CHAPTER ONE

Introduction

Geographical information science has recently emerged as a distinct interdisciplinary knowledge field involving many diverse areas such as geography, cartography, engineering and computer science. In this field, geographic information systems (GIS) have been used for analysing spatio-temporal data sets pertaining to social, environmental and economic studies. This has led to the integration of a variety of socio-economic and environmental models with GIS. Examples include the innovative GIS-based monitoring model developed by Blom and Löytönen (1993) to monitor current epidemics in Finland, including HIV. This model integrates spatial diffusion, spatial interaction and environmental modelling into a GIS-based model for monitoring the passing of infectious diseases between individuals. The goal of this model is to provide disease-specific forecasts for the future course of an epidemic.

The European Groundwater Project (Thewessen, Van de Velde and Verlouw, 1992) is one example of the integration of existing non-spatial simulation models with spatial data sets. The result is the design of a GIS-based environmental model that provides rapid and coherent access to the most significant causes and effects of groundwater contamination. Physical and chemical models have been integrated into the GIS-based model so it can identify serious threats to the quality and quantity of groundwater resources in the European Union.

The integration of the CLUE model (conversion of land use and its effects) with a GIS is an example of a dynamic, multi-scale, land use change model developed to explore the complexity of the interactions between socio-economic and biophysical factors in land use changes. It was applied to data from China, Ecuador and Costa Rica (Verburg *et al.*, 1997). The results indicate the importance of understanding the dynamics of land use within a multi-scale scenario. Implementation of such a model was essential to explore the spatio-temporal patterns of land use change under different scenarios of population growth and food demand.

Researchers and developers are continually uncovering different uses for GIS-based models in non-traditional applications. Burrough and Frank (1995) draw attention to the diversity of ways of perceiving the same knowledge domain, and consequently the proliferation of many models for handling the knowledge domain at different levels of complexity as well as aggregation in GIS. The study of common concepts and principles among these models is essential when formulating design criteria and strategies to support and advise users on how to integrate them in a GIS. An array of possibilities and new perspectives are expected to arise on how this could be achieved. This book proposes the *object-oriented paradigm* as a common framework to handle the complexity of semantics of spatio-temporal data defined within a knowledge domain.

1.1 OBJECT-ORIENTED ANALYSIS AND DESIGN

Object orientation in modelling spatio-temporal data has been widely recognised as a powerful tool that captures far more of the meaning of concepts within a problem domain (Rojas-Vega and Kemp, 1994; Milne, Milton and Smith, 1993; Worboys, Hearnshaw and Maguire, 1990). It enhances the level of abstraction in a way close to our perception of the real world, offering a mechanism for expressing our understanding of the knowledge domain. Jackson (1994) advocates the use of object-oriented modelling in regional science as a common framework for integrating different semantics defined within social models. Object orientation is presented as a systematic approach to modelling the conceptual descriptors of complex socio-economic models. It provides a way to formalise the handling of problems that need to be solved by the combined efforts of several people.

Bian (1997) has used the object-oriented paradigm to extend a two-dimensional static growth model into a three-dimensional dynamic framework. The aim was to study individual fish behaviour in an aquatic environment. In his object-oriented salmon growth system, the movement of individual salmon in a three-dimensional space was incorporated with the growth model to simulate the behaviour of salmon in selecting their habitat and their consequent growth. A number of simulations were run with five to ten adult salmon at a time for a period of several days.

However, the complexity of integrating object-oriented and geographic concepts into a spatio-temporal data model is an interesting challenge in its conception and its implementation. Choosing an object-oriented method is a laborious task. Object-oriented methods have been introduced into several distinct structures and representations, with over 50 published suggestions. 'They range from the complex and difficult notations of OMT, Ptech and Shlaer/Mellor to the simpler ones of CRC and Coad/Yourdon, from an emphasis on process to an emphasis on representation and from language dependence to the giddiest heights of abstraction.… None of these methods is complete in the sense that all issues of the software development life cycle are addressed or that every conceivable system can be easily described' (Graham, 1994, p. 287).

This book summarises a significant amount of research carried out in object orientation. Many of the concepts and implementations developed in this area are discussed and brought together within the context of GIS. The objective is to provide readers with a solid understanding of the object-oriented paradigm for designing a spatio-temporal data model.

1.2 SPATIO-TEMPORAL DATA IN GIS

Representing spatial data in a GIS has been achieved by defining entities in geometric space in an explicit manner (vector representation) or an implicit manner (raster representation); see Burrough (1986). In the vector representation, three main geometric elements are used: points, lines and polygons, which are sets of vectors with interconnected coordinates linked to given attributes. The relationship among elements is represented by the connectivity of a set of vectors at the time of their storage into a GIS. For example, a set of lines is represented by starting and ending points, and some form of connectivity (straight line, curve, etc.). In a raster representation, entities are sets of cells located by their corresponding coordinates. In this case each cell is linked to an attribute value. The location of each cell is used to determine the adjacency relationship between entities.

As Dutton (1987) points out, the debate on vector versus raster representations is nearly as old as the concept of GIS. Both representations of geographic space have been regarded as valid data models. Besides, data transformation algorithms to convert from one spatial representation to another have been developed, and the choice between them is taken by the user who selects the representation that is most efficient for implementing a particular application in a GIS. Consequently, GIS has fully developed into information systems that are characterised by capabilities for representing, querying and manipulating entities in space. Over the past decade, expectations about exploring spatio-temporal data in GIS have raised interest in a wider range of capabilities. Some of these capabilities can be described as update procedures that are coherent with previous stored data, version management mechanisms to track the lineage of data, and analytical tools to recognise patterns of change through time as well as to predict future changes.

Representing spatio-temporal data in a GIS has been regarded as implementing an additional dimension in a former spatial representation (vector or raster). The primary objective for most of the spatio-temporal representations is summed up in the idea *organising space over time.* A geographic space is organised into partitions (layers) and the entities that inhabit this space are embedded in these partitions. In fact, a partition serves as a skeleton for representing several entities located in the geographic space at a particular point in time. This is a *region-to-entity* representation: first choose a region of a geographic space, then identify and locate the entities that inhabit that region according to how alike they are or how they are composed. Space and time dimensions are incorporated by determining their singularity through their contents; for example, space by attributes and shapes of the elements (points, polygons, lines, grid cells) and time by succession of happenings (events, actions, change, motion) on these elements. So far, this approach has been used in GIS by making spatially depicted classifications grouped into layers or sets of themes (e.g. geology, hydrology and land cover) between points or periods of time. In other words, geographic space is

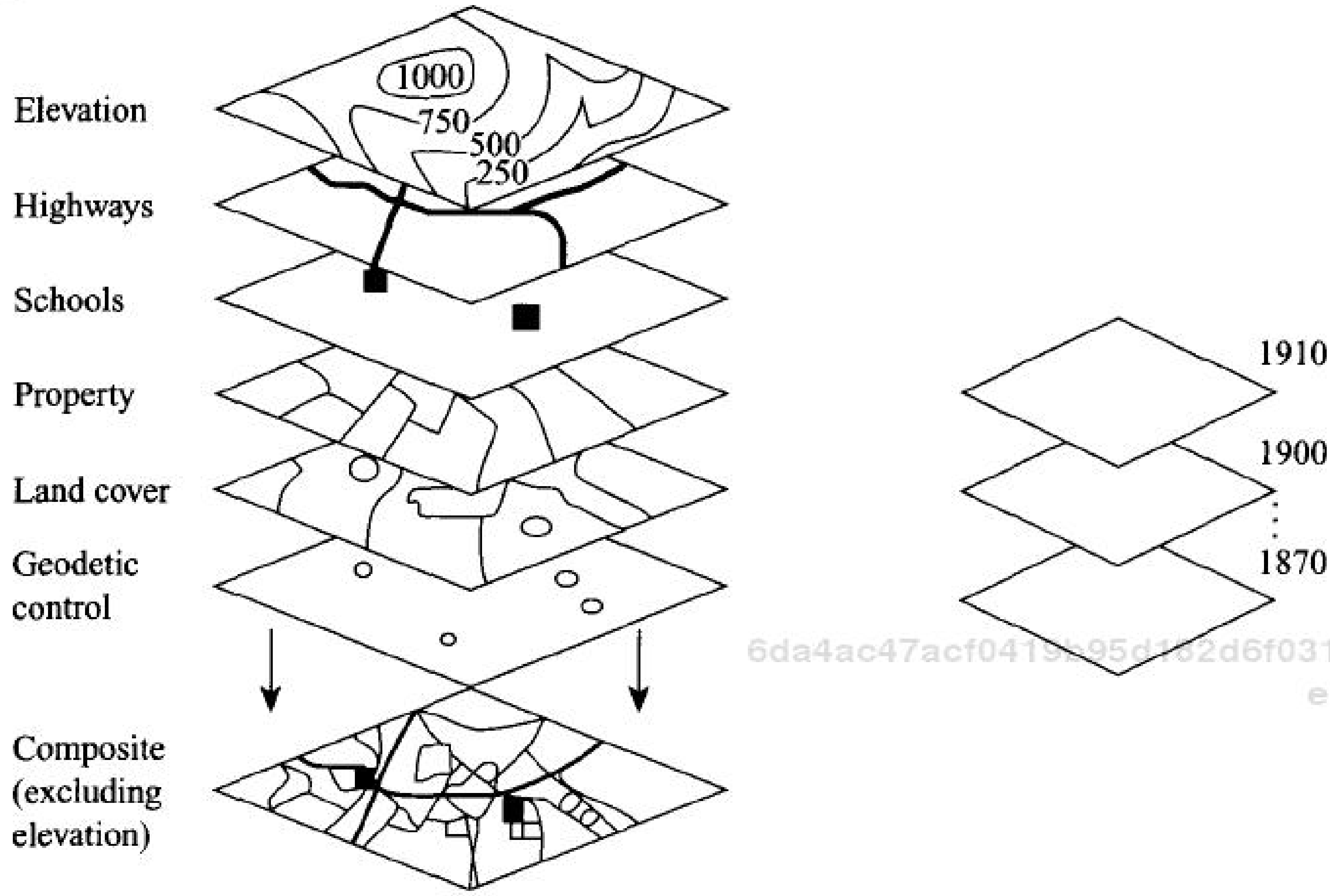

Figure 1.1 Spatio-temporal layers as the main representation being used in GIS (Reprinted with permission from Laurini and Thompson 1992, Academic Press Ltd)

grouped along the spatial dimension after some sort of categorisation, and time is grouped along the time dimension after some sort of periodisation. Constituting history is explained based on similarity or dissimilarity between aggregations (layers) at different points of time (Figure 1.1).

Although this four-dimensional representation is sufficiently homogeneous for capturing and storing spatio-temporal data in GIS, it does not provide a unified representation of the real-world. We are dealing with geographic space: a space that reflects our knowledge of the environment where time exerts its influence on place in terms of human tasks and lived experiences. If we could decide, once and for all, which real-world phenomena should be represented as entities, relations or attributes in a geographic layer, our modelling task would be extremely simplified. In fact, what we need is to understand the nature of time itself with respect to the real-world phenomenon that we are trying to represent in a GIS. In order to accomplish that, the emphasis must shift from organising space over time to *representing a real-world phenomenon in space and time.*

This representation gives us an entirely different perspective to how we handle spatio-temporal data in GIS. It attempts to capture the complexity of space and time at the level of an indivisible unit—the entity. Instead of creating layers or time periods, this representation deals with elements' coexistence, connection or togetherness. We are distinguishing two important concepts that are often regarded as interchangeable, an 'entity' and an 'entity embedded in space'. This distinction would be unnecessary if we could always define the precise location of entities and their corresponding classified layers or time periods. In fact, we are confronted with a rather different reality. Most likely is that we may be uncertain of their location and how they change or move in a dynamic way. Moreover, we may know the location of an entity in a geographic space but we are uncertain of how to classify it. The notion of having an entity unconstrained by its surroundings in space and time allows us to examine how a real-world phenomenon is represented independently of how geographic space is organised at a particular time.

This is a *space-time entity* representation: first identify the entities, and second ensure that based on these entities a geographic space can be created. An important characteristic of this representation is the ability to create the geographic space based on a specific task to be solved or a particular knowledge about the real-world at a particular point in time. Depending on the specific task to be solved or the human ability to see the world at a particular point in time, certain real-world phenomena may be represented as entities in a geographic space, and others become the relations we are interested in modelling. For other tasks or different perspectives in the world, these roles may change. Therefore, modelling spatio-temporal data in GIS becomes an exercise of understanding not only the similarities and dissimilarities between regions of geographic space, but also the coexistence (connection or togetherness) relationships between the entities that inhabit these regions.

A reliable space-time entity representation is needed when designing a spatio-temporal data model in GIS. As Peuquet points out, a variety of approaches for studying space-time phenomena has evolved in social, geographical and physical studies. 'Andrew Clarks's early work on historical geography demonstrated that changing spatial patterns could be studied as "geographical change" (Clark, 1959, 1962). Cliff and Ord (1981) later examined change through time by scanning a sequence of maps, searching for systematic autocorrelation structures in space-time in order to specify "active" and "interactive" processes. Perhaps the best-known efforts within the field of geography that made explicit use of time as a variable in the study of spatial processes are Hägerstrand's models of diffusion and time geography' (Peuquet, 1994, p. 441).

1.3 TIME GEOGRAPHY

Torsten Hägerstrand, a Swedish geographer, unfolded the Time Geography approach in the early 1960s. He examined space and time within a general equilibrium framework, in which it is assumed that every entity performs multiple roles; it is also implicitly admitted that location in space cannot effectively be separated from the flow of time. In this framework, an entity follows a space-time path, starting at the point of birth and ending at the point of death. Such a path can be depicted over space and time by collapsing both spatial and temporal dimensions into a space-time path. Time and space are seen as inseparable.

Time Geography has provided a foundation for recognising paths of entities through space and time and for uncovering potential spatio-temporal relationships among them. Moreover, its application in various areas has produced the concept of a 'continuous path' to represent the experience occurring during the lifespan of an entity.

This experience is in fact conceptualised as a succession of changes of locations and events over a space-time path. Most of the applications using Time Geography have been devoted to modelling individual activity paths within a period of time, analysing the pattern of activities for any individual path, as well as simulating individual activity paths.

This book proposes a new means for applying the time geography approach. Its goal is to employ the concept of a space-time path developed in time geography for representing spatio-temporal data within a spatio-temporal data model. The time geography framework introduces a robust space-time entity representation for conceiving a spatio-temporal data model. In this case, time geography plays an important role as a *modelling tool* for representing the passage of time and the mechanisms of change within a spatio-temporal data model. This approach for dealing with time and space within a GIS has not been explored up to now, and the book attempts to demonstrate a new and more encompassing perspective for integrating space and time domains within a GIS. The time geographic spatio-temporal data model proposed here will be known throughout the book as the spatio-temporal data model (STDM).

1.4 THE SPATIO-TEMPORAL DATA MODEL

The STDM proposed in this book involves conceptual and implementation considerations that present a variety of semantic and structural aspects to be dealt with. The range of aspects can vary from addressing the complex and subtle spatio-temporal semantics of a real-world phenomenon to the development required for the logical components (schema evolution, query language syntax) and the physical structure (storage structure, access methods, query optimisation) of the system.

Therefore, the analysis and design of such a spatio-temporal data model can be fraught with a whole assortment of problems. These are essentially related to our understanding of the knowledge domain, the modelling constructs, and the mapping between the model and its implementation in a GIS. The use of object orientation is required in order to obtain the space-time entity representation for the spatio-temporal data model and the design tool for implementing this model into a GIS. Object-oriented methods offer a concise methodology that allows us to focus our attention on the conceptual aspects of the system, and to concentrate on the details of the design without being overwhelmed (Rubenstein and Hersh, 1984).

The book also encourages readers to apply and explore the STDM by presenting a practical application of political boundary record maintenance (historical data). The chosen application deals with the evolution of public boundaries in England. The Ordnance Survey is the national mapping agency for Great Britain which 'has had a statutory requirement to ascertain, mere and record public boundaries since 1841. As a result, it has become the main depository for, and authority on, public boundaries in Great Britain' (Rackham, 1987, p. 6). On 1 April 1991 the Ordnance Survey created a spatial data set at 1:10000 scale containing the digital outlines of the public boundaries in England. In order to support this data set, the Boundary-Line system has been defined; it produces snapshots showing the location of public boundaries at specific dates. This pioneering initiative has been influential in consolidating the perspective of this research towards the design of a spatio-temporal data model that can contribute in a number of ways to the development of the Boundary-Line data management system used by the Ordnance Survey.

The implementation of the STDM in Smallworld GIS is undertaken as a 'proof-of-concept'. Implementing the STDM has been the means by which the ideas developed in the model could be empirically tested. This book describes the implementation aspects of STDM, highlighting the challenges for geographical information science.

1.5 AIMS OF THIS RESEARCH

This book introduces a spatio-temporal data model which integrates space and time domains in a GIS context, based on the concepts developed in the Time Geography and object-oriented approaches. The research had five aims:

1 Define the space-time entity representation as a new means of characterising spatio-temporal data in GIS.

2 Provide a deeper understanding of the meaning of space-time paths and use this to identify a suitable role for dealing with the passage of time and the mechanisms of change within a spatio-temporal data model in GIS.

3 Converge both approaches: Time Geography and object orientation, by associating space-time paths of a time geographic framework with the modelling constructs of an object-oriented method.

4 Contribute to the development of the Boundary-Line data management system of the Ordnance Survey by providing a different perspective about spatio-temporal data modelling in GIS.

5 Undertake the implementation of the spatio-temporal data model into a GIS system as 'proof-of-concept'.

1.6 ORGANISATION OF THIS BOOK

Chapter 2 introduces the main concepts involved in the Time Geography approach that have been used for developing the spatio-temporal data model. The feasibility of incorporating this approach into a GIS is discussed on the basis of the previous implementation efforts that have been found in the literature. Chapter 3 provides a historical background to object orientation by summarising the efforts in the areas of object-oriented methods, temporal databases and version management approaches. The object-oriented analysis design proposed by Booch (1986, 1991, 1994) is presented as the best-worked-out notation and technique for integrating the time geography framework into our spatio-temporal data model.

Chapter 4 presents the spatio-temporal data model based on time geography and object orientation concepts previously described in Chapters 2 and 3. Chapter 5 considers how to apply the spatio-temporal data model to boundary-making for public boundaries in England. A comprehensive set of diagrams demonstrates the important aspects of the spatio-temporal data model. Chapter 6 presents the results from implementing the spatio-temporal data model. A prototype implementation illustrates the working of the spatio-temporal data model. Chapter 7 discusses the emerging technologies relevant to geographical information sciences, and provides future research ideas for possible advances in spatio-temporal data modelling.

CHAPTER TWO

Concepts of space and time

Time and the way it is handled has a lot to do with structuring space.
E.Hall, *The Hidden Dimension*

This chapter is a brief guide to some concepts in the literature on temporal GIS. The Time Geography approach is introduced as a modelling tool for representing the passage of time and the mechanisms of change within a GIS. The main concepts involved in Time Geography which have been used for developing our spatio-temporal data model are described in this chapter. The feasibility of incorporating this approach into a GIS is discussed on the basis of previous implementation attempts.

2.1 THE SPACE-DOMINANT VIEW

Although time and space are concepts inherently related, we encounter difficulties in thinking and hypothesising about them in equal terms. Langran (1992a) has coined the term 'dimensional dominance' to illustrate how our discernment of space and time in GIS has been influenced by space-dominant or time-dominant representations. The space-dominant representations focus on the spatial arrangement of entities based on the geometric and thematic properties of those entities. In other words, attention is given to the spatial arrangement as an ensemble of phenomena in a geographic space and not so much to a phenomenon itself. The space arrangement is perceived as a *layer* that can combine a variety of themes and efficiently be used for storing and processing spatial data. Fisher (1997, p. 301) points out: 'The idea that the world can be broken up into its constituent themes (layers) which can be treated independently of each other is endemic…. It is seen as having the advantage of simplifying a complex world'.

The concept used here is of *absolute space,* which considers space as infinite, homogeneous and isotropic, with an existence fully independent of any entity it might

Table 2.1 Main characteristics of the space-dominant view.

- Space is viewed as a container
- Elements only exist when associated to a layer or theme
- Applied primarily in traditional mapping
- Layer-based raster and vector models
- Each layer is associated to a period or point in time
- Change- or update-based scenario
- Analysis based on similarity or dissimilarity between aggregations (layers) at different points of time

contain. Time is implicitly incorporated into the spatial arrangement every time some sort of change occurs. As a result, a snapshot of a layer is created every time an update occurs. A sequence of snapshots describes the passage of time. However, it is not possible to know how an updated layer might affect other associated layers of the same geographic space. Today GIS products support some sort of spatial-dominant representation, i.e. layer-based raster or vector models. These models present spatially depicted classifications grouped into layers or sets of themes (e.g. geology, hydrology and land cover) between points or periods of time. In other words, geographic space is grouped along the spatial dimension after some sort of categorisation, and time is grouped along the time dimension after some sort of periodisation. Constituting history is explained based on similarity or dissimilarity between aggregations (layers) at different points of time (Figure 1.1). Topographic mapping, navigational charting, utility mapping and cadastral mapping are some examples of space-dominant domains.

Peuquet (1994) points out that absolute space is objective since it give us an immutable structure that is rigid, purely geometric and serves as the framework in which entities may or may not change (change- or update-based scenario). This is probably the reason why most GIS products have adopted the space-dominant view within their data models (Table 2.1). Clifford and Ariav (1986) describe various examples of modelling change in the space-dominant domains. Most of the examples extend the relational database model by creating new versions of tables, tuples or attributes every time a change occurs. Their main conclusion was that change is best incorporated as a component of the database at the attribute level, rather than at the tuple or table level. The main reason was that by associating a time stamp with each attribute, the user has more control over the semantics of the data, and more flexibility in the kind of queries that can be posed. They also argue that time stamping attributes provide database management systems (DBMS) with greater flexibility in both storage and query evaluation strategies.

Langran (1989) also reviews temporal GIS research on the basis of dimensional dominance and concludes that attribute versioning is a hybrid organisation which offers the most adequate approach for GIS applications presenting spatial dominance. Although time is generally perceived as continuous, the preference for a discrete time representation stands out in space-dominant domains. Time is treated as a discrete subset of the real numbers ordered linearly. Therefore, changes are supposed to take place a finite number of times so that each change produces a sequence of historical states indexed by time.

2.2 THE TIME-DOMINANT VIEW

When time takes part explicitly in a representation, either with or without reference to space, the time dominance is generated and an absolute view of time is used within a model. In this case the chosen concept is *absolute time* as a fourth dimension, a time line marked out with intervals, and along which events, observations or actions can be located. This representation is effective in domains where the accuracy of the temporal information makes it possible to date or order events, observations or actions. It presents a time structure (temporal logic), and the statements about events, observations or actions are either true or false at various points in the time structure.

Al-Taha and Barrera (1990) present a first attempt to classify time-dominant representations into three categories:

- *Interval-based models* where temporality is specified using regular or irregular intervals (Allen, 1983). The representation deals with identifying temporal intervals by defining relationships between these intervals in a hierarchical manner. In this case, a specific date is not necessary; relationships between two intervals are instead defined in the model. The relationships are before, equal, meets, overlaps, during, starts and finishes. Allen (1983) asserts that with these relationships one can express any permanent relationship between two intervals.
- *Point-based models* where temporality is specified using explicit occurrences of an event, observation or action (Dean and McDermott, 1987). These models are usually implemented as time maps. A time map is a graph whose nodes refer to points of time that correspond to the beginning and ending of an event, observation or action. The edges represent the relationship between events, observations or actions.
- *Mixed models* where temporality is specified using an interval-based model combined with a point-based model (Shoham and Goyal, 1988).

These models have not been implemented in GIS, where temporal capabilities are not yet fully developed. But there is a need for handling large amounts of data that involve time. Archaeological data and geological data are two examples where precise dates for events are not known but the relative order can be deduced. On the other hand, inventory data and environmental data are examples of time series where the precise date of each observation on a particular variable is known, and the sequence of observations provides the occurrence of a real-world phenomenon (Table 2.2).

Table 2.2 Main characteristics of the-dominant view.

- Time is viewed as a time line
- Events, observations or actions are associated to a time line
- Applied in archaeology, geology and environmental sciences
- Interval, point and mixed models
- Space is not an entity in itself
- Event-based scenario
- Analysis based on the lineage of events, observations or actions

Nevertheless, the semantics of time have been incorporated in GIS using different approaches. They can be distinguished according to the assumption of time as a parameter or dimension (Effenberg, 1992). In the parameter approach, time is employed as a control argument within the system while possible effects over other variables are investigated. This approach is largely employed in simulation modelling in GIS. On the other hand, the dimensional approach has introduced a dynamic construct in GIS. The time dimension is implemented as a user-defined data type. For example, Illustra has implemented a time series data type that consists of information on the calendar observed by the time series, the starting time of the time series and the stride between observations, e.g. daily or monthly (Stonebraker and Moore, 1996).

2.3 THE ABSOLUTE SPACE-TIME VIEW

Both space-and time-dominant views have influenced research outcomes since the early 1980s. Armstrong (1988) has defined eight possible combinations of changes or updates which can occur in vector-based models. For each possible update procedure, a change is associated with the geometry, topology and thematic properties of an entity in space. Kucera (1996) has also advocated the need for developing data-driven update procedures in GIS, procedures based on where and when the change occurs.

TEMPEST (Temporal Geographic Information System), proposed by Peuquet (1994), is the first effort towards the integration of space-and time-dominant views in GIS. 'Location in time becomes the primary organisational basis for recording change. The sequence of events through time, representing the spatio-temporal manifestation of some process, is noted via a time-line; i.e., a line through the single dimension of time instead of a two-dimensional surface over space [see Figure 2.1].... Such a time-line, then, represents an ordered progression through time of known changes from some known starting date or moment to some known, later, point in time' (Peuquet and Wentz, 1994, p. 495).

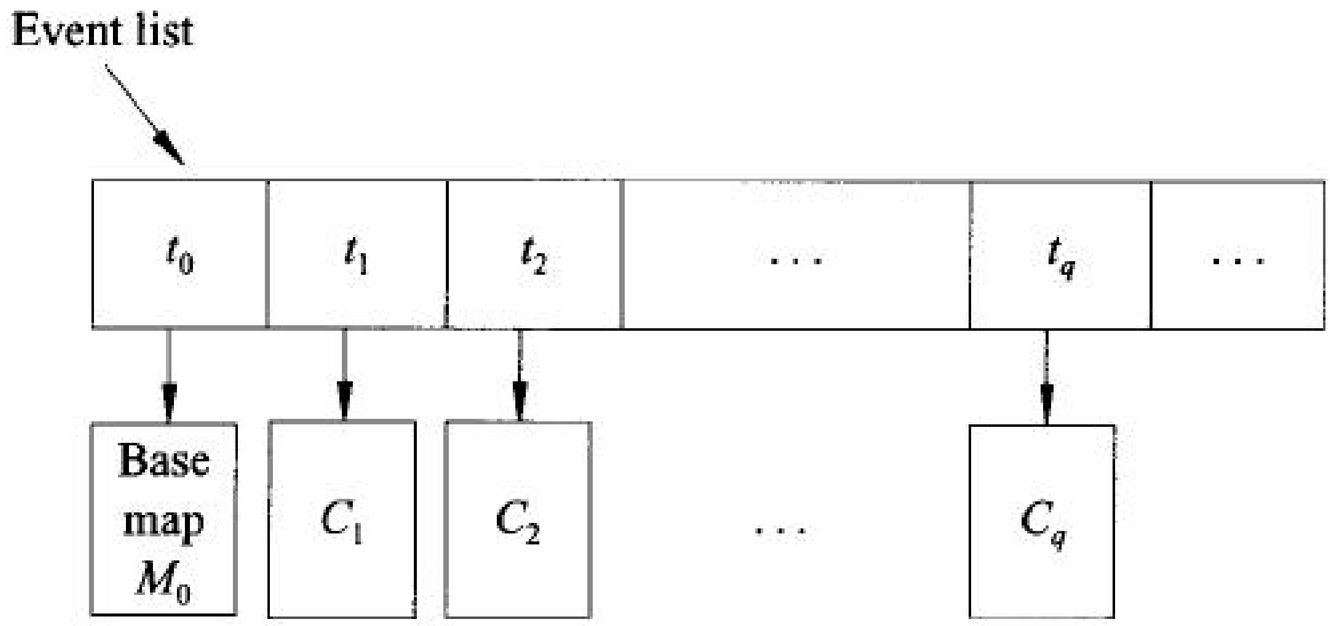

Figure 2.1 The representation of change organised as a function of time in the TEMPEST prototype

2.4 THE RELATIVE SPACE VIEW

For most of our spatio-temporal analysis, the relative view of space is of the most fundamental importance. The concept of *relative space* is more general and empirically more useful than the concept of absolute space. Jammer (1969, p. 23) defines relative space as 'an ordering relation that holds between bodies and determines their relative positions…a system of interconnected relations'. The profound implication is that any relation defined on a set of entities creates space. In other words, defining a relation automatically defines a space. Harvey (1969) provides an excellent review of the two perspectives, absolute space and relative space. The concept of absolute space overemphasises the absolute location of entities within a spatial representation. In contrast, relative space focuses on the relative location among entities. The relativistic point of view is usually associated with studies of forms, patterns, functions, rates and diffusion.

The study of gradual changes of topological relationships has recently emerged as a requirement in formalising a spatio-temporal representation in a GIS. Egenhofer and Al-Taha (1992) have investigated gradual changes in the location of an entity, such as translation, scaling and rotation, by formalising them using eight binary topological relationships for two spatial regions. The eight binary topological relations are depicted in the closest topological relationship graph showing the links between gradual changes in topology. Each gradual change allows many possible scenarios; one of them is illustrated in Figure 2.2.

2.5 THE RELATIVE TIME VIEW

Another important concept is *relative time*—time measured in relation to something, not constrained to a single dimensional axis. Cyclical time—the repeating of a day, week or year—is an example of relative time. In absolute time 13 August 1998 cannot be repeated. But in relative time, Thursdays keep returning. Most questions about change will be understood from this perspective (Ornstein, 1969).

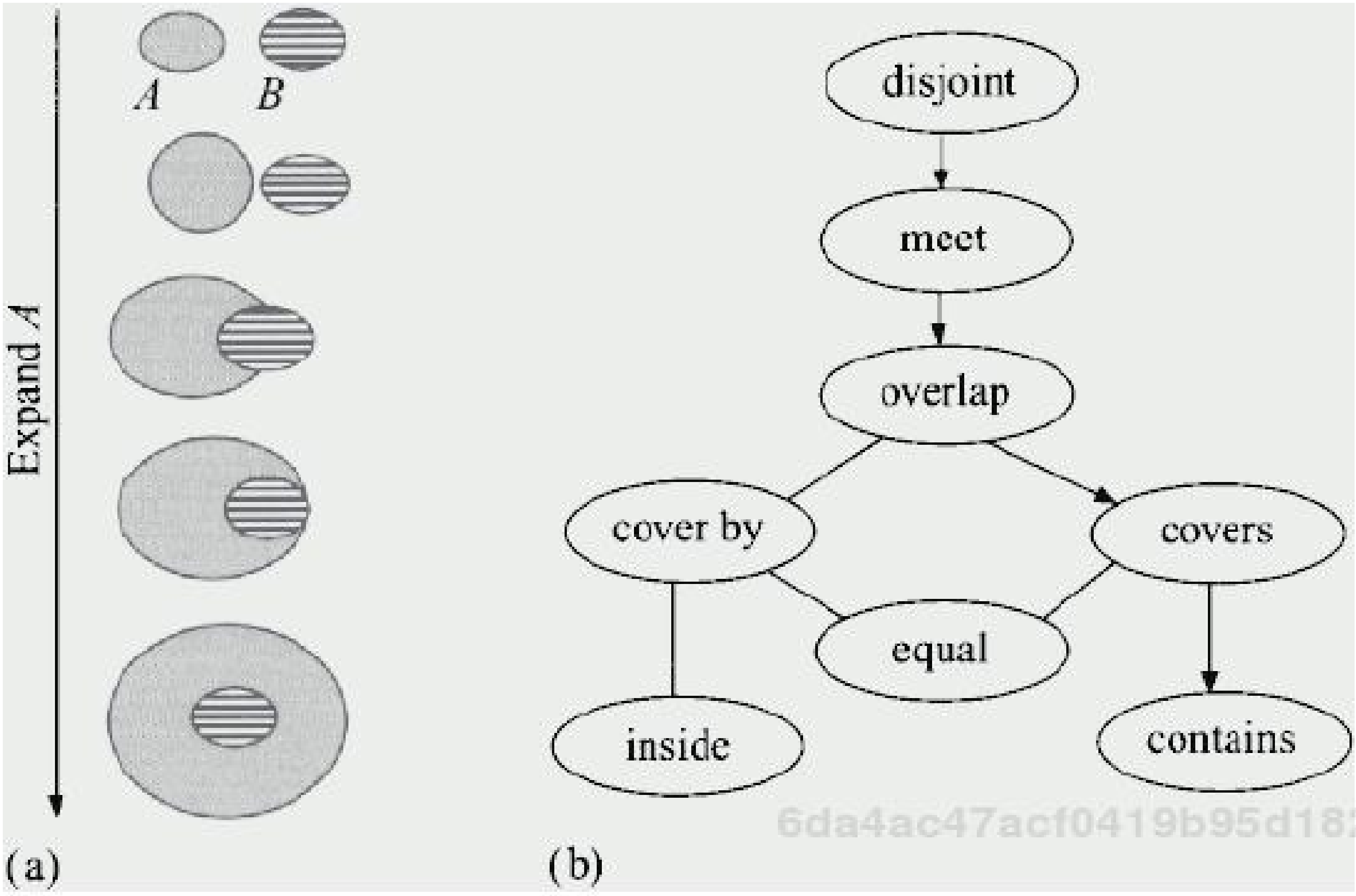

Figure 2.2 Example of a sequence of gradual topological changes between two entities

Relative time is subjective since it assumes a flexible structure that is more topological in the sense that is defined in terms of relationships between events. Frank (1994) suggested an ordinal model of time in which a chronological order is defined among events of a time line rather than attaching precise dates for these events. Some examples are the qualitative ordinal information about events that is typically encountered in archaeology and urban development. The precise dates for events are not known but the relative order of events can be deduced from observations.

2.6 THE RELATIVE SPACE-TIME VIEW

The relative space-time view embraces human activity over the real-world that results from studying processes within an application domain: 'A process study seeks to identify the rules which govern spatio-temporal sequences, in such a form that the rules are interpretable in terms of the results of the sequence, in terms of the exogenous variables which influence the sequence, and in terms of the mechanisms by which exogenous and endogenous influences give rise to the results which the sequence itself records' (*Dictionary of Human Geography,* 1994, p. 478). Table 2.3 summarises the main characteristics encountered in the relative space-time perspective.

Gatrell (1983) provides several examples of constructing space-time maps based on proximity relations among entities. The approach given is the multidimensional scaling (MDS) algorithm, in which relations are defined by numerical values in a matrix representing perceived distances between entities (main cities in New Zealand) or their rank orders over time. Figure 2.3 shows the result of an MDS algorithm for representing New Zealand in space and time.

Table 2.3 Main characteristics of the relative space-time view.

- Space and time are viewed as coexistence (connection or togetherness) relationships between changes and events
- Neither space nor time exists independently
- Applied in studies of forms, patterns, functions, rates and diffusion
- Topological models
- May involve non-Euclidean space or linear time
- Process-based scenario
- Analysis based on a process study

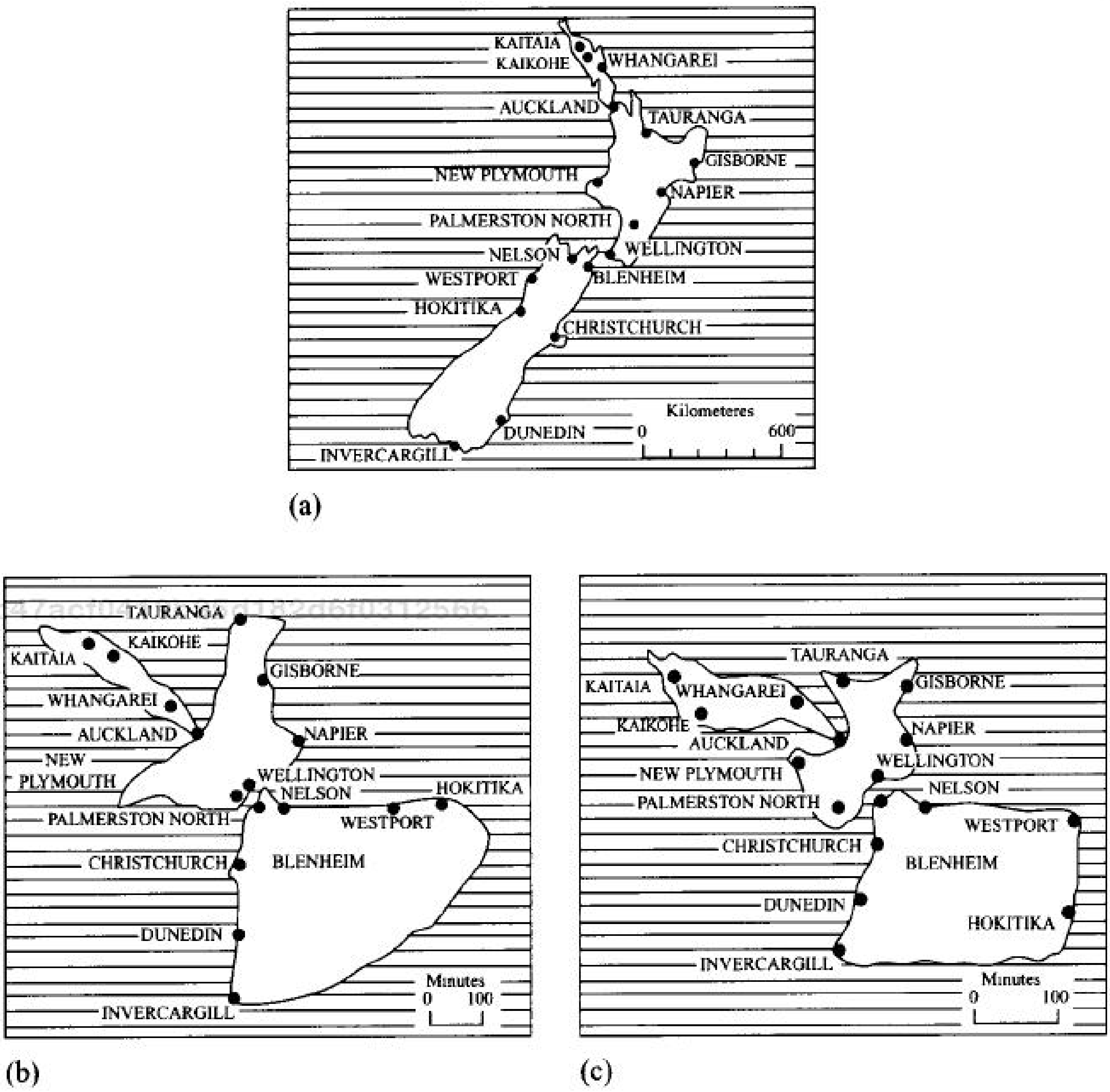

Figure 2.3 (a) New Zealand in absolute space (b) New Zealand in 1953 time space (c) New Zealand in 1970 time space. (Reprinted by permission of Oxford Press. *Source* Gatrell 1983, p. 111)

2.7 CHOOSING THE VIEW FOR A GIS

Harvey argues that we 'have (frequently) assumed a particular spatial language (i.e. absolute view or relative view) to be appropriate without examining the rationale for such a choice' (Harvey, 1969, p. 161). After all, we should not discriminate one over another. They are complementary. As Peuquet (1994) points out, the absolute view requires some sort of measurements referenced to a constant base, implying non-judgmental observation. The relative view, on the other hand, involves interpretation of processes and the flux of changing patterns within a knowledge domain.

However, a question still remains about integrating absolute and relative views. How can we have both perspectives placed in the same representation? Perhaps the answer lies in time geography: 'Owing to the circumstances under which…[Time Geography] has been developed, its contents, and its applications to date, there is a great danger that Hägerstrand's time geographic framework will be mistakenly construed as nothing more than a planning tool. On the contrary,…the potential usefulness of the framework…is of much greater range' (Pred, 1977, p. 213). Consequently, this book proposes that the concepts of Time Geography should be exploited by GIS to capture the absolute space-time view as well as the relative space-time view. The next section provides an overview of Time Geography.

2.8 TIME GEOGRAPHY

The pioneering work of Torsten Hägerstrand during the 1960s unfolded the Time Geography research that emerged from the Royal University of Lund in Sweden. The concepts developed in time geography have been mostly consolidated in the work of Hägerstrand and his students and collaborators Lenntorp, Mårtensson and Carlstein. Pred (1977) provides an overview of the main uses of Time Geography in several domains, among them domains concerned with regional development policies, nationwide physical planning, and urbanisation and settlement policies. The Swedish government has implemented many of the applications of Time Geography in order to provide adequate job-market opportunities, and a satisfactory level of social and cultural services. Some examples are the accessibility simulation of daily individual activities in urban environments and regions (Lenntorp, 1978), comparative studies of living conditions in different populated regions (Mårtensson, 1978), and analysis of various activities in the quaternary sector, mainly concerned with employment distribution (Olander and Carlstein, 1978).

Space and time in Time Geography are considered as orthogonal dimensions that become fused into a space-time path representing the trajectory for the lifespan of an entity (Figure 2.4). For simplification, as suggested by Hägerstrand, the representation of space is along only one dimension to maintain the clarity of the proposed representation framework and to give a better visualisation of the evolution of public boundaries. The same simplification has been adopted for the time dimension.

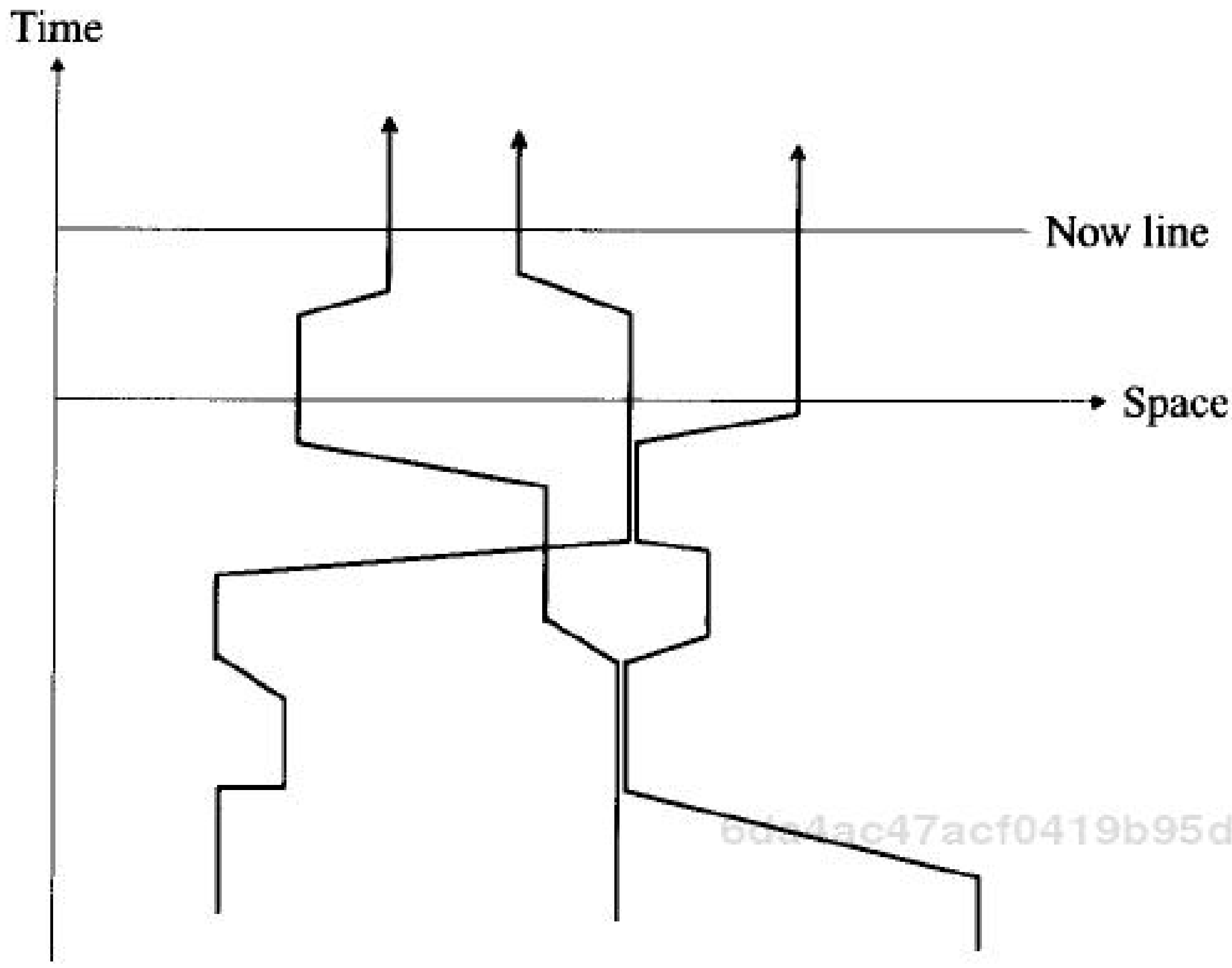

Figure 2.4 Space-time paths of three entities

Time is viewed as the dimensional axis that orders events, separates causes from effects, and synchronises and integrates human activity (absolute time representation). Space is viewed as the dimensional axis that represents the changes in the location of an entity in space (absolute spatial representation). Space and time are joined in a single space-time path. Space and time are considered inseparable within a path, and it is the timing component which gives structure to space and thus evokes the notion of *place*. Place is 'a pause in movement' (Parkes and Thrift, 1980, p. 120).

The Time Geography approach is an effort to capture the complexity of space-time interaction at the scale of the smallest indivisible unit in space and time, i.e. the space-time path (relative space-time view). However, by having space and time as orthogonal dimensions, Time Geography requires the absolute view of space and time. An absolute location in the space axis and an absolute location in the time axis are needed to define a place on a space-time path. The absolute location in the space axis may be determined with reference to a coordinate system, whereas the absolute location in the time axis may refer to location in time derived from a clock or calendar. A space-time path provides the starting time, the duration, the frequency, the sequential order, as well as the relative location of events and changes that have occurred in a lifespan of an entity.

The continuous line of a space-time path is the relative space-time representation of the lifespan of an entity. It is a descriptive form to reveal the interdependence and relationships between events and changes (Lenntorp, 1976). 'Space and time are to be jointly treated…because when events are seen located together in a block of space-time [paths], they inevitably expose relations which cannot be traced if those events are bunched into classes and drawn out of their place in the block, i.e., conventionally analyzed' (Pred, 1977, p. 210).

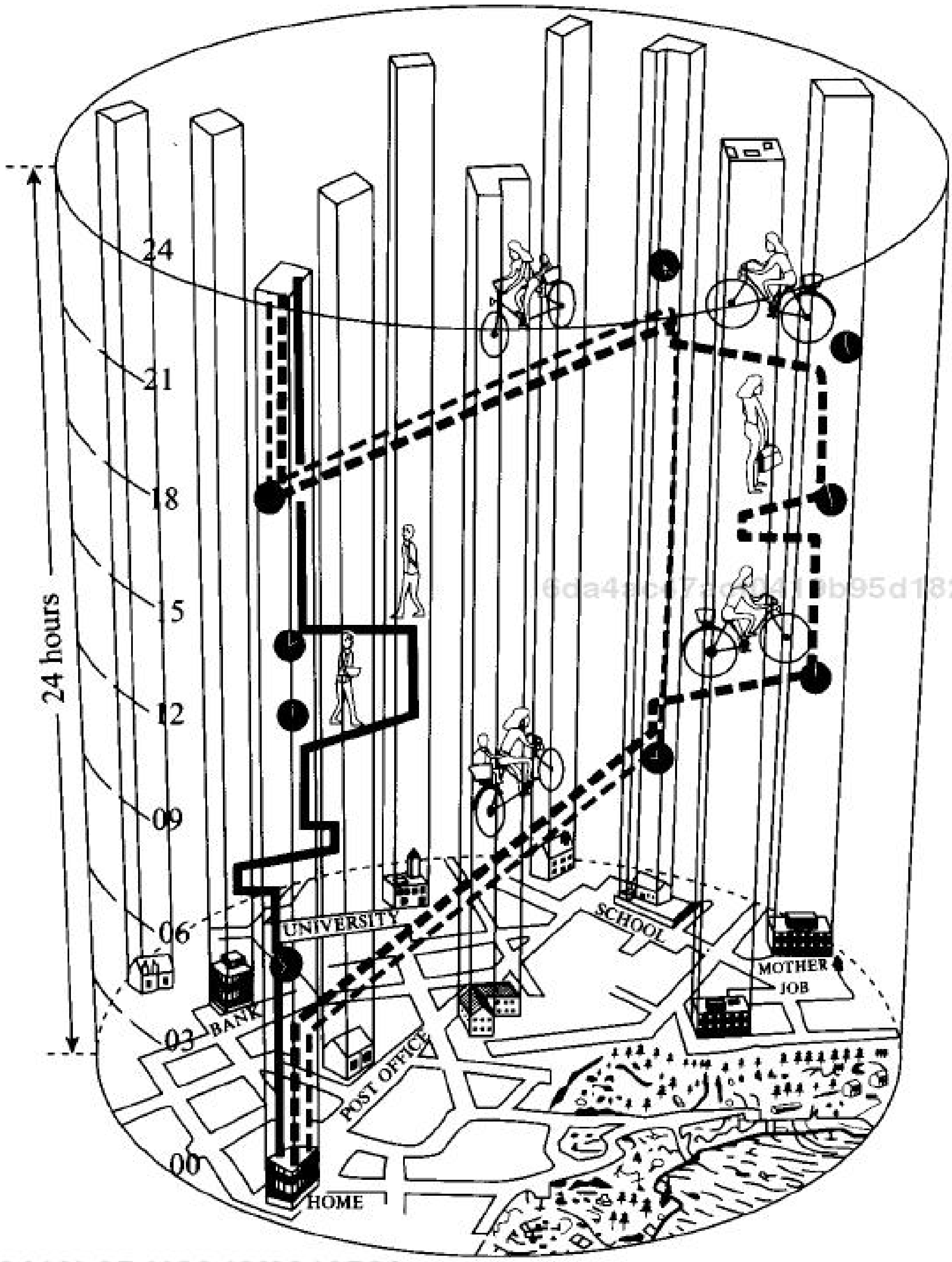

Figure 2.5 An example of potential path areas. (Reprinted with permission from Parkes and Thrift, 1980, John Wiley & Sons Ltd)

The sense of past, present and future depends on where the observer is placed in the space-time path. The observer has the awareness of coexistence (connection or togetherness) relationships between space and time at every place located in a space-time path (Hägerstrand, 1975). The motion of an observer can be limited to a set of circumstances described by the constraints which have been defined for a space-time path. Called the potential path areas (Figure 2.5), this set is represented as a prism in Time Geography. It comprises space-time positions for which the possibility of being included in the observer's trajectory is greater than zero (Lenntorp, 1976). A general procedure cannot be developed for deriving or calculating potential path areas from empirical data. Each knowledge domain has to be analysed in order to generate its actual potential path areas.

2.9 TIME GEOGRAPHY AND GIS

Although Time Geography is an effective approach to dealing with space and time in an integrated manner within a GIS, it has so far been neglected. After analysing the feasibility of handling space-time concepts of Time Geography within a GIS, Miller affirms that 'Geographic Information Systems, through their ability to manipulate and analyse spatial data, can allow more widespread use of the space-time perspective [of Time Geography] in spatial modelling and analysis' (1991, p. 300).

Few examples are available for illustrating the attempts at applying the Time Geography approach within a GIS. Miller (1991) has generated potential path areas (PPAs) for a transportation network application on the basis of arcs in the network that are feasible to travel. The mainframe version 5.0 of ARC/INFO was used for the implementation in order to handle a set of nodes and arcs, keep records of locations within the system, and handle numerous travel times at both nodes and arcs in the network. Although 'ARC/INFO NETWORK can meet the requirements for standard GIS applications; it is inefficient and unwieldy in meeting the more specialised needs of the network PPA procedure. Whereas ARC/INFO is certainly not representative of all GIS software, it does provide a benchmark which indicates the problems encountered by analysts who wish to use GIS technology in more specialized research and modelling' (Miller, 1991, p. 299).

Miller also points out the main requirements in applying Time Geography in a GIS:

- The Time Geography approach requires data at a detailed spatial scale in order to obtain an effective analysis in a GIS.
- The GIS must be able to address the behavioural aspects of data to generate more realistic operational PPAs.
- The favoured GIS to implement a time geographic framework must be able to store and manipulate topological relationships to avoid adding unnecessary complexity to the framework.
- The derivation and manipulation of PPAs in a GIS might be accomplished by developing the framework to support space and time constraints. A modular structure with inflexibility of key commands and procedures can render a GIS unable to derive the desired space-time prism framework.

Another example is the application of Time Geography for simulating an individual's daily shopping behaviour within a GIS (Makin, 1992). The results show how time and space constraints on people's shopping movements affect shops' potential earnings and profits. Makin explores the potential of using a GIS to structure spatial relationships according to which routes are accessible to each other, and where the buildings are located on the route network.

He also points out the potential benefits of having implemented his Time Geography model into Smallworld GIS for simulating the behaviour of people's movements:

- The data items are not generalised or aggregated within the GIS.
- The entities are allowed to move and interact with their constraints in space and time in a way that long-term behavioural patterns can be analysed.
- The model is expressed in terms that do not require abstraction into mathematics.
- The whole system can be organised in a modular fashion in which subsystems are created for reducing the complexity of the model by minimising the amount of data and the number of interactions.

These two examples illustrate the potential perspectives of applying Time Geography in a GIS. And Time Geography could be used to formulate space-time semantic abstractions in the design of a spatio-temporal model based on the object-oriented approach—something not thoroughly explored until now.

2.10 MAIN ELEMENTS OF A SPACE-TIME PATH

Space-time paths can be defined as image schemata that directly depict the lifespan of each singular entity in a knowledge domain. The space-time path is based on the fact that an observer can move anywhere along the space-time path, there is a starting location (in space and time), a direction (motion, change), and a sequence of continuous locations (in space and time) that the observer goes across in following the path. The space-time path embodies the structures of identity, location (in space and time) and direction that are the basic abstract metaphors for modelling spatio-temporal data in GIS.

Langran (1992b) asserts there are at least three sorts of spatio-temporal data in GIS: states, events and evidence. In extending this classification, Kraak and MacEachren (1994) point out a further differentiation between events and episodes. In essence, a *state* represents a version of what we know about an entity in a given moment. States can consist of different versions of an individual entity (the changes of an individual political boundary marking the variation on the distribution of a territory and its sovereignty) or an ensemble of entities (the changes in ecosystem conditions produced by reductions in atmospheric emissions of pollutants). An *event* is the moment in time an occurrence takes place. Events cause one state to change to another (e.g. a cadastral survey may take place due to changes on properties' boundaries). Events are also part of a process of change caused by action and reaction as well as the synthesis of both (e.g. the process of energy propagation and ozone hole formation). An *episode* is defined as the length of time during which change occurs, a state exists, or an event lasts. And finally, a piece of *evidence* is the datum describing the source of state and event data. No evidence should ever be stored in a GIS without referencing its source document, survey or update procedure.

This book proposes the space-time paths as ideal image schemata for representing and organising the spatio-temporal data categories in GIS (state, event, episode and evidence). The aim is a better understanding of the defined categories by distinguishing the three main structures of a space-time path: identity, location and direction. Any

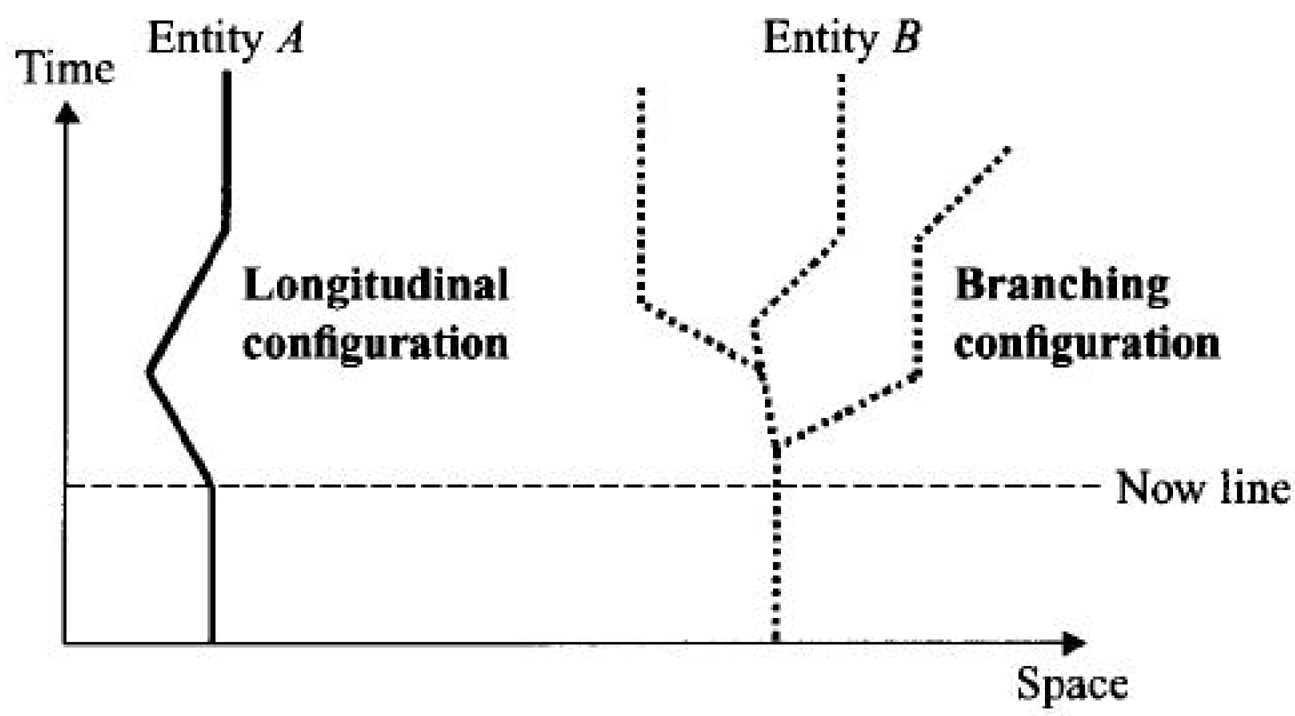

Figure 2.6 Possible configurations for a space-time path

knowledge domain contains a population made up of entities which are represented in the Time Geography as point objects. A singular space-time path describes a lifespan trajectory through time over space, from the point when and where the entity comes into being, to the point when and where the entity ceases to be. As a result, a singular space-time path must exist provided an entity exists. However, it does not necessarily mean that a space-time path must have a longitudinal linear configuration. On the contrary, space-time paths can have either longitudinal or branching configurations (Figure 2.6).

Longitudinal configurations imply there is no possibility of having two or more directions over the past or future during a lifespan of an entity. They also imply that the exact spatial location of an entity is known at all times. Most cases of short-term changes making up the history of day-to-day occurrences of an entity portray longitudinal space-time paths. Examples are transport maintenance of state roadways, public works of utility companies, and cadastral measurements. On the other hand, branching configurations are encountered in medium-and long-term changes in the lifespan of an entity. Examples are the effects of pollution given various climatic and economic scenarios, accident and disease patterns, and land use and demographic trends.

Each space-time path is in fact the spatio-temporal signature of any entity in a knowledge domain. And as such, it has the ability to reveal the connections and interrelations among different entities. The identity, location and direction of a space-time path are fundamental structures to connect and interrelate the spatio-temporal data categories (state, event, episode and evidence). The following sections describe how this can be achieved.

2.10.1 State as an element of the space-time path

A state can be depicted as a specific location in the space axis, illustrated here using two dimensions for clarity. In the lifespan of an entity, changes occur in its space-time path describing the evolution of its inner existence, or a mutation of its location in space. Historical evolution regards change as the adaptation of an entity to its

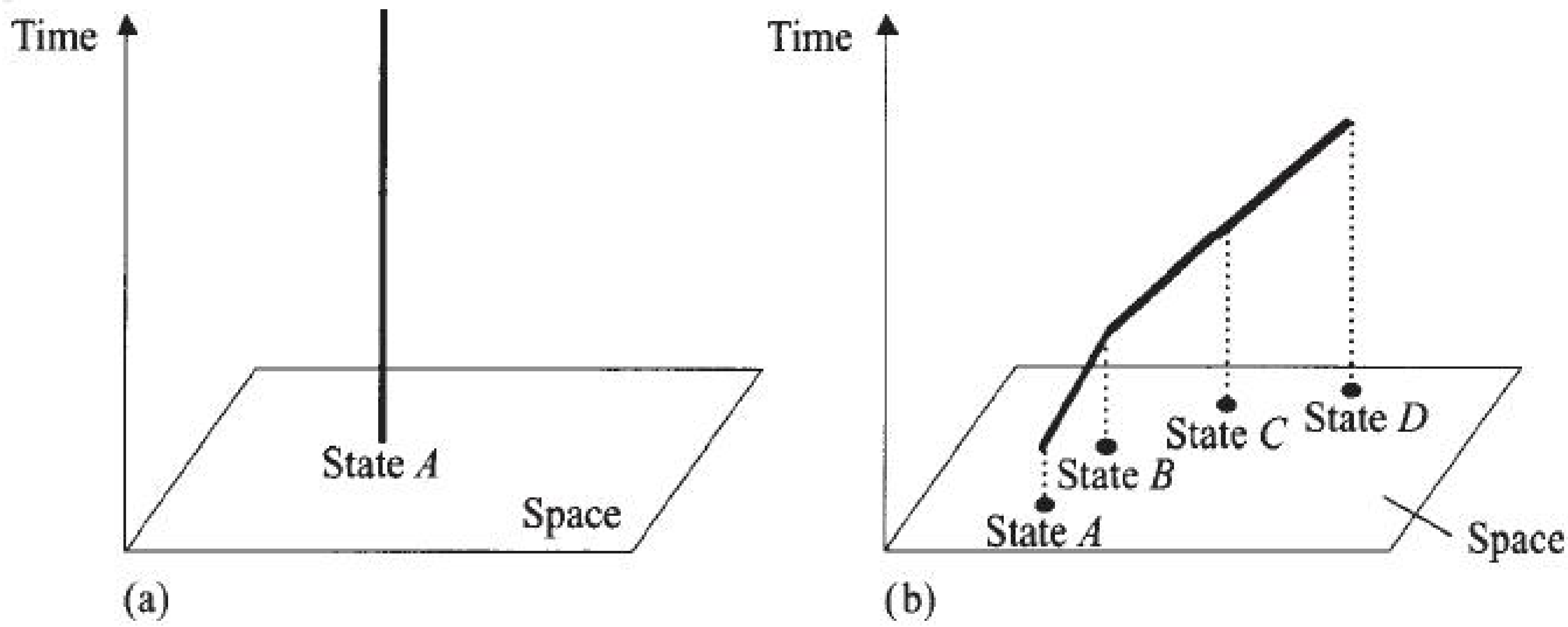

Figure 2.7 Examples of states as elements of the space-time path

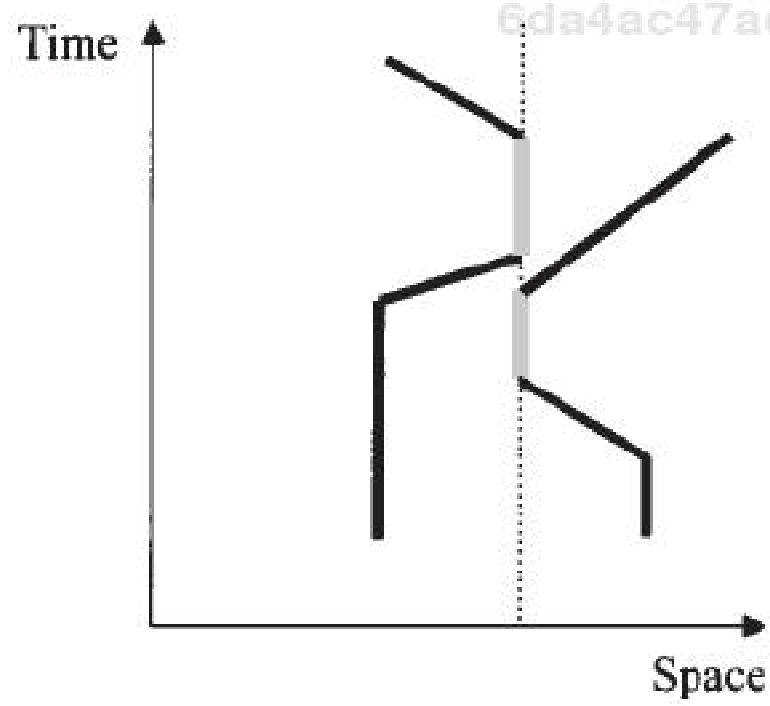

Figure 2.8 Co-location in space

environment by the process of differentiation and increasing structural complexity (Figure 2.7(a)). Mutation relates change to the theory of revolution, emphasising the importance of conflict or struggle as the principal mechanism of change. It characterises any alteration in the direction of the space-time path, hence the change of its location in space (Figure 2.7(b)).

States tend to represent the short-term changes which can occur during the lifespan of entities. Such changes can occur due to man-made alteration in the position of entities on the ground. In contrast, states can also be related to the long-term and medium-term changes such as environmental changes. Changes can also occur due to natural causes, and the most common example is displacement of watercourse for rivers and streams. In any of these cases the spatio-temporal path gives the co-location of changes in space and time, as illustrated in Figure 2.8.

2.10.2 Event as an element of the space-time path

Those familiar with event-oriented representation and update-oriented representation should not mistake the concept of event in Time Geography. Both representations

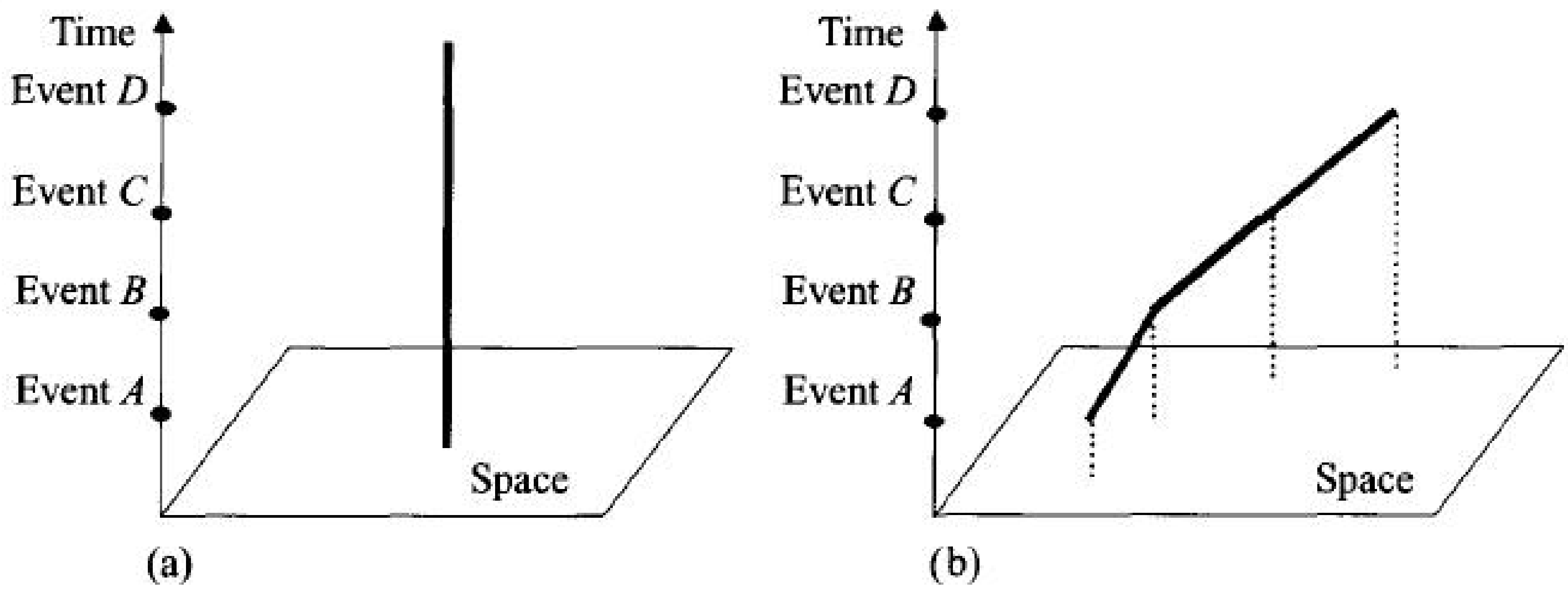

Figure 2.9 (a) The space-time shows a sequence of events that have occurred over the lifespan of an entity without causing any change in the spatial location of this entity, (b) The space-time path shows the ordering of the events and their respective associated changes over the spatial location of an entity

have been discussed as pragmatic solutions for representing spatio-temporal data in GIS (Langran, 1993). In an event-oriented representation, events are described by the moments of change. Only the events accountable for some sort of change over a state of an entity are represented. The occurrence of an event always causes the creation of a new version from a previous state of an entity. Conversely, in an update-oriented representation, events are related to the occurrence of updates of the data stored in a GIS. The lifespan of an entity is represented by a sequence of events that represent the occurrence of all kinds of updates, even those updates that are not accountable for any change in the state of this entity. These updates usually constitute a resurvey of an entire region, regardless of where or what change has occurred. Photogrammetric and remote sensing surveys are examples of collection-driven updates that are scheduled to occur in a given time interval.

A different perspective in representing events is found in the space-time path described in Time Geography. Events are not necessarily related to the creation of versions (states) or update activities in GIS. Time Geography emphasises the need for understanding geographic processes in which the mechanisms of change as well as the patterns of change have to be analysed through time. The sequence of events through time is viewed as the spatio-temporal manifestation of certain processes. The space-time path provides the connection, ordering and synchronisation of events, and their association with the respective changes (states) if they have occurred over a lifespan of an entity (Figure 2.9).

In placing events in the time axis of a space-time path, the meaning of an existence and mutation is given to a lifespan of an entity. Each space-time path captures the spatial and temporal sequence and coexistence of events. An ensemble of space-time paths belonging to several different entities can also represent the interaction among these entities. Such an interaction is given by the co-location of events in time (Figure 2.10). GIS can be used to keep the record of 'co-location of events' of space-time paths of a number of entities. The outcome is a web formed by the interrelations of individual trajectories of several space-time paths. Such a web can uncover processes

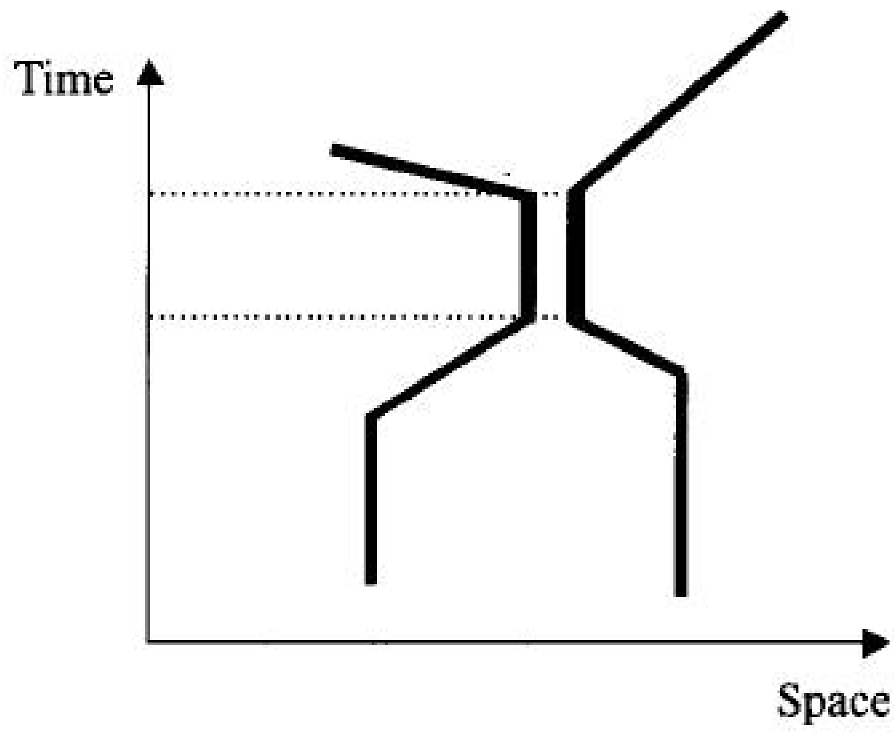

Figure 2.10 Co-location in time

that are responsible for the 'temporal connectedness' of common existence in time. Hägerstrand (1975) has previously named these processes as 'collateral processes'—processes which do not unfold independently but are observed from their common existence in time.

2.10.3 Episode as an element of the space-time path

An episode is defined as the length of time during which change occurs, a state exists or an event lasts. The length of the space-time path and its angularity with the time axis are important in classifying changes according to their respective duration: the larger the angle, the shorter the duration. Three main types of change can be characterised in a space-time path (Parkes and Thrift, 1980):

- Long-term changes modifying the environment
- Medium-term changes transforming cultures
- Short-term changes making up the history of day-to-day incidents

2.10.4 Evidence as an element of the space-time path

An entity is represented as a point object in Time Geography. Evidence is the data about entities, events and states that have occurred. Each place on the space-time path can only exist if there is a state associated with that place and evidence to confirm an event occurred (Figure 2.11). The space and time axes will determine the scale in which a space-time path occurs. In practice this is determined by the spatio-temporal data collected for a GIS.

2.11 UNCOVERING SPACE-TIME PATHS

The possibilities of defining the events, states and episodes that belong to a space-time path are immense for any knowledge domain in geographic information sciences.

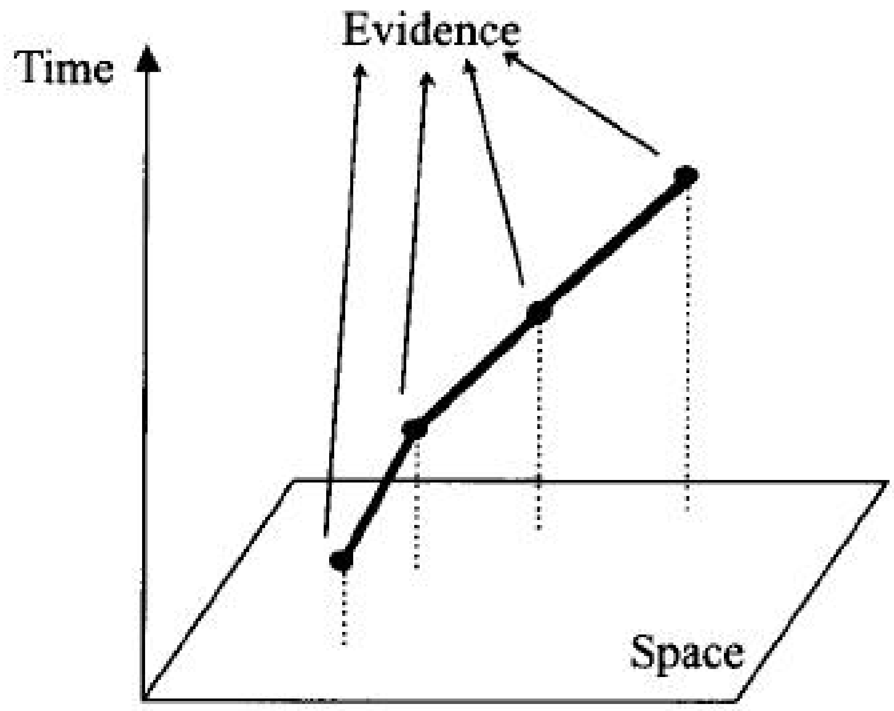

Figure 2.11 Evidence as an element of the space-time path

Consequently, a space-time path can be constructed according to an ensemble of *constraints* which define the circumstances what, where and when over space and time. These constraints operate on entities, events and states depending on a set of circumstances linked to the individual entity and its environment. This involves spatio-temporal data modelling of the behaviour of space-time paths.

Three types of constraint are described in Time Geography (Hägersrrand, 1975) and can be used in designing the spatio-temporal data model:

- *Capability constraints* limit the trajectories of the space-time paths. Space has a limited capacity to accommodate events because entities cannot occupy the same space at the same time, and every entity has a geometric boundary in space. Therefore every space has a packing capacity defined by the types of entities to be packed into it. Some constraints have a predominant time factor, at rather strictly regular intervals. Others can have a dominant space factor, forming bounded regions or volumes.
- *Coupling constraints* define where, when and for how long the events and states have to join a space-time path of an entity. Coupling constraints can reveal the pattern of space-time paths by exhibiting prism, area or volume configurations known as the potential path areas (PPAs).
- *Authority constraints* impose restricted access to space-time paths. The main purpose of defining authority constraints is to organise access to the data as well as to define domains of authority. In Time Geography the domain of authority is shown as a cylinder (Figure 2.5).

2.12 CONCLUSIONS

This chapter has focused on the main concepts of time geography. Many references in the literature introduce the Time Geography approach and its possible applications. The reader interested in an expanded coverage of these topics can find a good start with Hall (1966), Karlqvist, Lunqvist and Snickars (1975), Lenntorp (1976), Pred

(1977), Carlstein, Parkes and Thrift (1978), Parkes and Thrift (1980) and Golledge and Stimson (1997).

The main concepts of Time Geography discussed in this chapter play an important role in the design of spatio-temporal data models in GIS. Time Geography is not just another theoretical framework but it discloses how the integration between the absolute and relative views of space and time can be devised in GIS. Besides, the whole rationale of the Time Geography approach is the inseparability of space and time. In other words, states, events, episodes and evidence are all interrelated and connected through a space-time path of an entity. The space-time paths provide the image schemata for modelling spatio-temporal data of a knowledge domain in GIS. Very little information is available in the published literature on using time geography with GIS. This chapter has described two efforts made in this area, Miller (1991) and Makin (1992).

The semantics of states, events, episodes and evidence used in this chapter, in order to describe a space-time path, were not related to any particular level of abstraction, be it geographic (nation, region, centre), temporal (year, month, day) or demographic (population, group, individual). The purpose was to provide suitable semantics for modelling spatio-temporal data at multi-scales in space and time; readers may then adapt them to their specific knowledge domains. A practical example will be given in Chapter 5 to show how these semantics can be applied and implemented into a spatio-temporal data model based on knowledge domain areas such as historical geography.

The usefulness of Time Geography lies in providing space-time semantics to object-oriented analysis and design of spatio-temporal data models in GIS. Chapter 3 considers the concepts behind the object-oriented approach.

CHAPTER THREE

Object-oriented analysis and design

> Object-oriented methods cover methods for design and methods for analysis. Sometimes there is an overlap, and it is really an idealization to say that they are completely separate activities. I.Graham, *Object-Oriented Methods*

This chapter provides a historical background to object-oriented data management, illustrating the diverse efforts involved in object-oriented methods, temporal databases and version management approaches. It helps to explain the main concepts in the object-oriented paradigm that are essential for developing a spatio-temporal data model. A historical background on object orientation summarises the chronological developments from object-oriented programming languages to object-oriented design methods, and finally to object-oriented analysis methods. It can be difficult to choose which object-oriented method to apply in a spatio-temporal data model. For integrating the time geography framework within our spatio-temporal data model, the object-oriented analysis and design method proposed by Booch (1986, 1991, 1994) is presented as the best in terms of notation, completeness and technique.

The temporal database research is reviewed on the basis of concepts and techniques developed to establish appropriate temporal data management support for a spatio-temporal data model. Version management approaches are then described, emphasising approaches for ordering and updating versions within a model. The version management approach should be chosen so it can be effectively integrated with the spatio-temporal data model. In our spatio-temporal data model, *versions* are deemed to be distinct from snapshot series because they represent *states* that belong to the space-time path of an entity.

3.1 HISTORY OF THE OBJECT-ORIENTED PARADIGM

The history of object orientation starts in the early 1960s with the efforts of Dahl, Myrhaug and Nygaard in creating and implementing new concepts for programming