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Spatial representation: the scientist's perspective

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In this chapter, spatial representation is seen as providing a bridge between scientific theories and the 'real world', a bridge which is fundamentally important yet is also inherently bound by scientific conventions. Such conventions effectively prescribe the correspondence between geographical space and the constrained physics of forces and mass in the world. This much has emerged from a range of recent reappraisals of the general scientific world view, as well as from the more specific experience of generalising and modelling real-world phenomena using GIS. Having reviewed this work, we go on to explore some of the metaphysical, ontological, and epistemological considerations that underpin spatial and temporal representation. This is done in part through discussion of the general and specific conventions that characterise current GIS practice, but is also viewed more prospectively in relation to the emergence of 'geographic information science'. All of this suggests that GIS-based spatial representations should become richer than they are at present, and that they should be more firmly grounded in method. If spatial representation is to remain central to our theorising about the external world, it follows that the challenge for those who wish to create and use spatial representations is to employ existing GIS critically and to look for new ways to enlarge their scope and expressiveness. In this way, spatial representation will continue to open up new ways of exploring structure, relationships, and causality in the world.

1 INTRODUCTION

Spatial representation is essential to science. It provides science with a means to establish correspondences between theories and the world. If a theory states that the sun sets in the west every day, then spatial representation is required to establish the meaning of 'west' and to locate a viewpoint. However, science itself depends on a theory of knowledge that governs how spatial representations are made and used to reason about the world. For example, the map of the areas of darkness and light on the Earth's surface shown in Plate 1 permits the testing of the 'sun setting in the west' theory suggested above and poses a number of challenges to the assertion. However, this scientific form of spatial representation can only be related to observations of the world by understanding the scope of the theory in question and the nature of the observations which are made to test it. As a consequence, users of scientific spatial representations such as maps or models must know something of science and its conventions to relate such representations effectively to the external world (Raper 1996a).

A key aspect of scientific spatial representation is that it assumes a correspondence between geographical space and the physics of forces and mass in the world. There are different ways to express this: for example, the energy required to move an object from one place to another is related to the distance between them. The correspondence between geographical space and physics has been

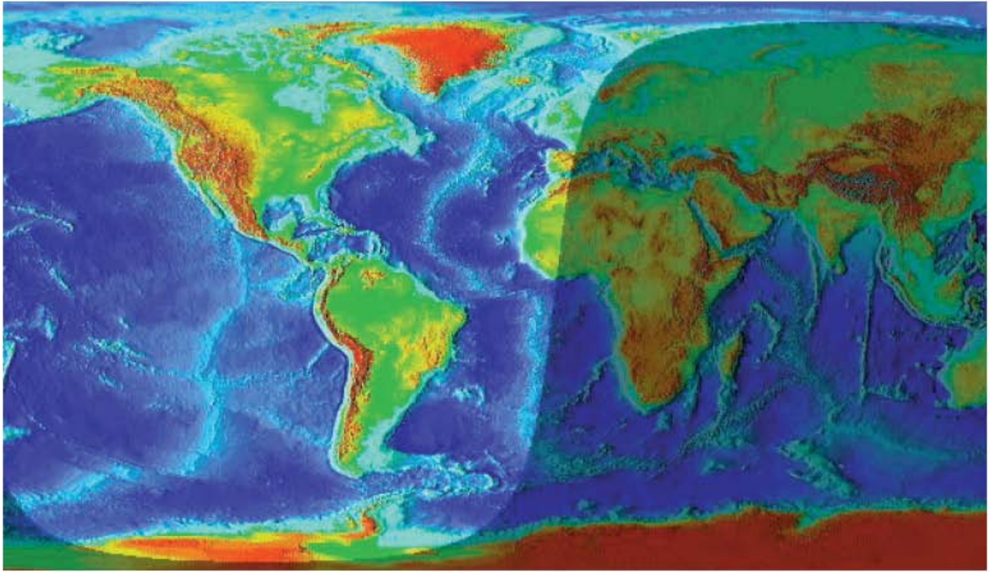

Plate 1
Spatial representation used to map the areas of darkness and light on the Earth's surface.

used to provide a foundation for many geographical models such as the theories of regionalised variables (Journel and Huibregts 1978) and spatial autocorrelation (Cliff and Ord 1973) in which distance is used as an explanation of spatial variation and association. Geographical space also creates physical constraints such as those upon interaction (e.g. at crossings, meeting points), on searching processes, and on topological conditions (such as junctions). The substitution of space for time (ergodicity) in process is also dependent on this correspondence. In the scientific world-view the explanatory power of spatial representations derives from these correspondences between the forces of physics and the dimensions of geographical space.

In the last three decades the scientific world-view has been challenged on the grounds that it cannot offer a universal theory of knowledge (for example, by Foucault 1972; Habermas 1978; Giddens 1979) and that its methods are flawed (Kuhn 1962; Feyerabend 1975; Lakatos 1976). Other theories of knowledge (epistemologies) have been defined which provide alternative frameworks for research. Johnston (Chapter 3) describes the three methodological world-views identified by Habermas (1978): the 'empirical–analytic' world-view (corresponding roughly to explanation in natural science); the 'historical hermeneutic' world-view (concerned with the understanding of meanings), and the 'critical' world-view (concerned with the underlying structures creating what we observe). In the 'historical–hermeneutic' world-view the correspondence between space and physics is denied *per se*, as it is considered that the world is entirely created within discourse and does not exist independently of an observer. In the 'critical' world-view, largely based on the critical realist philosophy of Bhaskar (1978), there is an external 'real' world but it is only observable via the empirical outcomes of mechanisms which structure the real world. This view implies that spatial representations do not necessarily have privileged explanatory status through generalisation, as causal relations are created by the local and particular interaction of the generative mechanisms.

Yet amongst these competing world-views science is intensively scrutinised and remains the pre-eminent methodology focused on explanation or causation, particularly in the natural sciences (Musgrave 1993). By contrast the 'historical–hermeneutic' world-view is essentially reflective, promoting understanding, ironically evaluating a world itself transformed by science (Collier 1994). Accordingly, scientific spatial representations remain widely used and are often highly successful when used in conjunction with modelling (for example, tidal predictions). In some cases the use of scientific spatial representation produces insights which have been found essential to human life such as hurricane warnings or quarantine measures in the control of disease. This is the essence of the process described by Hacking (1983: 31): 'we represent and we intervene'. The key issues in the appropriate use of scientific spatial representation are, therefore, whether the scientific world-view is appropriate for a particular use, and, if so, how spatial representation fits within the theory of knowledge used by science. This chapter will explore the nature of scientific spatial representation in more detail and then survey the implications for the emerging field of geographic information science.

2 THE NATURE OF SCIENTIFIC SPATIAL REPRESENTATION

The contemporary critique of the science world-view has renewed the importance of making an explicit justification for the use of spatial representations and showing how they lead to the production of new knowledge. Such a justification should involve a review of the phenomena and processes whose spatial dimensions are to be represented in spatial form in order to establish:

- the approach to conceptualisation of the world (metaphysics) employed;
- the methodology by which specific phenomena and processes that the world contains are given significance (ontology);
- the approach by which knowledge of the world is established and tested (epistemology).

Few researchers carry out such a justification explicitly, preferring rather to rely upon conventions already established in their application field. These conventions range from the informal ones associated with institutions (e.g. mapping agencies: see Smith and Rhind, Chapter 47) to the formal ones required by a profession or government (e.g. international standards: see Salgé, Chapter 50).

However, spatial representation has been made newly accessible by digital technology – opening the way for its much wider use (e.g. see Goodchild and Longley, Chapter 40). The development of a geographic information science (GISc: Goodchild 1992) as a counterpart to the use and application of geographical information systems (GIS) has as a consequence generated an interest in the proper methodological context for spatial representation. The goals of GISc are, therefore, to question the foundations of the conventions established in the application of GIS. This project will help to avoid the generation of dangerous 'spatial' fallacies with newly powerful computer tools. It is also perhaps the way to identify new avenues for research given the central role of spatial representation in the ontology of the physical world.

2.1 The scientific context of spatial representation

Most spatial representations are made within the scientific world-view since users of other epistemologies often do not regard spatial representation as especially significant in understanding the world. Spatial representation is essentially a product of the science world-view. Hence, monitoring the use of spatial representations involves critically examining the scientific context within which the conventions have been developed.

The conventions associated with spatial representation can be divided into the high level conventions of the science world-view and the low-level conventions associated with the implementation of representations. These low-level conventions can be identified with the 'disciplinary matrix' and 'paradigms' of GISc in the terms used by Kuhn (1962). Yet the high and low levels are thoroughly interwoven: the development of high-level conventions in 'general science' can generate a false sense of security for the implementors of spatial representations by suggesting that certain assumptions can be made quite generally. While 'general' science might suggest that judgements about the energy output of a chemical reaction can be made free of ethical considerations, the same assumption is not likely to be valid in the case of the regionalisation of a city for the determination of voting district boundaries. Implementors and users of spatial representations must, therefore, satisfy themselves that the high level implicit assumptions of general science are appropriate in the low-level implementation and use of spatial representation.

Consequently, the following sections provide short but explicit summaries of the issues that scientific users of GIS should reflect upon when employing these tools. If such assumptions and conventions are explored and spelled out publicly (i.e. in publication) it will go some way to exposing the methodological foundations of spatial representation to the critical examination suggested by Pickles (Chapter 4).

2.2 The metaphysics of spatial representation

Metaphysics may seem remote from the interests of most users of spatial representations. The way the world is conceptualised is usually considered to be subject to a wide and uncontroversial consensus; expressions such as 'real-world conditions' or 'ground truth' assume this. While in certain respects this assumption is robust (e.g. solar energy output is enduring and relatively unchanging), in most other ways it proves less universal both culturally and theoretically. In fact there are considered to be two distinct metaphysical positions (Musgrave 1993):

- *Idealism* argues that nothing exists outside the mind to create perceptions. In this view appearance and reality are one and external realities are merely ideas based on sensory data. Some social theoretic approaches to geographical research are associated with this view since they argue that social structures and beliefs control the way the world is conceptualised.
- *Materialism* argues that phenomena exist in the world independently of minds and that it is their true existence that causes sensory perceptions. This is the view which is associated with science.

These metaphysical positions illustrate that widely different views can be put forward for the cause of our sensory perceptions and the nature of the 'real' world. Since materialism is associated with science this is the commonly assumed position in the creation of spatial representations. A typical process of reasoning would be that if the 'real' world exists and can be observed, the goal of spatial representation should be to capture some particular essence of the world as in, for example, an environmental model. If this is satisfactorily achieved then the spatial representation can be studied and conclusions drawn from it that will prove applicable to the world (Collier 1994). However, in many circumstances this approach does not lead to satisfactory explanation of the world, making it difficult to decide whether the metaphysical position or the process of making the spatial representation is flawed. If it is the former case then science is inadequate; if it is the latter case then the conduct of science is at fault. Such conundrums illustrate the importance of understanding the metaphysical foundations on which spatial representations are constructed.

2.3 Ontological perspectives on spatial representation

The process by which phenomena are defined and given significance is the study of ontology; essentially, it is the study of what phenomena exist. Since the dimensions of space and time are pervasive in perception they are generally regarded as being critical to ontology (Heller 1990). There is, however, a range of distinct approaches to the understanding of space and time, each of which implies a different ontology. Users of spatial representations need to examine the possible ontologies to avoid making a commitment by default to an ontology that is not appropriate.

One ontological divide is between those who regard space and time as a universal physical reference framework and those who regard them as simply a set of relations between phenomena. The first view (absolute space and time) arises out of Newtonian physics and implies that phenomena can be defined in themselves by where and when they are found. Spatial representation simply requires the bounding or sampling of the phenomena. The second view (relative space and time) was first elaborated by Leibniz and suggests that space can be defined as the set of all possible relations between phenomena. By analogy time can be defined as the order of succession of phenomena. Here spatial representation must be fully spatio-temporal in nature: it is the (causal) connections and dependencies between phenomena which have ontological importance in this scheme.

Space and time can be seen as a kind of index to phenomena (first view) or as a domain through which phenomena can be causally interconnected (second view). Although the distinction between these two is highly theoretical, use of the second approach has offered some potentially new solutions to spatio-temporal representation for complex environmental problems. For example Raper and Livingstone (1995) argue that in some dynamic environments such as the coast it is not meaningful to attempt an *a priori* space and time partition where lines are drawn to separate distinct entities such as channels, beaches, and dunes. Rather, investigation should map all forms and measure representative processes over time in order to create a database of system states. This then allows the researcher to explore the range of movement in space and the evolution of identity through time for all the phenomena of interest, without the constraints of identifying spatial identity (for example by capturing boundaries into a GIS) at the outset. This approach means that an ontology is generated *from* the behaviour of the phenomena rather than imposed *onto* it through a space and time framework.

The ontological significance of space and time in representation is also not scale invariant since different ontologies apply to domains outside the direct experience of human beings such as the microscopic (the scale of subatomic particles) or the macroscopic (the scale of galaxies). Most spatial representation relates to the 'mesoscopic' or geographical domain which ranges in extension approximately from the size of a human being to the dimensions of the Earth. In this domain it has been suggested that concepts of space may be driven by cognitive processes scaled to the dimensions of the human body. Zubin (1989) suggests that different concepts of space are developed for domains which are directly manipulable by human beings (e.g. within rooms) compared to those developed for domains which can be viewed but not manipulated (e.g. landscapes). Do users of spatial representations in science preferentially scale the entities they decide to measure according to these built-in rules? Few implemented spatial representations reflect this cognitive variation in ontology or explicitly document their assumptions. Spatial representations also suffer from the modifiable areal unit problem (MAUP: Openshaw and Alvanides, Chapter 18; Openshaw 1984) in which spatial variation can be seen to differ spatially depending on the scale at which geographical units of aggregation for observations are set. This raises the question of which scale level has ontological primacy (see Openshaw and Alvanides, Chapter 18, for an empirical perspective upon this issue).

2.4 The epistemology of spatial representation

The contemporary world-view of science is associated with an epistemology (largely derived from Popper's 'critical rationalism') governing the way science is conducted. Popper (1959) argued that it is reasonable to believe deductively generated hypotheses that have withstood severe criticism (non-falsifiability) through empirical observation. However, important constraints on the creation and use of spatial representations are implied by the use of the critical rationalist epistemology which need to be incorporated in their use.

First, spatial representations are forms of observation. Yet observation is heavily contested epistemologically: the relativist critique suggests that observation cannot be either rational or theoretically neutral (Feyerabend 1975; Kuhn 1962; Lakatos 1976); critics of science have suggested that observation must inevitably be a product of the world-view within which it is defined (Foucault 1972; Habermas 1978); and critics of positivism have suggested that observation is fixated with external expression rather than internal meaning (Gregory 1994). The implication of this critique is that all observation is defined by and applicable to a certain domain: in other words it is acutely contextual. This is a conclusion that applies equally to observation when used to make spatial representations such as maps. Hence, the 'features' that public topographic maps capture were largely decided by eighteenth century army generals and nineteenth century civil engineers and emphasise engineering plant, street furniture, building outlines, and administrative boundaries at the expense of all the other features that could be included. Such observations rapidly become a 'standard' form of observation which may be commodified and used beyond its domain of original applicability.

Second, spatial representations provide an operational method by which correspondences between theories and the world can be established in science. However, if spatial representations are seen as catalogues of observation then their analysis may involve the fallacy of induction i.e. reasoning about one area of geographical space or time interval from evidence gathered elsewhere in space or time. Spatial representations may also reflect the ruling paradigm of observational theory (as for example in the sampling interval adopted when recording temporal change). If spatial representations are regarded as theories of process and implemented as models then their form must be stated in such a way that they can be tested and, if necessary, falsified (Popper 1959). The nature of the testing of spatial representation is of importance: maps as spatial representation can be characterised as 'normal' science, although the potential of digital spatial representation may facilitate the development of a critical science by the creation of emancipatory spatial representations. João (1994) analysed the generalisation effects embedded in British and Portuguese topographic maps, finding that they differed significantly across the scales of maps published; in one sense this study was an important attempt to falsify maps as a form of knowledge (see also Weibel and Dutton, Chapter 10).

2.5 Status of spatial representation

In summary, making and using spatial representations is a key part of the methodology of the scientific world-view. However, it is not merely a process of descriptive observation as critics of GIS have charged (Pickles 1995; see also Pickles, Chapter 4). The need to make metaphysical, ontological, and epistemological commitments when forming spatial representations requires theoretical work by users. Of these three, ontology now poses the greatest challenges and has stimulated work in several related fields outside geography, e.g. Smith (1995) on the philosophy of boundary drawing or Cohn (1995) on computable qualitative spatial reasoning. In developing the tools for the development of new ontologies of space, geographical information science has opened the way for the discovery of new spatio-temporal structures in the mesoscale geographic world.

3 THE IMPLICATIONS FOR THE DEVELOPMENT OF GEOGRAPHIC INFORMATION SCIENCE

Lying at the overlap of geography, geoscience, computer science, cognitive science and cartography, geographic information science has developed a new interdisciplinary focus on conceptual and computable aspects of spatial representation. However, questions such as 'whose real world' (metaphysics), 'what are the objects and at which scale' (ontology), and 'how are geographical conjectures tested' (epistemology) pose substantive challenges to geographic information science. If geographic information science is to contribute to (for example) the study of the risks of natural hazards, the epidemiology of disease, or prediction of the evolution of environmental systems then spatial representations must be richer than at present and firmly grounded in method (Raper 1996a).

Concrete steps towards these goals can be taken into two areas: first, in the connection of the 'high level' conventions of general science with the 'low level' conventions of geographic information science, specifically those being built into the next generation of GIS software systems; second, in the enrichment of spatial representation from the dominant 2-dimensional model in order to make them multidimensional.

3.1 Connecting the conventions of general science with those of geographic information science

The conventions of general science have counterparts in geographic information science (see also Forer and Unwin, Chapter 54). The process of conceptualising the external world in order to create a spatial representation is generally referred to as 'data and process modelling' in geographic information science, as in computer science generally (Herring 1991). This form of modelling is concerned with the way correspondences are established between geographical aspects of the 'real world' and the elements of the spatial representation. A distinction can be drawn between data and process modelling.

Data modelling in geographic information science has largely developed from techniques employed in database management systems: hence Tsitchizris and Lochovsky (1977: 21) defined a data model as 'a set of guidelines for the representation of the logical organisation of the data in a database . . . [consisting] of named logical units of data and the relationships between them'. Frank (1992: 410) put this in the context of geographic information science when he characterised a data model as 'a set of objects with the appropriate operations and integrity rules defined formally'. These definitions establish data modelling as concerned with essentially static interrelated and discrete entities. In geographic information science these entities have spatial extent and therefore the 'operations' and 'integrity' rules referred to by Frank (1992) must also apply spatially.

Data modelling procedures for natural science applications of GIS are generally ad hoc exercises (since there are few prototypical situations) starting with heterogeneous collections of data. Typical collections of data include direct observations of position, form, or behaviour for an entity of interest (such as a risk zone for incidence of a disease). To form a spatial representation in a GIS it needs to be georeferenced with respect to a global datum (e.g. using a Global Positioning System: see Lange and Gilbert, Chapter 33), a national datum (using the positions defined by National Surveys) or a local datum (specific to a particular project). The key issue in the handling of such data is how the entities identified should be represented by the available geometric primitives, viz. 0-dimensional points; 1-dimensional lines, 2-dimensional areas, and 3-dimensional volumes (note that many GIS have introduced their own terminology for these geometric primitives). *Vector* approaches to spatial data modelling involve using these points, lines, areas, and volumes to make representations, while *raster* approaches involve using tessellations of equal size cells in a grid of a fixed resolution, usually to represent areas.

An early convention developed in spatial data modelling was that entities must be described separately in terms of their nonspatial and spatial identity. This convention originated in the software architectures of the early GIS which integrated a geometry engine with an alphanumeric database management system. More recently, object-oriented languages (see Worboys, Chapter 26) have been used to build GIS with the result that spatial data models can now be constructed in most GIS without starting the data modelling from geometric concepts. This is done by identifying real-world entities (such as rivers and buildings) or conceptual entities (such as samples or boundaries) and specifying both their attributes (whether alphanumeric, spatial, or multimedia in form) and their interrelationships with other entities (see also Hutchinson and Gallant, Chapter 9). It is still rare to find any explicitly temporal concepts in the tools provided for spatial data modelling.

The user must now define how the dimensionality of the 'real' entity is represented by the selected geometric primitive and in which GIS will the result be stored. Hence, points in a spatially non-regular sample (e.g. rainfall observations) can be generalised to space-exhausting areas by creating Thiessen polygons (defined as that polygon bounding the space closer to the selected point than to any other point: see Boots, Chapter 36) from the point locations of the samples. Alternatively, entities extending over areas could be reduced to points by taking the geometric centroid of the area (a function available in many GIS if the boundary is stored), or the areas could be stored using tessellations of grid cells where each cell in the grid has an associated value. Often the spatial data are supplied to the user in a form that dictates the nature of the spatial representation to be used in the GIS. For example, satellite imagery is produced by a scanner generating raster data while new roads are surveyed along a centreline implying vector spatial representation. Some recent work has focused on the forms of spatial representation appropriate for entities with indeterminate boundaries (Burrough and Frank 1996; see also Fisher, Chapter 13).

The other key source of data beside direct observation is mapping. Cartographers have developed sophisticated conventions for the representation of a consensual view of the natural and built environment by using a well documented form of cartographic communication. Most national surveys now offer versions of their paper maps in scanned raster or digitised vector form. Paper maps employ a form of symbology considered appropriate to each case at each scale. However, in digital representations the form of paper map features must be transformed into georeferenced geometric data. Note that maps normally present a governmental or commercial perspective because of the high cost of creating maps for individuals or even for corporations. Hence, mapping has itself become both a reflection of public policy and a powerful influence on perceptions of space as the symbology of topographic maps is taught in schools and the terminology of the map is employed in law and professional practice.

Process modelling has generally developed outside geographic information science in fields such as environmental and ecological modelling (Kemp 1992). The aim of process modelling is to represent the behaviour of continuous 'real' physical systems and their change in status over both time and space (Ziegler 1976; Casti 1989). This is generally achieved by establishing a finite process model whose behaviour is distributed over space and time. Typically the spatial representation is a raster while temporal representation is based on application-specific intervals (Jørgensen 1990). There is a greater concern in process modelling than in data modelling about the establishment of correspondences between the 'real world' and the modelling environment since designing a simulation model is inherently conjectural in nature.

Spatial representations employed by process models are generally divided into finite difference models (based on raster grids) and finite element models (triangulated irregular networks). These 'finite' forms of spatial representation specify a limited number of topologically closed areas for which states of a physical system can be computed and stored. These process models are limited by the number of interactions permitted across the boundaries between grid cells or triangles and by the fixed scale of the spatial representation. Despite these limitations such models have been used successfully in a range of fields (Goodchild et al 1993; Goodchild et al 1996). Casti (1997) suggests that such models can be populated by autonomous elements called agents which inhabit the simulated environment and take decisions by reasoning about the knowledge they have of the system. This knowledge is implicitly and explicitly 'local' in nature since no agents have access to the global state of the system. Casti (1997) argues that such systems exhibit 'emergent' behaviour whereby outcomes emerge from the aggregate behaviour of the agents.

The wide availability of GIS and process models has led many users to adopt the representational tools of current systems as a basis for the expression of their world-view rather than the other way around. A set of well defined conventions has developed around GIS and process models in many disciplines and many scientists employ them. However, prospective scientific users of GIS and process models should distinguish between the mass of available systems and the rather richer prototypes which are available at the sophisticated end of the market and those emerging from research laboratories.

3.2 Enriching the spatial representations in current GIS

At present most GIS implement a continuous 2-dimensional geometric form of spatial representation mimicking that used on maps. However, 2-dimensional geometry is a rather limited representation of real surfaces such as terrains which frequently contain overfolds and holes. In the natural environment most physical processes operate in true 3-dimensional domains such as the solid earth, oceans, or atmosphere, making 2-dimensional geometry even more limited (Raper 1989). A variety of 3-dimensional GIS has developed to offer representational tools suitable for visualisation and analysis of volume property variation, structural reconstructions, and volume interpolation. New

3-dimensional data structures have evolved from solid modelling techniques (Mortenson 1985) which extend geometric representations from 2-dimensional raster and vector geometry to their 3-dimensional analogues (Raper 1992).

Three-dimensional raster representations are generally constructed from a block of volume elements (voxels). The values of these voxels may be directly generated from source data as in geophysical reconstruction, rasterised from vector data such as cross-sections, or interpolated by distance weighting, Kriging or spline-based approaches (Houlding 1994). The voxels may be visualised as cells in a 3-dimensional matrix or as isosurfaces (surfaces joining points of equal value) as in the model in Plate 2 where the interpolated value is mean particle size in the phi scale (fine grain is blue, coarse grain is orange). Three-dimensional raster representations are ideal for the calculation of volume and are easily logically partitioned, especially if indexed using octrees (Gargantini 1992).

There are fewer implemented examples of 3-dimensional vector representations as the data structures are more complex. Vector geometry in three dimensions requires an addition to the basic Euclidean point, line, and polygon primitives to include solids (polyhedra sometimes referred to as 'volygons'). While interactive reconstruction can give good results in some circumstances, the most widely used approaches build solids from points distributed non-regularly in 3-dimensional space. This can be done using a 3-dimensional triangulation (Mallet 1992) or by constructing tetrahedra as in Plate 3 (Lattuada and Raper 1996). Plates 2 and 3 are visualisations of the same cross-sectional block of a spit landform based on the same data showing how the interpolated raster approach gives superior visualisation whereas the exact-fit tetrahedron approach is more precise.

The concepts of time employed in spatial representations are also limited in the widely used systems (see also Veregin, Chapter 12). Time is usually assumed to be absolute, operating as a frame of reference where events partition a single universal timeline. By convention, representations of space in two or three dimensions are realised at an instant in time creating 'timeslices/time volumes' which can be operationalised as layers or volumes. Change can then be defined as geometric differences between 'timeslices/time volumes' (Langran 1992). There has been a variety of attempts to develop more sophisticated spatio-temporal data structures which can be queried and analysed in more complex ways: O'Conaill et al (1993) extended linear quadtrees to represent phenomena in a 4-dimensional space-time cube; Peuquet and Duan (1995) developed the event-based spatio-temporal data model (ESTDM) to handle forestry change; Wachowicz and Healey (1994) proposed a design in which 'events affecting spatial objects' create 'versioned spatial objects' such that temporally different versions of the same object can exist; Ramachandran et al (1994) propose a design called TCObject in which objects with geometric and non-geometric attributes are given past, present, and future states depending on the dates of birth and death for the object; and Raper and Livingstone (1995) proposed a system which assigned spatio-temporal references to all instances of all variables, thereby avoiding the use of a single timeline.

Spatial representations used by GIS and associated tools are generally made of geometric primitives. These basic primitives are treated as uncontroversially isomorphic with selected 'real world' objects to create a spatial representation; for example, a road is treated as a vector line, or a lake is treated as a connected set of grid cells. However, the process of establishing a geometric isomorphism between world and GIS reveals the extremely limited expressive power that this process currently gives. Although both vector and raster forms of representation link to certain fundamental concepts (vectors are associated with the cognitive importance of entification, rasters are associated with the visual field), both are limited to a sense of physical extension. There are other modalities in the human senses, notably motion parallax, sound, smell, and touch which are critical in the formation of spatial representations cognitively.

Digital video and sound offer new ways to make spatial representations which address these other senses. Yet these new forms of representation have been adopted in an extremely limited way in GIS where at present video and sound can generally be associated with just a single vector or raster primitive. Video and sound representational primitives are usually assumed to be spatially and temporally dimensionless as their internal times do not relate to 'world' time but to 'playback' time. No current GIS can operate on the fields of view or audible ranges of these primitives, neither can they be temporally related to any implemented 'timeline' in the system. Neither could a GIS reconcile multiple views of the

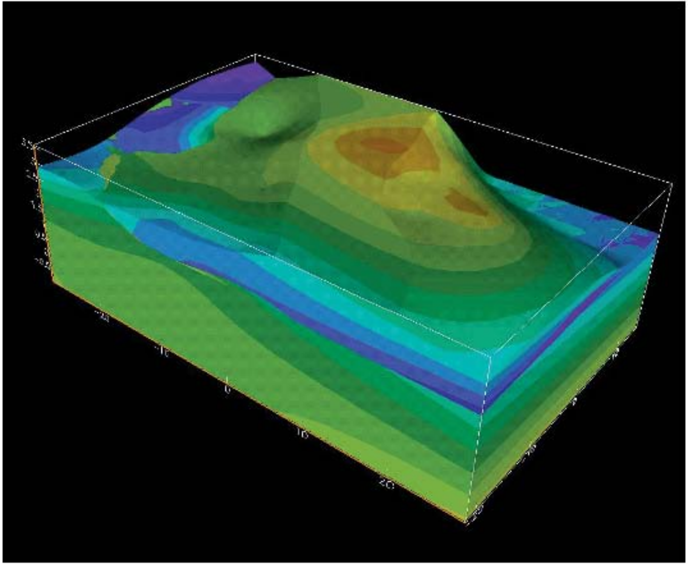

Plate 2
Raster (voxel) representation in a 3-dimensional matrix.

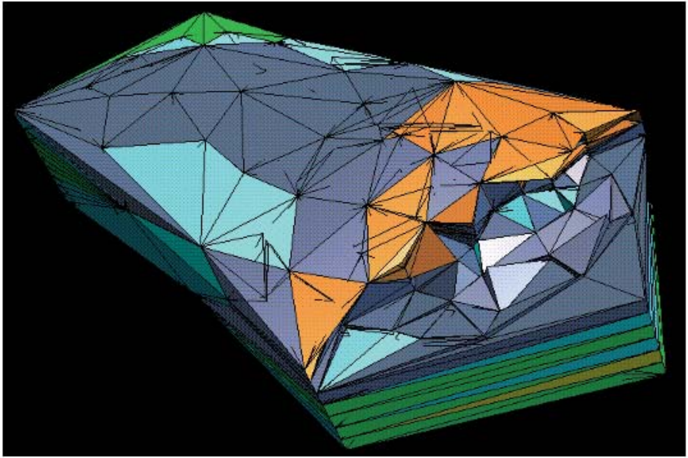

Plate 3
Vector representation of solids using tetrahedra.

same entity from different directions or deal with different sounds made simultaneously in different places. Such issues (even the latter) are however being addressed in multimedia information systems, often in an explicitly spatial and temporal framework (Raper 1996b; see also Shiffer, Chapter 52).

4 CONCLUSIONS

Spatial representation is at the heart of much theorising about the external world. However, the recent rapid growth in geographic information science has created new demands for GIS which often still use geometric concepts that are manifestly limited in scope. The challenge for those who wish to create and use spatial representations is to employ the existing systems critically and to look for new ways to enlarge their scope and expressiveness. Only then will spatial representation offer new means to explore conjectures about structure, relationships, and causality in the world.

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