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Derivation of Change from Sequences of Snapshots

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DERIVATION OF CHANGE FROM SEQUENCES OF SNAPSHOTS

By

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An Abstract of the Thesis Presented
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Current research in the domain of geographic information science considers possibilities of including another dimension, time, which is generally missing to this point. Users interested in changes have few functions available to compare datasets of spatial configurations at different points in time. Such a comparison of spatial configurations requires large amounts of manual labor. An automatic derivation of changes would decrease amounts of manual labor. The thesis introduces a set of methods that allows for an automatic derivation of changes. These methods analyze identity and topological states of objects in snapshots and derive types of change for the specific configuration of data. The set of change types that can be computed by the methods presented includes continuous changes such as growing, shrinking, and moving of objects. For these continuous changes identity remains unchanged, while topological relations might be altered over time. Also discrete changes such as merging and splitting where both identity and topology are affected can be derived. Evaluation of the methods using a prototype

application with simple examples suggests that the methods compute uniquely and correctly the type of change that applied in spatial scenarios captured in two snapshots.

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Chapter 1
INTRODUCTION

Geographic information systems (GISs) have capabilities for visualization and analysis of spatial scenarios and configurations. The temporal dimension of those information systems, however, is generally missing up to this point (Yang and Claramunt, 2003), as GISs mostly contain information about a single state of the world (Worboys, 1998). There are only few functions that users, who are interested in changes, can use to compare different compilations of spatial datasets taken at specific points of time (*snapshots*). An automatic derivation of changes would reduce manual labor. The objective of this thesis is to evaluate the use of qualitative spatial data from observations at different points in time and the observed alterations in these measures to reason about changes.

1.1 Change Derivation from Snapshots

Natural objects, such as lakes, islands, and forests and artificial objects, such as land parcels, undergo a multitude of changes over time, like changes in size and shape. These natural objects are of primary interest in this study where the only data describing change can be derived from discrete observations. Research has been focused on finding appropriate measures to model changes and to include into GISs spatio-temporal aspects, such as events and changes and important progress has been made in the integration of time within GISs (Langran, 1989; Frank, 1994; Peuquet, 1994; Claramunt and Theriault, 1996; Hornsby and Egenhofer, 2000; Worboys and Hornsby, 2004).

However, GISs often deal solely with data represented in snapshots so that changes can only be viewed as a sequence of mutual relations between entities (Peuquet, 1994; Worboys, 2005).

Capturing real-world phenomena can be a problem due to high costs for data collection, unavailability of data, or the huge amounts of data connected to the continuous observation of spatial phenomena in addition to the missing temporal dimension of GISs. To avoid the problems connected with the continuous observation of spatio-temporal phenomena, methods can be applied that are based on the available data, presented as snapshots, the current framework of temporal representation in GISs. This thesis explores how the identity of objects as well as their topological and metric spatial relations can be exploited to derive changes that occur between two consecutive snapshots.

Automatic derivation of changes from snapshots can add spatio-temporal reasoning power to GISs. This process will help replace the human intervention in the detection of changes, which might consequently result in the reduction of costs for parties with an interest in the evolution of spatial phenomena.

1.2 Example

Changes in objects often go along with changes to the topology of objects in a spatial scenario. For instance, the spatial extent of a lake may change over time, depending on precipitation or draught. Increased rain fall may result in alterations of amounts of water that rivers bring to a lake leading to an expansion of the lakes surface. Reversely, draught may lower the lake's surface, leading to a smaller surface area. When a lake grows or shrinks, this corresponds to the level of water in the lake. Due to the geological relief, when the water level sinks sufficiently low, the lake might split up into multiple disconnected, smaller lakes. Conversely, several isolated lakes may merge into a single lake when the water level rises.

This example shows how the identity of objects (i.e., different identifiable lakes) may be affected in a real-world scenario by changes in the objects' spatial properties. As a lake splits up into two lakes, people may perceive these two pieces of the original lakes as objects with a new identity. Topology is closely connected to identity in this scenario, as the new objects gain new topological relations to existing objects in the spatial configuration, for example to forests or wetlands surrounding the lake. Also, the combination of identity and topology adds a spatial reference to the concept of identity. Hence, modeling changes in identity and topology of a spatial scenario is a truly spatio-temporal approach.

1.3 Scope

Objects that are of concern in this thesis are spatial regions (Egenhofer and Franzosa, 1991), that is, simply connected areas in $\mathbb{R}^2$. Regions with holes or regions that consist of multiple parts are excluded from this study. Also excluded from this thesis are changes that occur to point and line objects. The types of change that can be derived from information available in snapshots are defined in Chapters 3 and 4. These types of change either preserve the topology of a spatial configuration (i.e., growing, shrinking and moving), or modify the identity and topology (i.e., merging and splitting).

This thesis presents methods that are capable of deriving changes that occurred to regions based on data available in snapshots. These data include topological data, that is, the binary topological relations between the region objects, identity data about the state of existence or non-existence of these region objects at different times and metric information.

The approach presented to derive changes from snapshots of qualitative spatial data uses spatial scenarios that include two or more spatial regions in a 2-dimensional space.

The methods described are mostly based on qualitative spatial data, including topology and identity. Such data are generic and, therefore, they have high value in the derivation of changes as they can be applied for situations where a spatial configuration is sketched or where highly detailed maps are available. Additional methods apply in those cases as well, enhancing the precision of the change derivation.

1.4 Goal

The goal of this thesis is to evaluate the use of qualitative spatial data, as available in snapshots describing a spatial scenario, for the detection and derivation of changes. The methods are based on either solely the detection of changes that influence the topological relations between objects, or on identity and topology of a spatial configuration in a combined way. Additionally, methods using semi-quantitative measures, such as metric refinements, are employed to achieve higher precision.

1.5 Approach

This thesis is concerned with the derivation of changes from qualitative spatial data in snapshots. First methods are created to detect and identify specific types of change that affect the topological relations and area ratios of the involved objects in the snapshots. For the other set of change types (i.e., merging and splitting) it is necessary to have an account for the effects these changes have on the identity and topology of the regions in snapshots. Therefore, a definition of these types of change is required. Also, the possible topological relations are derived for the regions that undergo such a change. This analysis results in the set of topological relations the objects can have to a reference object before merging or splitting occurs.

This approach is evaluated by analyzing the outcomes of the application of the combined set of methods to a complex example. This example is arbitrary, incorporating different types of change that affect the topology and topology and identity combined. The example includes multiple snapshots. Additionally, a prototype application tests the validity of the methods. The prototype works with rectangles representing regions. The methods are valid in case the intersection of the combined results of all the methods is not empty.

1.6 Research Questions and Hypothesis

Change derivation from snapshots using qualitative measures promises to infer information that is not directly available. The following questions have been identified as important question this thesis answers:

Question 1: Can the snapshot model be used to represent and derive changes?

Current GISs generally deal with representations of spatio-temporal phenomena at a particular time (snapshots) or collections of snapshots (Worboys, 1994). The snapshot model is not capable of representing change between snapshots explicitly. What are the extensions needed to incorporate changes? How can changes be derived from snapshots? These questions are relevant as they are directly related to the motivation for this work.

Question 2: How can the measures of identity and topology be combined to detect different types of change?

To develop different measures that can detect and derive changes from snapshots it is important to understand the way in which identity and topology change. How do different types of change affect the identity and topology of objects? How can knowledge about changes be used in methods to identify different types of change? These questions are related to the completeness and usefulness of measures. These questions are significant, as they are related to the way methods are developed based on identity and topology, and answers will show how such methods are systematically created.

The combination of research questions presented is addressed within this thesis.

We hypothesize that:

A sequence of snapshots, featuring identity states and topological relations of objects, allows an automatic derivation of changes that affect either identity, topology or a combination of identity and topology of objects.

1.7 Major Results

The exemplary application (Chapter 5) of methods in the *Change Explorer* application for change derivation from snapshots using topology and identity shows that the application of one method for change derivation at a time does not always yield unique results, but sometimes returns sets of possible changes. Yet, the combination of methods can derive unique results, identifying not only one type of change, but also other types of change that co-occur. Additional methods need to be employed to achieve higher precision in the derivation of change, for example, to find out what the underlying factors of the change might be. These extensions to the proposed methods for change derivation are discussed in Chapter 6.

1.8 Intended Audience

This thesis's intended audience consists of researchers interested in approaches to modelling qualitative spatio-temporal changes, and researchers and developers who are interested in methods for the derivation of changes using identity or topology as well as temporal additions to GISs. Furthermore, the content of this thesis may also be of interest for those with a research focus on spatial or spatio-temporal reasoning.

1.9 Organization of Remainder of Thesis

This first chapter provides a motivation for the work described throughout this thesis. Then it is discussed in this chapter how the model and methods in the following chapters address the problems. The remainder of this thesis is structured as follows:

Chapter 2 reviews related work in the field of spatio-temporal modeling and spatial reasoning. It also focuses on different measures, including topology and identity that can be used to describe spatial configurations. Additions to purely topological measures are also discussed, including metric refinements.

The third chapter then engages with the development of methods, based on solely topology, to derive changes between snapshots. It introduces and defines a set of types of change that can be derived by using these methods. The methods employ different measures, including topological descriptions of single objects at different points in time, binary topological relations between different objects at two snapshots, and also metric refinements for these topological measures.

Chapter 4 introduces two change operations that include alterations in topology and identity, merging and splitting. In addition to the definition of merging and splitting the chapter deals with the derivation of sets of possible relations between merged or split objects (objects after merging or splitting occurs) based on specific relations for to-be-merged or to-be-split objects (objects before a merging or splitting occurs) to a reference object. These sets of topological relations are essential in the development of methods that can track merging and splitting of objects in a spatial configuration.

The methods from Chapter 3 are evaluated in Chapter 5. The chapter explains the prototype developed for testing the functionality of the methods for changes in topology, such as growing, shrinking, and moving of regions. Examples are provided that show how the prototype can be used to specify states of a spatial phenomenon at two consecutive snapshots for regions represented as rectangles. While the current prototype application can derive changes only from scenarios with rectangles, it is shown in a more complex example including multiple objects that methods are not limited to the use of rectangles, but can handle other shapes as well.

Chapter 6 summarizes findings of the thesis, draws conclusions, and shows for the interested audience where there is potential for further research related to this work as in extensions and refinements.

Chapter 2

SPATIO-TEMPORAL MODELING AND REASONING WITH QUALITATIVE MEASURES

This thesis consists of two basic components: (1) the development of a spatio-temporal model for change, where change is described with respect to identity states of objects as well as binary topological relations, and (2) the derivation of types of change from the qualitative measures identity and topology. This chapter reviews different approaches in modeling change and the integration of time into GISs. Basic concepts of identity and topology are discussed, including mathematical definitions, importance and roles of these measures, and how identity and topology have been used in spatio-temporal modeling.

2.1 Time in GIS

Current GISs lack the capabilities for representing time and time-related concepts, such as change and events. Most GISs use a single snapshot model, describing a single state of a spatial phenomenon (Worboys and Hornsby, 2004). This way of managing databases is anchored in the traditional paper map model (Langran, 1992; Renolen, 1997). Many researchers in the domain of geographic information science have demanded alternatives to the snapshot model, for instance by considering processes and actions (Egenhofer and Golledge, 1994). The integration of temporal information, which is essential for predictions of future states of spatial phenomena and an understanding of change and events, has been requested (Frank, 1994). This is a particularly important issue as the base of GIS users is growing significantly. Therefore, it is essential that GISs are capable of representing spatial phenomena the way people conceptualize them, namely as phenomena that evolve over space and time. Therefore, GISs should have the capability of tracing and analyzing changes in spatial information. Two possible approaches have been identified for reasoning about time: (1) a change-based approach and (2) a time-based approach (Al-Taha and Barrera, 1990). Different models describe changes based on the snapshot model of space and time, where multiple snapshots are used that represent time (Langran, 1992; Peuquet, 1994). Additional research is concerned with the development of qualitative models of time (Allen, 1984; Frank, 1994) and spatio-temporal reasoning based on these new concepts of time (Claramunt and Jiang, 2000a). Spatio-temporal phenomena have been modeled by integrating concepts of time and topology (Claramunt and Theriault, 1995; Claramunt and Jiang, 2000b; Erwig and Schneider, 2002). A visual language was proposed to describe scenarios of changing topological relations of objects (Erwig and Schneider, 2003).

Further publications about spatio-temporal aspects of GISs and treatment of space and times are available in a comprehensive compilation (Al-Taha *et al.*, 1994).

2.2 Qualitative Spatial Data

Representing a spatial configuration of a snapshot by explicitly describing the topology and identity has advantages over using images of a spatial phenomenon, as this qualitative description of a scene can be used to derive changes. Utilizing qualitative spatial data to describe a spatial phenomenon that changes over time enables a user to reason about change. On the other hand, quantitative spatial data, such as images, may be hard to interpret, as the scales of the images might be different and sizes, shapes, and orientations of objects may be distorted. The description of a snapshot with qualitative spatial data has the advantage that only the significant information for change derivation is presented, abstracting from insignificant details.

2.2.1 Identity

Objects are representations of real-world phenomena in information systems (Kim, 1991). In snapshots, these can be any kind of spatial objects, including points, lines, and regions. Objects can be entities with physical boundaries or boundaries induced by human demarcation, referred to as *bona fide* and *fiat objects,* respectively (Smith, 1995). These objects have attributes representing them. Both identity and topology can be used to describe the state of a spatial phenomenon in the snapshot, with identity capturing existence or non-existence and topology the relative location of objects to another.

In every language—be it spoken language or programming languages—there must be a way to tell one object from another. Objects have unique identities which are independent of attribute values and by which objects can be distinguished from all other objects. With the concept of object identity, tracking of other properties of objects is unnecessary to fully capture the uniqueness of an object (Khoshafian and Copeland, 1986).

Object identity is a concept that is ubiquitous in object-oriented modeling and databases (Khoshafian and Baker, 1996). Researchers have pointed out the importance of the concept of object identity for the tracking of changes (Abiteboul and Kanellakis, 1989; Al-Taha and Barrera, 1994; Hornsby and Egenhofer, 1997; Hornsby and

Egenhofer, 2000). Identity is a property associated with an object, and the identity state may change while the identity of the object endures.

2.2.2 Identity Changes

Current spatial data models do not include capabilities to capture semantics of change completely. In order to integrate scenarios that change over space and time into GISs, it is essential to understand the underlying components and how people reason about change (Hornsby and Egenhofer, 1997). Gaining knowledge about change enables scientists to understand why changes happen to entities in a particular domain and allows predictions about states of these entities.

While researchers from multiple disciplines are interested in the representation of change, they use different approaches to model changes, but to this point there has not been a systematic treatment of change. Different approaches have been utilized to enrich GISs with models capable of representing change, including models that track identity changes.

Qualitative representation of change by modeling identity has been undertaken by different researchers over the past years. Formal solutions have been provided for the representation of the real world and construction of databases that can track change in the identity of objects. Medak (1999) introduces in the *lifestyle*s model basic operations to manipulate the identity of single objects, namely *create*, *destroy*, *suspend*, and *resume*, and operations that affect identities of multiple objects, namely *fusion*, *fission*, *segregation*, and *aggregation*. Fusion and fission yield a comparable definition as the operators affecting topology and identity in an integrated fashion, namely merging and splitting.

The Change Description Language (CDL) is a model for spatio-temporal change based on identity, which has been identified as a fundamental element in scenarios of change (Hornsby and Egenhofer, 1997; Hornsby and Egenhofer, 2000). The CDL constitutes a *change-based* approach to data modeling. It takes into account underlying factors and how humans reason about change. An extension of the CDL also deals with composite objects (Hornsby and Egenhofer, 1998).

The CDL is based on the explicit description of change with respect to states of existence and non-existence of identifiable objects. In the CDL existence stands for the physical presence or occurrence of an object or even belief in or perception of a conceptual object, for example a country. The model includes primitives related to the identity states of objects, and the transitions between the states

The model distinguishes between the following states of existence and non-existence for objects: an object can be *existing*, *non-existing with history*, and *non-existing without history*. The term history refers to the former existence of an object with that identity. The CDL derives also a complete set of identity-based changes, common in real-world scenarios. This set of change operators can be classified as they either preserve or change objects identities. The CDL is an iconic language that visualizes the primitives, that is, the states of existence or non-existence of objects in a snapshot and the transitions from one state to the next. The model includes a qualitative order of time. While the transition represents the changes to objects' identities in a specific time period, the state of the object to the left of the transition corresponds to the object's state *before* the transition, and the right of the transition to *after*. Such a temporal order without measurement on the time scale is less precise but nevertheless useful, as it is close to the way people use time (Frank, 1994). The visual nature of such an iconic language has the advantage that this alternative way to communicate with a computer system may be easier and clearer for users (Catarci *et al.*, 1993). Furthermore, spatio-temporal situations cannot easily be specified; therefore, a visual notation can be extremely helpful (Erwig and Schneider, 2003).

In the CDL three basic symbols are used to represent the state of existence and non-existence as well as symbols for transitions between the identity states (Figure 2.1).

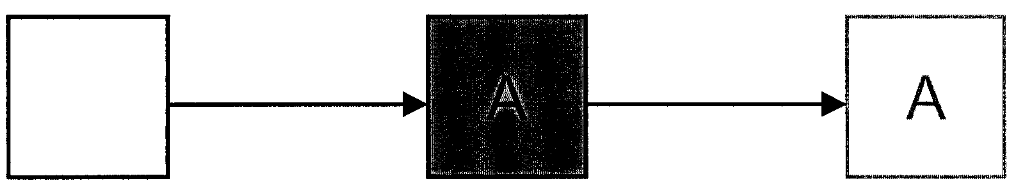

Figure 2.1: Transitions from non-existing without history to existing to non-existing with history.

By combining these basic symbols, simple operations that manipulate single individual objects can be modeled. Basic operations include *create*, *destruct*, and *continue* which are comparable to the basic operations *create*, *destroy* and *resume* in the *lifestyles* model (Medak, 1999).

An additional primitive of the CDL is a cross-object transition, which makes it possible to model changes such as merging and splitting (Figure 2.2)

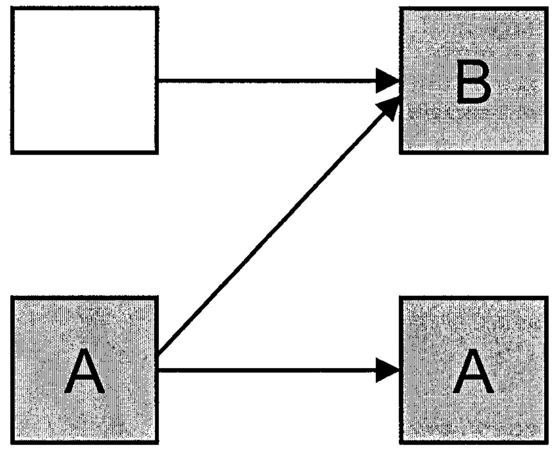

Figure 2.2: Cross-object transition between objects *A* and *B* represented by a diagonal arrow.

Complexity can be built by combining these basic operations to introduce new operations for the description of scenarios of change.

2.2.3 Qualitative Representation of a Snapshot with Topology

A spatial configuration in a snapshot may consist of multiple spatial objects. The snapshot can be described by using topology as a qualitative measure. The binary topological relations between objects *A* and *B* have been defined by the empty and non-empty intersection of their parts in the 9-intersection model (Egenhofer and Herring, 1991). Topological relations, which are a particular subset of geometric relations, are preserved under topological transformations such as translation, rotation, and scaling. Objects that can be described are 0-dimensional (points), 1-dimensional (lines) or 2-dimensional (regions).

This model, where objects are defined as point sets, describes binary topological relations represented by 9-intersection matrices. A point set *A* has an interior, denoted as

A°, a boundary, denoted as ∂A, and a exterior, denoted as A^{-}. The 9-intersection model defines the topological relation between objects *A* and *B* by the explicit description of the intersections between the parts of the objects, that is, the interiors, boundaries, and exteriors (Equation 2.2). This thesis also uses the closure $\bar{A}$ of an object *A*, which is the union of the interior and the boundary ($A^{\circ} \cup \partial A$).

While Ω is defined as the set of all the simply connected regions in $\mathbb{R}^2$, Ω^* defines the set of all the parts (interior, boundary, exterior) of the regions that are in Ω.

$$f : \Omega^* \times \Omega^* \rightarrow \{\varnothing, \neg\varnothing\}$$
$$f(C,D) = \begin{cases} \varnothing, & C \cap D = \varnothing \\ \neg\varnothing, & C \cap D = \neg\varnothing \end{cases} \tag{2.1}$$

$$R(A,B) := \begin{pmatrix} f(A^{\circ} \cap B^{\circ}) & f(A^{\circ} \cap \partial B) & f(A^{\circ} \cap B^{-}) \\ f(\partial A \cap B^{\circ}) & f(\partial A \cap \partial B) & f(\partial A \cap B^{-}) \\ f(A^{-} \cap B^{\circ}) & f(A^{-} \cap \partial B) & f(A^{-} \cap B^{-}) \end{pmatrix} \tag{2.2}$$

For each of the parts of *A* and *B*, the intersection can be empty ($\varnothing$) or non-empty ($\neg\varnothing$). There are 512 (2^9) intersection matrices that can be distinguished with the 9-intersection model.

2.2.4 Topological Relations between Regions in $\mathbb{R}^2$

From these possible intersection matrices only a small amount has been found realizable. For the 2-dimensional space assumed in this thesis, the 9-intersection model identifies eight distinct cases of intersection matrices that match a binary spatial relation for two simply connected regions, embedded in $\mathbb{R}^2$ (Figure 2.3). These topological relations have been called *disjoint*, *meet*, *overlap*, *coveredby*, *inside*, *equal*, *covers*, and *contains*. This set of topological relations is mutually exclusive and exhaustive.

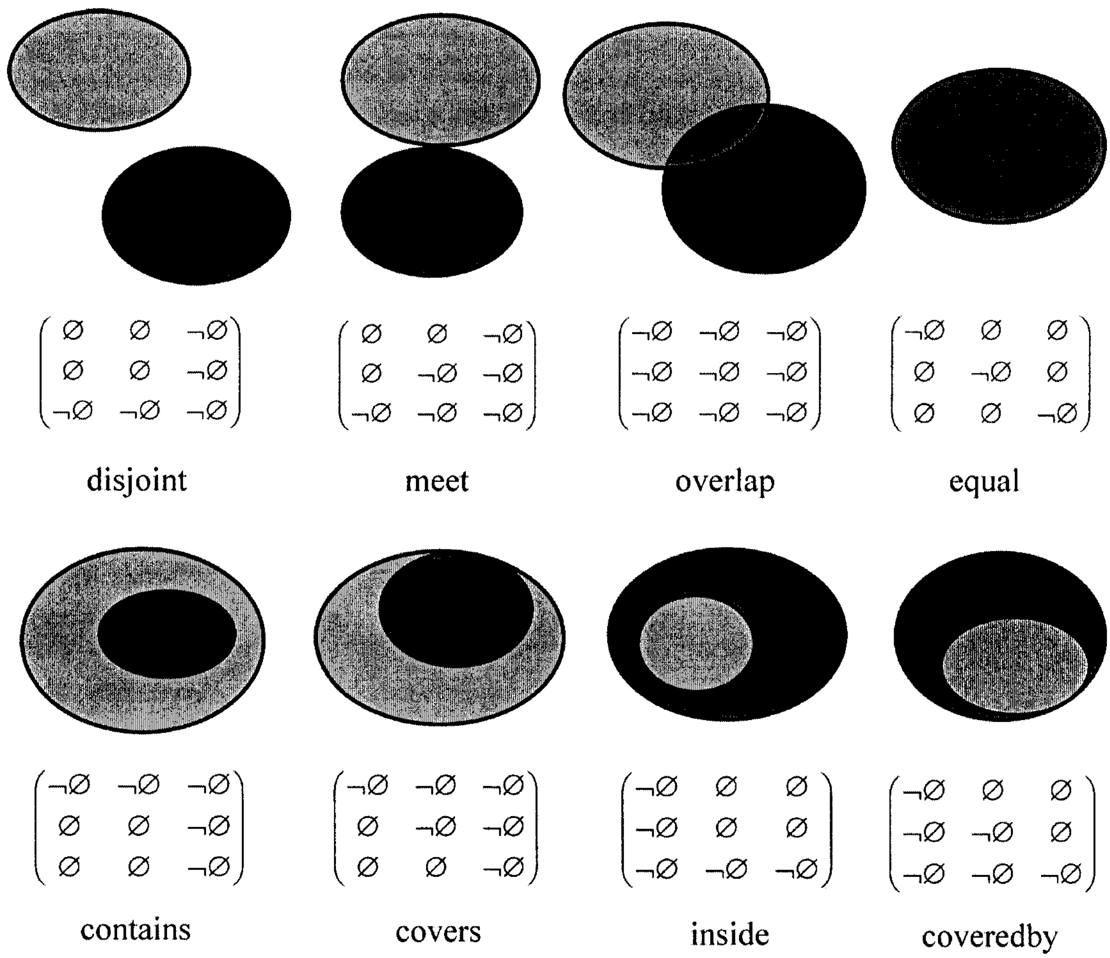

Figure 2.3: Eight realizable topological relations for regions in a 2-dimensional space (the topological relations apply for a region *A* represented by light grey color).

2.2.5 Metric Refinements

Topology can be seen as a highly abstract and qualitative spatial representation, but in many domains topological information is insufficient (Cohn, 1997). When people describe a spatial configuration, it is found that topology is among the most important types of information, while metric is typically of lesser importance. But metric is important in distinguishing particular cases and, therefore, is helpful in the derivation of changes. This thesis uses the premise that "topology matters and metric refines" (Egenhofer and Mark, 1995b). Different metric refinements have been developed to allow a distinction between cases where the same topological relations holds, for relations between lines and regions (Shariff, 1996) and between two regions in $\mathbb{R}^2$ (Egenhofer, 1997). From the set of metric measures we identify a subset that is particularly relevant for deriving changes from snapshots.

2.2.5.1 Splitting Measures

There are two splitting measures (Egenhofer, 1997) that are predominantly useful in the detection of changes between snapshots: (1) Inner Area Splitting (IAS) and (2) Outer Area Splitting (OAS). Both measures together describe how an object A is split up by the part of the boundary of the other object B that runs through A*'s* interior. IAS describes the part of A*'s* interior that is common for both objects, while OAS describes the part that of A that is located in the exterior of B. Due to the normalization of the splitting measures, the sum of IAS and OAS is always equal one.

The IAS value for an object A in relation to an object B is calculated by the common area of both regions relative to the full area of A (Figure 2.4, Equation 2.3). For a specific $A \in \Omega$ the IAS function is defined as follows:

$$IAS_A : \Omega \rightarrow [0,1]$$

$$IAS_A(B) = \frac{area(A \cap B)}{area(A)} \qquad (2.3)$$

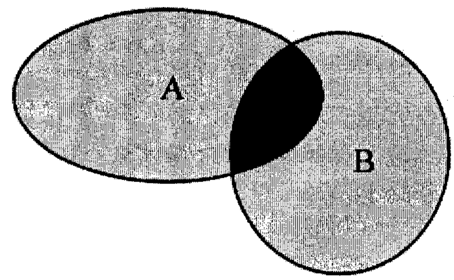

Figure 2.4: Illustration of the area of common interior that is used to calculate the IAS value with respect to total area of object A.

OAS of an object A in relation to an object B is defined as the part of A that is part of B's exterior, normalized by the area of A (Figure 2.5, Equation 2.4). For a specific $A \in \Omega$ the OAS function is defined as follows:

$$OAS_A : \Omega \rightarrow [0,1]$$
$$OAS_A(B) = \frac{area(A \cap B^-)}{area(A)} \tag{2.4}$$

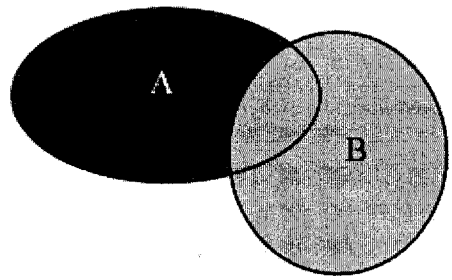

Figure 2.5: Illustration of the area of object A in the exterior of object B that is used to calculate the OAS value with respect to the total area of the object A.

2.2.5.2 Closeness Measures

There are two closeness measures (Egenhofer, 1997) that can be applied when an object A is a subset either of the interior of another object B (Inner Closeness) or a subset of the B's exterior (Outer Closeness).

Inner Closeness (IC) is the area of an inner buffer zone $(\Delta_I(A,B))$ that extends from the boundary of A through A's interior. The size of this buffer zone is defined by the minimal distance from any point on A's boundary to B's boundary (Figure 2.6, Equation 2.5). For a specific $A \in \Omega$ the IC function is defined as follows:

$$IC_A : \Omega \rightarrow [0,1]$$

$$IC_A(B) = \begin{cases} \dfrac{area(\Delta_I(A,B))}{area(A)} & , B \subset A \\ 0 & , B \not\subset A \end{cases} \qquad (2.5)$$

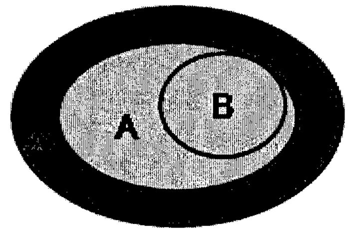

Figure 2.6: Inner closeness between two objects A and B.

Outer Closeness (OC), analog to Inner Closeness, is a buffer $(\Delta_o(A,B))$ that stretches from the boundary of A outwards into A's exterior while its size is defined by the minimal distance of any point on the boundary of A to B's boundary (Figure 2.7, Equation 2.6). For a specific $A \in \Omega$ the OC function is defined as follows:

$$OC_A : \Omega \rightarrow [1,\infty)$$

$$OC_A(B) = \begin{cases} \dfrac{area(\Delta_o(A,B)) + area(A)}{area(A)}, & B \subset A^- \\ 1 & , B \not\subset A^- \end{cases} \tag{2.6}$$

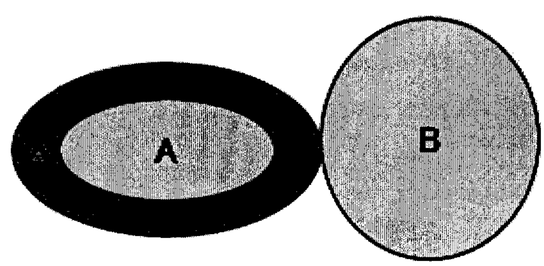

Figure 2.7: Outer closeness of object A and B.

2.3 Spatial Reasoning

The development process of the methods proposed in this thesis to derive changes from a qualitative description of snapshots is qualitative spatial reasoning. Spatial reasoning includes two distinct fields using alternative sets of measures, that is, qualitative and quantitative spatial reasoning. These two fields should not be viewed as substitutions for each other, but are rather complementary (Egenhofer and Mark, 1995b). Traditionally, GISs employ purely quantitative methods to represent and infer spatial information (Sharma *et al.*, 1994). Quantitative reasoning is in general more precise, but has shortcomings as it is unable to handle imprecise and incomplete spatial data. The essence of qualitative reasoning is to find ways to represent continuous properties of the world by discrete systems of symbols. Therefore, qualitative reasoning abstracts from information that is unnecessary and offers a focus on significant changes.

Current GISs do not sufficiently support intuitive or common-sense oriented human-computer interaction (Cohn and Hazarika, 2001). Qualitative reasoning has the aim of using everyday commonsense knowledge of human beings to make computer systems easier to use. Given this knowledge and appropriate reasoning methods, a computer could make predictions and diagnoses, even when a precise quantitative description is not available (Cohn *et al.*, 1997). While qualitative spatial reasoning is exact, the qualitative information that is the result of the reasoning may be a set of values including the correct result (Morrissey, 1990).

The foundation for a qualitative analysis of change is knowledge about the similarities of topological relations, in particular the research of conceptual neighborhood of topological relations. The conceptual neighborhood graph is based on the topological distance, which is defined by the count of differences of the empty and non-empty intersections between the intersection matrices representing different topological relations (Egenhofer and Al-Taha, 1992; Egenhofer and Mark, 1995a).

Gaps in the sequence of topological relations are filled with the most likely changes in the topological relation between objects *A* and *B*, as defined by the minimal topological distance throughout the path. The approach presented in Chapter 3 uses the path with the smallest topology distance that connects the topological relation in snapshot one with the one in snapshot two in the *conceptual neighborhood graph* (Egenhofer and Al-Taha, 1992), shown in Figure 2.8.

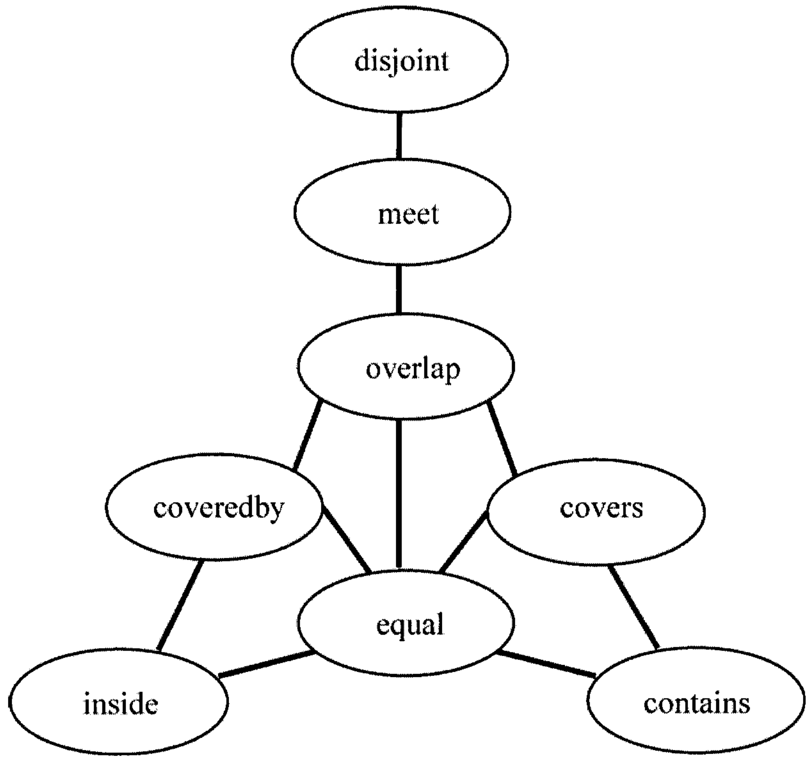

Figure 2.8: The conceptual neighborhood graph of the eight binary topological relations between two regions.

The conceptual neighborhood graph displays the topological relations and the possible transitions in between them for continuous changes. In the graph the topological relationships are represented as nodes, and those topological relations are connected where a direct transition is possible. The *closest topological relationship* is that topological relationship, which is most likely to hold true between to objects after a transition from a different topological relationship. These transitions are caused by the different types of changes, which is our aim to detect.

2.4 Summary

This chapter reviewed different measures that are of importance in the context of change derivation from snapshots. These measures include fundamental qualitative concepts and properties, such as identity and topology. A formal foundation and definition for topology and binary topological relations for region objects is provided based on the 9-intersection model and metric refinements for topological relations, which are useful measures in the derivation of change.

Chapter 3

CHANGE DERIVATION USING TOPOLOGICAL PROPERTIES

Current GISs often deal with collections of timestamped states (*snapshots*) of geographic data describing geographic phenomena, but changes cannot be captured by using solely snapshots. Higher-frequency observations of geographic phenomena could lead to better descriptions of changes in GISs by capturing additional information about changes that occur, but they are often impossible to obtain and even if so, they would create extremely large datasets. Therefore, an alternative approach describes a spatial scenario in two (or more) snapshots and derives information about changes that occurred in between these snapshots. This chapter develops qualitative and semi-qualitative measures, whose combination leads to a derivation of changes with unique results. It focuses on objects that maintain their identity (i.e., they do not split or merge). Changes that alter identity states of objects, such as merging and splitting, are investigated in Chapter 4.

3.1 Definition of Possible Changes in the Setting of the Model

In order to derive spatial changes from snapshots, it is important to have an account of all types of change that can occur between two entities. Real-world changes are fairly complex and multiple changes can occur at the same time, as they are caused by different underlying processes and depend on multiple variables. To derive these complex changes they need to be broken down into the basic concepts of change that can be detected by using regions' topological properties for regions in a 2-dimensional space.

A simply connected region A is observed at two times t_1 and t_0, where A is denoted as A_1 at time t_1 and A_0 at time t_0 while $t_0 < t_1$. We examine for this region A all cases of how A could evolve over time, with the restriction that A remains simply connected. In the following definitions the different changes that can occur to object A are distinguished so that the underlying concepts are distinct from each other. This knowledge is essential for methods that analyze these topological properties of regions at two snapshots to identify the type of the possible change (Section 3.3).

3.1.1 Growing

Growing is defined as a type of change where the size of a region object increases by changing the position of its boundary outwards. As a region object grows from t_0 to t_1 A_0 must be a true subset of A_1 (Equation 3.1, Figure 3.1).

$$Growing : A_1 \supset A_0 \tag{3.1}$$

There are two possible views of growing: (1) an *isotropic growing* such that the object's size increases equally in all directions (Hernandez *et al.*, 1995), and (2) an *anisotropic growing*, where the growth varies for different directions. The way an object grows depends on multiple factors. For example, the growth of a lake is influenced by the geologic relief of the region, where the lake is located, while the growth of a forest fire is affected by the existence of burnable material, the geologic relief, and acute climatic influences such as wind and rain.

In this thesis, growth of an object includes both the isotropic and anisotropic expansion of an object.

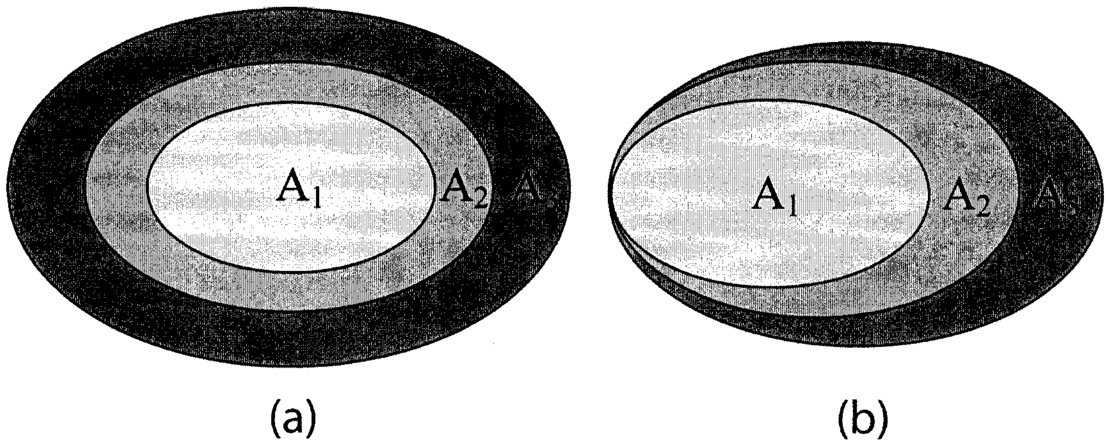

Figure 3.1: Different types of growing of object A between times t_1 and t_3: (a) isotropic growing and (b) anisotropic growing.

3.1.2 Shrinking

Shrinking is the reverse process of growing. Two types of shrinking are possible, *isotropic* and *anisotropic shrinking*. As a region object A grows from t_0 to t_1 A_0 must be a true superset of A_1 (Equation 3.2, Figure 3.2).

$$\textit{Shrinking} : A_1 \subset A_0 \tag{3.2}$$

We assume that shrinking does not change the dimension of the spatial objects in a snapshot, so the regions remain homogeneously 2-dimensional.

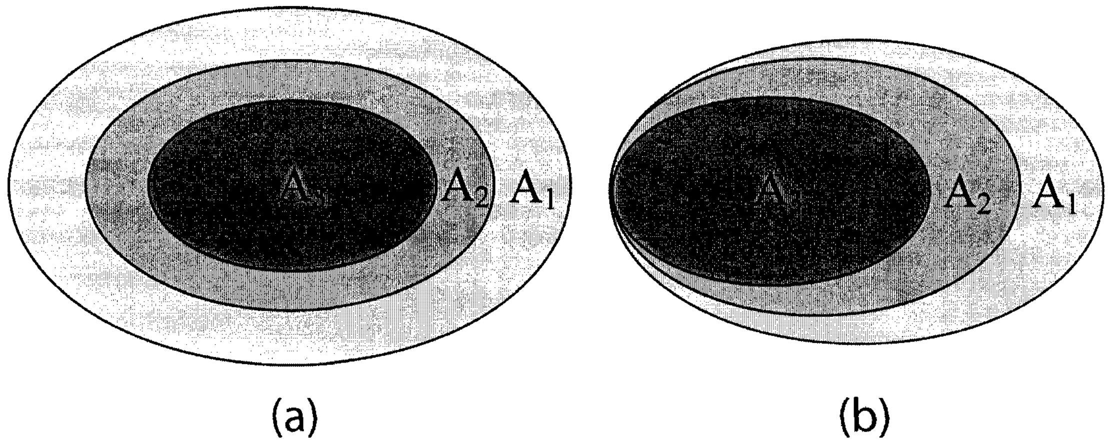

Figure 3.2: Object A shrinks in different ways between time t_1 and t_3: (a) isotropic shrinking and (b) anisotropic shrinking.

3.1.3 Moving

Moving is another type of change that alters the topology of a spatial scene significantly. Moving in this thesis is similar to the concept of translation. While moving changes the location of an object by a translation vector z, it preserves the shape and size of the object (Equation 3.3, Figure 3.3).

$$Moving: \exists z \in \mathbb{R}^2,\ z \neq 0:\ \{a_0 + z \mid a_0 \in A_0\} = A_1 \tag{3.3}$$

Examples of moving objects include vehicles in traffic situations and natural phenomena such as icebergs and landslides, where houses and other properties are moved by sliding layers of soil.

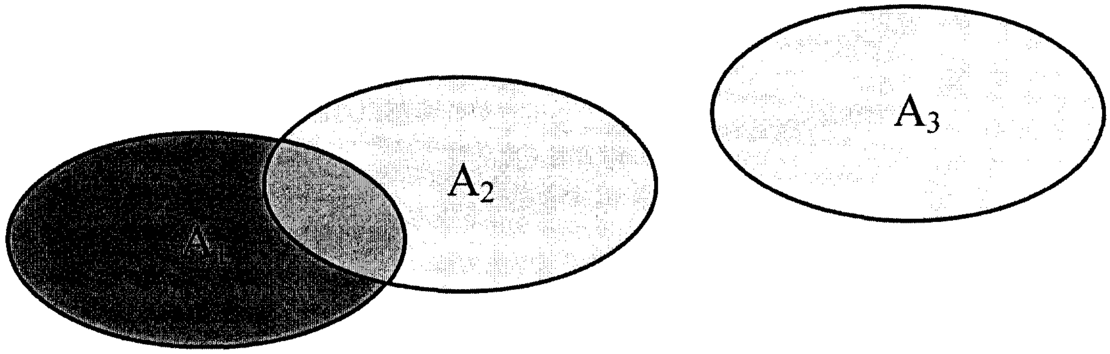

Figure 3.3: Moving of region A at times t_1, t_2, and t_3.

Another type of change is rotation, which is less likely to occur to spatial phenomena, and, therefore, is not discussed in this study. Furthermore, rotation can not be tracked by using the topological properties of regions, as, for instance, a circle that rotates could not change the topological relation to any other object.

3.1.4 No Change

Another possibility for the evolution of an object A is also the most obvious one. We assume that no change occurs when an object remains the same between two snapshots (Equation 3.4).

$$No\ Change: A_0 = A_1 \tag{3.4}$$

3.2 Goal and Approach

The framework for the derivation of changes presented in this chapter is *snapshots*, capturing information about spatial configurations. The goal is to identify changes that occurred between two (or more) snapshots. It is assumed that these changes are continuous and, therefore, modifications in the topology of the involved objects follow specific patterns (Egenhofer and Al-Taha, 1992). The detection of changes is based on the observation of topologically significant changes. All methods used in this chapter are based purely on topology and semi-qualitative measures. If the topological information between two snapshots differs, the question is what type of change occurred to cause these differences.

There are different ways in which the available topological information in the snapshots can be used to derive changes: (1) the analysis of individual objects at times t_0 and t_1 results in detecting changes, and (2) the observation of the binary relations between two objects at times t_0 and t_1 offers alternative information, that contributes to determining the type of change.

The approach used to identify possible changes between snapshots is a qualitative analysis of the topological relations of objects existing in the spatial scenario. With additional information from the metric refinements of topological relations, further details about the change can be derived.

3.3 Analysis of Individual Objects

A method to derive changes in a spatial scenario is the use of the topological relation of A_1 and A_0. These topological relations can be extracted from two snapshots at times t_1 and t_0 describing a spatial scenario. In this section the mappings between topological relations and the corresponding types of change are systematically derived. All eight topological relations possible between an object A and times t_1 and t_0 map onto one specific type of change.

This section derives changes from topological relations between one object at two different times. As the topological relations that are used for the derivation of changes are extracted from two snapshots while no information is accessible between the snapshots, it is possible that other changes occurred in the meantime. Therefore, the derivation of changes cannot guarantee that all the changes that occurred to real-world objects are derived by the methods in this chapter, but only those that manifested in the alterations in topological relations in the snapshots. For instance, when an object at t_1 is the same as in t_0 then sequential growing and shrinking could have occurred; also the object could have moved before returning to its original location; or no change could have occurred.

- In the case that the topological relation between an object A_1 and A_0 is *equal* we assume that *no change* occurred.
- If the topological relation between object A in snapshot zero (A_0) and one (A_1) is anything other than *equal*, then a significant change has occurred.
- In case that the topological relation between A_1 and A_0 is either *contains* or *covers*, object A must have grown in between snapshots. A_1 *covers* A_0 stands for anisotropic growing of A, while A_1 *contains* A_0 represents isotropic or anisotropic growing.

The topological relations for a shrinking region are the converse relations to those that hold for growing, that is, *inside* or *coveredby*. For A_1 *coveredby* A_0 or A_1 *inside* A_0, it can be derived that A decreased in size. The two topological relations that represent shrinking also represent possibly different types of shrinking.

Analogously to growing, if the topological relation between A_1 and A_0 is *coveredby*, then object A shrank anisotropically. If A_1 is *inside* A_0 then the shrinking of object A was either isotropic or anisotropic.

The three topological relations *overlap*, *meet*, and *disjoint* between objects A_1 and A_0 indicate moving. The change that occurred is moving if A_1 is not a subset of or equal to A_0 and the interior of A_0 is also not part of or equal to A_1 while shape and size of the object A are the same.

These different topological relations representing moving (*overlap*, *meet*, *disjoint*) generally also reflect different amounts of moving, as objects that *overlap* have common interior, while objects that are *disjoint* to each other do not. The topological relation *disjoint* between A_1 and A_0 stands for the most movement that can be detected using this method. If A_1 *meets* A_0, the object moves more than in the case where A_1 *overlaps* A_0.

Topological relations for $A_1 r A_0$	Type of change
equal	No Change
overlap, meet, disjoint	Moving
contains, covers	Growing
inside, coveredby	Shrinking

Table 3.1: Types of change and their correlation with specific topological relations between an object A at times t_1 and t_0.

In this section it was pointed out how the relation between an object A modeled at different times t_0 and t_1 indicate different types of change (Table 3.1). By applying this method to the individual objects in a spatial configuration, objects that are involved in changes are identified as well as the exact types of changes.

An object A was not involved in any change between two snapshots if the topological relation between A_1 and A_0 is *equal*. For the topological relations *contains* or *covers* (isotropic and anisotropic growing) and *inside* or *coveredby* (isotropic and anisotropic shrinking) the underlying types of change can be precisely identified. For the rest of the topological relations that can hold between A_1 and A_0, there is evidence for movement. A classification is possible for topological relations underlying moving objects regarding the extent of moving relative to other topological relations that would also indicate moving.

More exact measures defining how much of a change occurred are semi-quantitative measures, which use metric refinements of topological relations (Section 3.5).

3.4 Analysis of Scenarios with Two Objects

When changes occur to spatial objects, the topological relations between the objects involved in the change can be affected. Specific sequences of topological relations between objects for different types of change have been identified (Egenhofer and Al-Taha, 1992). If sequences of topological relations exist, different types of changes can be derived based on the knowledge of the characteristic patterns in which the binary topological relations change.

If the topological relation of a region A to another region B is the same at time t_0 as at time t_1, the most likely scenario is that the topological relations remained unmodified in between. Therefore, in this case it is assumed that the sequence of topological relations between t_0 and t_1 is complete.

Another possibility is that the topological relation between regions A and B are different in the two snapshots. This marks a topologically significant change from t_0 to t_1. According to the sequence of topological relations between the snapshots, the most likely scenario of change is derived. This method consists of two parts: (1) possible gaps in the sequence are filled (Section 3.4.1) and the complete sequence of topological relations is compared to the known sequences of topological relations for different change types (Section 3.4.2).

3.4.1 Filling Topological Gaps

When the shape, size, or location of an object is changed, this can affect the topological relations to other objects in the spatial configuration. The topological relation might change several times for the period that the change persists. Yet, since only snapshots are available, the whole sequence of topological relations between the changing object and other objects might not be completely captured.

If the topological relation between a region A and region B is different at two consecutive snapshots, some type of change must have occurred in between the snapshots. To be able to derive what types of changes might have caused the modification in the topological relation, it is important to have a complete sequence of topological relations. To find out if the sequence is complete the following approach is used:

1. If the topological relation between a region *A* and region *B* at time t_0 and t_1 is different, but the two topological relations at t_0 and t_1 are directly connected in the conceptual neighborhood graph, then the most likely scenario is that there was no transition to another topological relation in between the two known topological relations and the sequence is complete. For example, if the topological relation is *A disjoint B* at time t_0 and *A meet B* at time t_1, it is assumed, that there are no gaps in the sequence of topological relations (Figure 3.4).

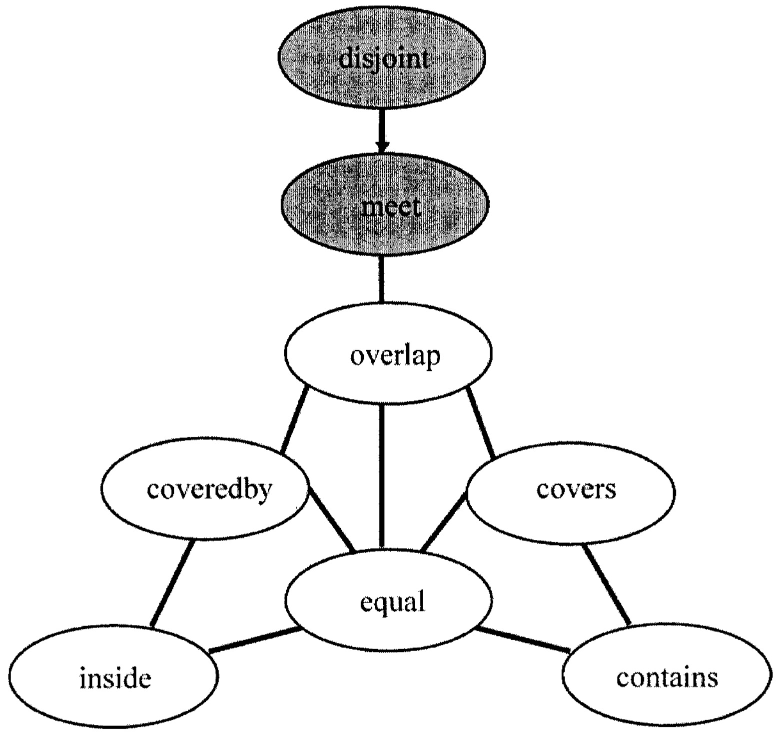

Figure 3.4: Disjoint and meet are closest topological relations, therefore, no gaps need to be filled.

2. If the topological relations between A and B at time t_0 and t_1 are different, but the two topological relations are not directly connected in the conceptual neighborhood graph, then the goal is to infer what other topological relation(s) may have occurred in between. The conceptual neighborhood graph describes all possible transitions, from which the one with the smallest topology distance is chosen as the most likely transition.

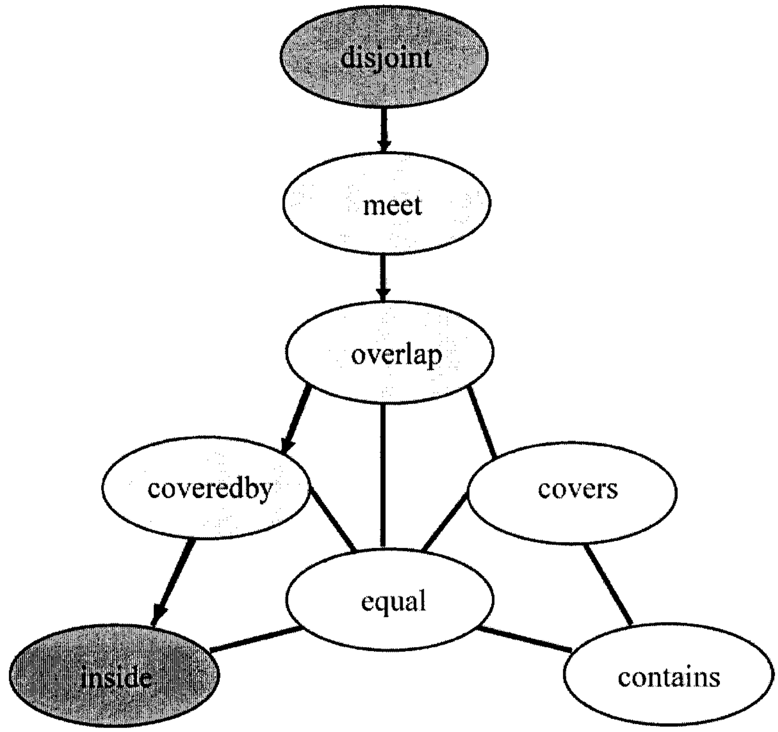

Figure 3.5 *Disjoint* and *inside* are not directly connected in the conceptual neighborhood graph, therefore, gaps are filled along the shortest path with *meet*, *overlap*, *coveredby*.

The relations along this shortest path, as found in the sequence of transitions connecting the topological relations of concern, are the most likely topological relations to complete the sequence. For example, if at time t_0 the topological relation is *A disjoint B* and at time t_1 it is *A inside B*, then the sequence of topological relations is incomplete and the gaps need to be filled with the topological relations along the shortest path in the graph (Figure 3.5), yielding the sequence *A disjoint B*, *A meet B*, *A overlap B*, *A coveredby B*, and *A inside B*. Transitions through equal are considered exceptions and are discussed in Section 3.4.2.

3.4.2 Analysis of Sequences of Topological Relations

After achieving a sequence of topological relations without gaps, this sequence can be matched to the characteristic patterns of topological relations for the different types of change. If this sequence is known, it then leads to one (or more) types of change that may have caused the topologically significant changes in the spatial configuration. For example, if the sequence of topological relations between a region A and a region B is *disjoint-meet-overlap-covers-contains*, moving of object A or object B, or growing of object A could be responsible for the differences in the topological relations in time t_0 and t_1 (Figure 3.6).

The application of this method can return a set of change types that may have occurred in between the snapshots, but it cannot answer the question which of the objects of concern was affected by the change and caused the alterations of the topological relations.

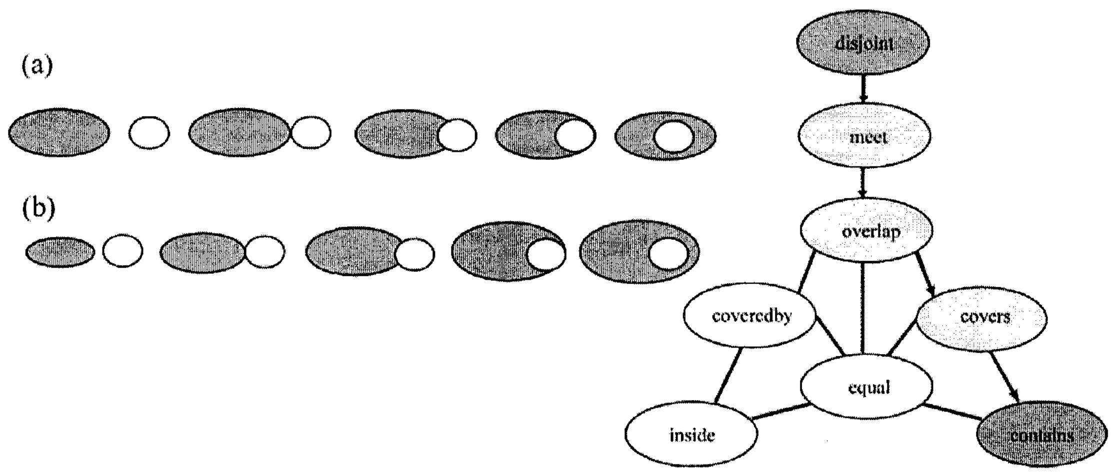

Figure 3.6: The sequence of topological relations matches with two characteristic patterns of different types of change: (a) *A* moves over a smaller *B*, or reversely *B* moves over a larger *A* and (b) *A* grows until it contains *B*.

Table 3.2 shows the characteristic sequences of topological relations for different types of change. For movement it cannot be identified to which of the objects the change applied. If, however, asymmetric topological relations (*coveredby, inside, covers, contains*) are in the sequence of topological relations, then for growing and shrinking, it can also be derived to which of the two objects *A* and *B* the change applies. If the full sequence of topological relations is available, the type of change can be derived using this sequence. If the sequence of topological relations matches one (or more) of the characteristic patterns for a type of change, then the type of change which matches this pattern of topological relations has possibly occurred.

Characteristic patterns of topological relations	Type of change
disjoint-meet-overlap-coveredby-inside	**Moving**
disjoint-meet-overlap-covers-contains	
inside-coveredby-overlap-meet-disjoint	
contains-covers-overlap-meet-disjoint	
disjoint-meet-overlap	**Growing**
disjoint-meet-overlap-covers-contains	Growing (*A*)
inside-coveredby-overlap-covers-contains	
disjoint-meet-overlap-coveredby-inside	Growing (*B*)
contains-covers-overlap-coveredby-inside	
overlap-meet-disjoint	**Shrinking**
contains-covers-overlap-meet-disjoint	Shrinking (*A*)
contains-covers-overlap-coveredby-inside	
inside-coveredby-overlap-meet-disjoint	Shrinking (*B*)
inside-coveredby-overlap-covers-contains	
Same topological relation in both snapshots	**No Change**

Table 3.2: Types of change and their characteristic patterns of topological relations.

Transitions through *equal* are less likely to occur. As objects need to have same sizes, shapes, and orientations, only those transitions are used where *equal* is the topological relation between objects *A* and *B* in one of the snapshots. The other transitions through *equal* are disregarded, but can be viewed in Table 3.3.

Characteristic pattern of topological relations containing *equal*	Type of change
disjoint-meet-overlap-equal	Moving
equal-overlap-meet-disjoint	
inside-equal-contains	Growing (*A*)
contains-equal-inside	Growing (*B*)
contains-equal-inside	Shrinking (*A*)
inside-equal-contains	Shrinking (*B*)

Table 3.3: Characteristic patterns containing the topological relation equal and the types of change associated with these patterns.

3.5 Using Semi-Qualitative Spatial Data

In addition to the purely qualitative measures and methods applied in the previous sections, semi-qualitative spatial measures have a high value in the detection and derivation of changes and contribute to a high precision. These semi-qualitative measures have been developed to describe spatial scenarios in combination with the purely topological measures, as topology alone is not always sufficient to fully capture the semantics of a spatial configuration (Egenhofer, 1997). So far, if there were no differences in the topological relations between two snapshots, then this setting has been interpreted in the analysis of scenarios with two objects as no moving, no shrinking, and no growing (Section 3.4). But this conclusion is not necessarily correct, as can be shown with metric refinements for topological relations. For example, the topological relations between objects A and B in Figure 3.7 are both *overlap*, and the application of the method described in Section 3.4 would result in *no change*, as the analysis is based purely on the prevalent topological relations.

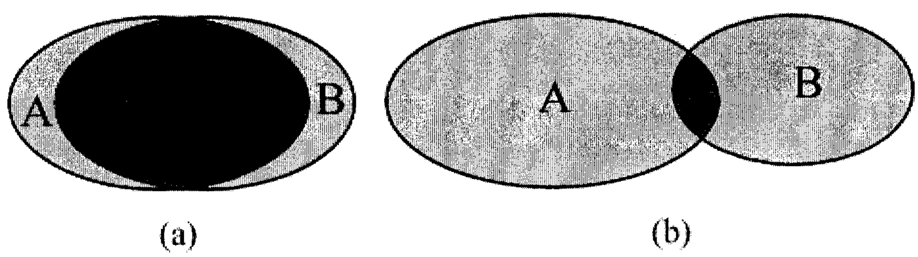

Figure 3.7: Two scenarios with an *overlap*, but still significantly different: (a) most of the interior of objects A and B is common interior, and (b) only very small parts of the interior actually intersect.

With metric refinements, however, the degree of *overlap* can be captured. Therefore, some cases with the same topological relation in two snapshots can be distinguished and changes can be derived. *Splitting measures* (Section 3.5.1) apply to those cases where two objects have a non-empty interior-interior intersection and measure how an object is split up by the other object's boundary. *Closeness measures* (Section 3.5.2) deal with those cases where the topological relations are either *disjoint* (Outer Closeness), *contains*, or *inside* (Inner Closeness) and measures how far objects would need to be extended to not be completely contained in the exterior or interior of a object of reference.

To derive types of change that occurred between snapshots and determine their extent, measures about areas and lengths are applied as refinements to the topological relations. From the complete set of measures for metric refinements of topological relations between regions (Shariff, 1996) those are selected that contribute to the derivation of changes. These measures (defined in Chapter 2) include splitting ratios as well as closeness measures that are suitable for different groups of topological relations. The measures are normalized values with respect to areas or lengths or interiors and boundaries of the objects of interest.

3.5.1 Application of Splitting Measures

The combination of inner area splitting (IAS) and outer area splitting (OAS) values provides further information about changes that might have occurred between snapshots (measures simplified in textual description by leaving out indices). IAS and OAS both apply to all topological relations between two region objects, but they only contribute significantly to the change detection if both objects have partly a common interior (*overlap*, *contains*, *covers*).

For the other topological relations, where the interior of *A* is completely contained in the exterior of *B* (*disjoint*, *meet*), the IAS value is always 1, while the OAS value is 0.

For the topological relations where *A*'s interior is a subset of (*inside*, *coveredby*) or coincides with (*equal*) *B*'s interior, the IAS value is always 1 and OAS is 0.

Therefore, unless a transition to a different topological relation occurs, no distinction can be made using the measures and no changes can be derived. If one of the relations *overlap*, *contains*, and *covers* holds at one of the snapshots, then it makes sense to use the

IAS and OAS values to detect changes and distinguish between cases. For those topological relations where both the IAS and OAS value are either 0 or 1, no further distinctions can be made, while for *overlap*, *covers* and *contains* distinctions can be made between configurations where one of these topological relations holds in all the cases (Table 3.4).

Topological relations ArB	$IAS_A(B)$	$OAS_A(B) = 1 - IAS_A(B)$
disjoint, meet	0	1
coveredby, inside, equal	1	0
covers, contains, overlap	$0 < IAS_A(B) < 1$	$0 < OAS_A(B) < 1$

Table 3.4: Range of IAS and OAS values for different topological relations.

Since IAS and OAS are normalized by the whole area of the region A, the sum of the two values equals 1. Therefore, if either IAS or OAS increases from one snapshot to another, the other value decreases, making only three cases possible.

There are multiple possibilities for the use of IAS and OAS values. As IAS and OAS values are defined for intersections between two regions and changes affect the IAS and OAS values for both the objects, a useful approach is to analyze the alterations for IAS and OAS in both objects. The results of this analysis can be displayed in a 3x3 matrix, as the IAS values can increase, remain equal, or decrease between snapshots for both objects. Table 3.5 shows the possible changes for the combinations of altering IAS values for A and B. Moving of an object A is denoted as M(A), shrinking of an object A is S(A), anistropic shrinking is $S_a(A)$, while $G(A)$ stands for growing of object A. Analogously, anisotropic growing is denoted as $G_a(A)$.

Moving of objects A or B is denoted as $M(A,B)$. The other changes are denoted in the same fashion, namely $S(A,B)$, $S_a(A,B)$, $G(A,B)$ and $G_a(A,B)$, if the changes apply to regions A or B.

	$IAS_{B_1}(A_1) > IAS_{B_0}(A_0)$	$IAS_{B_1}(A_1) = IAS_{B_0}(A_0)$	$IAS_{B_1}(A_1) < IAS_{B_0}(A_0)$
$IAS_{A_1}(B_1) > IAS_{A_0}(B_0)$	$M(A,B)$, $G(A,B)$, $S(A,B)$	$S_a(A)$, $G(B)$	$S(A)$, $G(B)$
$IAS_{A_1}(B_1) = IAS_{A_0}(B_0)$	$G(A)$, $S_a(B)$	No Change	$S(A)$, $G_a(B)$
$IAS_{A_1}(B_1) < IAS_{A_0}(B_0)$	$G(A)$, $S(B)$	$G_a(A)$, $S(B)$	$M(A,B)$, $S(A,B)$, $G(A,B)$

Table 3.5: Changes for the different alterations of IAS values of A and B.

The matrix is symmetric with respect to the type of change, only the objects to which the changes apply are exchanged.

The corresponding table of changes from OAS values can be derived easily from table 3.5 as one minus the IAS value equals the OAS value. Therefore, as IAS values increase over time, the OAS values decrease at the same time. Only the algebraic signs need to be exchanged in order to derive the corresponding table to table 3.5 for the OAS values.

None of the combinations of IAS values has a unique result as to what type of change caused them. All resulting types of change also include the converse type of change applied to the other object. The topological relation deals with a relative description of an object to another object, based on the intersection of their parts, which does not allow the derivation of what object has changed. Choices for the type of change, which caused the alterations in IAS and OAS values, can be narrowed down significantly if the object to which the change applied is identified. IAS and OAS values are based on the area of intersections relative to their complete size, allowing the derivation of the object to which the change applied.

One possibility is to assume that object *B* is static. If this is the case, then by using the IAS and OAS values for *A* and *B*, derivations of types of change can be performed as unique results can be returned.

Also the combination of the IAS-OAS analysis with the topological relation between A_1 and A_0 can show which of the objects *A* and *B* may have caused the change. Therefore, the converse relations in the matrix for IAS and OAS combinations can be eliminated.

The size ratio of area A_1 with respect to area A_0 is an additional measure to infer which of the objects may have grown or shrunk. If the size ratio A_1/A_0 is greater than 1, then object *A* grew; if it is 1, then object *A* kept its size; and if it is less than 1 then object *A* shrank (Table 3.6).

Area Ratio	Type of change
$\frac{area(A_1)}{area(A_0)} > 1$	Growing(A)
	Growing(A) + Moving(A)
$\frac{area(A_1)}{area(A_0)} < 1$	Shrinking(A)
	Shrinking(A) + Moving(A)
$\frac{area(A_1)}{area(A_0)} = 1$	No Change
	Moving(A)

Table 3.6: Ratio of areas of object A at the two snapshots and type of change that can be derived from that.

3.5.2 Application of Closeness Measures

The measure of Inner Closeness (IC) is used when the topological relation is *inside* or *contains*, while the Outer Closeness (OC) is appropriate mostly for the case where the topological relationship is *disjoint* and no other measures apply (Table 3.8). Also the closeness measures have been simplified by leaving out the indices in the textual description.

Topological Relations ArB	$\text{IC}_A(B)$	$\text{OC}_A(B)$
disjoint	0	$1 < \text{OC}_A(B) < \infty$
contains, inside	$0 < \text{IC}_A(B) < 1$	1
covers, overlap, meet, coveredby, equal	0	1

Table 3.7: Range of IC and OC values for different topological relations.

Similar to the analysis of splitting measures, inferences can be made about a spatial configuration by interpreting the differences in the closeness measures. When the measures remain constant, it indicates that no change occurred. On the other if the IC and OC values differ between snapshots, change must have taken place and can be identified.

$\text{IC}_{A_1}(B_1) > \text{IC}_{A_0}(B_0)$	$\text{IC}_{A_1}(B_1) = \text{IC}_{A_0}(B_0)$	$\text{IC}_{A_1}(B_1) < \text{IC}_{A_0}(B_0)$
G(A), M(A,B), S(B)	No Change	G(B), M(A,B), S(A)

Table 3.8: Derivation of types of change with IC value.

The differences in IC values are connected to a number of possible types of change that may have caused the alterations in IC values, namely growing, shrinking, and moving (Table 3.9). When the IC values remained unchanged we assume that no change occurred but the different types of change might have occurred without being captured in alterations of the IC values. In case it does change, and if the area ratio between A_1 and A_0 (analogous for B) remains the same, the object of interest moved, but the value does not include the notion of how much the object moved. The Inner Closeness value can also be combined with the splitting measures, which apply for the object that *contains* the other object, and gives us further information on the dimension of the change.

$OC_{A_1}(B_1) > OC_{A_0}(B_0)$	$OC_{A_1}(B_1) = OC_{A_0}(B_0)$	$OC_{A_1}(B_1) < OC_{A_0}(B_0)$
M(*A,B*), S(*A*), S(*B*)	No Change	M(*A,B*), G(*A*), G(*B*)

Table 3.9: Connection of alterations of OC value and types of change.

Table 3.10 shows what types of changes can be derived from the alterations in OC values. Alternative methods have to be applied to derive what object caused the changed (i.e., Section 3.3). If the Outer Closeness value changes, while the ratio of areas of an object remains the same, then the object of interest has moved. The differences in the OC value between the snapshots gives a relative measure of how much an object has moved, or changed its size, while it still has no intersections with another object.

3.6 Summary

This chapter started with a definition of changes that are of interest in this thesis and presented methods that enable us to derive changes based on them. Most of these changes deal exclusively with qualitative measures and their combination provides the possibility of tracing changes and narrowing down the set of possible changes. The additional use of semi-qualitative measures, which are relative percentages of areas of objects, adds more reasoning power, as these measures can detect changes even if no topologically significant (changes in the topological relations between the snapshots) changes occur. These methods can be applied individually as well as in combination to achieve a set of changes that occurred. The application of metric refinements is particularly useful, especially if data that can be used to derive the topological relation between the same object at different times is unavailable. An issue with this approach is that types of change that can be identified and derived are a small set, defined for this purpose and the tracking of a combination of these types of change may not result in the most prominent type of change. This will be addressed in the chapter on future work (Chapter 6).

Chapter 4

DERIVING IDENTITY CHANGES INCLUDING MERGING AND SPLITTING

While Chapter 3 focused on qualitative methods that describe change based on alterations in the topology of objects, this chapter addresses the development of methods that detect changes that affect the identity states of objects as well as topology. Types of change in this group are, for instance, merging and splitting. This chapter describes how merging and splitting are represented and how these types of change can be derived from snapshots. To derive merging and splitting, it is essential to understand the ramifications of such changes on the topology of the objects. Therefore, this chapter also includes a comprehensive derivation of the sets of possible topological relations. These sets are determined based on the application of rules. These rules derive for each topological relation an object or two objects can have to a *reference object* before merging and splitting, and what the possible topological relations of the objects that results from this type of change might have to a *reference object*.

4.1 Scenarios

In this thesis, such changes as merging and splitting are considered to be instantaneous and can occur for some natural spatial objects as well as administrative objects, such as land parcels. The levels of water bodies, for example, rise and fall as the climate changes over the year and can cause a water body to split into two or more water bodies and also merge two or more water bodies back into one as the water level rises again. The growing and shrinking that occurs while the water level rises and falls happens continuously, while the merging and splitting is instantaneous. Other possible scenarios include the merging and splitting of coral reefs leading to the creation of an atoll or the evolution of a forest fire over time.

In order to be able to reason about scenarios with such types of change as merging and splitting, it is important to define merging and splitting in terms of changes in the identity states and derive the topological ramifications based on those definitions. The following sections provide the definitions for merging (Section 4.2) and splitting (Section 4.3) and sets of possible topological relations for objects where merging and splitting occurred. The objects that merge and split are referred to as *to-be-merged objects* and *to-be-split objects*, while the objects that result from one of these change types are referred to as *merged objects* and *split objects*. For the qualitative spatial reasoning that can derive such changes, meaningful topological relations to other objects are needed. For merging and splitting the requirement exists that the to-be-merged and to-be-split objects *meet* before respectively after the change occurs and as this topological relation always holds between the objects of a merge or split, this information by itself cannot be used to derive changes.

Another object, whose binary topological relations with the to-be-merged and to-be-split objects are used, is referred to as *reference object.*

4.2 Derivation of Merging

Merging describes a process where two objects are combined into a new object. From an identity perspective, the two to-be-merged objects to this type of change are *eliminated*, while the merged object's identity is *created.* This change to the identity states is caused by the destruction of a piece of boundary that separated the two to-be-merged objects thereby creating the merged object. The topological relations of the merged object with a *reference object* can be derived based on the topological relations the to-be-merged objects held to the same *reference object.*

Merging has been researched in different contexts and sets of possible relations for to-be-merged regions and merged regions have been identified. Tryfona and Egenhofer (1997) evaluated topological relations with aggregates that *meet.* They use a procedure to derive possible relations for the merged object that is analog to the one used for the derivation of splitting (Section 4.3). Their approach uses the composition operation to find the 27 consistent combinations of topological relations for which the requirement, that the to-be-merged regions have to *meet*, holds true. A detailed analysis, based on rules is performed to find out the topological relation of the merged object with a *reference object* (Table 4.1).

A_1 \ A_2	*d*	*m*	*o*	*e*	*cv*	*ct*	*cb*	*i*
d	*d*	*m*	*o*	-	*cv*	*ct*	-	-
m		*m*	*o*	*cv*	*cv, ct*	-	*o*	-
o			*cv, ct, o*	-	-	-	*o, cv*	*o*
e				-	-	-	-	-
cv					-	-	-	-
ct						-	-	-
cb							*e, cb*	*cb*
i								*i*

Table 4.1: Possible topological relations between merged object and reference object for each combination of topological relations between to-be-merged objects and a *reference object*. *d* stands for *disjoint*, *m* for *meet*, *o* for *overlap*, *e* for *equals*, *cv* for *covers*, *ct* for *contains*, *cb* for *coveredby* and *i* for *inside*.

4.3 Derivation of Splitting

The derivation process used for the identification of possible sets of topological relations between split objects and *reference objects* is determined using an analogous procedure to the one utilized for merging.

In order to perform meaningful reasoning about spatio-temporal changes with respect to the splitting of spatial objects, an understanding of the effects of such a change on the identity states and topology of objects is essential. Particularly interesting in this context is the connection between the effects splitting has on identity states and the topological relations of objects. Therefore, this section provides a definition of splitting that explicitly describes the ramifications of splitting on the identity states of the involved objects and how this causes alterations in the topology. Based on this definition a derivation of the sets of topological relations for split objects is possible. This knowledge is then integrated in methods that automatically detect and derive changes such as merging and splitting.

Two steps lead to the derivation of the sets of possible topological relations between the spatial objects that exist as a result of a split. The post-condition for a split is that split objects must topologically *meet* after a split has occurred; therefore, (1) configurations are identified that are feasible and meet the post-condition and infeasible configurations are detected using the same requirement; and (2) for the feasible configurations possible splitting configurations are then derived systematically.

The first step can be performed by using composition properties of topological relations as a consistency check, while the second step includes a detailed elimination process that takes place based on rules for the objects parts (interior, boundary, exterior) of the newly existent objects (split objects) that were created as a result of the splitting.

In order to perform a systematic derivation of all possible sets of topological relations split objects can have to a *reference object*, first there must be a clear definition of the splitting operation.

4.3.1 Definition of Splitting

The change operation splitting affects both the identity states as well as the topology of objects. Before splitting of an object, only the to-be-split object exists, and after splitting, two objects with new identities are *created*, while the to-be-split object ceases to exist.

The new identities come into existence when during the process of splitting a new piece of boundary is created that connects two points on the boundary of the to-be-split object with the new piece of boundary running through the interior of the to-be-split object. This new piece of boundary separates the to-be-split object into two point sets, creating two objects with new identities. The new piece of boundary that splits the to-be-split object into two new objects, is common for both split objects, therefore, the topological relation for these two objects must be *meet*.

In the subsequent scenarios A and B are two simply connected regions in $\mathbb{R}^2 (A, B \in \Omega)$. A region A is defined by the three parts, namely the interior A°, the boundary ∂A, and the exterior A^-. The split objects, A_1 and A_2 *meet* topologically, and the union of A_1 and A_2 is equal to A. Let t define the time component in these scenarios, and in every snapshot t_i, distinguished by an index for the time variable t, a binary topological relation from the set of the eight possible topological relations for region objects, holds between every two existent regions.

4.3.2 Assessment of Feasible Configurations

Based on the definition of the splitting operation, it is known that the two objects created by the split must be topological neighbors (boundary coincides for some part, while interiors do not intersect), as the splitting operation creates a new piece of boundary that connects two points on the old boundary through the interior of the object. As this knowledge about the operation is available, it can be used as a post-condition for the operation splitting to identify a set of feasible topological relations that can hold between the split objects and a *reference object.*

The domain of topological relations between the split objects and a *reference object* is the set of eight topological relations for region objects in $\mathbb{R}^2$. Therefore, the upper limit for combinations of topological relations that can hold for both the split objects is 64 (i.e., $A_1 r_1 B \wedge A_2 r_2 B$, $r_1, r_2 \in$ {*disjoint, meet, overlap, coveredby, inside, covers, contains, equal*}). However, the number of feasible combinations is in reality much smaller than this, due to the requirement that A_1 and A_2 must *meet*. In order to derive a set of feasible topological relations for both split regions, the composition operation can be used (Egenhofer, 1994). Combinations, where this post-condition of a splitting operation is not met, can be excluded from the set of feasible combinations. For instance, A_1 *contains B* and A_2 *contains B* is inconsistent with the requirement that A_1 and A_2 must *meet.*

After applying the consistency check as it is performed by utilizing the composition operation, combinations for split regions A_1 and A_2 to a *reference object B* are available for each relation possible for an to-be-split region A to a *reference object B* (Table 4.2).

A_1r_1B	Feasible Relations for A_2r_2B
disjoint	*disjoint, meet, overlap, covers, contains*
meet	*disjoint, meet, overlap, covers, contains, coveredby, equal*
overlap	*disjoint, meet, overlap, coveredby, inside*
equals	*meet*
covers	*disjoint, meet*
contains	*disjoint*
coveredby	*meet, overlap, coveredby, inside*
inside	*overlap, coveredby, inside*

Table 4.2: Results of consistency tests that regions after split must be topological neighbors. For each topological relation between one split object A_1 the set of feasible topological relations of the other split object A_2 is displayed.

4.3.3 Derivation of Sets of Possible Topological Relations for Split Objects

Splitting a region A into two parts A_1 and A_2 requires the creation of a new non-self-intersecting line that starts at the boundary of the to-be-split region, extends through the region's interior, and ends up again at a point on the boundary of A. The introduction of this line (which becomes a common part of the boundaries of the split regions A_1 and A_2) implies that some properties can be derived from the topological properties before splitting. These properties rely primarily on the intersections of A's parts with the parts of a *reference object* B and, therefore, trigger propagations of empty and non-empty interior, boundary and exterior intersections from to-be-split region A to the parts A_1 and A_2. Since the new piece of boundary runs through the interior of the to-be-split region, some corrective measures must be taken to account for the introduction of corresponding boundary intersections.

Definition 4.1: The operator $\sqsubset$ means that a set C is subset of another set D. If C is subset of the union of multiple sets D_i, $i=1,\ldots,n$, then C must have a non-empty intersection with all the sets D_i, $i=1,\ldots,n$ and empty intersections with all the sets in the complement (Formula 4.1).

$$C \sqsubset \left(\bigcup_{i=1}^{n} D_i\right) := \begin{cases} C \subset D_n \ , & \text{if } n=1 \\ C \cap D_i \neq \varnothing, \forall i=1,\ldots,n, C \cap \left(\bigcup_{i=1}^{n} D_i\right)^{-} = \varnothing \ , & \text{if } n>1 \end{cases} \qquad (4.1)$$

4.3.3.1 Interior Propagations

The location of A's interior, A°, is defined with respect to the three parts of a reference object B, namely the interior of region B, B°, its boundary ∂B and the exterior of B, B^{-}. From all the possible combinations of non-empty intersections with B's three parts only three are realizable:

I1: A° is a subset of B's interior $(A^{\circ} \subseteq B^{\circ})$.

I2: A° is a true subset of B's exterior $(A^{\circ} \subset B^{-})$.

I3: A° has non-empty intersections with all three parts of B $(A^{\circ} \sqsubset (B^{\circ} \cup \partial B \cup B^{-}))$.

These three relations (**I1-I3**) contain all the possible cases that can exist for the intersections of *A*'s interior with all the parts of *B*. No other cases need to be considered in this 2-dimensional setting.

Since a region's boundary has no extent it cannot contain the non-empty interior of another region $(A^\circ \subset \partial B)$.

Also two other combinations are impossible due to the restriction that all surrounding disks of all the points on the boundary of *B* intersect *B* and its complement $(A^\circ \sqsubset (B^\circ \cup \partial B), A^\circ \sqsubset (\partial B \cup B^-))$.

$A^\circ \sqsubset (B^\circ \cup B^-)$ is impossible due to the fact that A° would not be connected if it only had non-empty intersections with the interior and exterior of *B* (because it would be divided into two pieces by the boundary of *B*).

Finally, the interior of a region cannot coincide with the exterior of another region $(A^\circ \neq B^-)$ as it is required that the regions are simply connected.

The three relations with respect to *A*'s interior give rise to Theorems *1-3*.

Theorem 1 (Case I1): $A^\circ \subseteq B^\circ \Rightarrow A_1^\circ \subset B^\circ \wedge A_2^\circ \subset B^\circ$

Proof: Since the split regions' interiors are true subsets of the to-be-split regions interior $((A_1^\circ \subset A^\circ) \wedge (A_2^\circ \subset A^\circ))$ and *A*'s interior is a subset of *B*'s interior $(A^\circ \subseteq B^\circ)$, the only possible combination is that both split regions' interiors are also true subsets of the interior of *B* (Transitivity for subsets). □

Theorem 2 (Case I2): $A^\circ \subset B^- \Rightarrow A_1^\circ \subset B^- \wedge A_2^\circ \subset B^-$

Proof: In analogy to the proof of Theorem 1, substituting B° with B^-. □

Theorem 3 (Case I3): If A's interior has non-empty intersections with all three parts of B $(A^\circ \sqsubset (B^\circ \cup \partial B \cup B^-))$, A's interior can be split up in the following ways:

3.1: $$A_1^\circ \subseteq B^\circ \wedge A_2^\circ \subset B^-$$

3.2: $$A_1^\circ \subset B^\circ \wedge A_2^\circ \sqsubset (B^\circ \cup \partial B \cup B^-)$$

3.3: $$A_1^\circ \subset B^- \wedge A_2^\circ \sqsubset (B^\circ \cup \partial B \cup B^-)$$

3.4: $$A_1^\circ \sqsubset (B^\circ \cup \partial B \cup B^-) \wedge A_2^\circ \sqsubset (B^\circ \cup \partial B \cup B^-)$$

Proof: If A° has non-empty intersections with all three parts of B, the interiors of the split objects can also have all the possible combinations of non-empty intersections with the B's parts $(((A^\circ \subseteq B^\circ), (A^\circ \subset B^-), (A^\circ \sqsubset (B^\circ \cup \partial B \cup B^-)))$ I1-I3$)$. Therefore, there are 9 possible combinations for the intersections of the interiors of the split regions with B. These combinations can be represented in a *3x3* matrix. Due, to the symmetry of A_1 and A_2, an upper triangular matrix is sufficient to account for all the combinations.

It is not possible that both A_1° and A_2° are subsets of B's interior. If we assume that A_1° and A_2° are true subsets of B°, then A_1 and A_2 would be true subsets of B, which is the union of B° and ∂B. Therefore, A, which is the union of A_1 and A_2, would be a true subset of the union of B's boundary and B's exterior, which is a contradiction, since A's interior has a non-empty intersection with B's exterior.

Analogously, it is not possible that A_1 and A_2 are both subsets of B's exterior, as A's interior also has non-empty intersections with B's interior.

The other combinations, however, are realizable depending on the location of the new piece of boundary. □

4.3.3.2 Boundary Propagations

A's boundary, ∂A, has six relations with respect to B and its parts:

B1: ∂A is a true subset of B's interior $(\partial A \subset B^{\circ})$.

B2: ∂A is a true subset of B's exterior $(\partial A \subset B^{-})$.

B3: ∂A is equal to B's boundary $(\partial A = \partial B)$.

B4: ∂A has non-empty intersections with B's interior and B's boundary $(\partial A \sqsubset (B^{\circ} \cup \partial B))$, but an empty intersection with B's exterior $(\partial A \cap B^{-} = \varnothing)$.

B5: ∂A has non-empty intersections with B's exterior and B's boundary $(\partial A \sqsubset (\partial B \cup B^{-}))$, but an empty intersection with B's interior $(\partial A \cap B^{\circ} = \varnothing)$.

B6: ∂A has non-empty intersections with all three parts of B $(\partial A \sqsubset (B^{\circ} \cup \partial B \cup B^{-}))$.

Other set-theoretic combinations of ∂A and B's parts are not meaningful or would not yield further insights when splitting A.

Considering only the non-empty intersections of ∂A with B's interior and B's exterior $(\partial A \cap B^{\circ} \neq \varnothing \wedge \partial A \cap B^{-} \neq \varnothing)$, while assuming that $\partial A \cap \partial B = \varnothing$ is impossible, due to the role of a region's boundary as a Jordan curve, the non-empty intersections of $\partial A \cap B^{\circ} \neq \varnothing$ and $\partial A \cap B^{-} \neq \varnothing$ imply that $\partial A \cap \partial B \neq \varnothing$ as well.

The boundary of A can also not be equal to the interior or exterior of B as it does not have any extent.

Finally, the boundary of A cannot be a true subset of the boundary of B, because in this case it would need to have a non-empty intersection also with either the interior or exterior of B.

These six relations with respect to A's boundary give rise to Theorems *4-9*.

Theorem 4 (Case B1): $\partial A \subset B^{\circ} \Rightarrow \partial A_1 \subset B^{\circ} \wedge \partial A_2 \subset B^{\circ}$

Proof: In case the boundary of the to-be-split object A is a true subset of B's interior, then A's interior must also be a true subset of B's interior because A is simply connected. As the new piece of boundary that is common to both the split objects A_1 and A_2 runs through the interior of A, this does not have any effect on the non-empty intersections of A's boundary, as this new part is also completely contained by B's interior. Therefore, the only possible combination for the boundaries of the split objects is that they are contained completely by B's interior $(\partial A_1 \subset B^{\circ} \wedge \partial A_2 \subset B^{\circ})$. □

Theorem 5 (Case B2): $\partial A \subset B^{-} \Rightarrow \partial A_1 \subset B^{-} \wedge \partial A_2 \subset B^{-}$

Proof: In analogy to the proof of Theorem 1, substituting B° with B^{-}. □

Theorem 6 (Case B3): $\partial A = \partial B \Rightarrow \partial A_1 \sqsubset (B^{\circ} \cup \partial B) \wedge \partial A_2 \sqsubset (B^{\circ} \cup \partial B)$

Proof: If the boundary of the to-be-split object A is equal to the boundary of the *reference object* B, then also the split regions' boundaries must have non-empty intersections with the boundary of B. Additionally, because a new piece of boundary that is common for A_1 and A_2 is added that runs through the interior of A, the boundaries of the split parts also gain non-empty intersections with the interior of $B(\partial A_1 \sqsubset (B^\circ \cup \partial B) \wedge \partial A_2 \sqsubset (B^\circ \cup \partial B))$. □

***Theorem** 7* (Case B4): In case the boundary of A has non-empty intersections with both the interior and boundary of $B(\partial A \sqsubset (B^\circ \cup \partial B))$, the new piece of boundary can be positioned in a way that two combinations are realizable:

7.1: $$\partial A_1 \subset B^\circ \wedge \partial A_2 \sqsubset (B^\circ \cup \partial B)$$

7.2: $$\partial A_1 \sqsubset (B^\circ \cup \partial B) \wedge \partial A_2 \sqsubset (B^\circ \cup \partial B)$$

Proof: Due to the requirement, that the union of the split objects is the to-be-split object A and only a new piece of boundary is created that runs through A°, the split objects' boundaries can only have non-empty intersections with (1) just the interior of B or (2) the interior and boundary of B. Therefore, there are four possible combinations for A_1 and A_2. Due to the symmetry of A_1 and A_2 this set of combinations can be reduced to 3. However, one combination where both A_1 and A_2 have non-empty intersections solely with the interior of B is not realizable, as A's boundary is a subset of the union of the split objects' boundaries and, therefore, also subset of B's interior, which is a contradiction to the requirement of the theorem that the boundary of A has a non-empty intersection with the boundary of B.

The other two combinations are realizable depending on the location of the new piece of boundary that separates A_1 and A_2. If the new piece of boundary is completely contained in the interior of B, then one of the split objects' boundaries will only have a non-empty intersection with the interior of B (*7.1*). In any other case both split objects' boundaries will have non-empty intersection with interior and boundary of B (*7.2*). □

Theorem 8 (Case B5): When A's boundary has non-empty intersections with B's boundary and exterior $(\partial A \sqsubset (\partial B \cup B^{-}))$, the following combinations of non-empty intersections with B's parts are possible for A_1 and A_2:

8.1: $\partial A_1 \subset B^{-} \wedge \partial A_2 \sqsubset (\partial B \cup B^{-})$

8.2: $\partial A_1 \sqsubset (\partial B \cup B^{-}) \wedge \partial A_2 \sqsubset (\partial B \cup B^{-})$

Proof: No new non-empty intersections with the interior of B are possible for the boundaries of the split parts. Therefore, the split objects' boundaries can only have the same non-empty intersections as A or a subset of the non-empty intersections, namely with just the exterior $(\partial A_1 \subset B^{-} \vee \partial A_2 \subset B^{-})$. From this set of 4 (*2x2*) possible combinations for A_1 and A_2 only 3 are realizable and two of the unique (as A_1 and A_2 are symmetric).

A_1's boundary and A_2's boundary cannot both be a true subset of B's exterior, as A's boundary, which is a subset of the union of A_1's boundary and A_2's boundary, has a non-empty intersection with B's boundary as well. □

Theorem 9 (Case B6): In case the boundary of A has non-empty intersection with the three parts of $B (\partial A \sqsubset (B^{\circ} \cup \partial B \cup B^{-}))$, A can be split up so the boundaries of the split objects have the following intersections with B's parts:

9.1: $\partial A_1 \subset B^{-} \wedge \partial A_2 \sqsubset (B^{\circ} \cup \partial B \cup B^{-})$

9.2: $\partial A_1 \subset B^{\circ} \wedge \partial A_2 \sqsubset (B^{\circ} \cup \partial B \cup B^{-})$

9.3: $\partial A_1 \sqsubset (\partial B \cup B^{-}) \wedge \partial A_2 \sqsubset (B^{\circ} \cup \partial B \cup B^{-})$

9.4: $$\partial A_1 \sqsubset (\partial B \cup B^-) \wedge \partial A_2 \sqsubset (B^\circ \cup \partial B)$$

9.5: $$\partial A_1 \sqsubset (B^\circ \cup \partial B) \wedge \partial A_2 \sqsubset (B^\circ \cup \partial B \cup B^-)$$

9.6: $$\partial A_1 \sqsubset (B^\circ \cup \partial B \cup B^-) \wedge \partial A_2 \sqsubset (B^\circ \cup \partial B \cup B^-)$$

Proof: There are many possible combinations of non-empty intersections the split objects' boundaries can have to the parts of the *reference object B* if *A* has non-empty intersections with all three parts of *B*. These include that the split objects' boundaries can have non-empty intersections with just B°, ∂B or B^-.

Impossible is $\partial A \sqsubset (B^\circ \cup B^-)$, because this would violate the restriction that *A* must be connected. Furthermore, it is not possible that one of the split objects' boundaries is a subset of *B*'s boundary, as the boundaries would also need to intersect either the interior or exterior of *B*. Also, A_1 and A_2's boundaries cannot be equal to *B*'s interior or *B*'s boundary, as the boundaries of A_1 and A_2 have no extent.

From all these combinations for A_1's boundary and A_2's boundaries, only 6 are realizable (***9.1-9.6***). Most combinations are impossible, because *A*'s boundary is a subset of the union of A_1's boundary and A_2's boundaries and, therefore, the union of A_1's boundary and A_2's boundaries must have at least the same non-empty intersections as *A*'s boundary.

Other combinations are not realizable where the intersection of A_1 and A_2 would be empty. By definition, the intersection cannot be empty, because the new piece of boundary that separates *A* is common for A_1 and A_2.

Finally, a combination where one of the split objects' boundaries (∂A_1) is equal to the boundary of B while the other split object's boundary (∂A_2) intersects with all three parts of B cannot be realized because A_1 would be equal to B and, therefore, also their interiors would be equal. Since ∂A_2 has non-empty intersections with all three parts of B, the intersection of ∂A_2 with the interior of A_1 would be non-empty which is not possible in our definition of splitting.

If A_1's boundary is a subset of B's exterior, then the new piece of boundary must be completely contained in B's exterior as well, therefore, A_2's boundary would have non-empty intersections with all three parts of B, because this is the condition for the boundary of A for this theorem (***9.1***).

Analogously, if A_1's boundary is a subset of B's interior, A_2's boundary must have non-empty intersections with all of B's parts (***9.2***).

In case A is split in such a way that A_1's boundary has non-empty intersections with B's boundary and exterior, A_2's boundary will have non-empty intersection with B's boundary and interior, if the new piece of boundary is equal to the piece of B's boundary that intersects with A's interior (***9.4***). In the other cases, A_2's boundary will have non-empty intersections with B's interior, boundary and exterior (***9.3***).

9.5. is analogous to ***9.3***, replacing B's interior with its exterior.

Finally, if the new piece of boundary has non-empty intersections with all of B's parts, so do A_1's boundary and A_2's boundary (***9.6***). □

4.3.3.3 Exterior Propagations

The exterior of A, A^-, has two relations with respect to B's parts:

E1: A^- is a subset of B's exterior $(A^- \subseteq B^-)$.

E2: A^- has non-empty intersections with all three parts of B $(A^- \sqsubset (B^\circ \cup \partial B \cup B^-))$.

These two relations cover all the cases possible. A^- always has non-empty intersection with all three parts of B unless the closure of A *covers* or *contains* the closure of B, then A^- will have only one non-empty intersection with the exterior of B.

A^- cannot be a subset of B° as it is required for A to be simply connected.

Also, A^- cannot have non-empty intersections with B's interior and boundary while it has an empty intersection with B's exterior because all surrounding disks of the point of the boundary of B also intersect B° and B^-.

Analogously, it is impossible for A^- to have non-empty intersections with B's boundary and exterior while the intersection with the interior is empty.

Another impossible case is that A^- is subset of the boundary of B, simply because the boundary of B has no extent.

Finally, it is impossible for A^- to have non-empty intersections with the interior and exterior of B and an empty intersection with B's boundary, because B is required to be simply connected.

These two relations give rise to Theorems *10-11*.

Theorem 10 (Case E1): In case the exterior of A has one non-empty intersection with the exterior of $B(A^- \subseteq B^-)$, A can be split up so the exteriors of the split objects have the following intersections with B's parts:

10.1: $A_1^- \subseteq B^- \wedge A_2^- \sqsubset (B^\circ \cup \partial B \cup B^-)$

10.2: $A_1^- \sqsubset (B^\circ \cup \partial B \cup B^-) \wedge A_2^- \sqsubset (B^\circ \cup \partial B \cup B^-)$

Proof: As the objects after splitting have a smaller area than the to-be-split object, the exterior of A_1 and A_2 is larger than the exterior of A. Therefore, A_1's exterior and A_2's exterior can have more non-empty intersections than just with the exterior of B. However, the split objects' exterior can only have non-empty intersections with B's exterior or with interior, boundary and exterior of B (Relations between exteriors of two sets E1 and E2). Three combinations are unique from the set of four possible combinations (*2x2*).

One of these is not realizable, as both split objects closures cannot contain B's closure in such a way that both split objects' exteriors can be subsets of B's exterior. If we assume that A_1 and A_2's exteriors would be subsets of B's exterior, then also the union of A_1's exterior and A_2's exterior $(A_1^- \cup A_2^- \subset B^-)$ which is the same as the complement of the new piece of boundary $((A_1 \cap A_2)^-)$. The exterior of the new piece of boundary, however, is everything but this very piece of boundary and cannot be a subset of the exterior of an area.

If the new piece if boundary is contained completely within the exterior of B (***10.1***), one of the split object's exteriors will be subset of B's exterior, while the other split object has non-empty intersections with all three parts of B.

In all other cases both exteriors of the split objects with have non-empty intersections with all three parts of B (***10.2***). □

Theorem 11 (Case E1):

$$A^{-} \sqsubset (B^{\circ} \cup \partial B \cup B^{-}) \Rightarrow A_1^{-} \sqsubset (B^{\circ} \cup \partial B \cup B^{-}) \wedge A_2^{-} \sqsubset (B^{\circ} \cup \partial B \cup B^{-})$$

Proof: As the areas of the split objects are larger than the area of the to-be-split object, the split objects' exteriors will keep the non-empty intersections with B's parts. □

4.3.4 Application of Theorems

To derive the topological relations of the split objects A_1 and A_2 to the *reference object B* from the topological relation A holds to the *reference object B* the theorems need to be applied in sequence. The application of theorems will result in sets of topological relations that can hold between split objects and the *reference object* for each of the eight topological relations the to-be-split object A can have to B. The results are displayed in Table 4.3.

disjoint	*meet*	*overlap*	*equal*	*covers*	*contains*	*coveredby*	*inside*
d - d	*d - m*	*d - o*	*cb - cb*	*d - cv*	*d - ct*	*cb - cb*	*i - i*
	m - m	*m - o*		*m - e*	*m - cv*	*cb - i*	
		m - cb		*m - cv*	*o - o*		
		o - o		*o - o*			
		o - cb		*o - cb*			
		o - i					

Table 4.3: Sets of topological relations split objects can have in relation to a *reference object* based for each topological relation a to-be-split object can have with the *reference object.*

The rules for the derivation of possible sets of topological relations for split objects based on the topological relations between to-be-split objects and a *reference object*, have been applied in a Java application, which prove the validity of the rules and, therefore, the validity of the results.

4.4 Detecting Modifications with Identity Changes

Between two snapshots, changes to the identity states and topological relations of objects can occur. These can be derived with the methods of the previous chapter that identify changes that affect, shapes, sizes and locations of objects and, therefore, influence the topology of the spatial configuration over time, or by the knowledge gained about merging and splitting.

In order to derive such changes as merging and splitting, changes to identity states of objects in a snapshot and the topological relations need to be tracked. If the identity states change, such that it matches the definition of merging and splitting and at the same time the topological relations of the split objects to another object changed according to the sets derived for the topological relation, the to-be-split objects had to another object, before the identity states changed, then it is assumed, that merging or splitting occurred.

However, at the moment it is difficult to track merging and splitting, if the snapshots provide insufficient information. This might be due to other types of changes that occur before or after merging and splitting take place, but that are not captured in snapshots. Additional methods that are capable of deriving merging and splitting even under such conditions, are to be developed in the future.

4.5 Summary

The sets of possible topological relations for the merged regions and split regions are coherent and consistent, as the operation of merging and splitting are basically converse operations by definition. If merging and splitting are applied consecutively it is assumed that the output object(s) of this change will have the same topological relation to the reference object as before merging and splitting were applied.

The knowledge about possible sets of topological relations for output objects of merging and splitting in combination with the definitions for merging and splitting allow for the development of methods that track these types of change. At this point, methods have been proposed that derive changes that occurred and manifest in alterations in the topological relations of spatial objects in a snapshot over time and identity states and topology at the same time. This provides fundamental capabilities to track and derive all the changes discussed in this thesis. While the methods in Chapter 3 are evaluated in Chapter 5 and applied in the automatic derivation of changes in the prototype, this chapter delivered solely theoretical information about the methods.

Chapter 5

EVALUATION OF METHODS: PROTOTYPE AND EXAMPLES

This chapter contains the evaluation of methods developed in Chapter 3 that are purely based on the detection and derivation of alterations in the topological relations between objects and metric refinements for the topological relations. We use a prototype application for region objects represented as rectangles to test the model of the derivation of changes based on topological relations in a spatial scene and to prove its functionality. Examples are run in the prototype and results are displayed. Additionally, a more complex example is provided with multiple objects and arbitrary values that further examines the functionality of methods proposed in Chapter 3.

5.1 Prototype

A prototype application has been developed to evaluate the usefulness of the methods for deriving changes from snapshots. The prototype was implemented in an object-oriented environment using the programming language Java and its core libraries. Java swing classes were used to create the graphical user interface. The prototype can be executed on any operating system where the Java virtual machine is installed. The prototype was developed to show the capabilities of methods proposed in this thesis (Figure 5.1). Objects that are analyzed in the prototype application are solely rectangles.

A user can draw two snapshots corresponding to different times t_1 and t_2 of a spatial scene including multiple regions represented as rectangles in the prototype. For this drawn scenario, the methods are applied to calculate the changes that occurred in between snapshots and results are displayed for each object. The objects in snapshot one are visualized with a *blue* outline while the objects in snapshot two have a *red* outline.

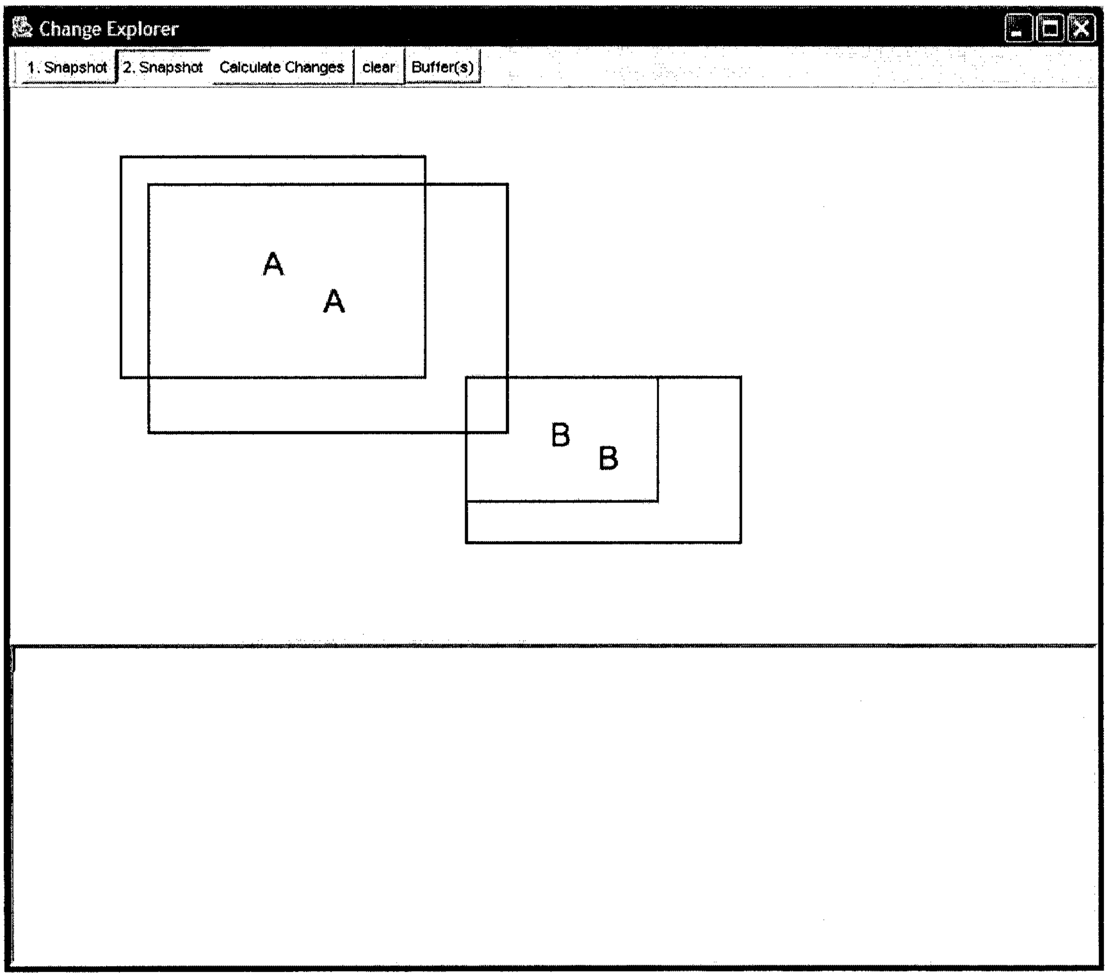

Figure 5.1: Screenshot of the Change Explorer.

5.2 Guided Tour

In Chapter 3 methods were provided to derive changes in scenarios where identities of objects remain unchanged while the topology might alter between snapshots. These methods are tested in the prototype application. The process of deriving changes from a specified scenario is illustrated in terms of a guided tour of the prototype application. This section explains how the prototype application can be used in order to derive changes from data in two snapshots. Upon launching the prototype, the application window is drawn on the screen. The application window consists of three basic parts: (1) the *toolbar*, including buttons to choose the snapshot to draw in, a button to calculate changes, a clear button, and a buffers button (2) a drawing pane, where the state of a spatial scenario at each snapshot can be specified by drawing rectangles, and (3) the output pane where results are presented (Figure 5.2).

The task of deriving changes from a spatial scenario including rectangles consists of two steps: (1) the description of the spatial phenomenon at two snapshots, and (2) the application of methods to derive changes from the entered information and presentation of results. In the first step, the user defines a state of a spatial scenario in the first snapshot. In order to add a region, the user must specify the upper left and lower right corners of each rectangle representing a region in the drawing pane. In the prototype application the regions are defined by two attributes, label and color. The color defines in what snapshots the region is situated, the regions of the first snapshot have a *blue* outline, while the regions for the second snapshot have a *red* outline. Also the rectangles are labeled with numbers in the order they were drawn. Color coding is also done for the visualization of closeness measures, the area used in outer closeness is displayed with a *green* outline whenever if the objects in a snapshot are *disjoint* and the rectangles for inner closeness are displayed with a *cyan* colored outline if the topological relation is *contains*. The rectangles used for outer closeness and inner closeness can be enabled or disabled by clicking on the buffers button. The system can calculate changes based on two or more regions. Therefore, the user must draw at least two rectangles, while there is no upper limit for regions that can be drawn and computed. Then the user can proceed to drawing the spatial configuration by clicking on the button “2. Snapshot” in the toolbar area.

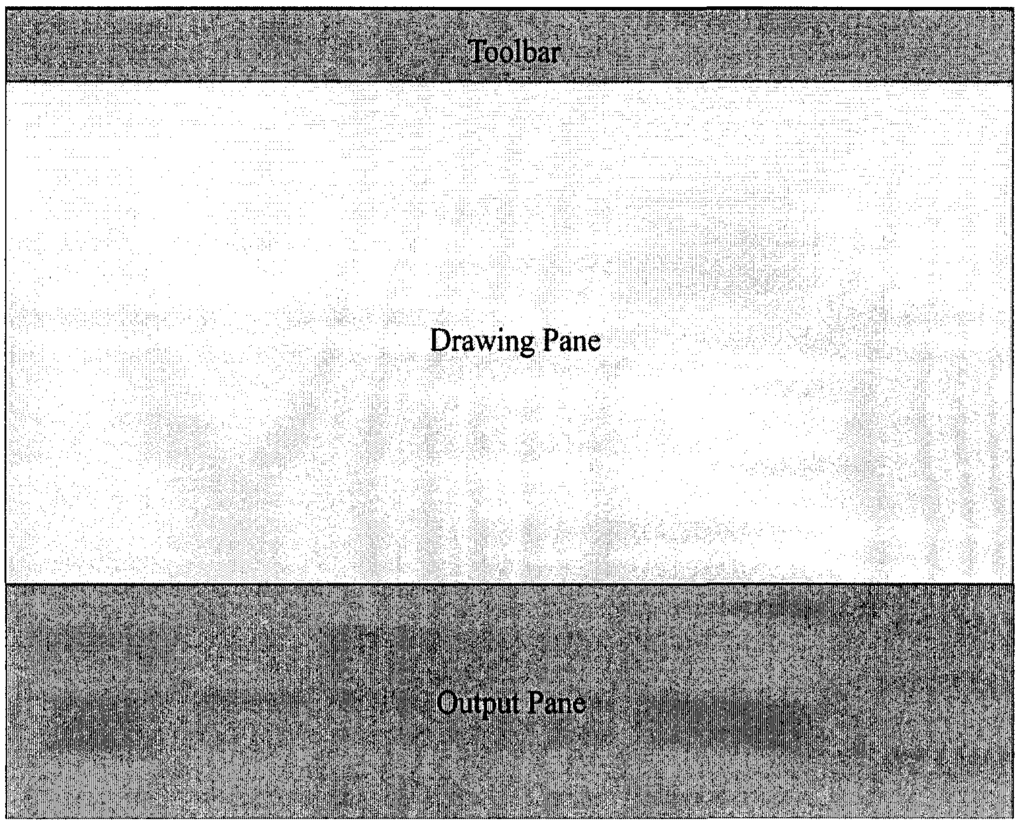

Figure 5.2: Segmentation of application window.

When the user has entered the same number of rectangles for this snapshot as in snapshot one, the button for the derivation of changes becomes enabled. By clicking on this button, the change derivation methods are applied to this particular scenario and results are presented in the output pane. If, however, the user wants to make changes to the description of snapshots and wants to start over, he or she can start over by clicking on clear at any point. When the scenario is being reset, the user will have to start entering rectangles for the first snapshot again.

5.3 Examples for a Change Derivation in the Prototype

This section provides some examples that show various aspects of the functionality of the prototype application. The first example includes two rectangles for each snapshot representing region *A* and *B* (Figure 5.3).

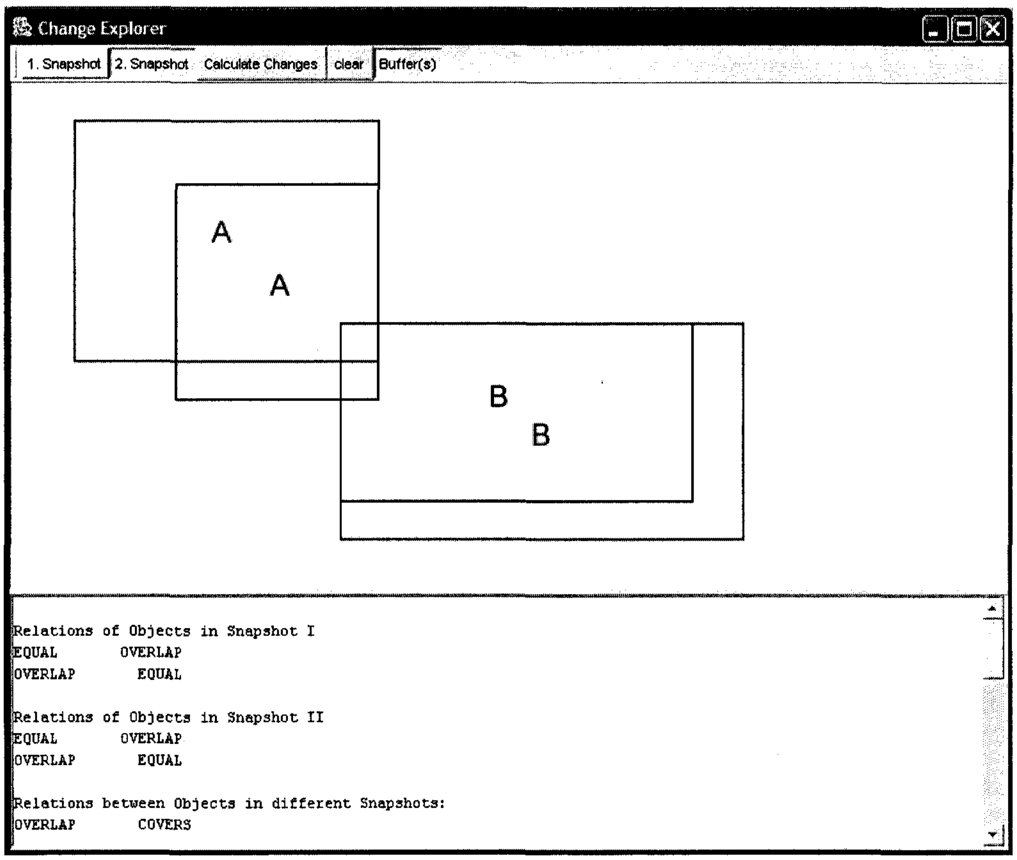

Figure 5.3: Example including regions *A* and *B* that *overlap* at t_1 and at t_2.

The objects in snapshot one are represented by the *blue* outline while the objects in snapshot two are represented by a *red* outline. In the output pane results are displayed.

The results consist of multiple calculations that lead to the changes that occurred to the objects. From the rectangles that are drawn in the drawing pane the topological relations are calculated — between the objects in the snapshots and between one object with itself in different snapshots. Then the methods of Chapter 3 are applied and combined to acquire unique results for each object. In both snapshots the topological relation between object *A* and *B* is *overlap*. The topological relation of object *A* at the two snapshots is *overlap*, while object *B* at snapshot two *covers* object *B* at snapshot one. The results for this scenario of change are displayed in Figure 5.4.

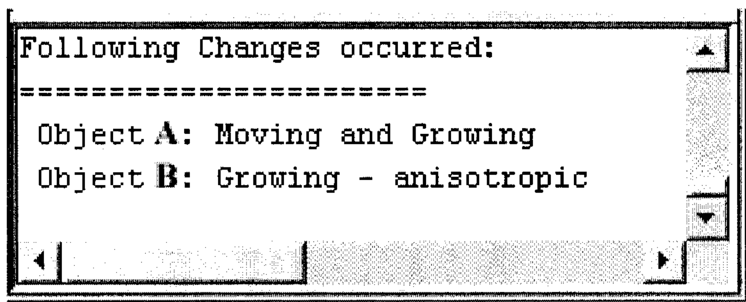

Figure 5.4: Results of scenario drawn in Figure 5.3.

The results show that object *A* moved and grew, while object *B* grew anisotropically. This is consistent with the visual analysis of the drawn scene. The results illustrate that not only can the primary type of change be derived by the methods, but also combinations of change types.

The next example includes a topologically significant change, as the topological relation between the objects in snapshot one is different from the topological relations between the same objects in snapshot two (Figure 5.5).

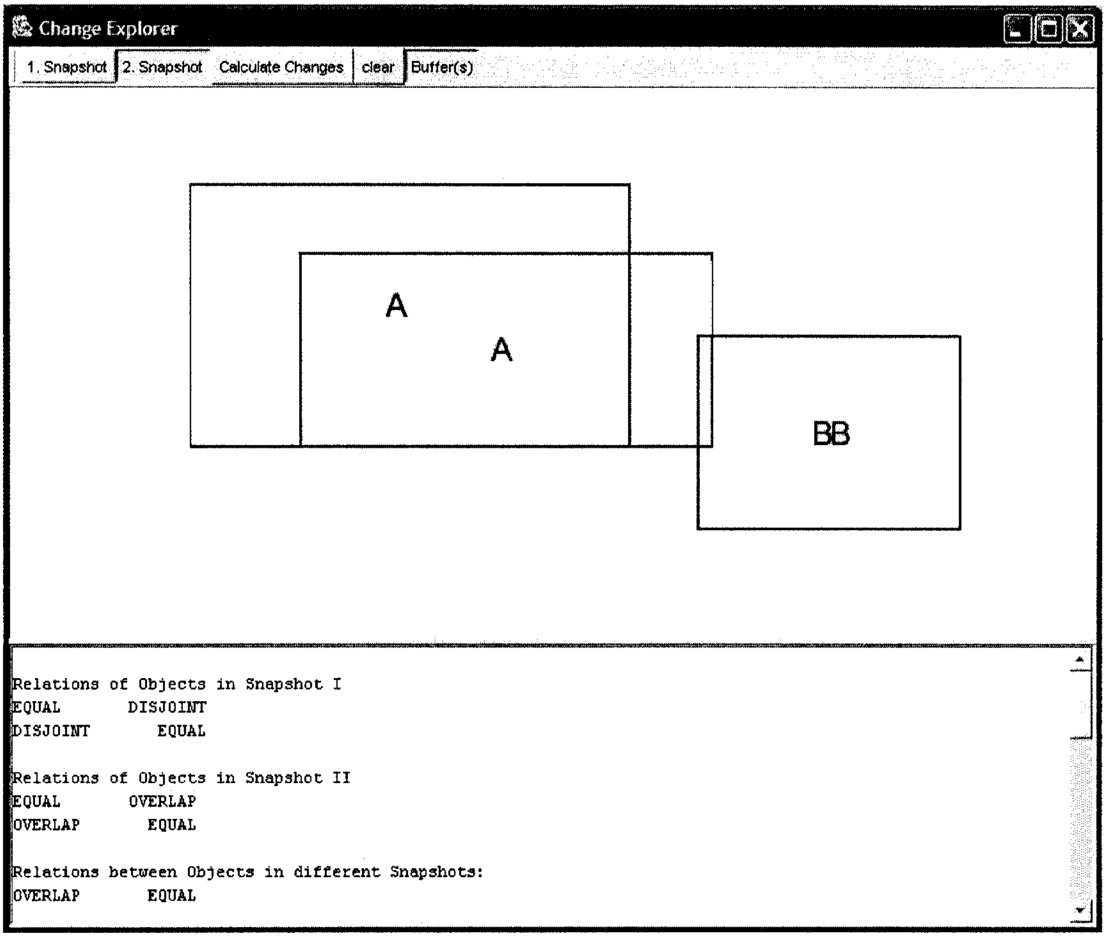

Figure 5.5: Example including regions *A* and *B* that are *disjoint* in snapshot one while object *A overlaps* object *B* in snapshot two.

While in the first snapshot object *A* is *disjoint* from object *B*, the topological relation between these objects changed to *overlap* in snapshot two. Changes in values for IAS and OC as well as the topologically significant change from *disjoint* to *overlap* help determine what type of change occurred. The results of the change derivation process are displayed in Figure 5.6.

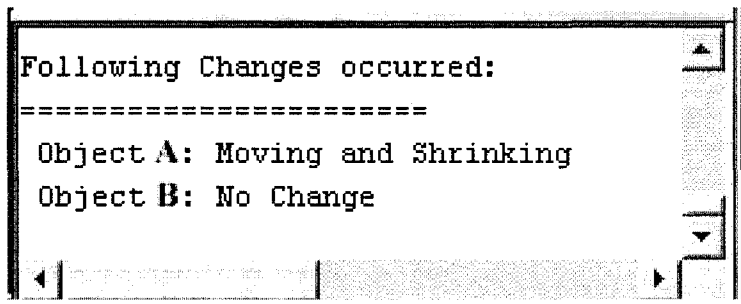

Figure 5.6: Results of scenario drawn in Figure 5.5.

According to the prototype, object *A* moved and shrank, while no change occurred to object *B*. These results are consistent with the visual analysis and two distinct results for object *A* do not have any contradictions.

A third example shows objects *A* and *B* where object *A* *contains* object *B* in each of the snapshots (Figure 5.7).

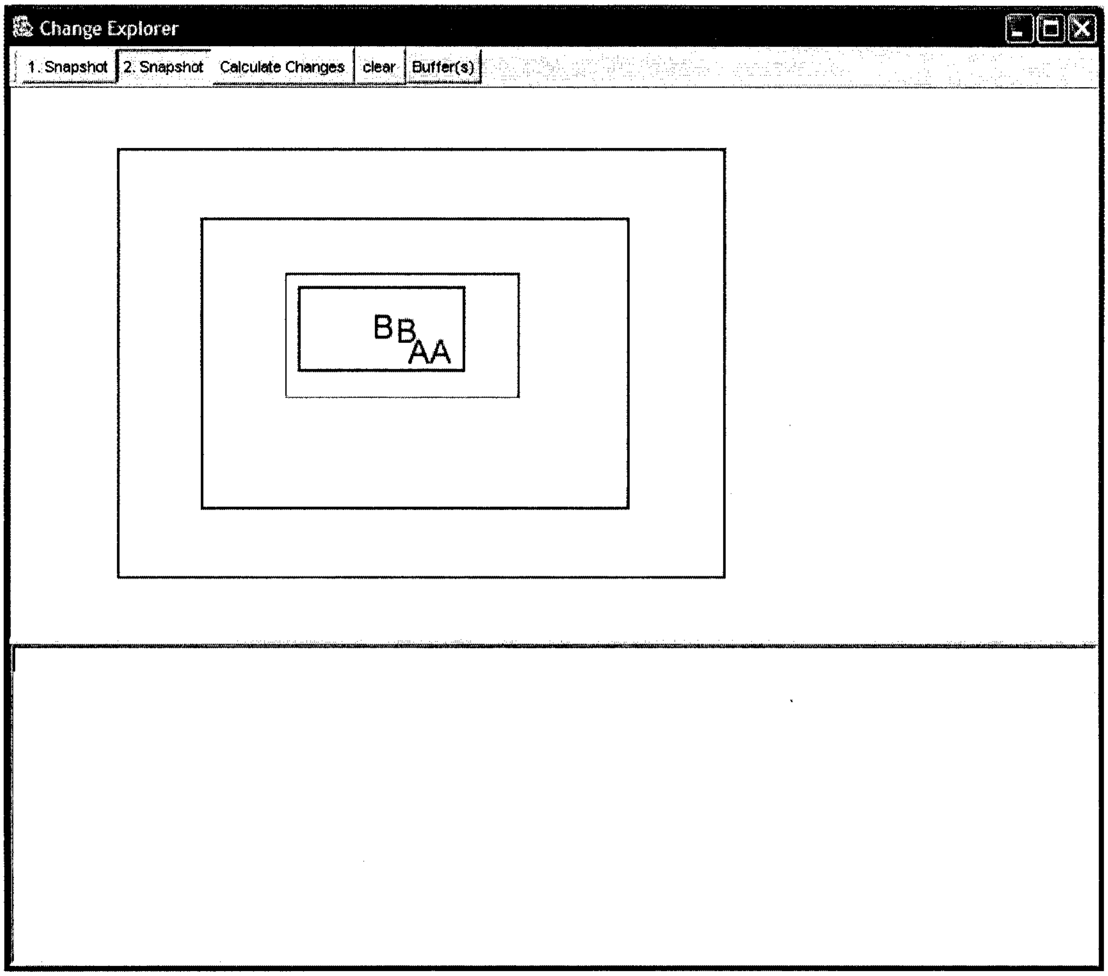

Figure 5.7: Example including regions A and B where object A *contains* objects B at both at t_1 and t_2.

Methods for IC values, IAS values, the sequences of topological relations, and the relation of objects at different times are applied in this case. The IC measure can be applied as object A *contains* object B in the first snapshot and second snapshot. Therefore, the IAS measure is also applicable as the two objects share common interior in both snapshots. Results are displayed in Figure 5.8.

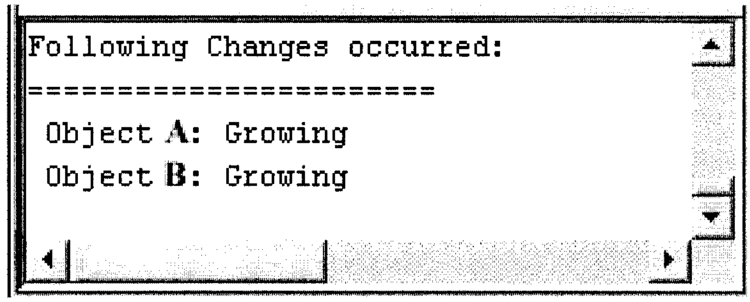

Figure 5.8: Results of scenario drawn in Figure 5.7.

The methods applied in this scenario return that both objects *A* and *B* grew between the snapshots, which caused alterations in metric measures while the topological relation remained unchanged.

Again, the results matched the expected outcome of the scenario drawn. Overall, in several tests, anticipated results were consistently returned with the methods implemented in the prototype. Therefore, it is concluded that the methods work in the framework of this prototype application for rectangles representing regions. It was also found that the methods meet expected capabilities by returning changes and combinations of changes that occurred to the spatial regions. All the combinations were valid and no contradictory combinations, like growing and shrinking of the same object, were returned.

5.4 Example of Qualitative Methods for Change Derivation

This section provides a more complex scenario than the ones described in section 5.3. It extends examples shown in the prototype by using different shapes, ovals in this case, and multiple objects. Figure 5.9 shows the application of the methods described in Chapter 3 on a detailed scenario that contains four different region objects *A*, *B*, *C*, and *D*. Figure 5.9a shows a drawing of the spatial configuration of these objects at time t_1 and t_2.

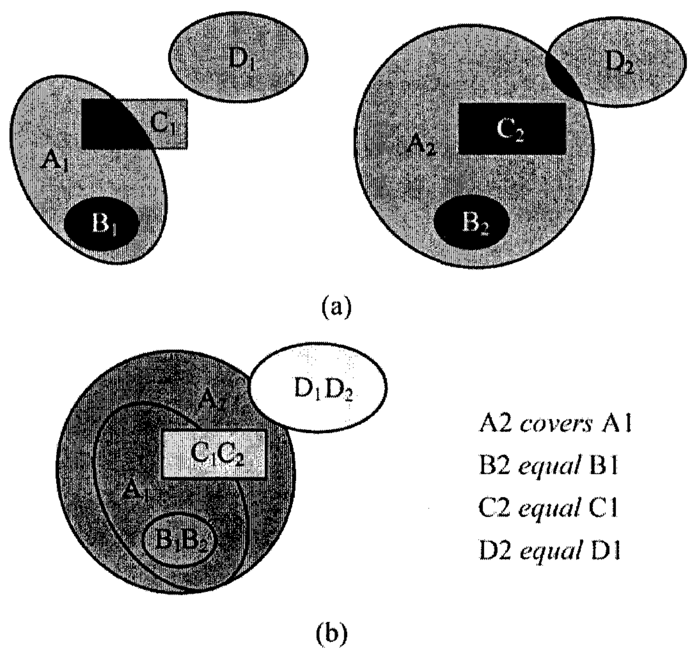

Figure 5.9: Visual representation for two snapshots (a) of the spatial configuration of objects *A*, *B*, *C*, and *D*, and (b) the relation between the same objects at time t_2 and t_1.

Figure 5.9b shows the overlay of the spatial configuration in snapshot one and two, resulting in the topological relations between the same objects at different times. The interpretation of these topological relations results in the most likely scenario that change occurred to object *A*, in fact the object grew, while no change applied to objects *B*, *C*, and *D*. Table 5.1 shows the sequence of topological relations of object *A* to the other objects.

Objects	Sequence of topological relations
ArB	*contains-contains*
ArC	*overlap-contains*
ArD	*disjoint-overlap*

Table 5.1: Sequence of topological relations between *A* and other objects.

After filling of the gaps the sequence of the topological relations is complete (Table 5.2). The analysis of these sequences also leads to the conclusion that object *A* grew or object *A* moved, because two of the sequences stand for both growing or moving. The analysis requires the application of additional methods to find out exactly, which type of change occurred to object *A*.

Objects	Sequence of topological relations
ArB	*contains-contains*
ArC	*overlap-covers-contains*
ArD	*disjoint-meet-overlap*

Table 5.2: Complete sequence of topological relations is achieved, after the gaps have been filled.

Table 5.3 shows the values the splitting and closeness measures between the four objects in the scene for the first snapshot and the values for the second snapshots are being displayed in Table 5.4.

	A_1	B_1	C_1	D_1
A_1	IAS = 1.00 OAS = 0.00	IAS = 0.17 OAS = 0.83 IC = 0.06	IAS = 0.19 OAS = 0.81	IAS = 0.00 OAS = 1.00 OC = 2.16
B_1	IAS = 1.00 OAS = 0.00	IAS = 1.00 OAS = 0.00	IAS = 0.00 OAS = 1.00 OC = 3.96	IAS = 0.00 OAS = 1.00 OC = 12.27
C_1	IAS = 1.00 OAS = 0.00	IAS = 0.00 OAS = 1.00 OC = 2.48	IAS = 1.00 OAS = 0.00	IAS = 0.00 OAS = 1.00 OC = 1.27
D_1	IAS = 0.00 OAS = 1.00 OC = 2.65	IAS = 0.00 OAS = 1.00 OC = 4.81	IAS = 0.00 OAS = 1.00 OC = 1.14	IAS = 1.00 OAS = 0.00

Table 5.3: Splitting and closeness measures for the objects involved in the sketched example at time t_1.

	A_2	B_2	C_2	D_2
A_2	IAS = 1.00 OAS = 0.00	IAS = 0.07 OAS = 0.93 IC = 0.11	IAS = 0.17 OAS = 0.83	IAS = 0.04 OAS = 0.96
B_2	IAS = 1.00 OAS = 0.00	IAS = 1.00 OAS = 0.00	IAS = 0.00 OAS = 1.00 OC = 3.96	IAS = 0.00 OAS = 1.00 OC = 12.27
C_2	IAS = 0.54 OAS = 0.46	IAS = 0.00 OAS = 1.00 OC = 2.48	IAS = 1.00 OAS = 0.00	IAS = 0.00 OAS = 1.00 OC = 1.27
D_2	IAS = 0.11 OAS = 0.89	IAS = 0.00 OAS = 1.00 OC = 4.81	IAS = 0.00 OAS = 1.00 OC = 1.14	IAS = 1.00 OAS = 0.00

Table 5.4: Values for semi-qualitative measures between the objects at snapshot two.

The splitting and closeness measures offer a more precise description of the spatial scene in the two snapshots than using solely binary topological relations. To derive changes it is necessary to analyze whether splitting and closeness measures increase, remain the same, or decrease from the first to the second snapshot (Table 5.5).

	A	*B*	*C*	*D*
A	$IAS_{A_2} = IAS_{A_1}$ $OAS_{A_2} = OAS_{A_1}$	$IAS_{A_2} < IAS_{A_1}$ $OAS_{A_2} > OAS_{A_1}$ $IC_{A_2} > IC_{A_1}$	$IAS_{A_2} < IAS_{A_1}$ $OAS_{A_2} > OAS_{A_1}$	$IAS_{A_2} > IAS_{A_1}$ $OAS_{A_2} < OAS_{A_1}$ $OC_{A_2} < OC_{A_1}$
B	$IAS_{B_2} = IAS_{B_1}$ $OAS_{B_2} = OAS_{B_1}$	$IAS_{B_2} = IAS_{B_1}$ $OAS_{B_2} = OAS_{B_1}$	$IAS_{B_2} = IAS_{B_1}$ $OAS_{B_2} = OAS_{B_1}$ $OC_{B_2} = OC_{B_1}$	$IAS_{B_2} = IAS_{B_1}$ $OAS_{B_2} = OAS_{B_1}$ $OC_{B_2} = OC_{B_1}$
C	$IAS_{C_2} = IAS_{C_1}$ $OAS_{C_2} = OAS_{C_1}$	$IAS_{C_2} = IAS_{C_1}$ $OAS_{C_2} = OAS_{C_1}$ $OC_{C_2} = OC_{C_1}$	$IAS_{C_2} = IAS_{C_1}$ $OAS_{C_2} = OAS_{C_1}$	$IAS_{C_2} = IAS_{C_1}$ $OAS_{C_2} = OAS_{C_1}$ $OC_{C_2} = OC_{C_1}$
D	$IAS_{D_2} > IAS_{D_1}$ $OAS_{D_2} < OAS_{D_1}$ $OC_{D_2} < OC_{D_1}$	$IAS_{D_2} = IAS_{D_1}$ $OAS_{D_2} = OAS_{D_1}$ $OC_{D_2} = OC_{D_1}$	$IAS_{D_2} = IAS_{D_1}$ $OAS_{D_2} = OAS_{D_1}$ $OC_{D_2} = OC_{D_1}$	$IAS_{D_2} = IAS_{D_1}$ $OAS_{D_2} = OAS_{D_1}$

Table 5.5: Changes to the values for metric refinements between objects over time. The arguments for the measures in the specific columns are in the first row of the table.

With these alterations in the values for the metric refinements of topological relations it is now possible to derive changes that occurred between objects. All values on the diagonal of this matrix can be disregarded, because the topological relation between the same object is always *equal* with specific values for metric refinements connected to this relation. It is obvious that alterations in the values only appear where object *A* is involved, while the values between objects *B*, *C*, and *D* remain the same over time. Therefore, the conclusion is that changes occurred to object *A*, leading to the elimination of possible types of change that affect *B* (Table 5.6).

	IAS	OAS	IC	OC
ArB	$G_a(A)$	$G_a(A)$	$G(A)$	-
ArC	$G_a(A)$	$G_a(A)$	-	-
ArD	$M(A)$, $G(A)$	$M(A)$, $G(A)$	-	$M(A)$, $G(A)$

Table 5.6: Possible types of change that can be derived for object *A* based on the values for the metric refinements to other objects.

The analysis of the alterations the values for the metric refinements took between the two snapshots indicate that object *A* either grew anisotropically or it moved. By using the ratio of area it can be decided, which of these changes occurred. As the ratio of the area of A_2 to the area of A_1 is greater than 1, it can be derived that the change that occurred to *A* was anisotropic growing.

5.5 Summary

This chapter outlined the implementation of the methods provided in chapter three for the derivation of changes from snapshots based on tracking of alterations in topological relations and measures for metric refinements. It described how the prototype application can be used to detect changes based on these methods from a description of a spatial phenomenon including rectangles representing regions. The chapter then showed a complex scenario where the states of multiple objects were analyzed. This example shows the functionality of the methods for objects with shapes other than rectangular ones. The prototype application and example visualize the usability and functionality of the methods. Through several tests in the prototype we found that the snapshot model is suited for the description of states of a spatial phenomenon while the knowledge about change integrated in the methods enables us to automatically derive the types of change that were defined in this thesis, namely growing, shrinking, and moving which confirms the hypothesis stated in Chapter 1. The expectation of deriving the primary type of change are not only met but exceeded, as the combination of methods returns not only a primary type of change but also other types of change that happen at the same time.

Chapter 6
CONCLUSIONS

This thesis presented an approach to deriving changes from qualitative spatial information, including identity and topology. Different methods were described that can be used to detect changes that occurred between two snapshots, describing spatial configurations of region objects explicitly by their identity states and topological relations. This chapter summarizes the work in this thesis, draws conclusions, and depicts what additions and enhancements can be made for higher precision and performance of the change derivation.

6.1 Summary

The research described in this thesis is concerned with the derivation of changes that occur to a spatial phenomenon based on the description of identity states and topological relations of objects at two consecutive snapshots. The main goal of this thesis is to develop and evaluate a snapshot-based approach to modeling and automatically deriving changes. Changes are derived by methods that analyze characteristic alterations in topology and identity states of objects over time. While the alterations in identity do not cause the topology to change directly, there is a correlation between the alterations in identity and those in topological relations between objects.

Different methods were proposed for the derivation of changes that maintain identity while topological relations are altered, namely growing, shrinking and moving, and a set of change types that affect identity and topology at the same time, merging and splitting.

The functionality of the first set for topological changes was evaluated using examples in a prototype application and complex scenario.

The conclusions that can be drawn from this study are presented in the following section and extensions and refinements are discussed in section 6.3.

6.2 Conclusions

In this thesis methods were developed for two categories of change: (1) changes that affect the topological relations and metric refinements of those relations, while identities of objects are not altered, and (2) those changes that manipulate the identities, and, therefore, also the topological relations of objects.

The hypothesis is: A sequence of snapshots, featuring identity states and topological relations of objects, allows an automatic derivation of changes that affect either identity, topology or a combination of identity and topology of objects.

This hypothesis was supported by the results of the evaluation conducted using the prototype application. Furthermore, it was found that the results exceed the expectation of capabilities of the combined methods. The methods cannot only derive a single type of change but also changes that occur at the same time. Common combinations that also occur in the real world are that objects move and grow at the same time or move and shrink. The results of the evaluation are, therefore, very beneficial.

6.3 Future Work

Further methods can be employed to enhance the results given by the application of the change derivation. This section points out possible refinements and extensions for modeling and deriving such changes that manifest in alterations in identity and topological states of objects.

6.3.1 Additional Measures for Derivation of Changes

In order to refine results produced by a combination of methods for change derivation additional methods can be considered.

In this study mostly two objects were considered and all methods were based on binary relations between two objects or the same object at different times. In more complex scenarios, however, there are more than just two objects. In such a case also more information is available, which can contribute to determining changes. For instance, another method derives the object the change applied to by analyzing the IAS/OAS values of multiple objects. The objects, whose IAS/OAS values change most in relation to other objects, are most likely to be directly affected by the change. Generally, we expect that expanding the reasoning to multiple objects with multiple relations to each other will offer more reasoning power.

Among the measures considered are topological and metric properties, but no cardinal direction information has been used so far (Goyal, 2000). Differences due to direction may occur for instance, when an object takes a different path while moving around the reference object. By considering direction information, additional refinements about changes may be derived, such as '*B* moved around *A* to its left' versus '*B* moved around *A* to its right' (Figure 6.1). Therefore, the integration of this measure may help improve the reasoning power of the combined methods by adding additional information about the location of the objects.

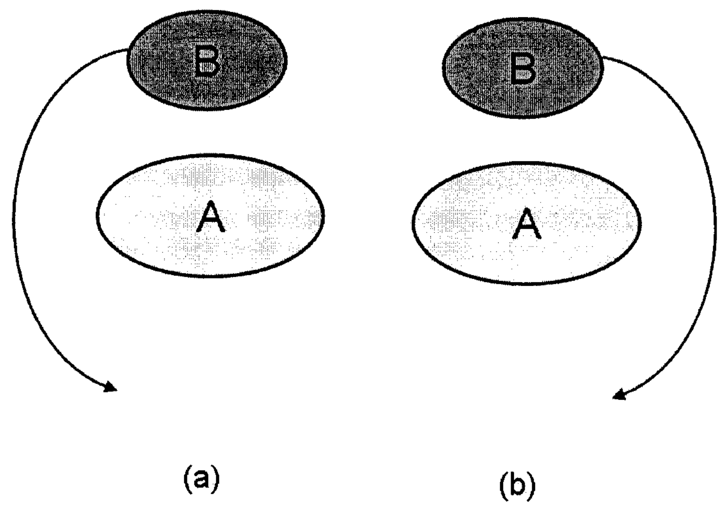

Figure 6.1: Cardinal directions could distinguish different cases of movement, where an object *B* moves around object *A* around its left (a), and to its right (b), respectively

There are also certain semantic restrictions that, if implemented, will eliminate choices for types of change, and, therefore, produce a higher precision of the change derivation. For instance, water bodies cannot move but only grow or shrink. Also the pre- and post-conditions for merging and splitting would be different considering an example with water bodies, as water bodies merge as they *meet* and they must be *disjoint* before the merge. This leads to the idea to define these semantic restrictions for classes of objects and analyze the impact this approach will have on the results and application of methods.

6.3.2 Sequence of Snapshots and Future Extrapolation

So far this study only dealt with the derivation of changes that occurred in between snapshots with information about topology and identity available for these time-referenced snapshots. An interesting research topic is the investigation, how methods for change derivation can be used and what extensions are needed to make predictions about changes that might occur after the last snapshot of a sequence. This could be done based on qualitative measures and a linear order of snapshots, or using metric refinements and exact referencing of time so that the time period in between snapshots would be known. Using quantitative values for time would also allow for a better analysis of how much an object changed over time. For instance, distances between objects can be tracked over time and then it can be determined, how far objects will be apart at a later point in time. With the combination of semantics it can also be concluded that two coral reefs, where the distance decreases, are likely to merge at a later point in time and it can be possible to predict with relative precision, at what time this will happen.

6.3.3 Refined Implementation

The measures to derive merging and splitting have not yet been implemented. It would be beneficial to have an implementation visualizing the functionality of all the methods proposed in this study. Also, the prototype application is limited to rectangles. Future work includes addressing these shortcomings of the prototype application.

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