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Space, time, geography

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Specific notions of space and often also time underlie every GIS application. This chapter reviews the conceptual roots of space and time representations in the four traditional disciplines of geography, mathematics, philosophy, and physics, recently augmented by cognitive and sociocultural perspectives. It then assesses the place of GIS as information technology at the intersection of several different views of space and time, and addresses the tension between that plurality and GIS's strong basis in a single view (the 'map' view). Finally, it outlines four challenges for GIS research in the domain of spatio-temporal representation: the seamless integration of space and time, the representation of relative and non-metric spaces, the representation of inexact geographical entities and phenomena, and the accommodation of multiple spatio-temporal perspectives to meet a variety of user purposes and needs.

1 INTRODUCTION: WHY 'GEOGRAPHICAL' INFORMATION SYSTEMS?

Of the many millions of users of GIS, only a small fraction have any formal ties with the discipline of geography. Planners, foresters, natural and social scientists, utilities managers, marketing consultants, transportation engineers, and many others now use these systems on a daily basis without giving too much thought to what the 'G' in GIS might stand for. Obviously 'geographical' refers to something of very broad import that far transcends the bounds of a particular discipline. The 'geo' in 'geography' is in fact a great common denominator for all of us living on the surface of the Earth, as we are all more or less familiar with the same basic things that populate our planet. There are, in particular, two large categories of geographical concepts with which most people are acquainted either through their professional activities or simply as part of everyday life: geographical entities and phenomena, and the spatial and temporal properties and relations characterising these. Geographical information systems derive their name from the fact that they are designed around both these categories of concepts: they are not just about the things listed in geographical atlases, nor are they just 'spatial' information systems.

The first class of widely shared geographical concepts are thus the entities and phenomena of the world at geographical scales, and their changes over time. These entities can be as small as a village square or as large as the planet itself: this is the range that the notion of geographical scale covers. Typical geographical entities are mountains, rivers, valleys, and coastlines, but artificial features such as cities and roads are also among them. Phenomena are the things that happen, rather than those which are on the landscape: brush fires, weather systems, floods, droughts, erosion, land reapportionment, urban growth. Often the most useful applications of GIS have to do with the complex interactions between relatively static geographical entities and the dynamic phenomena through which these entities themselves evolve.

The second category of universally shared geographical concepts concerns the notions of space and time applicable at geographical scales, and in particular the spatial and temporal relations among geographical entities and phenomena. Where something *is* in geographical space is still the quintessential geographical question, though both the question and its possible answers are usually less simple than might appear at first sight. 'Where' may mean on which continent as well as at what precise coordinates or address, or in what direction, how far, next to what, where else, in which part of a region. A useful answer to the 'where' question may be given in latitude/longitude terms, or be something like 'near the lake but not too close to the forest'. Similarly, questions regarding the temporal dimensions of geographical entities and phenomena go well beyond simple 'when' inquiries about clock time and date: what changes since, how fast, what could have caused this, what else happened at about the same time, what came first. As an example of this latter kind of question, GIS is already being used to help arbitrate in debates arising from charges of 'environmental racism', where a critical question is often whether the noxious land-use or the affected minority population was there first. But at what point in time is a land-use or a population 'there'? Even disregarding the difficulty of pinning down the spatial component in this question, we are clearly dealing with two possibly interconnected spatio-temporal processes neither of which can be neatly time-stamped.

Geography and a number of related disciplines have developed an array of methods and tools to help answer these kinds of questions through the spatial and temporal analysis of data about geographical entities and phenomena. Many of these have been incorporated in GIS, and their underlying assumptions about space and time are reflected in the systems' data models, functions and graphic user interfaces. Thus, while few users of GIS may be concerned with space and time *per se*, they all have to live with the consequences of how a particular GIS implicitly treats these notions, and deal with the problems of spatio-temporal representations that may be mutually conflicting or inappropriate for the task at hand.

The purpose of this chapter is threefold: first, it will review the conceptual roots of space and time representations generally, and particularly in the case of GIS. Second, it will assess the place of GIS as information technology at the intersection of several different perspectives on space and time. Third, it will examine the challenges GIS faces in striving to embody appropriate conceptualisations of space and time to meet increasingly complex and sophisticated user needs.

2 DISCIPLINARY ROOTS OF SPATIO-TEMPORAL PERSPECTIVES

2.1 A brief history of space and time

Though invisible and nonsensible, space and time have preoccupied people since antiquity (Jammer 1964). Systematic thinking about space in particular has its roots in four traditional disciplines: mathematics, physics, philosophy, and geography. These represent, respectively, the formal, theoretical, conceptual, and empirical perspectives on the subject. Each of these comprises a large number of different fields or views. For example, mathematics includes geometry, topology, and trigonometry; philosophy comprises epistemology and the philosophy of science; theoretical physics includes classical and relativistic mechanics and quantum theory; and geography is subdivided into human and physical. All these fields, and several others, have developed their own perspectives on space and time (indeed, each of them may encompass a number of substantially different such perspectives). The multiple overlaps among these four major disciplines, and the particular fields and subfields within them, have given rise to additional insights and ways of thinking. This is illustrated in Figure 1. Time has often, though not always, been considered along with space, either as an extension of space or in analogy with it.

Surely the oldest of the four, the geographical way of looking at the world represents the empirical perspective on the subject of space and time at geographical scales. Throughout their history as a

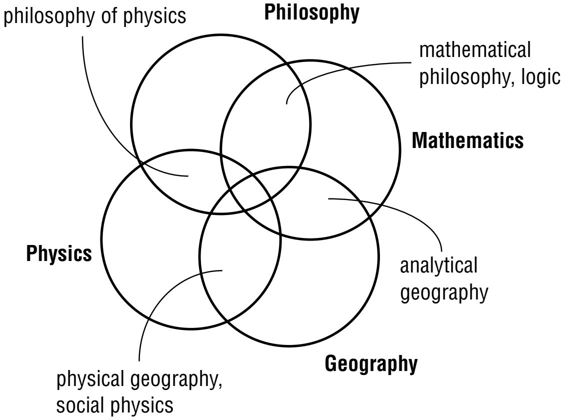

Fig 1. Historical roots of spatio-temporal perspectives.

species humans have always had to deal with rivers, mountains, lakes, oceans, bogs, forests, weather systems, and eventually also roads, cities, and dams. Over the millennia people have evolved a very sophisticated practical knowledge of the spatial and other properties of these entities, the spatial relations possible among them, the range of their variations from place to place, and the changes these may undergo at different timescales (daily, seasonal, or longer term). That knowledge has been recorded by geographers since ancient times, has been codified in maps and nautical charts, has been made increasingly more precise through advancing surveying and positioning technology, and has become to a large extent quantitative and analytical in more recent years.

In their attempts to describe accurately, explain and solve problems relating to the geographical environment, people from early on have turned to mathematics. By some accounts geometry, 'the language of space' (Harvey 1969), originated in ancient Egypt where land surveyors needed to re-establish property boundaries annually following the seasonal flooding of the Nile. The Greek mathematicians, Euclid and the Pythagoreans in particular, brought the science of geometry to a level of perfection that remained unsurpassed for two millennia, while the seventeenth-century work of Newton on the calculus also provided a language for time. Mathematics represents the formal perspective on space and time, bringing its formidable deductive power to the representation, manipulation, and analysis of these elusive concepts.

Of the many kinds of space represented in mathematics, only a few appear to be naturally applicable to geographical-scale entities and phenomena and are thus of direct interest to GIS (Worboys 1995). Euclidean space, the space described by Euclid's five axioms, is an abstraction of people's experience with the spatial properties of the local to medium-scale environment. The basic elements it deals with – points, lines, areas, and volumes – have intuitive interpretations in the geographical world. Euclidean space is also an instance of a metric space, that is, a space in which the notion of distance between two points and its properties are axiomatically defined and quantifiable. The Euclidean distance metric is defined as:

$$d_{ij} = \sqrt{[(x_i - x_j)^2 + (y_i - y_j)^2]}$$

where d is the distance between two points i and j with coordinates (x_i, y_i) and (x_j, y_j). There exist other metrics defining other geometries. The 'Manhattan' or 'taxicab' metric works well in gridded spaces where distance measurement must follow the grid lines (e.g. the gridiron road network in Manhattan). Taxicab distance is defined as follows:

$$d_{ij} = |x_i - x_j| + |y_i - y_j|$$

It behaves differently from Euclidean distance but shares with it the properties of all metrics: it is symmetric (the distance from i to j is the same as that from j to i), and it obeys the 'triangle inequality', meaning that for any three points, the distance between any two of them is never greater than the sum of the distances from these points to the third one. These conditions are easily violated in real environments: distances are usually not symmetric in areas with one way streets, and, if measured in terms of travel time rather than miles, the shortest route between two points is often not the direct route. Variable-metric spaces in which the variation is not systematic are very difficult to represent mathematically.

Genuine non-metric spaces are more general and very powerful. Topological spaces are those dealing with the properties of figures that remain invariant under continuous transformations (e.g. stretching, twisting, squeezing, folding, but not cutting or puncturing). More formally, topological spaces are sets of arbitrary elements (called 'points' of the space) in which a concept of continuity, based on the existence of local (neighbourhood) relations, is defined: it is precisely these relations which are preserved in a continuous mapping from one figure onto another (Alexandroff 1961). Familiar concepts such as inside and out, right and left, touching and overlapping, being connected with, and so on, also express topological relations because they do not depend on metric properties such as shape, size, and distance. Connectivity in particular is a central topological property and is at the basis of the definition of relative spaces, briefly discussed below. What is known as topology in vector GIS is thus a very restricted view of a much broader and more fundamental notion. Topology is a popular area of inquiry among a number of GIS researchers who rightly see it as a rich source of formal insights about how geographical entities may relate to each other in space (Egenhofer and Franzosa 1995; Egenhofer and Mark 1995; Worboys 1995).

The most recent of the four traditions as a distinct discipline, physics has its roots in mathematics and philosophy. Indeed, well into the nineteenth century physics was synonymous with either natural philosophy or applied mathematics. Through physics people were gradually able to organise their formal and conceptual understanding of the world (consisting in large part of the geographical world) into a systematic framework connecting the different pieces of knowledge together. Prominent in that edifice, though not always explicitly so, were the notions of space and time, upon which physics lent its distinct theoretical perspective. Newton's work on classical mechanics could not have been developed in the absence of an underlying model of space and time. Much of the modern understanding of these concepts is attributed to the work of Newton in the seventeenth century, even though the essence of the Newtonian space–time concept was already contained in Aristotle's *Physics.*

Newton's mechanics presupposes a space conceptualised as a neutral container of things and events. Newton himself called this absolute space, in contradistinction to relative space which came to be associated with Newton's contemporary and rival, Leibnitz. Relative space emerges out of the relations among things and events: contrary to absolute space, there can be no such thing as empty relative space. Absolute space is endowed with a 3-dimensional Cartesian frame of reference, to which time may be added as a fourth orthogonal axis. Relative space by contrast does not depend on any frame of reference extrinsic to the spatio-temporal relations represented, and its dimensionality and general properties can vary widely with the geometry entailed by these relations. The triumph of classical mechanics ensured that the notion of absolute space became orthodoxy for three full centuries. It is only in recent decades, following the formulation of alternative notions of space-time in both general relativity and quantum mechanics, that interest in relative space has been revived. Thus for Gatrell (1991) 'space is taken to mean "a relation defined on a set of objects"'. Gatrell goes on to argue for the relevance of that view of space for GIS, which thus far has been based almost exclusively on the absolute-space model. However, the contributions of general relativity and quantum mechanics to our understanding of space and time go well beyond the absolute–relative controversy. It is an open question whether these new conceptions (some of which are downright bizarre), developed for the immensely large and the vanishingly small, have any relevance for space and time at geographical scales and for GIS in particular.

Finally, philosophy is another ancient tradition representing the conceptual perspective on the issues of space and time. From Pythagoras to Russell, Poincaré and Heisenberg, the best philosophers of space and time have often been the great physicists and mathematicians striving to clarify the implications of their own discoveries for our conceptual understanding of the world. Of the debates that took place for over two millennia, a few are directly relevant to GIS. Prominent among these is the question of whether things or properties are the world's primary ingredients (Hooker 1973). This is the fundamental controversy between the 'atomic' and 'plenum' ontologies, allowing two conflicting hypotheses to be formulated (for a discussion of the implications of these hypotheses for GIS, see Couclelis 1992):

- There exist things in time and space which have (known and unknown) attributes;
- The spatio-temporal clusters of known attributes are the things.

The first hypothesis leads to an ontology of objects, the second one to an ontology of fields. Both are in principle compatible with either a relative or an absolute view of space-time, though an advanced exploration of the plenum ontology is likely to lead to a relative view whereby the properties of the space itself come to depend on the properties of the field. According to Einstein (1920: 155):

> 'There is no such thing as empty space, i.e. space without field. Space-time does not claim existence on its own, but only as a structural quality of the field.'

Another old philosophical debate recently found to be of great relevance to GIS is that regarding the ontological status of space and time: are these objective properties of the world, or are they constructs of human understanding? The latter, less popular position was taken by Kant in his *Critique of Pure Reason* (see Friedrich 1977), who argued that space is a 'synthetic *a priori*': something that appears to be the way it is because human minds are such as they are. In recent years a neo-Kantian view of space has been adopted by many geographers and GIS researchers exploring the cognitive dimensions of our understanding of space.

2.2 Spatio-temporal conceptions in the age of GIS

Newton and his contemporaries and followers set the tone for the modern intellectual tradition which was marked by the search for objective knowledge independent of any observer. With the decline of that tradition in the second half of the twentieth century and the advent of postmodernity, two new perspectives on space and time were added to the traditional four: the cognitive and the sociocultural. Both are based on the premise that there is no single objective reality that is the same for all, but that different realities exist for different minds or for different sociocultural identities. This implies that the world as described by mathematics and physics is not the only world there is, and that in fact the world so described may be of little relevance to people's thinking and activities. On the cognitive side of the argument, the experiential perspective in particular, propounded primarily by Lakoff and Johnson (1980) and Lakoff (1987), has attracted a lot of attention among a number of GIS researchers (Mark, Chapter 7; Mark and Frank 1996), while the multiple realities viewed from the standpoint of different sociocultural perspectives have been the subject of investigation by a growing number of critical theorists and cultural geographers (see Pickles, Chapter 4). Thus we may view the four historical 'objective' approaches to space and time as being embedded in the intersubjectivity of the cognitive individual on the one hand and the sociocultural group on the other. This is illustrated in Figure 2. This means that, far from being resolved, the question of space and time has become more complex over the centuries. It is this growing conceptual quagmire that GIS is being called to address in practical terms.

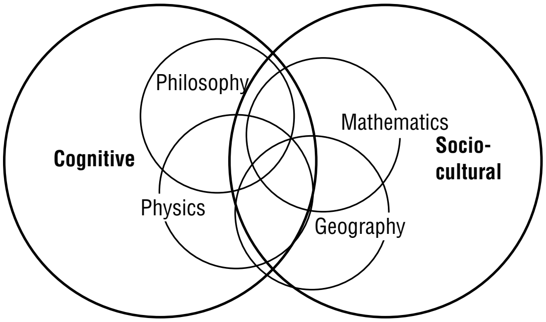

Fig 2. Spatio-temporal perspectives in the age of GIS.

For historical reasons the current generation of GIS embodies the spatial views of a small number of applied disciplines: cartography, computer aided design, landscape architecture, remote sensing. From these it has inherited a strong basis in Euclidean, analytical and computational geometry and a dual spatial ontology of fields (the remote-sensing legacy) and objects (the landscape-architecture legacy), while the temporal aspect, which was mostly absent in the parent disciplines, has been largely neglected until recently and is still often treated almost as an afterthought.

Of the several contributing disciplines cartography has surely had the strongest and most lasting impact on GIS. In fact, GIS may be described (or criticised) as presenting the 'map' view of the world, tied to the notion of an absolute space equipped with a Cartesian or other system of 2-dimensional coordinates. The representation and manipulation of geographical coordinate systems under different geometric projections, and the association of attribute information with specific (x,y) coordinates (geocoding), is as central to GIS as it is to cartography. Much of the power of GIS derives from its strong roots in that ancient discipline which over the centuries has evolved a formidable arsenal of methods for recording, measuring, and representing the surface of the Earth. However, that strength is also the source of several of GIS's weaknesses, as the map view of the world can have serious limitations if stretched beyond its intended purposes: maps are static, flat, 2-dimensional, precise, and not well suited for conveying the fact that the level of knowledge or certainty over their range is often far from uniform (Goodchild 1996). Section 4 below includes a brief discussion on how these limitations are currently being addressed, and what research challenges remain for the future.

3 AN INFORMATION SCIENCE FOR SPATIO-TEMPORAL PHENOMENA

As an information technology the purpose of GIS is not to add another perspective or view on space and time to the many already available, but rather to help convey to the users spatio-temporal information in a form suitable for the task at hand. This simple-sounding requirement is in fact very complex because of the multiple spatio-temporal views simultaneously present in a GIS. There are indeed four critical aspects or players here (see also Goodchild and Longley, Chapter 40):

1. the builder of the database, who is driven by an empirical understanding of the geographical entities and phenomena being measured;
2. the data model on which the database is mapped, which has to conform to the spatio-temporal 'understanding' of the digital computer;
3. the user of the database, who needs to extract the information necessary for a given task from the primarily graphical representations presented by the system;
4. the sociocultural (including disciplinary) context of the task, which determines, among other things, what kinds of questions are to be asked, and what forms of answers are acceptable.

There are thus four qualitatively different spatio-temporal perspectives involved in this process: an empirical one, attempting to capture the spatio-temporal and other properties of cities, lakes, forests, rivers, and so on as accurately as possible; a formal one, based on the properties of points, lines, areas, or pixels, and on the constraints of digital representations; an experiential one, using spatial metaphors and other cognitive devices to convert graphics and other computer-generated signs back into expert geographical understanding; and a social one, focusing inquiry and determining what the ontologies of interest should be. These views are partially conflicting. For example, the point–line–area data model view of vector GIS is ill adapted to the need to represent fuzziness and uncertainty in geographical entities and phenomena as apprehended from either the empirical or the experiential or the social perspectives (Burrough and Frank 1996); on the other hand, the discrete field view represented in raster data models contradicts two basic intuitive notions prominent in the experiential perspective: that geographical space is continuous, and that it is populated with individual things (Couclelis 1992). As another example of such internal conflicts, the temporal aspect is implicitly present in the experiential perspective, explicitly absent or superficially added on in the formal view represented by most current data models, and either absent or present, as the case may be, in the empirical and social views.

Clearly there are issues here that far transcend the technical. Geographical information science has developed out of the maturing GIS technology to address just these kinds of questions that cannot be resolved merely through smarter software and better system design (Goodchild 1992). Elsewhere I have proposed a framework for geographical information science anchored on four vertices representing the above four perspectives: the empirical, the formal, the experiential, and the social (Couclelis 1997). The edges and faces of the resulting tetrahedron represent particular research perspectives in geographical information science, while the core questions, partaking of all four perspectives, are represented by the tetrahedron's interior (Figure 3). Prominent in that scheme is the base triangle defined by the empirical–formal–experiential triad of vertices, which represents the map view of the world, critically augmented by the temporal consciousness and intersubjectivity inherent in the experiential perspective. The 'social' vertex is a more recent addition, marking the growth of the GIS field from a computer-aided technology to a discipline capable of reflecting on the multiple two-way connections between that technology and its social, political, cultural, and philosophical context.

4 CHALLENGES FOR GIS

Geographical information science is a 'meta' science: it is not about the geographical world, it is about information about the geographical world. Contrary to some common misconceptions, information is not a thing – i.e. a bunch of bits – but a relation between a sign and an intentionality: the sign(s) being, in this case, the various graphic and other

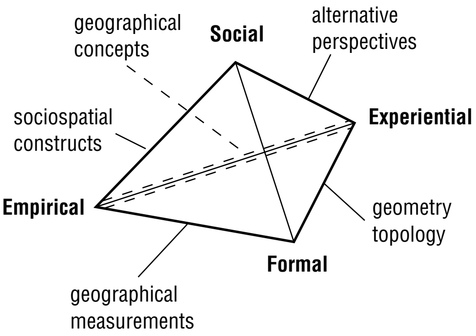

Fig 3. A framework for geographic information science: dimensions of time and space representations for GIS.

forms of GIS output, and the intentionality, the purposeful human intelligence giving meaning to these signs (Couclelis 1997). This implies that the right way to represent geographical information is a function of who is looking at it, and for what purpose: there can be no single right way. What is true of all information is complicated fourfold by the fact that in GIS there are always the four concurrent perspectives (empirical, formal, experiential, and social), each of them with its own preferred views of time and space. In the domain of spatio-temporal representation, the greatest challenge for GIS is thus to move beyond its traditional quasi-exclusive identification with a single view – the map view – useful though this may be for so many purposes, and to permit the simultaneous accommodation of the multiple views required in each case.

Looking back at the variety of approaches to space and time outlined in section 2, it is clear that the map view of the geographical world is only one of many possible. Whether in the 'fields' or 'objects' version, the map view is rooted in absolute Newtonian space and Euclidean geometry. The former is ill matched with the explicit representation and treatment of relations (witness the intractable problem posed in Newtonian physics by the 'three-body problem'); the latter deals with discrete figures, volumes and surfaces defined through infinitely small points and infinitely thin and crisp lines and surfaces. Both presuppose a homogeneous, isotropic space that is a neutral container, and neither is integrated with time (indeed, time cannot even be defined within Euclidean geometry). These properties contradict many aspects of real-world geographical entities and phenomena, which are strongly time dependent, not precisely bounded in either space or time, inhomogeneous and anisotropic as to their attributes and dynamic properties, not properly representable either as geometric figures or as fields, and have complex relations in both space and time with other entities and phenomena.

Researchers have long recognised the limitations of the map view and have proposed several useful extensions of standard GIS that try to address one or the other of these problems, as many of the chapters in this Section demonstrate. Some of these limitations, such as the difficulty of representing more than two dimensions in GIS, are primarily technical. Other efforts focus on more fundamental problems. These may be discussed under the following four headings:

- Integration of space and time
- Representation of relative and non-metric spaces (and times)
- Representation of inexact spaces (and times)
- Representation of commonsense views of space and time.

4.1 Integration of space and time

The static quality of the map has been the primary reason why the integration of the temporal perspective in GIS (and the representation of dynamic phenomena and changing features) continues to be so difficult. Efforts to do justice to the temporal essence of geographical phenomena are relatively recent (Peuquet, Chapter 8; Langran 1992; Langran and Chrisman 1988; Peuquet 1994; Worboys 1995). Standard approaches to representing change within the map view are mostly variations of the 'timeslice' model, consisting of producing a sequence of time-stamped maps corresponding to different time points within a given time interval. The resulting sequence may be represented in GIS either as an ordered set of independent maps, or as a space–time composite layer, or as a 3-dimensional spatio-temporal structure. While sufficient for many purposes, this kinematic (as opposed to dynamic) representation breaks up the continuity of phenomena, may miss temporal orderings indicating causal connections between events, and leaves open the question of what may have happened in the intervals between timeslices.

Advances in temporal GIS involve various departures from the notion of time as a single extra axis added to a Cartesian spatial frame. Two-dimensional time defined on both a real-world time dimension and a database time dimension, and nonlinear time (in the form of forward or backward branching time) have been successfully implemented by several researchers (Snodgrass 1992). Even more advanced notions of time as defined through events, change, motion, and process have also been proposed, though most of these remain at the conceptual level (Clifford and Tuzhilin 1995; Kelmelis 1991). Thus, while great progress has been made in developing data models for GIS that go beyond the timeslice approach, the creation of a truly spatio-temporal GIS remains an unmet challenge (see also Peuquet, Chapter 8).

4.2 Representation of relative and non-metric spaces (and times)

Many geographical phenomena are defined in whole or in part through relations holding among relevant entities. These relations may be material exchanges such as fluid flows or human or animal migration flows between places, functional connections of influence, communication, accessibility, potential interaction, and so on, or cognitive properties of ordering, classification, association, or differentiation. In all but the simplest cases these relations are best seen as defining a relative space, i.e. a space whose properties depend on the configuration of the relevant relations. Handling relative space well will become increasingly important for GIS as cyberspace, the space of electronic connections, continues to expand its hold on every aspect of society.

There are two problems here for GIS. First, rooted as it is in absolute space, GIS does not represent relations well. This is because in absolute space geocoded locations are bound to *a priori* existing relations of geometry and topology among the corresponding points in the space, whereas in relative space the definition of a set of arbitrary relations comes first and the geometry and topology follow. Thus even relations that can be represented on the plane, such as those defined by communication or movement over physical networks, are confounded by the underlying Euclidean metric. For example, a relation of proximity among a set of places cannot be properly represented by the transportation network connecting these places if proximity is defined in terms of travel time rather than distance. While it is often possible to represent well-behaved time distances by subjecting the original map to an appropriate geometric transformation, in other cases the resulting space is non-metric or non-planar and cannot be so represented. More generally, the conflicting properties of absolute and relative space prevent the satisfactory representation of relations in GIS. This is also largely the reason why the proper integration of GIS with geographical models, especially those describing social phenomena, continues to be so difficult. Takeyama and Couclelis (1997) present a partial solution to this problem by formalising the notion of a relational space combining properties from both absolute and relative. Points in relational space behave as in absolute space but are also linked to information on their functional neighbourhoods, i.e. their place in the relative space(s) of which they are part. Elements of this idea are also contained in Tomlin's (1992) map algebra.

A further problem is that for the most part relative spaces are *n*-dimensional, where *n* can be any arbitrary integer. Such spaces defy not only map-based GIS but any analogue (visual or material) representation medium. However, formal and digital representations of *n*-dimensional spaces abound, along with several very useful analysis techniques (e.g. multidimensional scaling, cluster analysis, Q-analysis). There is no reason why these could not be part of GIS data models through which users could derive appropriate partial views linking relative and absolute spaces. An illustration of this possibility is given by Portugali and Sonis (1991), where a 7-dimensional space of labour relations is sequentially projected on an ordinary map of Israel. A more general approach to this problem is known as spatialisation, whereby arbitrary *n*-dimensional spaces (not necessarily derived from geographical phenomena) are transformed into and analysed as familiar (often geographical) spatio-temporal representations.

4.3 Representation of inexact spaces (and times)

In contrast to the more general challenges of space-time and relative-space representation, this one is of GIS's own making. Euclidean geometry, georeferencing and the map view together conspire in forcing GIS into one or the other end of a representational spectrum ranging from crisply delineated, internally homogeneous objects to continuously varying attribute fields. Most geographical entities and phenomena or their most useful representations do not fall neatly into either category (Burrough and Frank 1996). In the literature this problem has usually been treated in terms of fuzziness and uncertainty. The distinction made is that between the geometrical properties of the entities and phenomena themselves, which may or may not be crisply delineated (fuzziness), and the state of our knowledge about these properties, which may or may not be accurate (uncertainty). The latter aspect is being attacked with the tools of probability theory (Goodchild and Gopal 1989), while a growing number of researchers are applying fuzzy set theory to address the many cases where the lack of clear boundaries is an intrinsic property of the entities studied (Burrough 1996). The graphic representation of fuzziness and uncertainty, especially where both aspects coexist, is currently an active area of investigation.

The fuzziness/uncertainty perspective on the issue of inexact spaces decomposes the problem into an objective and a subjective component, whereby a clear distinction is drawn between how things really are out there in the empirical world, and how they are known to be by imperfect human observers. The simplicity of that perspective has fostered much robust research, but it seems likely that alternative views will soon be required in order to deal with more sophisticated demands on future GIS. Thus Couclelis (1996) distinguishes 480 different potential cases of geographical entities with ill-defined boundaries, based on different possible combinations of empirical characteristics, observation mode, and user purpose. While that number in itself is not significant, there are two points worth noting: first, only a few of these cases are fully accounted for through the fuzziness/uncertainty perspective; and second, the variety of cases calls for a corresponding variety of different models of space and time, not all of which can be supported by GIS based on the map perspective.

4.4 Representation of commonsense views of space and time

Introducing purpose and the user perspective into the picture calls for some radically different approaches to the treatment of space and time in GIS. First, this requires the ability to present multiple views of the same information so as to meet different individual interests, skill levels, and needs. Second, the construction of these alternative views must be thoroughly informed by the active ongoing research on the cognitive and social dimensions of space and time. Third, the presentation of the information must be flexible enough to conform to how people use graphic representations of spatio-temporal configurations and phenomena (from sketch maps and flow diagrams to photographs and animations) in reasoning, problem-solving, collaborative work, public debate, teaching, and communication. Work on space and time in GIS is thus expanding well beyond the traditional domain of geometry and topology, investigating issues of language, culture, semantics, metaphor, cognitive configurations, and social constructions (Kuhn 1995; Mark and Frank 1991, 1996; Pickles 1995). Translating these multiple and sometimes conflicting insights into data models that work is no mean task. One of the major research frontiers in GIS lies in this area.

5 CONCLUSION

GIS has come a long way since it was little more than the latest in computer mapping software. With the rapidly increasing technical and conceptual sophistication of the technology came increasingly complex demands and expectations from an ever expanding and diverse user community. Directly or indirectly, the representation of space and time has been central to the pressures for better GIS. Advanced applications require better integration of space and time and ways to represent the entities of interest that go beyond the objects/fields dichotomy; the introduction of the social perspective demands more attention to the issues of subjective perceptions and multiple views of spatio-temporal entities and phenomena; and the establishment of the information age challenges absolute physical space as the sole, undisputed framework for representing geographical reality. We are learning that the geographical is not just the mappable, the spatial is not just the visible, the temporal is not an independent domain, and not all users see the world through the same eyes. The purpose of this chapter has been to review the field of spatio-temporal representation and highlight the unresolved issues, which are many. Research in GIS is moving so rapidly that the next edition of this book is bound to report on some spectacular progress – as well as on the next set of challenges.

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