CHAPTER 4

A Representation of Relationships in Temporal Spaces

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4.1 INTRODUCTION

Time is probably one of the most essential and paradoxical concepts that human beings face. Time is always present in our everyday life from the perception of events to the development of human thinking behaviours. However, time is still a difficult concept to describe and formalise as it has no obvious physical characteristics and properties. We can only establish a temporal statement from the observation or prevision of changes. The relationship between time and space is a consequence of the observation of changes as the perception of spatial alterations denotes the existence of time.

The representation of time within Geographical Information Systems (GIS) is still an important and expected development to make these systems more suited to the temporal analysis of real-world phenomena. Over the past years, the representation of spatio-temporal data has been extensively discussed by different research communities such as the Artificial Intelligence domain that provides a mathematical foundation to the representation of changes in space (Vieu, 1997), temporal database approaches that develop database models and query languages for the description and manipulation of spatio-temporal objects (Wu *et al.*, 1997) and studies oriented to the temporal extension of current spatial data models within GIS (Langran, 1992; Cheylan and Lardon, 1993; Peuquet, 1994; Frank, 1994; Worboys, 1994; Claramunt and Thériault, 1995 and 1996).

This chapter proposes a new reasoning and computational approach that integrates space and time within an integrated temporal space referential. The principles underlying temporal spaces are derived from time geography concepts, spatial and temporal reasoning formalisms. A set of minimal relationships and configurations in a temporal space are identified from the possible combinations of relationships in time and geographical space. Such a model allows the representation and computational study of independent trajectories in space and time. The algebra is illustrated with a case study that outlines some potential benefits of the temporal space model.

The remainder of this chapter is organised as follows. The next section briefly reviews current approaches in the combined representation of space and time. Then we introduce temporal and spatial relationships used for the development of our model. The following sections develop the concept of temporal space, propose a formal model for representing relationships in a temporal space, and illustrate the application of the temporal space model on a case study. The last two sections discuss some implications of our model and draw some perspectives.

4.2 TIME AND GIS

Despite its impenetrable nature, the understanding of time is still an important challenge in the comprehension of the evolution of Earth and the distribution of natural and anthropic phenomena. Until the XX Century the absolutist (chronological) and relationist (topological relationships) conceptions of time were largely used and discussed by scientific communities. Then, the relativist revolution introduced a new relationship between time and motion that impacted the whole scientific community. Particularly, the relationship between motion, time and space was not henceforward representable using a constant and linear rapport. At present, many disciplines are implicitly integrating some of the outcomes of the relativity concept, cognitive sciences are yet discussing the influence of the environment on time perception. For example, an estimated duration is dependent on the degree of perceived changes or in other words the more static the environment the shorter the perceived duration (Zubek, 1969; Block, 1979; Glicksohn, 1996).

Nowadays the representation and understanding of time and motion are still an active research issue in many sciences related to the representation of real or abstracted phenomena. Particularly, the representation of time within GIS is an important research challenge. GIS is by nature a multi-disciplinary area that combines different sciences and techniques. Therefore, it is not surprising to notice that different research advances are contributing to the development of temporal GIS (TGIS). Over the past years, the representation of spatio-temporal data has been extensively discussed by different research communities. Various models have been proposed and examined, among others:

- Artificial Intelligence approaches that provide a mathematical foundation to describe the spatial changes of an individual region (Vieu, 1997 for an overview). The objective of these models is the reduction of the representation of spatial changes to a minimal set of primitive concepts that can be used in spatial reasoning and computational implementations.
- Temporal database approaches that develop models and query languages for the description and manipulation of spatio-temporal objects (Wu *et al.*, 1997 for a bibliography). The integration of the temporal dimension is generally considered as an extension of current database models and query languages. Such extensions integrate the time component as a representable and specific dimension and provide design patterns, temporal data types and operators that can be integrated at the data definition and manipulation levels.
- Temporal GIS research that aims at the extension of spatial data models towards the integration of time (Langran, 1992; Peuquet, 1994; Frank, 1994; Claramunt and Thériault, 1995). Current proposals extend the cartographical foundation of spatial data models towards the temporal dimension and attempt the identification of new spatio-temporal models for TGIS.

These different disciplines pursue a common objective: the representation and manipulation of the spatial changes of an individual region. They are complementary in terms of their achievements as they deliver formal, database or TGIS models, respectively.

Significant progress has been made in the qualitative description and manipulation of changes in space. Taxonomies of spatial changes (Claramunt and Thériault, 1995;

Claramunt *et al.*, 1998; Horsnby and Egenhofer, 1998), and transitive changes of spatial relationships have been identified (Randell *et al.*, 1992; Egenhofer and Al-Taha, 1992; Galton, 1995). Representing individual changes in space (i.e., endogeneous changes) is a first step toward the integration of time within GIS. A complementary theoretical issue is the development of formal models for studying spatio-temporal patterns that involve the interaction of several regions in space and time (i.e., exogeneous changes). Interactions in space and time have been widely studied in time geography, individual trajectories are analysed and compared using an integrated time and space referential (Hägerstrand, 1967). The study of individual trajectories is particularly relevant for the analysis of diffusion mechanisms, crime patterns or the propagation of epidemics.

However, current spatio-temporal models still need some formal extensions oriented towards a qualitative and cross-comparative description of individual regions in both space and time, that is, the study of independent trajectories in space and time. The manipulation within GIS of individual trajectories in space and time still implies the development of formal operators that combine spatial and temporal properties. The objective of this research is the investigation and formalization of a set of minimal operators that support the cross-comparison of individual regions within an integrated space and time referential.

A formal foundation, i.e., a language and a set of minimal operators, is still required for the manipulation and comparison of regions in space and time. The research described in this chapter addresses the development of a formal language that can identify a set of basic operations between individual regions in space and time. Our objective is not to replace current spatial or temporal algebra with an unified language, but instead to present a complementary view of the possible spatial and temporal interactions of regions in space and time.

4.3 TEMPORAL AND SPATIAL RELATIONSHIPS

Representing time and space as an integrated referential implies the combination of temporal and spatial relationships within an integrated framework. This section introduces the temporal and spatial relationship principles used for the development of our model. Firstly, we introduce some basic temporal hypotheses. We assume time to be continuous, T is the set of measured times isomorphic to the set of real numbers and I is the set of time intervals. Let i be a time interval of I, $i = [t_1, t_2]$ where $t_1, t_2 \in T$ and $t_1 < t_2$. Relationships between these temporal intervals are defined using Allen's temporal operators that define mutually exclusive relationships between time intervals {*equals*, *before*, *meets*, *overlaps*, *during*, *starts*, *finishes*} and their inverses {*after*, *met*, *overlapped*, *contain*, *started*, *finished*}, respectively (does not apply for equal which is a symmetric operator) (Allen, 1984). They are defined in Figure 1. Begin(i) and End(i) are temporal operators which provide respectively the beginning and ending instants of a time interval i of I.

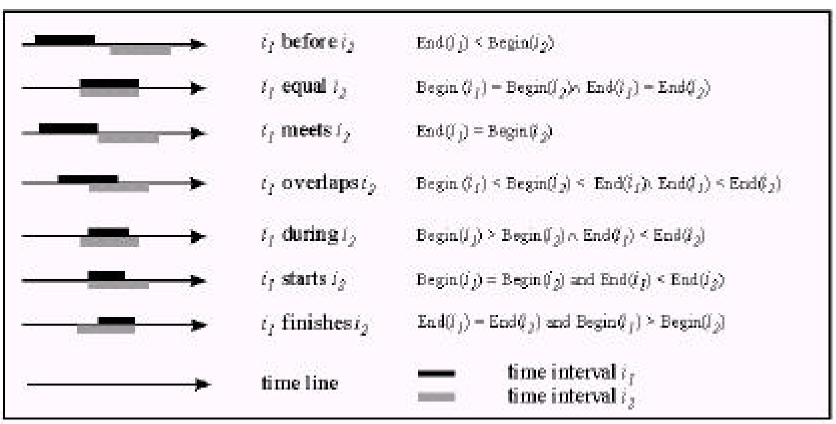
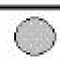
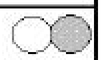
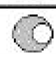
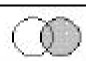
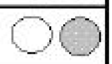


Figure 1. Temporal relationships

Similarly, we consider spatial relationships in a two-dimensional space. Different convergent languages have been proposed, using different primitive concepts and calculus, for the identification of exhaustive and pairwise disjoint spatial relationships (Pullar and Egenhofer, 1988; Egenhofer, 1991; Cui *et al.*, 1993; Clementini *et al.*, 1993). The basic relationships identified within these models are convergent. Let us consider the eight basic spatial relationships identified in two-dimensional spaces, i.e., {*equal*, *touch*, *in*, *contain*, *cover*, *covered*, *overlap*, *disjoint*} (Table 1). Let r_1 and r_2 be two regions in a two-dimensional space, r° denotes the interior of a region of space r, ¶r the boundary of a region of space r. Spatial relationships between r_1 and r_2 are expressed as follows (adapted from Clementini *et al.*, 1993).

Table 1. Spatial relationships between two regions in a two-dimensional space

r_1 *equal* r_2	$\Leftrightarrow$	$(r_1^\circ \cap r_2^\circ = r_1^\circ \cup r_2^\circ) \wedge (\partial r_1 \cap \partial r_2 = \partial r_1 \cup \partial r_2)$	
r_1 *touch* r_2	$\Leftrightarrow$	$(r_1^\circ \cap r_2^\circ = \emptyset) \wedge (\partial r_1 \cap \partial r_2 \neq \emptyset)$	
r_1 *in/contain* r_2	$\Leftrightarrow$	$(r_1 \cap r_2 = r_1) \wedge (\partial r_1 \cap \partial r_2 = \emptyset)$	
r_1 *covered/cover* r_2	$\Leftrightarrow$	$(r_1 \cap r_2 = r_1) \wedge (r_1 \neq r_2) \wedge (\partial r_1 \cap \partial r_2 \neq \emptyset)$	
r_1 *overlap* r_2	$\Leftrightarrow$	$(r_1 \cap r_2 \neq r_1) \wedge (r_1 \cap r_2 \neq r_2) \wedge (r_1^\circ \cap r_2^\circ \neq \emptyset)$	
r_1 *disjoint* r_2	$\Leftrightarrow$	$r_1 \cap r_2 = \emptyset$	

4.4 REPRESENTATION OF TEMPORAL SPACES

A combined representation of spatial and temporal relationships is a non straightforward task from both cognitive and formal points of view. Some of these difficulties are linked to the problem of perceiving and representing time in space, and formalising space with time. Spatial and temporal views provide an appropriate description of the relationships that apply in either the spatial or temporal dimensions, respectively. However, none of these views provides a significant understanding of binary relationships in both space and time. Firstly, spatial relationships identified in a spatially-oriented view are valid only during the intersection of the life spans of their operand regions. Secondly, temporal relationships identified by a temporally-oriented view do not provide any information about the spatial relationships of their operand regions. Temporal animation techniques can be used to provide a global view of geographical changes. However, the analysis of individual trajectories using a temporal animation is not suited for the evaluation of precise relationships and is limited to the potential of visual interpretation tasks which are irrelevant when the number of regions is high. Therefore, experimental representations still need to be explored in order to identify relationships in space and time between several individual regions.

We introduce a concept of temporal space that combines the temporal and spatial dimensions. Our model aims at the representation of the minimal combinations of temporal and spatial relationships between two regions in a temporal space. A region in a temporal space is defined as a region of space valid for a temporal interval. In order to construct a temporal space, binary relationships in two-dimensional spaces are mapped (not projected) towards corresponding binary relationships in a one-dimensional space. The second dimension of a temporal space is given by time. Therefore, relationships in a temporal space are derived from the combinations of the minimal spatial and temporal relationships. In order to maintain the properties of time, the temporal dimension of the temporal space is directed, i.e., a region cannot move backward in time. Moreover we assume that a region cannot be in two different locations in space at the same time.

Let us consider two regions in a temporal space, denoted $e_1(r_1, i_1)$ and $e_2(r_2, i_2)$, respectively. Let i° be the interior of an interval of time i, ¶i the boundary of an interval of time I, $i=[t_1, t_2]$, $i^\circ=]t_1, t_2[$, $\partial i=(t_1, t_2)$. Then the minimal set of relationships between two regions in a temporal space is deduced from the combinations of spatial relationships with the possible set-theoretic intersections between the interiors and boundaries of their temporal intervals (TR denotes a temporal relation, SR denotes a spatial relationship, TSR denotes a relation in a temporal space). Table 2 describes the possible combinations that lead to eight relationships in a temporal space by analogy to the relationships identified in a classic two-dimensional space (EQUAL for equals, TOUCH for touch, IN for in, CON for contain, CVR for cover, CVRD for covered, OVLP for overlap, DISJ for disjoint). The TSR relationships space qualify the semantics represented in a temporal space: two regions "intersect" in a temporal space if and only if they share a common region of space and a common instant of time, otherwise they are DISJoint. Such a representation provides an algebra that describes relationships using atomic operators. It presents the computational advantage of using existing spatial relationships and operations on temporal intervals.

Table 2. Relationships in a temporal space (TSR)

SR	$i_1^\circ \cap i_2^\circ$	$\partial i_1 \cap \partial i_2$	$i_1^\circ \cap \partial i_2$	$\partial i_1 \cap i_2^\circ$	TSR
Any	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	DISJ
$\neg$disjoint	$\varnothing$	$\neg\varnothing$	$\varnothing$	$\varnothing$	TOUCH
Disjoint	any	any	any	any	DISJ
Touch	$\neg\varnothing$	any	any	any	TOUCH
in	$\neg\varnothing$ $\neg\varnothing$ $\neg\varnothing$	$\neg\varnothing$ any $\varnothing$	$\varnothing$ $\neg\varnothing$ $\varnothing$	any any $\neg\varnothing$	CVRD OVLP IN
Contain	$\neg\varnothing$ $\neg\varnothing$ $\neg\varnothing$	$\neg\varnothing$ any $\varnothing$	any any $\neg\varnothing$	$\varnothing$ $\neg\varnothing$ $\varnothing$	CVR OVLP CON

Cover	¬∅ ¬∅	any any	any ∅	∅ ¬∅	CVR OVLP
Covered	¬∅ ¬∅	any ∅	∅ ¬∅	any any	CVRD OVLP
Overlap	¬∅	any	any	any	OVLP
Equal	¬∅ ¬∅ ¬∅ ¬∅	¬∅ ∅ any any	∅ ¬∅ ∅ ¬∅	∅ ¬∅ ¬∅ ∅	EQUAL OVLP CVRD CVR

Table 3 summarises the resulting eight minimal and orthogonal TSR relationships in a temporal space obtained from the combination of minimal spatial and temporal relationships. Another interest of this classification is the identification of the different relationship configurations: we define a configuration as a triplet (SR, TR, TSR). Table 3 also represents the 71 configurations, 104 with their TR inverse (does not apply for the TR operation equals which is a symmetric one). Inverse temporal relationships lead to inverse TSR relationships in the temporal space, otherwise inverse TSR relationships in the temporal space are given.

The temporal space used for the definition of this algebra considers the spatial relationships line as a dimensional line and the temporal dimension as a second dimensional line. This two-dimensional representation of relationships in a temporal space integrates some visual similarities with the representation of spatial relationships. The main idea of that graphic representation is to project spatial relationships in the vertical spatial relationship axis (i.e., the notion of spatial distance is lost, however that is not a limitation as the spatial distance is a spatial measure available in the spatial dimension). TSR relationships have the computational advantage of being derived from existing spatial and temporal relationships so their implementation can be realised on top of existing TGIS models. Moreover, the different configurations can be represented with a visual language. As the spatial relationship dimension is qualitative only (i.e., the notion of distance between regions is not represented), the 71 configurations of relationships (104 with their TR inverses) in the temporal space are relatively complete in terms of their visual expression. The only minor variation is the possible stretch of the visual relationships in the temporal space (and not along the temporal dimension as the temporal line integrates the concept of temporal distance).

Table 3. Visual representation of TSR

TR SR	equals	before/ after	meets/ met	overlaps/ overlapped	during/ contain	starts/ started	finishes/ finished
equals	EQUAL	DISJ	TOUCH	OVLP	CVRD/CVR	CVRD/CVR	CVRD/CVR
touch	TOUCH	DISJ	TOUCH	TOUCH	TOUCH	TOUCH	TOUCH
in	CVRD	DISJ	TOUCH	OVLP	IN/OVLP	CVRD/OVLP	CVRD/OVLP
contain							

	CVR	DISJ	TOUCH	OVLP	OVLP/CON	OVLP/CVR	OVLP/CVR
cover	CVR	DISJ	TOUCH	OVLP	OVLP/CVR	OVLP/CVR	OVLP/CVR
covered	CVRD	DISJ	TOUCH	OVLP	CVRD/OVLP	CVRD/OVLP	CVRD/OVLP
overlap	OVLP	DISJ	TOUCH	OVLP	OVLP	OVLP	OVLP
disjoint	DISJ	DISJ	DISJ	DISJ	DISJ	DISJ	DISJ

Relationships in a temporal space provide a set of low-level operations that can be reclassified according to application needs. For example a distinction can be made in terms of set operations. That leads to a distinction being made between DIS and other relationships in a temporal space (EQUAL, TOUCH, IN/CON, CVRD/CVR, OVLP) that can be reclassified to a CONNECT user-defined operation in a temporal space. Such an operation is of interest for identifying individuals in space whose trajectories intersect somewhere and sometime.

4.5 APPLICATION TO A CASE STUDY

In order to illustrate the potential of temporal spaces, let us consider a simplified example which presents five regions located in space (A, B, C, D, E) and valid for some interval of times. Two representations are possible with respect to the application of binary relationships in either time or space. Firstly, Figure 2 presents a spatially-oriented view in which spatial relationships between these regions are represented independently of the temporal dimension.

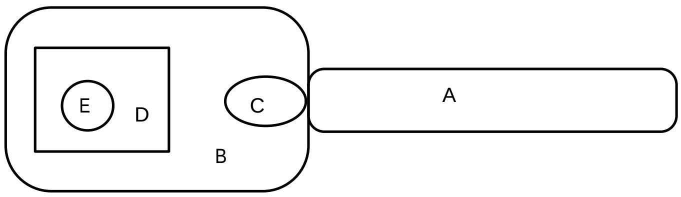


Figure 2. Spatially-oriented view (case study)

Accordingly, Table 4 presents the binary spatial relationships (SR) that apply for these regions:

Table 4. Spatial relationships SR (case study)

SR	A	B	C	D	E
A	equals	touch	touch	disjoint	disjoint
B	touch	equals	cover	contain	contain
C	touch	covered	equals	disjoint	disjoint
D	disjoint	in	disjoint	equals	contain
E	disjoint	in	disjoint	in	equals

Similarly, Figure 3 presents the set of temporal relationships that hold between these regions independently of the spatial dimension; assuming that the regions of our example hold for some intervals of time.

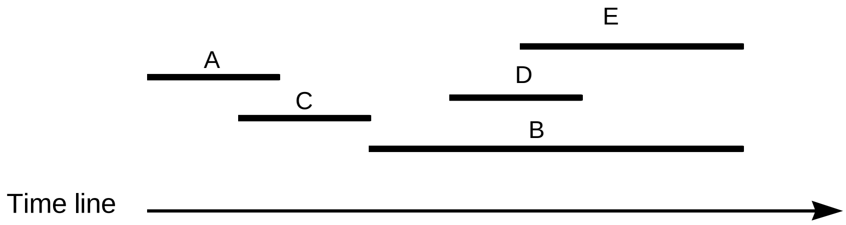


Figure 3. Temporally-oriented view (case study)

Temporal relationships between these regions can be expressed. Table 5 illustrates the temporal relationships (TR) between the regions of the above example.

Table 5. Temporal relationships TR (case study)

TR	A	B	C	D	E
A	equal	before	overlaps	before	before
B	after	equal	met	contains	finished
C	overlapped	meets	equal	before	before
D	after	during	after	equal	overlaps
E	after	finishes	after	overlapped	equal

In order to construct the representation of these regions in the temporal space, spatio-temporal relationships are mapped to their corresponding relationships in a one-dimensional space. The resulting spatial relationships are represented as follows (Figure 4).

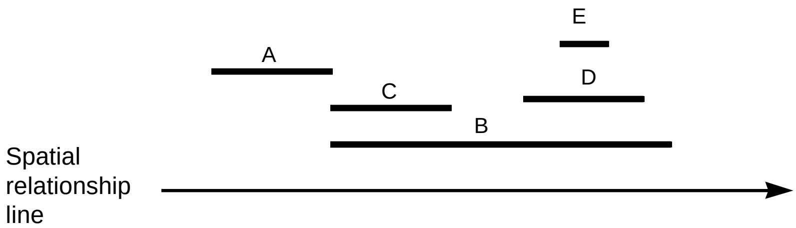


Figure 4. Spatially-oriented view (case study)

Therefore, a two-dimensional representation of relationships in a temporal space for our case study is proposed in Figure 5. This representation provides some nice properties as relationships in a temporal space integrate both the semantics of relationships in space and time, e.g., B contains D both in space and time, A touches C in space and overlaps C in time.

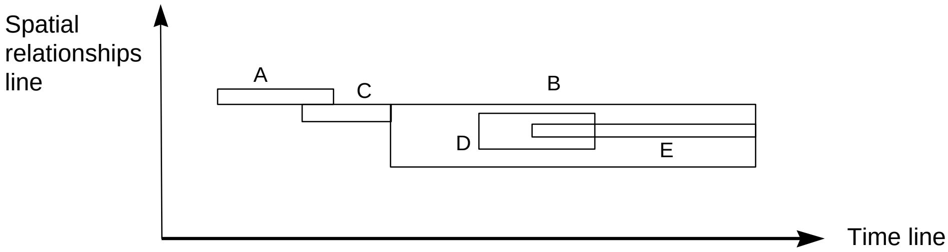


Figure 5. Visual representation of TSR (case study)

Accordingly, Table 6 summarises the relationships in the temporal space (TSR) that apply for our example:

Table 6. Relationships in the temporal space - TSR (case study)

TSR	A	B	C	D	E
A	EQUAL	DISJ	TOUCH	DISJ	DISJ
B	DISJ	EQUAL	TOUCH	CON	CVR
C	TOUCH	TOUCH	EQUAL	DISJ	DISJ
D	DISJ	IN	DISJ	EQUAL	OVLP
E	DISJ	CVRD	DISJ	OVLP	EQUAL

TSR relationships in a temporal space can be analysed in cascade. For example, A and E are DISJoint in a temporal space. However they are CONNECTed in cascade through C then B, and through C then E. Such a transitive property is fundamental for many applications such as epidemiological studies.

4.6 DISCUSSION

The concept of temporal space provides a new experimental approach to the representation of spatio-temporal relationships within GIS. A temporal space has the advantage of providing two levels of relationships: the corresponding 8 relationships commonly identified in two-dimensional spaces and the 71 configurations (104 with their TR inverses) directly derived from the combinations of temporal and spatio-temporal relationships. Temporal spaces do not replace the spatially-oriented or temporally-oriented views of space, instead they allow a different perspective and an integrated view that supports the identification of relationships in space and time. This algebra is suited to the analysis of distinct trajectories in space and time, and their effects in cascade. We can remark that the application of temporal space concepts to the life and motion process of an individual region is not relevant as temporal relationships between the successive regions that represent the evolution of an entity will be limited to meet/met, or even disjoint in the extreme case of a re-incarnation, relationships. Then the range of resulting TSR relationships in a temporal space for these regions will be represented as TOUCH relationships (or DISJ in the case of a reincarnation process).

Qualitative representations of geographical spaces introduce the notion of conceptual neighbourhood to identify the direct transitions that can be made between spatial relationships (Freksa, 1991). Similarly, the temporal space model can be discussed with regard to the possible transitions of its TSR relationships. A set of axioms can be derived from the combination of the possible combination of spatial relationships identified in (Randell *et al.*, 1992; Galton, 1995), and from the study of the possible transitions of temporal intervals. The following diagram summarises the possible transitions of spatial relationships (adapted from Cohn *et al.*, 1998). It can be read as, for example, if two regions touch for an interval of time, and both continue to exist after the end of this interval of time, then the spatial relationships between these two regions for the immediate following interval of time are either touch, disjoint or overlap.

disjoint	←→	touch
touch	←→	overlap
overlap	←→	equal, cover, covered
cover	←→	contain
covered	←→	in
equal	←→	cover, covered, in, contain

Immediate transitions of temporal relationships between two regions in a temporal space can be analysed from the study of the possible relationships between the beginning and ending instants of the intervals of time of these regions as we consider the time line as continuous. For example, if the ending instants of the intervals of time of two regions in a temporal space are equal, and if these regions continue to exist after these intervals of time, the beginning instants of the immediate intervals of time of these two regions are equal, then the temporal relationships between these two regions for the immediate following intervals of time are either equal, starts or started. The possible transitions of temporal relationships between two regions in a temporal space are presented in Table 7.

Table 7. Transitions of temporal relationships between two regions in a temporal space

End(i_1) < End(i_2)		Begin(i'_1) < Begin(i'_2)
before meets overlap during starts	→	before meets overlap contain finished
End(i_1) = End(i_2)		Begin(i'_1) = Begin(i'_2)
equal finishes finished	→	equal starts started
End(i_1) >End(i_2)		Begin(i'_1) > Begin(i'_2)
after met overlapped contain started	→	during after met overlapped finishes

The above table can be read as, for example, if the temporal interval of a region in a temporal space is before the temporal interval of a second region in the same temporal space, and if these two regions continue to exist after the end of this interval of time, then the temporal relationships between these two regions for the immediate following interval of time are either before, meets, overlap, contain or finished. The analysis of possible transitions of relations in a temporal space are also deductible from the possible transitions of their temporal and spatial relationships. Informally, a general axiom can be formulated: there is a possible transition between two TSR configurations in a temporal space (SR_1, TR_1, TSR_1), (SR_2, TR_2, TSR_2) if and only if there is both a possible transition between SR_1 and SR_2, and between TR_1 and TR_2. The application of conceptual neighbourhood principles is particularly interesting in situations in which the knowledge represented is incomplete. The evaluation of possible relationships between non well-defined locations in space and time can be derived and estimated from the analysis of preceding and posterior situations.

4.7 CONCLUSION

Many scientific and administrative studies require a combined representation of spatial and temporal relationships in order to analyse trajectories in space of time. For example, a spatial proximity of two regions in space can be relevant when these two regions exist for at least a common interval of time. Such requirements are important for epidemiological, crime pattern or spatial diffusion studies. This chapter experiments and proposes a concept of temporal space that provides a new approach to the representation of spatio-temporal data within GIS. Temporal spaces do not replace the spatially-oriented or temporally-oriented views of space. Instead they allow a different perspective and an integrated view that support the identification of relationships in both space and time.

From the identification of relationships in space and time, we propose a model that defines a set of minimal relationships within a temporal space that combines the spatial relationship and temporal dimensions. A set of basic relationships and configurations in a temporal space has been identified. As this model is based on an integration of relationships in space and time, its implementation is upward compatible with spatial and temporal models commonly identified within GIS. The proposed model is flexible enough to be applied and adapted to different application contexts. User-oriented relationships can be also defined using generalisation mechanisms. Further work implies the implementation of the formal algebra and the validation of its interest in real application contexts.

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