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Fields and Objects in Space, Time, and Space-time

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The well-known distinction between field-based and object-based approaches to spatial information is generalised to arbitrary locational frameworks, including in particular space, time and space-time. We systematically explore the different ways in which these approaches can be combined, and address the relative merits of a fully four-dimensional approach as against a more conventional 'three-plus-one'-dimensional approach. We single out as especially interesting in this respect a class of phenomena, here called *multi-aspect phenomena*, which seem to present different aspects when considered from different points of view. Such phenomena (e.g., floods, wildfires, processions) are proposed as the most natural candidates for treatment as fully four-dimensional entities ('hyperobjects'), but it remains problematic how to model them so as to do justice to their multi-aspectual nature. The paper ends with a range of important researchable questions aimed at clearing up some of the difficulties raised.

Keywords: Fields, objects, space and time, geo-ontology

1 Introduction

For a considerable time now it has been acknowledged by researchers in geographical information theory that the next generation of Geographical Information Systems (GIS) will incorporate time (Langran, 1992; Worboys, 1994; Peuquet, 1994, 2001, 2002; Raper, 2000). Despite this, there is as yet no consensus as to just what 'incorporating time' should mean, or how it should be accomplished. In this paper I propose to investigate a number of general theoretical issues bearing on the question of how time should be incorporated into GIS, in particular the ex-

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tent to which a thoroughgoing four-dimensionalism is warranted as opposed to a more conservative 'three-plus-one' dimensional approach in which the temporal dimension is held separate from space and not combined with it to form a single locational framework.

We can distinguish a number of possible 'grades of temporal involvement'. Even with a GIS that has no inbuilt facility for handling time, presenting the user with a purely static snapshot of the world, one can *simulate* temporality by means of a series of separate snapshots, each labelled with a different time. This is not, of course, 'temporal GIS', since the system provides no means for operating on data across different snapshots. The temporal reference comes from the way in which the user interprets the relation between the snapshots. By contrast, a truly temporal GIS must provide an intrinsic way of handling temporal references.

An obvious next step is therefore to incorporate the temporal indexing of snapshots into the GIS itself. At the very least, this indexing must reflect the most basic properties of time: certainly the qualitative *ordering* of times, and probably also the quantitative *metric* relations between times. Both of these features can be secured by assigning numerical date-stamps to the snapshots. Combined with some mechanisms for handling the logical and mathematical properties of the temporal ordering, this opens up a number of new possibilities. An ordered sequence of snapshots can be regarded as sampling a set of mathematical functions over time; in the case of continuously varying quantities (such as certain types of field data, or the positions of moving objects), this leads to the possibility of interpolating between snapshots to estimate the values of those quantities at times not represented in the data. Again, a sequence of snapshots can be interpreted cinematographically, to provide animated sequences of some feature of interest. And if the snapshots contain named objects, one can retrieve information about states in their life histories, and from there go on to construct a chronicle of some of the events constituting those histories.

In real life, spatio-temporal information does not necessarily come bundled in complete snapshots. The data may consist of many observations at different times, without there being anything like a complete snapshot at any one time. There may, for example, be data about many specific events relating to different objects—a chronicle in the sense that this term was used above. Taken together, the events in a chronicle might allow one to make many inferences about the state of the world at a given time, thereby in effect allowing one to construct at least a partial snapshot of the world at that time. This is dual to the situation envisaged above, where given snapshots are used to construct chronicles; here, instead, given chronicles are used to construct snapshots. In order to allow this kind of operation, a GIS needs to be able to do more than merely assign date-stamps to a series of separate snapshots; rather, what is required is that each piece of data should be date-stamped separately (with perhaps the possibility of 'timeless' or 'universal' data that is understood to be valid over the full range of times under consideration in a given application).

The duality between snapshot-based views and chronicle-based views can be thought of as the temporal analogue of the well-known distinction between field-based and object-based approaches to geographical information (Peuquet, 1984; Couclelis, 1992; Worboys, 1995; Galton, 2001a, 2001b). A spatial field is a mapping from spatial locations to values from some range—which may be ordered or unordered, and if ordered, continuous or discrete; fields provide answers to questions of the form 'What is the world like at such-and-such a place?'. A spatial object, on the other hand, is an individual entity to which various attributes can be ascribed, including its location (or different locations at different times). A world-view organised around spatial objects thus provides answers to questions of the form 'Where is such-and-such an object?'. Whereas the field-based view treats locations as the prime bearers of spatial information (which thus takes the form of attributes of locations), the object-based view gives this role to objects, spatial information then taking the form of locational attributes of objects. If we replace space by time here, then we see that a temporal field is a mapping from temporal locations to values—so a snapshot may be thought of as composed of the values of a set of temporal fields at a given temporal location. A temporal object, on the other hand, is an independent unity to which may be ascribed, amongst other attributes, a location in time—it is, in other words, a piece of history, i.e., an event or process. These ideas will be made more technically precise below.

The above remarks presupposed that there is a clean separation between (spatial) objects and (temporal) events, but in the real world we find many phenomena of sufficient spatio-temporal complexity that it is not easy to shoehorn them into a simple object/event dichotomy. These include processes such as storms, wildfires, migrations, epidemics, and traffic jams, all of which can present very different aspects when viewed from different perspectives. For example, a meteorologist tracking a tropical cyclone will naturally view it as an object which comes into existence at a certain place and time and moves along a well-defined path, eventually fading away and ceasing to exist. From the point of view of an inhabitant of a town in its path, the cyclone is much more like an event: the sudden onset of strong winds and rain, bringing destruction to the town and then dying away leaving the inhabitants to pick up the pieces. The ontology by which we organise our spatio-temporal data thus needs to go beyond the object/event dichotomy.

One way of thinking about this, which has attracted a number of advocates, is to adopt a thoroughgoing four-dimensionalism, modelling all elements of the ontology as four-dimensional extents. This refers both to the divisions of the spatio-temporal framework itself and to the entities which populate it. Purely temporal intervals and purely spatial regions are replaced by 'chunks' of space-time of various kinds,[1] and the entities will be material extents (‘hyperobjects’) occupying those chunks. Complete four-dimensionalism of this kind has been advocated in the context of spatial reasoning theory by, amongst others, Muller (1998a, 1998c, 1998b) and Hazarika (Hazarika & Cohn, 2001). Hayes (1979, 1985), while not espousing fully-fledged four-dimensionalism, includes four-dimensional entities (‘histories’) in his ontology. Sider (2001) provides a detailed treatment of four-dimensionalism from a philosophical point of view. Zemach (1970) gives a useful overview of the different kinds of ontology arising from different ways of treating space and time.

If we adopt this spatio-temporal point of view then the object/field dichotomy takes on a new aspect. A spatio-temporal field is a mapping from space-time locations to values, and a spatio-temporal object is a hyperobject. In a thoroughgoing four-dimensionalist account of the world, all talk of objects and events must be replaced by talk of hyperobjects, and similarly all spatial and temporal fields must be replaced by spatio-temporal fields. It is clearly a matter of some importance whether such replacements can, in fact, be carried out in a coherent way.

The plan for the rest of this paper is as follows. The next two sections lay some preparatory groundwork for the sections which follow. In §2 I make a few preliminary remarks about the distinction between the (3+1)D ‘endurantist’ and 4D ‘perdurantist’ viewpoints, and in particular I attempt to dispel any suggestion that the latter has to be relativistic in the Einsteinian sense. Then in §3 I discuss the field-based and object-based approaches in a general setting which can be specialised to apply equally to space, time, or spacetime. The next four sections investigate the (3+1)D/4D controversy in the light of different ways of organising the data in terms of the field/object dichotomy. In §4 I look at what happens if all the data are presented in the form of fields; in §5 I consider the case in which the spatial data are object-based but the temporal data are still field-based. In §6 I turn to the case in which all the data are object-based, with spatial objects and temporal objects (i.e., events) handled separately. This leads naturally on to §7, in which I look at fully four-dimensional object-based models which subsume objects and events under a single category of hyperobjects. Finally, in §8, I note some researchable questions to direct further investigations.

2 Endurantism vs perdurantism

Amongst proposals for incorporating time into GIS, we may distinguish between conventional ‘three-plus-one’ dimensional approaches (‘space with time’) and more radical, strictly four-dimensional approaches (‘space-time’). Raper (2000) calls these approaches ‘hybrid’ and ‘integrated’ respectively, and identifies them with the philosophical positions of endurantism and perdurantism. On the for-

[1] These are called ‘histories’ in (Hayes, 1979)—not to be confused with the use of the same term in a somewhat different sense below.

mer, he quotes Peuquet (1994): 'homogeneous four-dimensional representation is not sufficient for use in GIS because time and space exhibit important differences'. On the latter he refers to (Raper & Livingstone, 1995), and mentions as one possible approach 'the use of a Minkowski space-time manifold that is fully four-dimensional in nature'. The reference to Minkowski might suggest introduction of the Special Theory of Relativity (STR), but this has little or no relevance to geography. On the scale of the earth, STR can be replaced by its Newtonian approximation, in which there is a clean separation between the time dimension and the three dimensions of space. Even on the scale of the Solar System, just about the only non-negligible relativistic effect is the precession of the perihelion of Mercury.

Raper, in common with many other authors, also tends to espouse a 'relative' approach to space and time, by which is meant that rather than positing an independent ('absolute') spatio-temporal framework which is then populated by objects, processes, or what have you, it is the objects and processes (or their four-dimensional correlates) which come first, space and time, or space-time, being logical constructs from the relationships amongst those entities.

These two doctrines—the integration of time and space, and the primacy of entities over locations—correspond to two ways in which one might render one's modelling 'non-Newtonian'. Newton famously advocated a view of space and time as absolute frameworks existing independently of any objects and events that might populate them. His dynamics is also predicated on the notion that space and time are *separate* frameworks: given two events, their spatio-temporal separation can be cleanly resolved into a temporal component and a spatial component, and these components, for those two events, are absolute, i.e., the same for all observers. With regard to the former point, Newton's view is opposed to that of Leibniz, who argued that space and time have no absolute, independent existence but only exist by virtue of the things that exist and the events that occur: in other words that space and time are *relational*. There is no evidence, I believe, that Leibniz was in any way opposed to Newton's second tenet, the absolute separability of space and time. This second tenet is opposed not to Leibniz's relationalism but rather to Einstein's relativity—and indeed, it is only with the hindsight afforded by relativity that it makes sense to explicitly attribute the separability doctrine to Newton and his contemporaries. Einstein showed that space and time are not cleanly separable in the way that Newton (and common sense) supposed: that (i) resolution of the separation between two events into a spatial component and a temporal component is not absolute, but dependent on the state of motion of the reference frame within which they are considered, and (ii) there is no privileged reference frame which can be regarded as giving the 'true' picture. In that sense, space and time are relative—to one another, and to the observer. One can accept this and still hold onto a Newtonian view of space-time as existing independently of any objects or events, the only difference being that it is not space and time separately that enjoy this independent existence, but an integrated space-time.[2]

What is the upshot of all this for GIScience? First, although it is perfectly possible to advocate a four-dimensional point of view in GIScience, one is not thereby advocating a relativistic point of view—as I have indicated, the Theory of Relativity is largely irrelevant to GIScience. Second, if one wishes to have an object-based or event-based approach, renouncing a fixed spatio-temporal coordinate system in favour of specifying positions and times purely in relation to given objects or events, that can be done independently of whether or not one adopts a four-dimensional point of view—only the details being dependent on which choice one makes. Thus in principle, as Raper demonstrates, there are four choices open to us here: absolute integrated, absolute hybrid, relative integrated, and relative hybrid.[3]

The philosophical positions known as *endurantism* and *perdurantism* are characterised by the view they take of objects and change. An endurantist holds that what exists at any one time are complete objects, and that these objects have properties which can vary across time while preserving the identity of the object. The object is extended in space—it has spatial parts—but on the endurantist view it would not be correct to describe the persistence of the object through time as extension, since the different temporal phases of the object's existence are not parts of the object. Thus an object, endurantistically conceived, can be in the same place at different times, but not in different places at the same time. The perdurantist takes a more even-handed view of how an object is situated in space and time: the object, for the perdurantist, should be identified with its complete spatio-temporal extent. This means that the perdurantist object does not change: rather, what the endurantist would call change is built into the perdurantist object as an inhomogeneity in the temporal dimension, entirely comparable to inhomogeneities in the spatial dimensions.[4] An object, on the perdurantist view, can have parts which occupy different places at the same time, and also parts which occupy the same place at different times, but the object as a whole—or hyperobject as we have termed it—just occupies a single chunk of space-time.

[2] Admittedly, in *General* Relativity, this view becomes less tenable, at least to the extent that the very form of space-time becomes dependent on what it contains.

[3] Raper also has a third dichotomy cutting across these: discrete vs continuous. This is not relevant for my present purposes.

[4] Geach (1965), in arguing vehemently against the perdurantist view, put it thus: "On this view, the variation of a poker's temperature with time would simply mean that there were different temperatures at different positions along the poker's time-axis. But this . . . would no more be a *change* in temperature than a variation of temperature along the poker's length would be."

3 Field-based and object-based representations

In this section I briefly review the distinction between field-based and object-based approaches in sufficient generality that they may be applied indifferently to space, to time, and to space-time. In general, a *locational framework* is a set whose individual elements are called locations. For a given locational framework L, an L-*field* is any function mapping elements of L to values. In this general setting we impose no restriction on the set from which the values are taken, but we can assume that a given L-field f has a value-set V_f associated with it, so the functional type of f can be given as

$$f : L \rightarrow V_f.$$

Any finite number of distinct L-fields can be overlaid to give a single field, according to the following scheme (Galton, 2001b): from the fields

$$\begin{array}{ll} f_1 : & L \rightarrow V_1 \\ f_2 : & L \rightarrow V_2 \\ \vdots & \vdots \\ f_n : & L \rightarrow V_n \end{array}$$

we derive the field

$$f_1 \times f_2 \times \cdots \times f_n : L \rightarrow V_1 \times V_2 \times \cdots \times V_n$$

such that

$$f_1 \times f_2 \times \cdots \times f_n : l \mapsto \langle f_1(l), f_2(l), \ldots, f_n(l) \rangle.$$

The upshot of this is that we can consider all our field data (assumed finite in amount!) as given by a single field.

The field-based approach is contrasted with the object-based approach, and this too can be described in relation to a general locational framework. An L-object is, essentially, a bundle of attributes associated with a position in L. An L-ontology is a collection of L-objects. The position of an object may span more than one individual location.[5] If o is an object, we may denote its position by $pos(o)$, so the function pos is of type[6]

$$pos : O \rightarrow 2^L,$$

[5]The terminology used here—'position' vs 'location'—is not meant to reflect any prior distinction in the usage of these terms, and may be regarded as somewhat arbitrary and provisional. The locations are primitive, non-decomposable elements of the framework (think of points or cells), whereas the positions are aggregates of these ('regions') that can be occupied by extended objects.

[6]2^L is the power set of L, that is, the set of all subsets of L. Thus $X \in 2^L$ if and only if $X \subseteq L$. In general, one would not expect all sets of locations to be possible positions of objects, but on the other hand most attempts to restrict the class of positions to some more narrowly circumscribed subset of 2^L involve questionable assumptions. There is no harm in setting the codomain of pos to be the full power-set, so long as there is no expectation that pos should be a surjective function.

where O is the L-ontology. It is characteristic of objects that they are assigned to various types, and this is an extremely important aspect of the development of any ontology in practice. For my present purposes, there is no need to make reference to types and I shall therefore remain silent about them.

There are a number of important distinctions between fields and objects. First, objects often involve a higher level of abstraction than fields: fields provide the raw data in the form of what properties are ascribed to individual locations, whereas objects are 'chunks' that are 'carved out' of the raw data and referred to as unities with their own (higher-level) properties.[7] Second, as noted by Couclelis (1992), the field-based view aligns with the view of the world as a plenum, with properties ascribed to every location, forming a continuous fabric, whereas the object-based view is discrete, atomistic, allowing for the existence of locations void of content—the overall picture being one of objects as inhabitants of an otherwise empty space. The plenum aspect of fields fits in well with the term 'coverage' which is often used to refer to geographical data in field form. The reference to space here should not detract from the fact that this field/object opposition has been presented in a way that is neutral between time and space, and therefore equally applicable to both.

The contrast between fields and objects is usually drawn in the context of space. In this case the locational framework is a set S of spatial locations, providing a spatial framework which can support spatial fields and objects. A spatial field (S-field) is a mapping from spatial locations to values—it is what is normally understood by a field in GIScience. The value associated with a location may be a real number, an integer, a character string, or indeed any other data structure. In principle there is no limit to the kinds of information which can be 'attached' to a spatial location. The crucial point about a field, though, is that it provides a coverage of space, that is, it is, in principle, defined at every point in space (or more exactly, at every minimal location—here allowing the possibility of a discrete model of space in which there are irreducible minimal regions which are not decomposed into subregions). Spatial objects (S-objects) are what we normally refer to as objects; but to avoid confusion, I shall here use the term *continuant* from the philosophical tradition. Continuants come in a variety of kinds, for example (i) mobile objects (e.g., people, cars), (ii) fixed objects sharply distinct from their environment (e.g., trees, buildings), (iii) fixed objects that form part of the environment (e.g., roads, rivers, mountains), and (iv) conventional ('fiat') objects which only exist by virtue of human convention (e.g., administrative units, land registry parcels). Needless to say, the distinctions amongst these kinds are not hard and fast, and in particular the distribution of objects between categories (ii)

[7] To say this is not to pre-judge the issue as to whether objects really exist in their own right or are merely cognitive artefacts arising from how we (as human objects!) interpret and interact with fields—on any level-headed view, surely, some objects are of the former kind and some are of the latter.

and (iii) may be quite sensitive to changes in point of view (e.g., as to what counts as 'the environment').

If the locational framework is instead taken to be a set T of times, then we can speak of a temporal framework, temporal fields, and temporal objects. A temporal field (T-field) is a mapping from times to values, and therefore a *history* in the sense used above; the values can be thought of as specifying the state of the world, or some part of the world, at different times. Thus temporal fields provide a state-based view of the changing world. A temporal object (T-object) is an event or process, a bounded episode of change that forms a salient landmark in the history of a place, object, or group of objects in the world.[8] Thus temporal objects provide an event-based view of the world; a description of the world's history formulated in terms of events may be called a *chronicle*.[9]

We may distinguish instantaneous (punctual) events from those which take time (durative). Strictly punctual events mark the onset or termination of states of affairs (e.g., an object's starting to move, or coming to rest, or ceasing to exist, or two objects' coming into contact or separating). These are the temporal analogues of the surfaces of spatial objects. In addition there are events which it is often convenient to regard as punctual because, although strictly durative, they only last a very short time—essentially a period of time that is indivisible at the temporal granularity with which the event is represented (more like a skin or membrane than a surface in the strictest sense). Because of granularity dependence, the events which count as punctual in this sense depend strongly on the context. In the context of describing the hundred years' war, whole battles may for the most part be treated as punctual; if the focus shifts to the day-to-day activities of individual combatants, a battle may have significant duration. Amongst events treated as durative we may distinguish *atelic* events, which consist of some repetitive or non-cumulative process subsisting over a period of time (e.g., an episode of rain), from *telic* ones, which move towards some termination point after which they cannot be continued (e.g., the construction of a building).

The third kind of locational framework we shall consider is the product $S \times T$ consisting of spatio-temporal locations each of which has a spatial component and a temporal component: it is a spatial location at a time. This may be viewed as a spatio-temporal framework which can support spatio-temporal fields and objects. A spatio-temporal field ($S \times T$-field) is a mapping which assigns a value to each location at each time. A spatio-temporal object ($S \times T$-object) is the material content of some 'chunk' of space-time, an entity with both spatial and temporal

[8] In the philosophical literature, continuants (i.e., our S-objects) are generally contrasted with *occurrents*; but it is not entirely clear to me whether this term should be used for T-objects, $S \times T$-objects, or both.

[9] Thus 'history' and 'chronicle' are here being used as technical terms of art with specific and well-defined meanings. No assumptions should be made concerning any possible relationship between the way these terms are used here and the ways in which they have been used elsewhere, either as technical terms or in an everyday sense.

extent: what I call a hyperobject. From the perdurantist point of view, hyperobjects are all the material objects that there are. This will be discussed further below.

4 Snapshots and histories

The simplest way of incorporating time is by means of an indexed sequence of 'snapshots'. A snapshot is a static representation of the world as it exists at one moment in time. Let us write $snap(t)$ to denote the snapshot corresponding to time t. Then a sequence $snap(t_1), snap(t_2), \ldots, snap(t_n)$, where $t_1 < t_2 < \cdots < t_n$, does indeed incorporate time. If we want to know the state of the world at one of our times t_i, then we need only consult the appropriate snapshot $snap(t_i)$. If we want to know the state of the world at a time t which is not in the sequence, then depending on the nature of the information presented in the snapshots it may or may not be possible to make inferences from the snapshots using some form of interpolation. The restriction to a finite set of t_i merely reflects the practical impossibility of amassing an infinite quantity of information; theoretically, it is appropriate to think of $snap$ as a function mapping every time t in the range of time under consideration to a snapshot representing the state of the world at that time; it is, in fact, a temporal field, or *history*.

The information contained in the snapshots may take various forms, but we can broadly classify it into information about places and information about things—the former relates to the field-based approach, the latter to the object-based. In practice, any reasonably sophisticated GIS will be able to handle both kinds of information, but for the sake of simplicity let us for the moment assume that the snapshots $snap(t)$ are pure in the sense that either they contain information about fields, or they contain information about objects.

We consider the field case first; objects will be considered in §5. A (spatial) field is a function which assigns to each spatial location a value of some kind, and as noted in §3, we can assume that all the information in a snapshot is bundled together into a single field. Thus a snapshot can be specified by a single function $snap(t) : S \to V$, where S is the set of all minimal spatial locations and V is the set of possible values that the field can take. The snapshot function now takes the form:

$$snap : T \to (S \to V),$$

where T is the set of times. The function $snap$ is a *global history* since it gives the state of the entire space at each time.

Mathematically, the function $snap$ defined above is equivalent[10] to the function

$$hist : S \to (T \to V)$$

[10] Here and in what follows, when two functions are described as 'equivalent', what is meant is that there is a canonical way of deriving the values of either function from the other.

defined by the equivalence $[hist(s)](t) = [snap(t)](s)$. The point of this manoeuvre is that it presents us with a rather different perspective on the same set of data. The function $hist$ is a spatial field, since it assigns a value to each spatial location, but the value that it assigns is itself a mapping from times to values—in other words a temporal field, or history: $hist(s)$ is the history of the location s, assigning to each point in time the state of affairs obtaining at location s at that time. We may therefore call $hist(s)$ a *local history*, in contrast to the global history $snap$.

Both these functions, $snap$ and $hist$, are equivalent to the function

$$state : S \times T \rightarrow V$$

defined by the equivalence

$$state(s, t) = [hist(s)](t) = [snap(t)](s).$$

This is a spatio-temporal field. The value $state(s, t)$ gives the state of the world at location s and time t. The 'raw data' might well take the form of a collection of values of this form. The functions $snap$ and $hist$ organise this data in two orthogonal ways, either collecting together all the values pertaining to different places at a given time, or collecting together all the values pertaining to a given place at different times. Thus there is a natural duality between snapshots and histories, but either way of organising the raw data may be regarded as '(3+1)-dimensional' because it treats time and space differently, as opposed to the raw data themselves which impose no preferred organisation on the collection of spatio-temporal locations and may therefore fittingly be described as 4-dimensional. The equivalence of all these points of view suggests that if our data are presented in this field-based way, with values assigned to locations, then it should make little difference whether we think in terms of 4D or (3+1)D representations.

In practice it can make a difference, however. This is because our data are never complete: we do not know the value of $state(s, t)$ for every $s \in S$ and $t \in T$. There are various possibilities, as follows.

1. One possibility is that we have a discrete sequence of snapshots corresponding to times $t_1, t_2, t_3, \ldots, t_n$, and that each snapshot gives the value of the field variable at the same fixed sample set of spatial locations s_1, s_2, s_3, …, s_m. In this case, there are three mathematically equivalent and equally viable ways of viewing the data:

   (a) As a sequence (or 'temporal array') of snapshots:

   $$snap(t_1), snap(t_2), snap(t_3), \ldots, snap(t_n).$$

   (b) As a spatial array of local histories:

   $$hist(s_1), hist(s_2), hist(s_3), \ldots, hist(s_m).$$

(c) As a spatio-temporal array ('hyperarray') of individual values:

$$\begin{array}{lllll} state(s_1,t_1), & state(s_1,t_2), & state(s_1,t_3), & \ldots, & state(s_1,t_n), \\ state(s_2,t_1), & state(s_2,t_2), & state(s_2,t_3), & \ldots, & state(s_2,t_n), \\ state(s_3,t_1), & state(s_3,t_2), & state(s_3,t_3), & \ldots, & state(s_3,t_n), \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ state(s_m,t_1), & state(s_m,t_2), & state(s_m,t_3), & \ldots, & state(s_m,t_n). \end{array}$$

The first two ways may be regarded as having a (3+1)D flavour because they treat the spatial and temporal aspects of the data differently, but the the third way might equally be regarded as having a 4D flavour.

2. A second possibility is that we have a discrete sequence of snaphots corresponding to $t_1, \ldots, t_n$, but the spatial locations at which values are known may be different at different times. In this case we cannot in general reconfigure the data as a spatial array of histories, since it is quite possible that for most of the spatial locations represented the value is known for only a single time. We can still accommodate this possibility within a (3+1)D picture. For example, if we wanted to use interpolation to estimate unobserved values, we could first interpolate spatially within snapshots, and then temporally between snapshots, with no necessity for mixing the spatial and temporal aspects.

3. A third possibility is the dual of this, in which we have a spatial array of histories, corresponding to the locations $s_1, \ldots, s_m$, but the times for which field-values are known may be different for different locations. If there is little or no agreement from one location to the next as to which times are represented, then it will not be possible to reconfigure the data as a sequence of snapshots, but as in the previous case, space and time are still sufficiently separate to accommodate this case within a (3+1)D picture.

4. The fourth and final possibility is that the space-time points for which values are known are 'dotted about' unsystematically, so that it is impossible to present the data either as a sequence of snapshots or as a spatial array of histories. In this case one cannot perform spatial and temporal interpolation separately, and must instead embark on the problematic enterprise of fully spatio-temporal interpolation—problematic because there is no fixed way of relating spatial distances and spatial modes of variation to temporal distances and temporal modes of variation. Whatever solution is adopted in this case is likely to have a more 4D flavour.

The problems concerning fully field-based data primarily concern how the data are organised (e.g., whether the temporal organisation takes priority over the spatial, or vice versa, or alternatively no distinction is made between them) and the effect this can have on data-manipulation—which in the field-based world view consists primarily of statistical methods such as interpolation, averaging, etc. Although some of these issues do present problems, it does not seem that the choice between 4D and (3+1)D representations is critical so long as all the data are in field form.

5 Snapshots and life-histories

I turn now to the second case, in which our information about the world is still organised in the form of snapshots, but now the information contained in the snapshots is object-based: that is, it specifies the locations and attributes of some set of continuants constituting an ontology. For the sake of simplicity, I shall assume that location is in fact the *only* attribute of continuants that we are interested in. If we wish to include other attributes, this will complicate the account, but will not substantially alter the overall structure of what is presented here. Just as a collection of fields can be overlaid to produce a single compound field using the Cartesian-product construction, so too a collection of attributes could be bundled together to produce a single compound attribute whose values track the variation, across time and between individuals, of its components. We can, if we wish, interpret 'position' in what follows as referring to a compound attribute of this kind, including spatial position, narrowly conceived, as just one of its components.

An object-based snapshot of the world specifies the position of each continuant at a given time: we could call this the *configuration* at that time. Thus the snapshot can be specified by a mapping $\mathit{config}(t)$ giving the position of each continuant at that time, that is, a function

$$\mathit{config}(t) : C \to 2^S,$$

where C is the set of continuants. The temporal field is then given by the function config which maps each time onto the configuration obtaining at that time:

$$\mathit{config} : T \to (C \to 2^S).$$

Mathematically, this is equivalent to having a function

$$\mathit{life} : C \to (T \to 2^S)$$

which assigns to each continuant its (positional) life-history consisting of a mapping from times to positions (so $[\mathit{life}(c)](t) = [\mathit{config}(t)](c)$).[11] And of course it is also equivalent to a function pos mapping continuant-time pairs to positions:

$$\mathit{pos} : C \times T \to 2^S,$$

[11] If we replace 'position' by a more comprehensive description of the attributes of a continuant, then the life-history becomes correspondingly enhanced to include changes in attributes other than position.

where

$$pos(c,t) = [life(c)](t) = [config(t)](c).$$

In all of these cases, the time dimension is treated differently from the space dimension, so our model is (3+1)D rather than 4D. The 4D equivalent of this picture is the familiar idea of 'space-time worms'. The worm corresponding to a continuant c is the set of space-time points

$$worm(c) = \{\langle s,t\rangle \mid s \in pos(c,t)\},$$

the functional type here being

$$worm : C \to 2^{S\times T}.$$

The cross-section of $worm(c)$ at time t is $pos(c,t)$. A snapshot of the world at time t is the world-state $config(t)$ which maps all continuants to their positions at t.

Within this mathematical model we can characterise the differences between endurantism and perdurantism as follows:

1. On the endurantist view, the continuant c does not have a position *tout court*, but rather occupies different positions at different times: at time t, continuant c occupies position $pos(c,t)$.

2. On the perdurantist view, the continuant c is replaced by a hyperobject—let us call it h—which has as its single space-time position the four-dimensional region $worm(c)$.

3. What the endurantist regards as the presence of the complete continuant c occupying position $pos(c,t)$ at time t, the perdurantist regards as an instantaneous cross-section of the hyperobject h.[12]

4. What the perdurantist regards as the position of hyperobject h, the endurantist regards as a composite derived from the successive positions occupied by c during its lifetime.

5. What the endurantist regards as motion of the continuant c over a time interval (t_1,t_2) appears from the perdurantist perspective as the circumstance that the portion of $worm(c)$ between the hyperplanes $t = t_1$ and $t = t_2$ does not run parallel to the t-axis.[13]

It is important to stress that this picture, whether viewed endurantistically or perdurantistically, does not treat time on the same footing as space. This is because

[12] Hayes (1985) calls such a cross-section a *state*.

[13] Of course this can be *called* 'motion' on either view—a point not always appreciated by endurantists arguing against the perdurantist position.

we are working with a notion of 'object' which is essentially derived from the traditional endurantist view. The life-histories $worm(c)$ all have a preferential 'direction', elongated roughly parallel to the time axis like the grain in a piece of wood or the constituent fibres of a rope. One can translate between the two views, and the differences are largely a matter of how one describes the phenomena. The perdurantist view can only come into its own if we are prepared to embrace a wider variety of spatio-temporal objects, not just four-dimensionalised versions of familiar spatial continuants. In that case the 4D view allows the possibility, in principle, for us to consider arbitrary spatio-temporal extents to be the locations of hyperobjects. We shall investigate this possibility in §7 in connection with a class of phenomena, neither clearly continuants nor clearly events, which I call 'multi-aspect phenomena'.

6 Continuants and Chronicles

What happens to the object-based view of the world if we extend the object idea to the temporal dimension as well as the spatial? That is, instead of considering the life-histories of continuants, modelled as temporal fields, we record all change by means of discrete events happening to discrete continuants or groups of continuants. This is a fully object-based (3+1)D representation; it contains references to spatial objects—continuants—and temporal objects—events—and nothing else. A given event may involve one or more continuants, and a given continuant may be involved in any number of events. The events in which a continuant is involved constitute landmarks or salient episodes in its life-history.

Formally, we have two ontologies, a spatial ontology C consisting of continuants, and a temporal ontology E consisting of events. The ontologies are linked because events affect the attributes of continuants—in particular, their positions. The effect of an event is thus to change the positions (or other attributes) of one or more continuants, which we may regard as the *participants* in the event. Thus given $e \in E$ we may put

$$\mathit{effect}(e) = \{\langle c_1, p_1, p'_1\rangle, \langle c_2, p_2, p'_2\rangle, \langle c_3, p_3, p'_3\rangle, \ldots, \langle c_n, p_n, p'_n\rangle\},$$

where $c_1, c_2, \ldots, c_n$ are the participants in e, and the effect of e on c_i is to change its position from p_i to p'_i. Creation and destruction of a continuant can be regarded, perhaps with some artificiality, as special cases of this, where either p_i or p'_i is instantiated to the null region $\emptyset$. The functional type of *effect* is thus

$$\mathit{effect} : E \to 2^{C \times 2^S \times 2^S}.$$

The time of occurrence of an event is given by another function

$$time : E \to T \times T,$$

giving the interval $time(e) = \langle t, t' \rangle$ (where $t \leq t'$) over which the event takes place. For a punctual event, we can set $t = t'$.

As an example of a completely object-based approach to modelling a changing world one might consider the work of Hornsby and Egenhofer on ‘identity-based change’ (Hornsby & Egenhofer, 1998, 2000). They consider geographical continuants such as islands, buildings, mountains, and states, and classify the various kinds of changes (‘operations’) they can undergo which have implications for their identities over time, devising a simple graphical notation for representing these changes in an intuitively accessible way. Operations on a single continuant include creation, destruction, elimination, recall, reincarnation and various kinds of continuation. Operations involving two or more continuants are merging, generation, mixing, aggregation, compounding, uniting, amalgamation, and combination. A further set of operations covers the splitting up of continuants: splintering, division, secession, and dissolution. Amongst these operations are some which may seem superficially similar, but each is given a precise definition in terms of the identity status of the various objects involved before and after the change.

This kind of classification of varieties of change is by no means of purely theoretical interest. Consider, for example, the following classification of boundary changes published by the Oregon Department of Revenue:

> An *annexation* occurs when one district extends its boundaries outside of its previous service area. …
> A *merger* occurs when two or more districts formed under the same statutory authority, providing the same services, agree to operate as one district. One of the districts is the “surviving” district. …
> A *consolidation* occurs when two or more districts agree to dissolve and form a new district providing the same services as the old districts. …
> A *division* occurs when an existing district is divided into two or more smaller districts. … The “existing” district is dissolved.…
> A *new district* is formed after an election or action of the county governing body. …
>
> (Oregon Department of Revenue, 1999)

Both in the general spirit of the kinds of changes proposed and, to some extent, in some of the specific details, this set of definitions is strikingly reminiscent of the scheme proposed by Hornsby and Egenhofer.

This work is most naturally applicable to man-made (‘fiat’) continuants such as political and administrative divisions. Natural phenomena, by contrast, may seem more amenable to a field-based approach. None the less, an object-based approach to natural continuants should not be ruled out, and in some cases may be entirely appropriate. This is particularly the case where one is dealing with a mixture of natural and conventional objects and is interested in the relation between them.

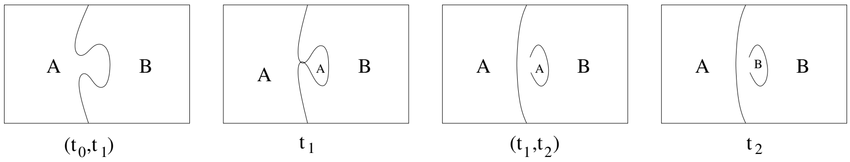

Figure 1.: Evolution of a river boundary

As an example, consider a simple scenario consisting of a stretch of river R and two nation states A and B sharing a common stretch of border (see Figure 1). The shared border is fixed by treaty at time t_0, when it is stipulated that it should coincide with the river R; it is further stipulated that so long as changes to the course of the river are gradual, the border between A and B should remain coincident with the river, but in the event of a sudden change in the river's course, the section of border coincident with that part of the river that undergoes sudden change should remain in the position that it occupied prior to the change.[14] From t_0 to t_1, the river undergoes only gradual change, but at t_1 a meander (of which the land on the concave side belongs to region A) is broken through, isolating a stretch of the former river course as an ox-bow lake. In accordance with the treaty, the piece of land enclosed between the ox-bow and the new river course remains allocated to A, even though it is now on B's side of the river. Subsequently, at time t_2, a new treaty is agreed according to which the border between A and B is once again stipulated to coincide with the course of the river; this has the consequence that the aforementioned piece of land is transferred from A to B.[15]

In a wholly object-based model, this scenario can be described by means of the following set of data structures:

1. CONTINUANTS. For each continuant we specify its type, ID, and associated events (creation, modification, destruction). Our scenario requires the continuants

CONTINUANT	Type:	Border
	ID:	AB
	Events:	$Treaty1, Treaty2$
CONTINUANT	Type:	River
	ID:	R
	Events:	$MCO, RCD1, RCD2$

[14] Gradual and sudden changes of this kind are known in legal contexts as 'accretion' and 'avulsion' respectively. From a mathematical point of view, these can be idealised as continuous and discontinuous changes.

[15] This scenario is not by any means fanciful: precisely such a sequence of events has happened many times along the U.S.-Mexican border where this follows the Rio Grande (Boggs, 1940).

2. EVENTS. For each event we specify its type (punctual or durative), ID, time, and initial and final states.

EVENT	Type:	Punctual
	ID:	MCO ('Meander Cut-Off')
	Time:	t_1
	Initial:	Position of R is P_1
	Final:	Position of R is P_1'

EVENT	Type:	Punctual
	ID:	$Treaty1$
	Time:	t_0
	Initial:	–
	Final:	AB coincides spatially with R so long as the position of R changes continuously

EVENT	Type:	Punctual
	ID:	$Treaty2$
	Time:	t_2
	Initial:	–
	Final:	AB coincides spatially with R so long as the position of R changes continuously

EVENT	Type:	Durative
	ID:	$RCD1$ ['River-Course Development']
	Time:	(t_0, t_1)
	Initial:	Position of R is P_0
	Final:	Position of R is P_1

EVENT	Type:	Durative
	ID:	$RCD2$
	Time:	(t_1, t_2)
	Initial:	Position of R is P_1'
	Final:	Position of R is P_2

It will be noted that the positions of continuants are not given directly in the continuant data-structures; this is reasonable since position of a continuant is not, in general, an attribute that is fixed over the lifetime of the continuant. Positions are ascribed to continuants at times through specific events by which their positions are changed.[16]

[16]This raises the question of how continuants come to have positions in the first place. There are two distinct cases here. First, a continuant may come into existence at a particular time and place: in that case, we will include in our database a *creation* event, which specifies as its final state that the

If the chronicle of events in a continuant's life is given in sufficient detail, it might be possible to reconstruct its entire life-history, that is, the temporal field $hist(c)$ which gives the attributes of the continuant at each time; but it is by no means a precondition of the viability of the object-based model that it should be complete in this sense, and in reality we usually have to be content with a state of partial ignorance.

In the context of our overall investigation, the key thing to notice here is that this model is still essentially (3+1)D, since it distinguishes sharply between spatial objects and temporal objects. In the next section, we consider what a truly 4D model might look like, and whether there are phenomena in the real world which require this kind of model for their accurate representation.

7 Beyond continuants and events: multi-aspect phenomena

In a fully four-dimensional object-based model, there is really only one kind of object, whose position is specified as a 'chunk' of space-time. We call such an entity a 'hyperobject'. In principle, arbitrarily shaped chunks of space-time could be used to specify a hyperobject, and indeed the more hospitable we are to admitting a wide variety of different four-dimensional forms into our ontology, the more clearly we may be said to espouse the four-dimensionalist viewpoint. In practice, four-dimensionalism represents a considerable departure from our commonsense (3+1)D way of looking at things, and for this reason the kinds of hyperobject that will most readily occur to us are precisely those which admit alternative descriptions in (3+1)D terms.

Starting from a (3+1)D point of view, the types of hyperobject which it is natural to consider include:

1. *Region-histories*. These occupy hyperprisms of the form
$$R \times I = \{\langle s, t\rangle \mid s \in R, t \in I\},$$
where R is a region of space and I is a time interval.

2. *Continuant-histories*. For a given (endurantist) continuant c, its history occupies the space-time chunk $worm(c)$ defined in §5.

3. *Events*. An event may be a delineated episode in the life-history of a continuant, in which case the event-location could be a part of a continuant-history; or it may be an instantaneous change in an continuant, so its location is not *part* of the life-history so much as an 'infinitely thin slice' through

continuant in question exists and is located at a particular position. Second, for continuants which exist throughout the period of time handled by the database (so there is no creation event to record), we require an *initialisation* event which establishes the attributes of the continuant at the base time ("Year 0").

> it. But an event may have more than one participant, in which case its location must include parts of several individual continuant-histories; and of course an event need not involve readily-individuated continuants at all—e.g., a flooding event, whose spatio-temporal location might consist of a set of $\langle s, t\rangle$ such that the (normally dry) land at s is under water at time t.

Moving beyond these, one might say that hyperobjects may be specified to exist on arbitrary chunks of space-time, but this statement is essentially vacuous unless some indication is given as to how such chunks might be defined. The methods listed above are the obvious starting point, but do not seem to take us much beyond a (3+1)D point of view. Perhaps there is good reason for this: perhaps fully-fledged four-dimensionalism is unattainable because space and time—or at any rate our experiences and conceptualisations of them—simply *are* different.

Of the examples mentioned above, it is the flooding event that comes nearest to escaping the bonds of the (3+1)D view. A flood is not unambiguously either a continuant or an event. It has, we might say, both continuant-like and event-like aspects, and as such might *best* be represented as the occupant of a chunk of space-time. In its continuant-like aspect, a flood resembles a lake, a pond, or a puddle. It is a body of water situated in a specific bounded region. You can stand at the edge of the flood and look out over it, you can row a boat over it or swim in it, you can measure its area—all these things you can do with a lake as well. The difference between a flood and a lake is that the flood is ephemeral, occupying a region that most of the time is dry land. But, you might argue, on a geological time-scale most lakes are ephemeral too, so the difference between a lake and a flood is one of degree rather than kind. And puddles, which we usually treat as objects like lakes, are just as ephemeral as floods—more so, indeed. In its event-like aspect, a flood resembles the occupation of a sovereign state by an invading army. Like the occupation, it has a beginning, a duration, and an end. 'What did you do during the occupation?' and 'What did you do during the flood?' are comparable questions (try replacing 'flood' by 'lake' here!). Like an occupation, different spatial locations may succumb to the flood at different times—the event as a whole has a structure and can be broken down into notional sub-events with greater or lesser degrees of artificiality.[17] [18]

If our conceptual model of the phenomena is so structured that every object must be presented either as a continuant or an event, then we cannot model the flood as an object without first deciding which of these it is—and the preceding

[17] Hayes (1985) gave the classic treatment of the ontology of liquids; while he has much to say about lakes and is sensitive to the dynamic aspects of aquatic phenomena, he does not specifically refer to floods.

[18] One reviewer complained that in their idiolect 'flood' only refers to the event, not to the resulting floodwater. But in fact my argument does not critically depend on our using the same word for both aspects—it seems that we have here a multi-aspect phenomenon independently of the language we use to describe it. Which is not to deny that language and ontology are intimately bound up together!

paragraph suggests that neither decision would do full justice to the phenomenon itself.

One way out of this difficulty might be to renounce all pretensions to viewing the flood as an *object* at all. Instead, we work with a field-based model in which presence or absence of standing water is an attribute that may be applied to each spatial location at each moment in time. This takes us back to the kind of model discussed in §4, and it may be that every query one wishes to ask of one's database can be adequately answered on the basis of information of this kind. But even if the raw data are organised in this rather low-level way, one might reasonably expect a sophisticated information system to provide some assistance with the task of deriving higher-level descriptions of the data, for example grouping together instantiations of the same raw attribute over a connected region as an object that may be referred to as a unitary whole and then related to other objects of the same or different kinds (e.g., the temporary displacement of the human population as a result of the flood, the effect on agriculture, the likelihood of a flood of comparable severity occurring next year, and so on). And if we are to do this, we need to establish what kind of object it is we are creating.

There are numerous phenomena in the world which, like the flood, can with equal facility be viewed either as continuants or as events. I call these *multi-aspect phenomena*—multi-aspect rather than dual-aspect because as I shall argue below, there are sometimes more than just two distinct ways of viewing them. Some of these phenomena have been recognised in the philosophical literature too, witness the following quotation from Davidson:

> If a wave crosses an ocean, that is an event from the point of view, so to speak, of the ocean. But the wave is also an object [i.e., continuant] in its own right, keeping to a general shape while rapidly exchanging waters. Examples like this are easy to multiply. A lenticular cloud, unlike other clouds, stands still relative to the surface of the earth while the flow of wind on which it depends carries newly condensed particles of water into its defining area while subtracting others by vaporization. From the point of view of the air which contains it, the lenticular cloud is an event; from the point of view of the mountains which caused it, the cloud is an object.
>
> (Davidson, 1985, p.176)

But Davidson backs away from espousing the kind of four-dimensionalism which would unite the multiple aspects of such phenomena into a single hyperobject.

Examples of multi-aspect phenomena include

> *floods, wildfires, storms, weather fronts, epidemics, pollution incidents, invasions, processions, protest marches, traffic jams, bees swarming, a plague of locusts.*

It will be seen that in many cases these phenomena involve large numbers of similar units acting together in a more or less coordinated way; but the phenomenon does not *consist* of those units since the units can have lives separate from the phenomenon and the phenomenon may outlast the participation of any individual unit. Thus the unity of the phenomenon as a whole goes beyond the separate unities of its constituent parts.

To illustrate how these phenomena can exhibit more than two aspects, consider the case of the protest march. There are at least three very natural points of view to take of a protest march: the view of a participant, the view of a spectator situated somewhere along the route, and the view of a police surveillance helicopter flying back and forth above the marchers. For the participant, the march is certainly an event, but because it has a certain homogeneity (the marcher spends all the time marching), it is perhaps best thought of as a (bounded) process. For the onlooker, it is more clearly an event, beginning when the first marchers reach the onlooker's position and ending when the the last ones have gone past. For the police in their helicopter the continuant-like aspect comes to the fore: the march consists of people moving in a more-or-less coherent fashion along a particular route—but it is not just the sum of those people, since, for example, individuals may join or leave the march in mid-course, or people may become caught up in the march without being participants (e.g., someone simply trying to cross the road and becoming embroiled with the marchers and carried along by them a certain distance before breaking free). All these points of view are 'correct' in that they give a true partial picture of the total phenomenon. Assuming that we want to record the phenomenon in such a way that these partial views can all be retrieved from what we have recorded, the question arises as to what conceptual model we should employ to record it. Consider the various possibilities:

- A series of snapshots, each giving the region occupied by marchers at one time.
- A series of snapshots, each giving the position of each participant at one time.
- A collection of life-histories, one for each participant.
- A collection of histories, one for each of some selected set of locations along the route.
- A collection of individual records of the form 'participant X was in position P at time T'.

Alongside these, consider the various questions we might want to ask; here is just a sample:

- When did the first marchers reach point P?
- How many marchers joined the march after the beginning, or left it before the end?

- Who was leading the march at the beginning, and were they still leading it at the end?
- Where was individual X at time T?
- When was individual X at position P?
- Which individuals were close to position P at time T?
- Where were the marchers at time T?
- How long did it take them to pass point P?
- How long did the march last altogether?
- Where did the marchers go after the march was over?
- Were there distinct groups identifiable within the march?
- How many marchers were there altogether?
- What if the march splits into two, each part going its separate way?
- Or two or more originally separate marches come together to form a single march?

These questions draw attention to the complexity of the phenomenon. The last two in particular raise the thorny problem of identity: this is not just a philosophical question but concerns the practical discipline of how we attach labels to constituent parts of our representations. Comparable representations and comparable questions arise for all multi-aspect phenomena. It is with these phenomena, if any, that a four-dimensional representation is most called for. But a committed four-dimensionalist might wish to go further than this and say that *all* phenomena are to some extent multi-aspectual.

Consider any geographical object: a town, a country, a forest, a river, a lake, an island. All these things change over time—most of them change position, growing or shrinking even if they do not actually move. All of them can be divided into smaller parts which enter as participants into the history of the larger unit. In some cases this subdivision can be done in two quite different ways—e.g., for a lake we might look at different positions within the lake, or we might look at different portions of water in the lake, and unless it is completely stagnant, these two subdivisions, even if initially agreeing, will diverge radically over time. Or think of a country as an object successively occupying various different tracts of territory as it annexes portions of neighbouring countries or loses other portions in its turn—while the inhabitants of a particular village within the disputed territory might experience a succession of changes of sovereignty, coming to identify a country with an episode in their history, subtly eroding the distinction between continuants and events.

8 Researchable questions

The foregoing discussion suggests a number of topics for further more detailed investigation.

First and foremost is the question of what data structures one should use to represent multi-aspect phenomena. Hand in hand with this it is necessary to specify operations on those data structures which can generate the multiple aspects of those structures. Thus we are looking for some way of representing a storm, say, which will allow us as accurately and efficiently as possible to track the sequence of locations visited by the storm, the sequence of events associated with the storm at a given location, and the life-history of the storm itself. Can all this be accomplished within an ontological framework consisting of distinct categories of continuants and events, or should we, on the one hand, introduce a third category such as hyperobject to incorporate the multi-aspect phenomena, or on the other hand, conflate the categories of continuant and event, subsuming both in a single over-arching category?

We have emphasised the distinction between field-based and object-based representations as an important aspect of modelling geographical information. If both these forms of representation are important, then the relationship between them is crucial. Moreover, the encounter between field/object issues and space/time issues, which has been a main theme of the paper, gives rise to further questions which we have not had space to consider up to this point. There are a number of topics to be considered here.

First, there is the question of how crisp the distinction between fields and objects really is. Plewe (as reported in (Peuquet, Smith, & Brogaard, 1998)) pointed out that there are intermediate forms of representation between the pure field view and the pure object view. A categorial coverage is a subdivision of space on the basis of a set of qualitative field values such as soil type or land-cover type. The subdivisions, which are areas of land homogeneous with respect to the field in question, can be treated somewhat as objects while being determined entirely by the underlying field. Even closer to the pure object view is the hard partition, which is a subdivision imposed on space rather than carved out of space in conformity with a pre-existing field. This includes the subdivision of territory into political or other administrative units, census tracts, to record land ownership, and so on. Each unit in a subdivision is a well-defined object to which may be ascribed a range of attributes, but the subdivision as whole is like a field in that it provides a coverage of the land to which it applies.[19]

These intermediate cases have exact analogues in the temporal dimension: for example, the division of the local time-line into day and night is a categorial coverage with just two values, whereas the division of time into calendar days is a hard

[19] In (Galton, 2001b) I modelled this as an 'object-field', i.e., a field whose values are objects; see also (Cova & Goodchild, 2002)).

partition. In principle, we can apply them to 4D spatio-temporal representations as well. For example, the day/night coverage can only be applied locally, since daytime and night-time differ from one location to another. But if we take the whole of space-time (meaning, in this case, the Cartesian product of the Earth's surface with the time-line), then each point $\langle s, t \rangle$ can be assigned to 'day' or 'night' according as the sun is or is not above the horizon as seen from position s at time t, and this gives us a spatio-temporal categorial coverage—hard to visualise, to be sure, but arguably of greater utility than the purely temporal coverages associated with individual locations (which in any case can all be derived from the spatio-temporal coverage). Analogously, we can define a spatio-temporal hard partition which takes account of the fact that a given calendar day occupies different portions of the time-line in different time-zones.

Second, from the coexistence of fields and objects arises the possibility of deriving objects from fields and vice versa. Categorial coverages illustrate the former case, but do not exhaust it. Other objects derivable from fields include maxima and minima (e.g., mountain summits are maxima of the elevation field), boundaries (e.g., the coastline), isolines joining locations with the same value in a continuous field (e.g., ordinary elevation contours), and areas in which the field values fall within a certain range (e.g., land below sea-level).

There are obvious temporal and spatio-temporal analogues—some purely temporal cases, continuing the theme of day and night, would be midday and midnight (times of maximum and minimum solar elevation), and sunrise and sunset (boundaries between day and night). These are local, differing from place to place on the earth's surface; in an integrated spatio-temporal treatment, these events become continuous surfaces in space-time (again hard to visualise)—and the continuous 'sunset surface' intersects the history of a fixed location on the Earth's surface at a succession of discrete sunset events at daily intervals. Whether anything is to be gained from explicitly representing this surface as a single spatio-temporal object, as opposed to providing a procedure for computing, on the fly, individual spatio-temporal loci that it contains, is a question which again takes us back to our ruminations on multi-aspect phenomena.

Another possibility is the derivation of fields from objects, a classic spatial example being population density—which can be computed in many different ways, depending on the size and shape of areas over which the density is averaged. The temporal analogue is the frequency of occurrence of events of a specified type. The spatio-temporal analogue is problematic since it requires us to have a measure of the size of a chunk of space-time (its 'hypervolume'), which in turn requires us to find a standard of conversion between spatial and temporal distances.[20] Some of our multi-aspect phenomena might show up as objects derived from a density

[20]In astronomical contexts it is common to equate one spatial unit with the distance travelled by light in one temporal unit, but since this equates 300,000 km with 1 second, it seems inappropriate for earth-bound use.

field—e.g., an episode of congestion on a road system could be picked out as a chunk of space-time in which the density of traffic exceeds some value recognised as the maximum that will allow free flow at that location.

Once we start creating objects out of fields or out of collections of other objects, questions of identity become critical. Some of the work mentioned above on identity-based change is relevant here, and could be extended to a consideration of objects defined in terms of the aggregation of large numbers of smaller units (such as a flock of migrating birds) or carved out of a continuous field in some of the ways suggested above. If we model a flock as an continuant on the basis of an above-normal density of individuals that can be tracked through time, then we have to be able to say under what conditions of change the continuant retains its identity—e.g., if a small splinter group moves away from the flock, this need not compromise the continuing identity of the flock, but if the size of this group approaches half the size of the flock, we might want to describe what happens as a splitting of the flock into two new flocks, neither of which shares its identity with the original flock. These are familiar questions, no doubt often to be resolved by stipulation rather than further investigation, but they take on a new flavour in the context of a four-dimensional view of the world, since it is no longer a question of the criteria of identity for a continuant as it undergoes changes through time, but rather a question as to which chunks should be carved out of spatio-temporal reality and dignified with the name of object.[21] The criteria which might be brought to bear on the two questions look rather different (even if ultimately equivalent)—for example, for the latter, perdurantist question we can think about the four-dimensional 'shape' of the object as supplying possibly relevant criteria, language which seems inappropriate on an endurantist view.

Finally, a third set of questions relate to the relationship between 'bona fide' and 'fiat' objects (Smith, 1995, 2001), the former being those grounded in features of physical reality, the latter being the artificial products of human cognitive acts. This has cropped up in some of our earlier discussions, for example the location of an international border along the line of a continuously changing river. It also has some bearing on the distinction between categorial coverages and hard partitions, the latter having a clearly more fiat character than the former. A town might be defined as a built-up area that can be identified as a coherent unit on the basis of the distribution of values of various fields (e.g, land-use, ground-cover, population density), and as such it is unlikely to have very sharp boundaries but is still reasonably bona fide; but it might alternatively be defined in a purely fiat way as an administrative unit and in this capacity the boundaries will tend to be as sharp as people can make them. Both these objects might change over time, but typically the bona fide entity will undergo gradual change whereas the fiat entity undergoes sudden change (as a result of the boundary being redrawn from time to time)—except where, as in the case of our river boundary, the fiat boundary is

[21] For further discussion, see (Galton, 2003).

stipulated to coincide with some bona fide feature of reality. Because human fiats take place against the background of the usual 'common-sense' endurantist world-view, the life histories of fiat objects can look distinctly odd when conceived in perdurantist terms, a sudden discontinuous change in a boundary showing up as a double right-angled kink in the surface of the corresponding hyperobject. It needs to be investigated whether perdurantism offers any useful perspective on how such objects should be represented.

To sum up, a more complete investigation into the relative merits of hybrid and integrated approaches to space and time will have to consider the implications of all the following issues when they are translated from a purely spatial setting to a more general spatio-temporal one:

- Data-structures and operations on them, including possible subsumption of the continuant/event dichotomy within a broad class of multi-aspect phenomena.
- Diversification of the field/object dichotomy to include intermediate cases such as categorial coverages and hard partitions.
- Relationships between fields and objects, and in particular the derivation of fields from objects and vice versa.
- Questions concerning identity.
- The relationship between bona fide and fiat objects, and in particular differences in their behaviour over time.

This is an enormous area for investigation, encompassing many of the most interesting themes that are currently under discussion in geographical information science. While many of the questions may seem somewhat abstruse and far removed from the practicalities of actually using real-life geographical information, all of them do, ultimately, lead to definite technical questions which must be considered by anyone seeking to develop a new generation of GIS that will exploit the considerable powers of modern information technology to meet the needs of users in the twenty-first century.

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