way since then.

The first temporal model was developed in Denmark in 1819 from Christian Jürgensen Thomsen's (d. 1865) use of a system of three successive ages — stone, bronze and iron — as the basis for displaying Danish antiquities in the Museum of Northern Antiquities in Copenhagen (Montelius 1888). The model was subsequently developed by Thomsen's successor, J.J.A. Worsae (d. 1885). Using the principle of superimposition, it was possible to verify empirically the ordered technological sequence of stone, bronze and iron artefacts. Thomsen's model was the first to establish the principle that prehistory could be divided into separate phases, and thus provided modern archaeology with one of its key foundations.

The use of type localities as a basis for identifying geological stages was well established in 19th century geology, a practice soon introduced into archaeology by Gabriel de Mortillet. It was then a simple matter to note the correspondence of archaeological material with associated fauna or other index fossils. Sir John Lubbock (1865:2) used exactly this principle to define the Palaeolithic and Neolithic periods, the former being an association of flaked stone tools with extinct fauna, and the latter an association between polished stone tools with extant fauna.

Archaeology therefore proceeded on the basis of utilising a few temporal categories as time periods which were 'homogeneous with respect to their formal content,' (Stoltman 1978:704). Childe refined the model by changing the emphasis on 'ages' to 'stages', having noted that the global applicability of 'ages' was inappropriate because technological development occurred at different rates in different places (Childe 1935, 1944). This provides a significant conceptual breakthrough. As Stoltman perceptively observes: 'With Childe, the principle, if not the practice of recognizing the independence of time and form in archaeology had been clearly established,' (1978:704), but the distinction is often lost even today. For example, the Palaeolithic period is often regarded as a temporal unit, when it should be viewed as a cultural period in the Pleistocene.

Post-war archaeology saw the fluorescence of absolute dating. Relative dating techniques were still useful however, and far from losing its impact, well developed relative dating was able to overturn some early radiocarbon estimates, and so bring about improved radiometric advances. The combination of radiometric and relative dating procedures has proved of inestimable benefit in archaeology.

Now that a wide array of dating techniques and cultural chronologies had become well established, it fell to Spaulding (1960) to provide a formal discrimination between form, space and time, thereby identifying the three principal independent dimensions of empirical archaeology. Interestingly, he also states that in 'the attempt to describe clearly the fundamental operation of archaeology ... Behavioral inferences may creep in, but they will be evidence of weak-mindedness,' (*ibid*.:437). However, beyond identifying these three dimensions, and a few somewhat cursory operational suggestions for measuring them, his model remains largely undeveloped.

Although there are currently a wide range of chronological schemes integrating data from geology, geomorphology, biology, climatology, physics, and other disciplines, there are few attempts to develop *temporal models*, as opposed to *temporal frameworks*; that offered by Stoltman (1978) for the North American Archaic period is a rare example. In Stoltman's view, time is 'the warp that constitutes human prehistory, and artefacts and assemblages are the weft,' (*ibid*.:703). The problem of devising temporal models is held to be a classificatory one in which sequent increments of time are established for a specific area (*ibid*.). In his commentary on Stoltman's paper, Klejn (1978) showed that both Newtonian and Russellian concepts of time have a part to play in elucidating concepts of time relevant to archaeology. Klejn suggests that time can be conceived as,

> 'an unlimited box within which all actions and processes take place... [with] a set of coordinates that are handy for the synchronization of events, their "proper" location in time, the comparison of their time positions and the measurement of time intervals,' (*ibid*.:732).

If it is not to be tautological, the time dimension has to be independent of the formal properties of artefacts; archaeological stratigraphy is held to provide a direct analogue for spatio-temporality, and an indirect analogue in horizontal stratigraphy. However, although the Newtonian view of a universal regular periodization remains arbitrary and difficult to apply on a global basis, temporal models which are space-specific are more likely to be of value for cultures within the same geographical area (*ibid*.:733). Thus Klejn's paradigm recognises that while a universal time-scale is workable in everyday life, it has no real referents to the past, and cannot be used to synchronise our fleeting glimpses into it; temporal schemes relative to the observer are most appropriate. In his quest for conceptual manageability, Klejn manages to combine advantages of the two fundamental perspectives on time. Both absolute and relative concepts of time are needed — but not mixed together; not all cultural manifestations occur in every interval of time.

In one of the more recent considerations of time and archaeology, Bailey (1983) identifies two main theoretical perspectives: (1) the thinking by archaeologists and their interpretation of prehistoric behaviour, and (2) the thinking and behaviour of prehistoric communities.

Associated with these two paradigms are two distinct archaeological protocols. First there is an environmentalist position, exemplified by ecological approaches and the notion of palaeoeconomy, which is derived from the natural sciences and focuses on the role of the environment and biology as constraints on behaviour. Second, in contrast, is what Bailey terms the 'internalist' perspective, which is derived from social theory, and emphasises 'the inherent dynamic of social relations and structures of meaning,' (*ibid*.:166). It is Bailey's view that,

> 'contradictory notions of time are more or less explicit in archaeological thinking and have resulted in misguided rivalry between alternative approaches to the interpretation of past behaviour,' (*ibid*.).

Such difficulties can be assuaged by clarifying the relationship between concepts of time and their application to different problems in archaeology. So what is the relationship between the study of the past and the study of the present?

On the one hand there is the view that because historical processes in the past contributed to the state of the world in the present, the present is explainable only in terms of the past. A contrary position is that because material remains of the past survive to the present, because archaeology is conducted in the present, and because the past is, by definition, past, and cannot be reconstructed, the past is only able to be explained in terms of the present. This position seems to be the one taken by Shanks and Tilley (1987), when they state that their aim is 'an attempt to emphasize archaeology as event and experience in the present, as social practice which cannot escape the present,' (*ibid.*:7). They further emphasize that 'there can be no objective link between the patterning perceived in material culture and processes which produced that patterning,' (*ibid.*:14). However, this gives rise to a paradox. If the past can only be explained by the present, when our present becomes the past, it can only be explained by a present yet to come, i.e. the future.

The crux of the problem seems to be the nature of the relationship between past and present. As Bailey observes, there is no philosophical reason why an epistemology of the past should be substantially different from an epistemology of the present. The question obviously hangs on the extent to which we admit the role of objectivity or subjectivity in scientific processes.

For Bailey, time is both a function of events and processes, *and* our representations of them. Seen in these terms, contradictory approaches, perspectives, and attitudes, need not be mutually exclusive. The error hinges on an implicit assumption that there is a single concept of time, when there are really two interrelated ones: time as process and time as representation. Our knowledge of time depends on effects, as well as on our mental templates for perceiving them (cf. Whitrow 1972:39, 1988:5).

Because behaviour manifests itself at different levels, different approaches are needed, each appropriate to the scale at which behaviour occurs. Archaeological phenomena can be seen as separable and divisible because they operate over differential time spans. Long term processes, such as evolutionary trends, economic patterns and demographic changes are perhaps best addressed by environmentalist approaches, and shorter term processes by internalist approaches which focus on social or psychological issues. This position has been eloquently advocated by Flannery and Marcus when they counsel 'neither mindless archaeology, nor a glorification of mind divorced from the land,' (1976:383).

By adopting an appropriate temporal perspective we can not only avoid misleading and inimical forays into entrenched epistemological positions within the discipline, we can also gain an improved perspective on the interrelationship between change and stability. Both manifest themselves in the archaeological record, but any succession of events can be interpreted differently depending on whether one is interested in long-term strategies (stability and continued duration), or short term events (change and dynamic processes). So by removing artificial polarities (general/particular; diachrony/synchrony; past/present), and utilising interplay based on differential applications of the concept of time, many of the counter-productive forces within archaeology can be nullified (Bailey 1983:184).

The thrust of much of Bailey's argument is echoed and developed by Gamble (1987) in his consideration of the common aims of archaeology and geography. Once archaeologists realised that space was measurable (cf. Hodder & Orton 1976), and thereby provided a useful analytical framework, they were essentially using geography to do archaeology (Gamble 1987:228). Small scale analyses (e.g. Clarke 1977; Hietala 1984) were performed on the level of site, larger scale research was undertaken at the regional level (e.g. Johnson 1977; Hodder 1978). But it quickly became apparent that although space is measurable, the temporal dimension is not, beyond the utilisation of linear chronologies (Gamble 1987:230).

The absence of an appropriate handle on time means that many intriguing aspects of the prehistoric past remain locked away. A number of significant transformations have occurred in the past, such as the evolution of humanity; the switch from two million years of hunting and gathering to food production; and the rise of urbanism. These are critical events which obviously cannot be understood without reference to the localities in which they occurred (*ibid.*). But while the archaeology of space is a vital factor in advancing our understanding of changing behaviour, time depth is also a critical component. Storage, scheduling of resources and alliance networks can be seen not only as risk-reduction strategies but also as elements in the developmental process. It is important not only to measure changes in the archaeological record, we also need to measure their social importance (*ibid.*:236), and for that we need to apply a sensitive temporal perspective. As Stuart Piggott noted some three decades ago 'any inquiry into the past which does not reckon with the dimension of time is obviously nonsense,' (1959:51).

Having established the importance of integrating concepts of time and space in archaeology, we now have to consider how we can use them in an operational setting, and for that we need carefully to consider how best to establish an interface between these theoretical perspectives and a pragmatic approach.

13.3a Help from geography

As Gamble (1987) has observed, in the development of spatial archaeology much use was made of quantitative methods from geography. But as well as providing many useful methodological techniques, there are also many useful time-based models of human behaviour which archaeologists might find of value. Particularly useful work in this area has been carried out by one of the pioneers of temporal approaches to geographical analysis, the Swedish human geographer Hägerstrand. The main interests of Hägerstrand are the basic concepts which underlie the relationship between people, space and time (1975a, 1975b). A useful summary of this work is to be found in Thrift (1977), and much of what follows is taken from this source. The basic model is simple, and, like Occam's razor, begins from the premise that, when faced with a complex entity like the phenomenology of human social systems, start with the basics and see how far they take us.

The starting point is that the world consists of human populations and the interrelated phenomena of time and space, which can be seen as activity-related resources. Within a given unit of space, we allocate use-specific parcels of that space, and for a given allotment of time use-specific intervals of time are assigned. All activities take place in space, and all activities occupy a span of time. Both time and space are therefore finite resources which can be exploited for specific purposes. This model of time-geography is not just time-budgeting with a locational label, but rather a basis for investigating human activity: the basis of the model is human populations. The model can be worked inductively for pattern building, or deductively for testing propositions and evaluating theories (*ibid.*).

All humans operate within environmental systems, the realities of which levy constraints on social and cultural practices, but commensurate with such constraints are a series of options or choices, with preferences being conditioned by prevailing norms or values (cf. Carlstein 1983). Time budgeting stresses choice rather than environmental determinism. Activities are therefore the consequence of selective choices. In archaeology, obviously, we will always be faced with a bias towards material consumption, as most of what survives in the archaeological record are traces of material culture.

One of the fundamental problems is the relationship between the individual and the group of which he or she is part. Archaeology is more than biography, but between the extremes of individual on the one hand and social conglomeration and statistical population on the other there is a nebulous median point which reflects both extremes. If the model is seen to be equally applicable to individuals as well as to society, then we can be confident that the model is working (Thrift 1977:5–6).

All humans have goals which are attained through a series of tasks (projects). These projects can be variously classified under broad headings (transportation; storage; and moulding, composition or decomposition of materials, for example). Some of these are time-specific, others are space-specific, some are rooted in both time and space. But the basic problem is how projects can be accomplished in the time and space available, and from there it will be necessary to consider the role of situation-specific capabilities, resource management and factors of accessibility and control.

This model is specific to human geography, but many elements are applicable, *mutatis mutandis*, to archaeological domains. The advance on many existing methods is that metric space and spans of time are given functional identities, and thereby more analytical power. Also, the model is population-specific; it attempts to relate human responses to real-world constraints. Human society is therefore seen in organizational and integrated terms of time and space. The next question is how best to represent these.

13.4 The temporal dimension in GIS

In the above sections my aim was to establish the importance of integrating concepts of time and space in archaeology, and I now turn to a consideration of time, space and GIS. As many archaeologists are now only too well aware, GIS are a well established and indispensable tool for archaeologists operating at the regional scale (cf. Kvamme 1986b, 1989; Wansleeben 1988; Allen *et al.* 1990). Some major studies like the investigations in the Valley of Oaxaca, Mexico, which were carried out before GIS was available, would probably never again be contemplated without recourse to GIS (Peregrine 1988).

Wonderful innovation though it is, GIS technology is limited and one of the most severe limitations is the lack of a temporal dimension. Because GIS are atemporal, the data with which they deal are merely tenseless snapshots of a single state of the data at a single instant of time (Ariav 1986; Langran 1989b). In the continuing absence of a facility for dealing with changing spatial information, we can never hope to identify temporal patterns or understand fully the nature and effect of dynamic processes, so it is quite reasonable to expect that effort should be directed towards developing a temporal GIS (Langran 1989b:216).

The problem has been recognised, and a considerable amount of front-line research is being directed towards this goal, as well as the question of temporal databases generally (Langran & Chrisman 1988; Langran 1989a, 1989b, forthcoming; McDonald 1989; NCGIA 1989; Price 1989; Vrana 1989; Barrera & Al-Taha 1990; Barrera *et al.* 1990). It is a mark of the intensity of such research that several comprehensive literature surveys have been conducted (e.g. Bolour *et al.* 1982; Soo 1991).

Stine and Lantner (1990:85–86) give the impression that the operational development of a temporal GIS is a relatively straightforward undertaking. Their summary review of the problem understates the case. The problems are many, and centre on at least three areas: temporal modelling, temporal databases and GIS architecture (see Ariav 1986; Barrera & Al-Taha 1990; Barrera *et al.* 1990).

13.4a Temporal models

When it comes to the problem of defining temporal models, several fundamental questions need to be addressed. As discussed in section 13.2, everyone has an intuitive knowledge of time, but there are many different meanings of time within a variety of context-specific situations. However, most temporal research seems predicated on a linear model of time. Representations normally fall into two categories: points in time and intervals of time. Closely allied to these structural categories is the notion of change. Time manifests itself by changes in the state of an entity, and decisions need to be made as to whether change or time is to be modelled. If change is to be the focus of an operation, then the temporal aspect is largely redundant. The advantage of a time-based procedure is that much more flexibility is available; changes in states

Relation	Symbol	Inverse Symbol	Pictorial Image
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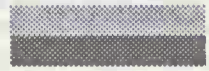
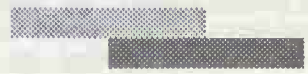
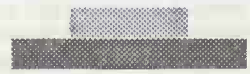
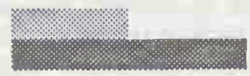
X equal Y	=		
X meets Y	m	mi	
X overlaps Y	o	oi	
X during Y	d	di	
X starts Y	s	si	
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Figure 13.1: Possible relationships between two one-dimensional temporal intervals (source: Barerra & Al-Taha (1990), p.15, after Allen & Kautz (1985)).

may be idiosyncratic, but if the changes are few and relatively homogeneous, a change based approach may be easier to establish operationally.

A time-based approach can be modelled using either points in time or intervals in time (Barrera & Al-Taha 1990:14). An interval model is somewhat easier to conceptualise, because intervals have duration or breadth, and, being substantive are somewhat easier to formalise because there are many parallels and analytical analogues on which they can be based. However, even with only two intervals of time, some representational complexity is involved. To give some idea of the potential difficulties, Fig. 13.1 depicts the 13 permutations of possible relationships between two 1-dimensional units of time, represented by X and Y.

A point-based approach seems more difficult to represent because the points themselves are less substantive, necessitating some form of intermediate linkages, such as a path system or network (Barrera & Al-Taha 1990:18–20). However, the parallel with nodes, vertices and arcs immediately suggests itself, with the attendant advantages this has for the establishment of a topological framework. Pairs of points also have the additional advantage that they can be used to define intervals of time.

13.4b Models of Spatio-Temporality

The operational development of temporality is not an isolated endeavour, modelling time also involves modelling space, and many spatial issues in GIS remain currently unresolved. Burrough (1990), amongst others, raises the question of fuzzy boundaries, and the point must be stressed that GIS technology has the potential to delimit boundaries with considerable precision. But precisely demarcated polygons may not necessarily be appropriate in all situations. Spheres of influence, for example, will traditionally be represented by Voroni diagrams (also known as Thiessen polygons). Wobst (1974, 1976) has suggested that hexagons represent quite well the social networks of hunter-gatherer bands in the Palaeolithic period and beyond. However, social domains are not always so neatly amenable to geometric representations, and the question of how best to represent such boundaries is an intriguing one.

Some useful research has been conducted on both the archaeological and geographical concept of boundaries (e.g. Jones 1959; Dyson-Hudson & Smith 1978; Proudfoot 1981; Gold 1982; de Atley & Findlow 1984; Green & Perlman 1985), and while the focus here has been on spatial boundaries, there are obviously parallels to be drawn with the question of temporal boundaries. Similarly, spatial topology is of fundamental importance in GIS, and attention will need to be devoted towards developing temporal topology so that events in time can be related to each other.

If such problems are evident in static, atemporal GIS, the effects of the problem are likely to be magnified, especially if the temporal element is going to be grafted on to existing GIS architectures. But for many archaeologists, these will be technical questions best addressed by technical specialists. Unfortunately this is a short-sighted view. If archaeologists are able to develop models that will facilitate analyses of spatial

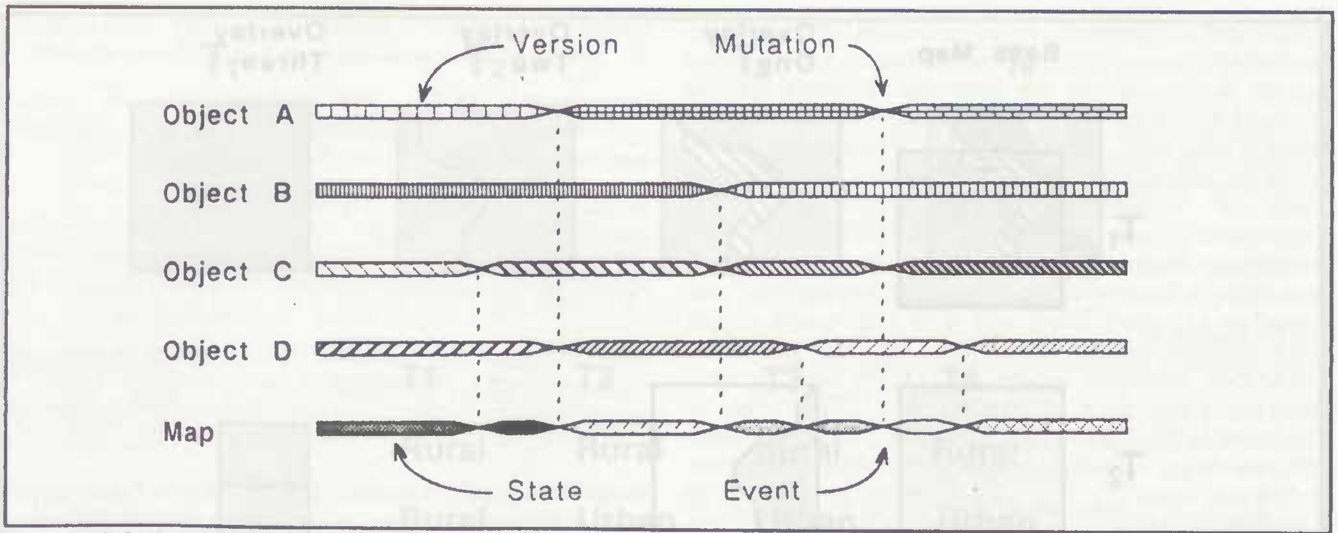

Figure 13.2: Relationship between object versions and state (source: Langran & Chrisman 1988:5).

and temporal phenomena, they will not only be in a better position from which to understand the integration of spatial and temporal phenomena, they stand every chance of developing cooperative links with technical specialists who may be able to provide the operational technology with which the models can be animated.

However, this does not preclude archaeologists from developing appropriate temporal models. Front-line researchers are endeavouring to satisfy the temporal needs of everyone in the GIS community who wants to deal with time-transgressive phenomena, and in doing so they are attempting to provide a universal temporal GIS (TGIS) for all applications in all disciplines and sectors. But not all TGIS issues are directly relevant to archaeology; the needs of archaeologists are very different from those dealing with administrative/cadastral information, navigation systems, military applications or local government. Although there may well be some overlap in these areas with archaeologists working in heritage conservation or cultural resource management, for most archaeological purposes the temporal requirements will be highly idiosyncratic. So if archaeologists can ask the right questions, and specify exactly how they want to see an operational temporal dimension in GIS, there is every possibility that this will attract the attention of those involved with designing temporal systems. It is quite clear from the current literature on TGIS research and development that case studies (and many of them) are clearly needed. If archaeological applications can be first on the test-bench, there is every likelihood that they will provide the template for an operational system. Not only would this be of immense importance for the discipline for actual applications, it would also run counter to the trend, seen so often in recent years, where archaeologists make considerable use, often uncritically (Moore & Keene 1983), of methods and approaches from outside the discipline, rather than developing and designing purpose-built 'in-house' strategies.

Obviously there are a large number of theoretical issues to be resolved. We need to avoid the potential methodological problem whereby GIS influences what is feasible, but, on the other hand, we must be able to abstract our concepts of time and space, and our archaeological data, and represent these in a GIS-compatible format in such a way that we do not irreparably distort them. Some very useful advice has been offered by Rene van der Schans (1990) who has developed a model relating to information handling and process description, rather than guidelines to the analysis of information *per se*. In our attempt to represent, analyse and model the world using GIS, van der Schans suggests that we employ a four-part paradigm. First, there is the world as the object of our enquiry. Next there are both digital and graphical representations of it. Finally, we ourselves have mental templates for perceiving the world, and filtering information about it. The elements of the model can also be combined in any of 16 possible combinations; world-digital, world-graphics, world-world, and so on.

This is a very useful model by which to evaluate the success of a GIS application, as all foreseeable applications need to be sensitive to it, not the least because it stresses the human factor. People select information systems technology to process information about the world, but in the final analysis, we ourselves are also processors.

13.4c Temporal databases and associated operations

A database management system for a temporal GIS will need to incorporate a means for storing temporal data and an appropriate query language for identifying and retrieving temporal information. As Worboys *et al.* (1990:369) point out, one of the most important elements of a potential solution hinges on the structural representation of the problem at issue; the nature and structure of the data base will therefore be a crucial factor (cf. Stinton 1978). This is a complex topic, and there is a substantial literature on this question to which the interested reader is referred (e.g. Langran & Chrisman 1988; Langran 1989b and forthcoming; NCGIA 1989; Barrera *et al.* 1990; Burrough 1990; Kim 1990; Worboys *et al.* 1990).

Several important questions arise here in the context of temporal perspectives and relational models, and in particular, how we keep track of an entity over time.

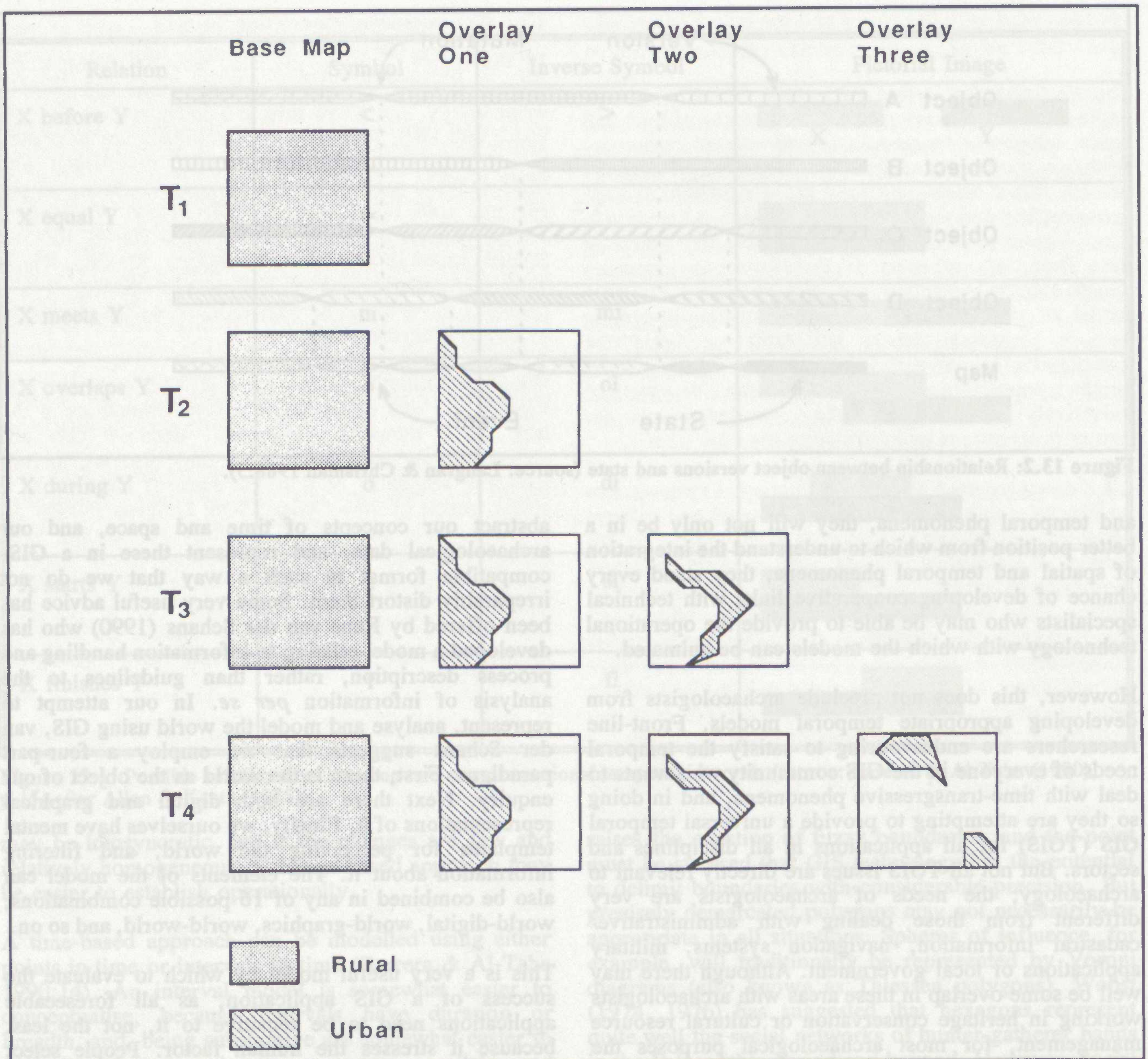

Figure 13.3: Space-time model of Urban encroachment into rural space — Base map/overlay sequence (source Langran & Chrisman (1988), p.10).

At what stage does an entity change from one identifiable state to another, and how can we (a) recognise, and (b) represent different versions of the same object? Relational databases are widely used, and operate on the basis of entities (e.g. people) and their attributes (e.g. height, weight, IQ, etc.). The database structure is essentially one of rows and columns, and hence is conceptually very simple. If relational data models are to be used, decisions obviously need to be made about where the point of change is to be focused, and what role is to be played by operator functionality. Are changes in time to be represented by new tables, or new attributes (columns), or new tuples (rows)? Creating new tables for every new version of an object will obviously entail redundant data, which militates against optimal storage. But if the changes are to be referenced within relational tables, much greater complexity is called for in system algebra. These questions are discussed in some detail by Langran (1989b:220–225) and Langran and Chrisman (1988).

As an alternative to relational data structures, Object-Oriented databases operate on the basis that specific identifiers are assigned to an entity, and hence a track can be kept on different versions of the entity (Langran & Chrisman 1988; Kim 1990; Barroca & Rahtz, this volume). This facility is not available in relational systems however. Object-Oriented databases are more complex than are relational systems, but have the distinct advantage that different versions of the same entity can be manipulated, and could therefore correspond to different states of the object at different times. However, GIS utilising Object-Oriented databases are expensive, and generally unavailable for widespread use. Hence relational databases are utilised more often than any other type, and it is therefore reasonable to expect that relational databases will be the first to incorporate operational temporality (Langran 1989b:219).

When it comes to logical operations, decisions need to be made as to whether we rely exclusively on Boolean

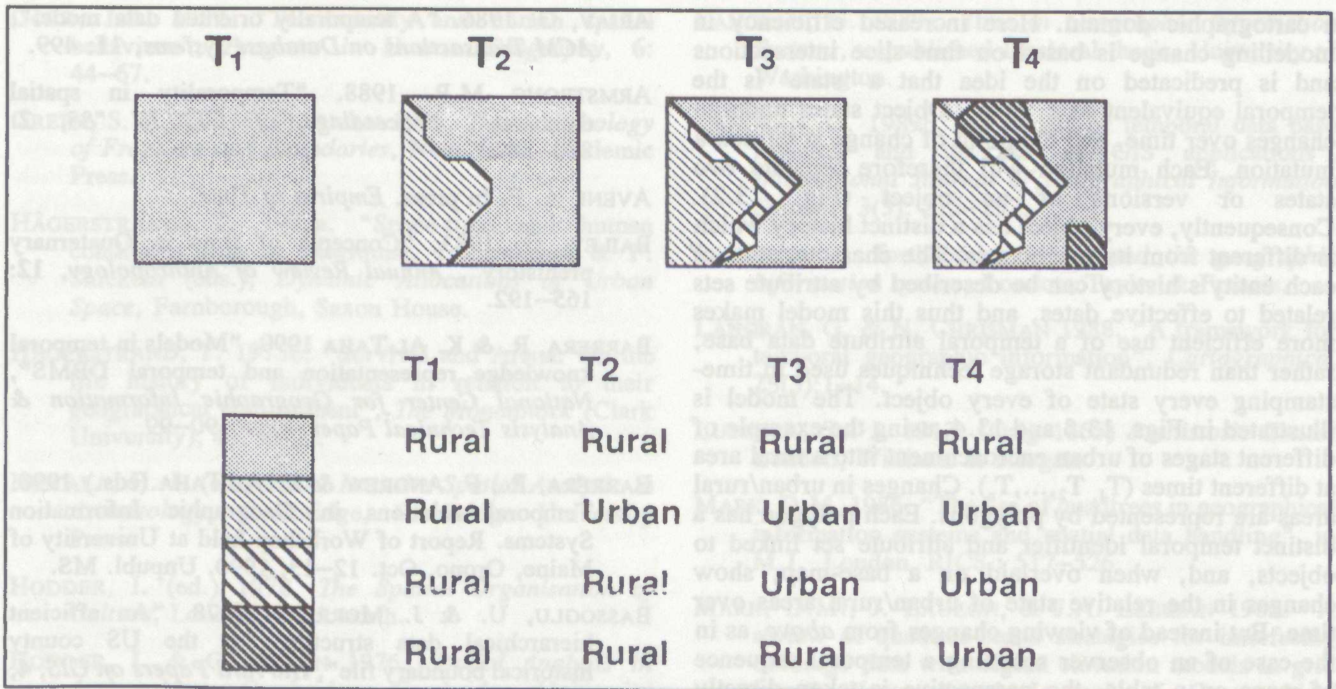

Figure 13.4: Space-time model of Urban encroachment into rural space — Polygonal Composite with each polygon having a distinct history (Source Langran & Chrisman (1988), p.12).

algebra, or develop customized temporal logic (see Barrera & Al-Taha 1990). Are algorithms the only analytical functions available, or is there room for heuristic approaches such as those used in spatial archaeology? In any event, Kvamme (1990) has shown that different algorithms purporting to perform the same task (such as interpolations) can and do produce markedly different results when used on the same data sets.

13.4d GIS architecture

Constraints of space preclude a detailed discussion of the implications that temporal representations have for existing GIS structures. But mention will be made of one model, based on the Octree data structure, that has potential to become a vehicle for a TGIS. Octrees (also known as voxels) are a recent development of the quadtree method, which is operational in relatively few GIS and is particularly associated with Tydac Technologies' SPANS package. A quadtree combines the advantage of raster structure with considerably more efficient use of storage (Mark 1986; Mark *et al.* 1989). A grid is placed over the entity and subdivided into four equal quadrants, or quad cells. If the attributes of the entity within any quad cell are homogeneous, the process of subdivision (enquadding) halts; otherwise the decomposition continues until homogeneity is achieved, or until a predetermined level of resolution is reached (Mark *et al.* 1989). The Octree structure similarly employs hierarchical nesting and is simply a three dimensional version of a quadtree in which enquadding also occurs along a z axis in addition to the x and y axes. The obvious advantage of octree data structures lies in three-dimensional applications, such as geology or other multi-layer surfaces (Jones 1989). However, the octree model also has considerable potential for temporal applications, with the additional (z) axis being used for temporal attributes.

13.4e Operational models for a temporal GIS

It would be misleading to suggest that there have been no attempts to develop a temporal GIS. Armstrong (1988) suggests that a temporal system can be implemented by tagging a geographical object with a temporal identifier as well as a spatial address. This idea was first used by Bassoglu and Morrison (1978) when they utilised time-stamps on US county boundaries in order to identify changes from 1790 until 1970. However, more recent research has identified flaws in this technique, particularly with respect to data integrity. As Langran and Chrisman observed: 'It cannot ensure that all mapped space belongs to *some* county at all possible times,' (1988:3). Current GIS are not yet able to deal optimally with all aspects of space, time and spatio-temporality, and a choice has to be made as to which feature is to take precedence (Langran 1989b:220).

Van West (1990) researched the effects of climate on Anasazi settlement in the northern San Juan region of southwest Colorado, USA from AD 901–1300. Extensive use was made of a suite of regional dendroclimatic records to retrodict 1070 annual (AD 901–1970) measures of stored soil moisture for area-specific soils in terms of their local equivalent in potential maize yield. These data were then coordinated on to annual maps of the potential agricultural environment and associated measures of carrying capacity. The 400 annual maps were then each captured on video, and an animated sequence used to display the data.

However, effective though this exercise undoubtedly was, it was clearly a very labour intensive undertaking to complete, as a long sequence of tenseless snapshots is not a particularly efficient way of showing change. An alternative way to represent temporal change has been suggested by Langran and Chrisman (1989). Their approach is based on the need to embody change within a cartographic domain. Here increased efficiency in modelling change is based on time-slice intersections and is predicated on the idea that a 'state' is the temporal equivalent of a 'map'. Object states undergo changes over time, and the point of change is termed a mutation. Each mutation will therefore separate two states or versions of an object (Fig. 13.2). Consequently, every object has a distinct history which is different from its neighbours. The characteristics of each entity's history can be described by attribute sets related to effective dates, and thus this model makes more efficient use of a temporal attribute data base, rather than redundant storage techniques used in time-stamping every state of every object. The model is illustrated in Figs. 13.3 and 13.4, using the example of different stages of urban encroachment into a rural area at different times ($T_1, T_2, \ldots, T_n$). Changes in urban/rural areas are represented by polygons. Each polygon has a distinct temporal identifier and attribute set linked to objects, and, when overlaid on a base-map, show changes in the relative state of urban/rural areas over time. But instead of viewing changes from *above*, as in the case of an observer scanning a temporal sequence of maps on a table, the perspective is taken directly from the *time-line* in order to produce graphical views of changes in the past (or future).

This model has a number of direct archaeological parallels, such as the spread of food production, the so-called Neolithic wave of advance, as well as the diffusion of stylistic changes in material culture.

13.5 Conclusion

The problem of developing an operational Temporal GIS is one that will take a great deal of ingenuity, imagination, and sheer hard work involving many case studies. Archaeologists are supposed to have an unparalleled knowledge about events in the past and changes over time. If we can clarify exactly what time is, and, more particularly, how its effects can be represented, we stand an excellent chance of attracting the attention of GIS and database designers. Working together in this way there is every likelihood of being instrumental in pioneering what may turn out to be one of the most significant technological developments in the human sciences: a temporal dimension in GIS.

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