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Citation for final published version:


Publishers page: http://dx.doi.org/10.1142/S0218213097000232

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ORDER IN SPACE: A GENERAL FORMALISM FOR SPATIAL REASONING

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In this paper we propose a general approach for reasoning in space. The approach is composed of a set of two general constraints to govern the spatial relationships between objects in space, and two rules to propagate relationships between those objects. The approach is based on a novel representation of the topology of the space as a connected set of components using a structure called adjacency matrix which can capture the topology of objects of different complexity in any space dimension. The relationships between objects are represented by the intersection of the space components. The approach is also shown to be applicable to reasoning in the temporal domain and is used to explain the conceptual neighbourhood phenomenon related to the reasoning process. The formalism is also used to explain composition resulting in indefinite and definite relations. A major advantage of the method is that reasoning between objects of any complexity can be achieved in a defined limited number of steps. Hence, the incorporation of spatial reasoning mechanisms in spatial information systems becomes possible.

Keywords: Spatial reasoning, knowledge representation, spatial relations, qualitative reasoning.

1. Introduction

Spatial reasoning is a field of AI research which studies formalisms for encoding qualitative spatial knowledge. The ability to handle a certain level of indeterminacy makes techniques of spatial reasoning attractive to many application domains, such as computer vision, image processing, medical and geographic information systems (GIS). Precise information required in quantitative methods are sometimes neither available nor needed. Techniques for representing and reasoning over qualitative spatial knowledge are valuable in complementing traditional computational geometry in these domains. For example, in a GIS the fact that the river Thames is in Britain can be inferred directly if the facts that it passes through London and London is in Britain are known, without needing to execute a line-in-polygon geometric computation.

Qualitative treatment of the temporal knowledge is an established research area where different approaches exist for the representation of temporal entities and their relations (interval and point algebra) and reasoning over them (composition tables and constraint networks). A similar general treatment of spatial knowledge is still
lacking. Composition tables (result of the reasoning process) need to be built for
every new type of objects considered and techniques to derive them automatically
presents a challenge to theorem provers. Phenomena such as conceptual neighbour-
hood needs explanation.

Some research work tried to exploit the well developed treatment of temporal
knowledge in handling the representation in the spatial domain. However, the
multi-dimensionality and complexity of the topology of spatial entities, as opposed
to the uni-dimensionality of temporal entities and their simpler topology prevented
the generality of these approaches. General approaches which handles reasoning
over objects of different types and random complexity are not yet achieved.

In this paper a general reasoning formalism for qualitative spatial relations is
proposed. Section 2 describes the proposed approach by describing the underlying
representation methodology and the reasoning formalism. Examples are given to
show how the approach can be used to represent and reason over relationships
between objects with random complexity. In section 3, analysis of the composition
results is presented and a possible explanation on how the phenomenon of conceptual
neighbourhood occurs is discussed and the application of the same approach to the
representation and reasoning in the temporal domain is given. Section 4 gives a
comparative description of related approaches and some conclusions and a view
over future work are given in section 5.

2. The Formalism

The first part of the paper addresses the problem of qualitative representation of
objects with random spatial complexity and their topological relationships. In the
second part the reasoning formalism is presented, consisting of a) general constraints
to govern the spatial relationships between objects in space, and b) general rules
to propagate relationships between those objects. Both the constraints and the
rules are based on a uniform representation of the topology of the objects, their
embedding space and the representation of the relationships between them. The
representation methodology is first described and examples are used to demonstrate
how relationships between objects of random complexity can be represented.

2.1. The General Representation

Objects of interest and their embedding space are divided into components accord-
ing to a required resolution. The connectivity of those components is explicitly
represented. Spatial relations are represented by the intersection of object compo-
nents in a similar fashion to that described but with no restriction on object
components to consist only of two parts (boundary and interior).

2.1.1. The Underlying Representation of Object Topology

Let $S$ be the space in which the object is embedded. The object and its embedding
space are assumed to be dense and connected. The embedding space is also assumed
Order in Space

Figure 1: (a) Possible decomposition of a concave-shaped object and its embedding space. (b) Adjacency matrix of the shape in (a). (c) Half the symmetric adjacency matrix is sufficient to capture the object representation.

to be infinite. The object and its embedding space are decomposed into components which reflects the objects and space topology such that,

1. No overlap exists between any of the representative components.

2. The union of the components is equal to the embedding space.

The topology of the object and the embedding space can then be described by a matrix whose elements represent the connectivity relations between its components. This matrix shall be denoted *adjacency matrix*. In figure 1(a) a possible decomposition of a concave shaped object (for example an island with a bay) and its embedding space is shown and in 1(b) the adjacency matrix for its components is presented. The object is represented by two components a linear component $x_1$ (the shore line of the island) and an areal component $x_2$ and the rest of its embedding space is represented by a finite areal component $x_3$ (representing the bay of the island) and infinite areal component $x_0$ representing the surrounding area. The fact that two components are connected is represented by a (1) in the adjacency matrix and by a (0) otherwise. Since connectivity is a symmetric relation, the resulting matrix will be symmetric around the diagonal. Hence, only half the matrix is sufficient for the representation of the object’s topology and the matrix can be collapsed to the structure in figure 1(c). In the decomposition strategy, the complement of the object in question shall be considered to be infinite. The suffix 0 ($x_0$) is used to represent this component.

Note that different decomposition strategies for the objects and their embedding spaces can be used according to the precision of the relations required and the specific application considered. The higher the resolution used (or the finer the components of the space and the objects), the higher the precision of the resulting
set of relations in the domain considered. For example, consider the objects in figure 2(a) which represents an island with a lake represented by \( x_1 \) and \( x_2 \) and a river represented by the components \( x_5 \), \( x_6 \) and \( x_7 \). The adjacency matrix for the map in (a) in given in (b). This example demonstrates the ability of the adjacency structure to represent complex objects such as a whole map. At a lower resolution the river object may be omitted by removing the rows and columns of components \( x_5 \), \( x_6 \) and \( x_7 \). This representation can also be used to represent virtual components as was seen in figure 1 which makes the method flexible for representation in any application domain.

2.1.2. The Underlying Representation of Spatial Relations

In this section, the representation of the topological relations through the intersection of their components \(^8,9\) is adopted and generalized for objects of arbitrary complexity.

Distinction of topological relations is dependent on the strategy used in the decomposition of the objects and their related spaces. For example, in figure 3 different relationships between two objects representing a ship (\( x \)) and an island (\( y \)) are shown, where in 3(a) the ship is outside the bay and in 3(b) the ship is inside the bay. The concave region representing the island (\( y \)) is decomposed into two components \( y_1 \) and \( y_2 \) and the rest of the space associated with \( y \) is decomposed into two components (\( y_3 \) representing the bay and \( y_0 \) representing the rest of the ocean). Note that the component \( y_3 \) is a virtual component, i.e. with no physical boundary to delineate its spatial extension. It is the identification of this component that makes the distinction between the two relationships in the figure. The complete set of spatial relationships are represented by combinatorial
Figure 3: Different qualitative spatial relationships can be distinguished by identifying the appropriate components of the objects and the space.

intersection of the components of one space with those of the other space.

If \( R(x, y) \) is a relation of interest between object \( x \) and object \( y \), and \( X \) and \( Y \) are the spaces associated with the objects respectively such that \( m \) is the number of components in \( X \) and \( l \) is the number of components in \( Y \), then a spatial relation \( R(x, y) \) can be represented by one state of the following equation:

\[
R(x, y) = X \cap Y = \left( \bigcup_{i=1}^{m} x_i \right) \cap \left( \bigcup_{j=1}^{l} y_j \right) = (x_1 \cap y_1, \ldots, x_1 \cap y_l, x_2 \cap y_1, \ldots, x_m \cap y_l)
\]

The intersection \( x_i \cap y_j \) can be an empty or a non-empty intersection. The above set of intersections shall be represented by an intersection matrix, as follows,

\[
R(x, y) = \begin{pmatrix}
x_0 & y_0 & y_1 & \cdots \\
x_1 & y_0 & y_1 & \cdots \\
x_2 & y_0 & y_1 & \cdots \\
\vdots & \vdots & \vdots & \ddots
\end{pmatrix}
\]

For example, the intersection matrices corresponding to the spatial relationships in figure 3 are shown in figure 4. The components \( x_1 \) and \( x_2 \) have a non-empty intersection with \( y_0 \) in 4(a) and with \( y_3 \) in 4(b).

Different combinations in the intersection matrix can represent different qualitative relations. The set of valid or sound spatial relationships between objects is dependent on the particular domain studied. For example, in considering relationships between two line objects in a network analysis application we might be interested in only those relationships where end points of lines are in contact. Also, properties of the objects would affect the set of possible spatial relationships that
can exist between them. For example, if one object is a solid object and the other is permeable, there cannot be any intersection of the inside of the solid object with any other component of the other object. Also, objects of different size or shape cannot be involved in certain spatial relations such as equal or contain between the smaller and the larger object.

The example in figure 5 demonstrates the six possible spatial relations that can exist between two solid objects, one having the shape of a convex region and the other a concave one along with their intersection matrices. The example can be used to represent many situations, for example, a solid object falling into a container full of liquid, a ball thrown into a net, or a ship entering a bay of an island, etc. Note that since object $y$ is a solid object, the component $y_2$ will always have only one intersection relation with $x_0$.

2.2. The General Reasoning Formalism

The reasoning approach consists of: a) general constraints to govern the spatial relationships between objects in space, and b) general rules to propagate relationships between the objects.
2.2.1. General Constraints

The intersection matrix is in fact a set of constraints whose values identify specific spatial relationships. For example, part of the constraints used to represent the relationship in figure 3(a) are \( x_1 \cap y_1 = 0, x_1 \cap y_2 = 0, x_1 \cap y_3 = 0, x_1 \cap y_4 = 1, \cdots \)

The process of spatial reasoning can be defined as the process of propagating the constraints of two spatial relations (for example, \( R_1(A, B) \) and \( R_2(B, C) \)), to derive a new set of constraints between objects. The derived constraints can then be mapped to a specific spatial relation (i.e. the relation \( R_3(A, C) \)).

A subset of the set of constraints defining all spatial relations are general and are applicable to any relationship between any objects. These general constraints are a consequence of the initial assumptions used in the definition of the object and space topology. The identification of these constraints complements the reasoning rules and shall be used later in the paper to give some insight in the propagation of spatial relations.

The two general constraints are:

1. Every unbounded (infinite) component of one space must intersect with at least one unbounded (infinite) component of the other space.

   Intuitively this rule says that it is impossible for an infinite component in the space to only have an intersection with finite component(s). In this case the infinite component becomes a subset of the finite component(s) which is not possible. In figure 5, \( x_0 \) and \( y_0 \) always have a non-empty intersection.

2. Every component from one space must intersect with at least one component from the other space.

   If one component of one space does not intersect with any component of the other space, either the two spaces are not equal or the spaces are not dense or connected. Both conditions are excluded by the initial assumptions. This implies that there cannot exist a row or a column in the intersection matrix whose elements are all empty intersections, hence the combinatorial cases in the matrix where this case exists can be ignored.

2.2.2. General Reasoning Rules

Composition of spatial relations is the process through which the possible relationship(s) between two object \( x \) and \( z \) is derived given two relationships: \( R_1 \) between \( x \) and \( y \) and \( R_2 \) between \( y \) and \( z \). Two general reasoning rules for the propagation of intersection constraints are presented. The rules are characterized by the ability to reason over spatial relationships between objects of arbitrary complexity in any space dimension. These rules allow for the automatic derivation of the composition (transitivity) tables between any spatial shapes \(^{10,2}\).

Reasoning Rules

Composition of spatial relations using the intersection representation approach is based on the transitive property of the subset relations. In what follows the following subset notation is used. If \( x' \) is a set of components (set of point-sets)
\{x_1, \ldots, x_m\} in a space X, and y_j is a component in space Y, then \( \subseteq \) denotes the following subset relationship.

- \( y_j \subseteq x' \) denotes the subset relationship such that: \( \forall x_i \in x' (y_j \cap x_i \neq \phi) \land y_j \cap (X - x_1 - x_2 \cdots - x_m) = \phi \) where \( i = 1, \ldots, m' \). Intuitively, this symbol indicates that the component \( y_j \) intersects with every set in the collection \( x' \) and does not intersect with any set outside of \( x' \).

If \( x_i \), \( y_j \) and \( z_k \) are components of objects \( x \), \( y \) and \( z \) respectively, then if there is a non-empty intersection between \( x_i \) and \( y_j \), and \( y_j \) is a subset of \( z_k \), then it can be concluded that there is also a non-empty intersection between \( x_i \) and \( z_k \).

\[
(x_i \cap y_j \neq \phi) \land (y_j \subseteq z_k) \rightarrow (x_i \cap z_k \neq \phi)
\]

This relation can be generalized in the following two rules. The rules describe the propagation of intersections between the components of objects and their related spaces involved in the spatial composition.

**Rule 1: Propagation of Non-Empty Intersections**

Let \( x' = \{x_1, x_2, \ldots, x_m\} \) be a subset of the set of components of space \( X \) whose total number of components is \( m \) and \( m' \leq m; x' \subseteq X \). Let \( z' = \{z_1, z_2, \ldots, z_n\} \) be a subset of the set of components of space \( Z \) whose total number of components is \( n \) and \( n' \leq n; z' \subseteq Z \). If \( y_j \) is a component of space \( Y \), the following is a governing rule of interaction for the three spaces \( X \), \( Y \) and \( Z \).

\[
(x' \supseteq y_j) \land (y_j \subseteq z') \rightarrow (x' \cap z' \neq \phi)
\]

\[
\equiv (x_1 \cap z_1 \neq \phi \lor \cdots \lor x_1 \cap z_n' \neq \phi) \land (x_2 \cap z_1 \neq \phi \lor \cdots \lor x_2 \cap z_n' \neq \phi) \land \cdots \land (x_m' \cap z_1 \neq \phi \lor \cdots \lor x_m' \cap z_n' \neq \phi)
\]

The above rule states that if the component \( y_j \) in space \( Y \) has a positive intersection with every component from the sets \( x' \) and \( z' \), then each component of the set \( x' \) must intersect with at least one component of the set \( z' \) and vice versa.

The constraint \( x_i \cap z_1 \neq \phi \lor x_i \cap z_2 \neq \phi \cdots \lor x_i \cap z_n' \neq \phi \) can be expressed in the intersection matrix by a label, for example the label \( a_r \) \( (r = 1 \text{ or } 2) \) in the following matrix indicates \( x_1 \cap (z_2 \cup z_4) \neq \phi \) \((x_1 \) has a positive intersection with \( z_2 \), or with \( z_4 \) or with both). A – in the matrix indicates that the intersection is either positive or negative.

\[
\begin{array}{cccccccc}
  & z_1 & z_2 & z_3 & z_4 & \cdots & z_n \\
x_1 & - & a_1 & - & a_2 & - & - \\
\end{array}
\]

Rule 1 represents the propagation of non-empty intersections of components in space. A different version of the rule for the propagation of empty intersections can be stated as follows.

**Rule 2: Propagation of Empty Intersections**
Let \( z' = \{ z_1, z_2, \ldots, z_{n'} \} \) be a subset of the set of components of space \( Z \) whose total number of components is \( n \) and \( n' < n \); \( z' \subset Z \). Let \( y' = \{ y_1, y_2, \ldots, y_{l'} \} \) be a subset of the set of components of space \( Y \) whose total number of components is \( l \) and \( l' < l \); \( y' \subset Y \). Let \( x_i \) be a component of the space \( X \). Then the following is a governing rule for the spaces \( X, Y \) and \( Z \).

\[
(x_i \subseteq y') \land (y' \subseteq z') \rightarrow (x_i \cap (Z - z_1 - z_2 \cdots - z_{n'}) = \phi)
\]

Remark: if \( n' = n \), i.e. \( x_i \) may intersect with every element in \( Z \), then no empty intersections can be propagated. Rules 1 and 2 are the two general rules for propagating empty and non-empty intersections of components of spaces.

Note that in both rules the intermediate object \( (y) \) and its space components play the main role in the propagation of intersections. Indeed, it shall be shown in the next example how the first rule is applied a number of times equal to the number of components of the space of the intermediate object. Hence, the composition of spatial relations using this method becomes a tractable problem which can be performed in a defined limited number of steps.

**Soundness and Completeness of the Reasoning Rules**

Applying the reasoning rules over relations between objects \( x \) and \( y \) and \( y \) and \( z \) results in an intersection matrix between objects \( x \) and \( z \). Values of elements in the result matrix will be either 0 or 1 or \(-\) (indicating an indefinite intersection of 0;1). These values are the result of the following conditions:

\begin{align*}
\text{a. } x_i \cap z_k &= 1 \text{ if } x_i \cap y_j = 1 \land y_j \cap z_k = 1 \land (x_i \supseteq y_j \lor y_j \subseteq z_k). \\
\text{b. } x_i \cap z_k &= 0 \text{ if } (x_i \cap y_j = 0 \land y_j \supseteq z_k) \lor (x_i \subseteq y_j \land y_j \cap z_k = 0). \\
\text{c. } x_i \cap z_k &= - \text{ if } x_i \cap y_j = 1 \land y_j \cap z_k = 1 \land (y_j \not\subseteq x_i \land y_j \not\subseteq z_k).
\end{align*}

I. If the formalism is not sound then one or more of the values in the derived matrix will be incorrect. A value of 1 or 0 or \(-\) will be driven instead of 0 or 1 or (either 0 or 1) respectively. From the above three conditions, this is true if:

- the entries of the original matrices are wrong, for example, \( x_i \cap y_j = 1 \) instead of 0 and vice versa.
- the intermediate space \( Y \) is not dense or the three space \( X, Y \) and \( Z \) are not equal, for example space \( Y \) is smaller than spaces \( X \) or \( Z \), (i.e. \( x_i \subseteq y_j \) is wrongly interpreted).

The latter problem contradicts the original assumptions while the former one can result from an initial error in the initial intersection matrix.

II. If the formalism is not complete then one or more values in the derived matrix will have a definite value of 0 or 1 instead of an indefinite value of \(-\). Again this is possible only if,

- the entries of the original matrices are wrong, for example \( x_i \cap y_j = 0 \) instead of 1.
The intermediate space \( Y \) is not dense or spaces \( X, Y \) and \( Z \) are not equal.

Similar to the above this problem contradicts the original assumptions or an indication of initial errors in the initial intersection matrix.

### 2.3. Example of Spatial Reasoning with Complex Objects

The example in figure 6 is used for demonstrating the composition of relations using non-simple spatial objects. Figure 6(a) shows the relationship between a concave region \( x \) and a region with a hole \( y \) and 6(b) shows the relationship between object \( y \) and a simple convex region \( z \) where \( z \) touches the the hole in \( y \). The intersection matrices corresponding to the two relationships are also shown.

Given that the possible set of relationships that can occur between \( x \) and \( z \) in a certain domain are as shown in figure 5, it is required to derive the possible relationships between these two objects given the situation in figure 6.

The reasoning rules are used to propagate the intersections between the components of objects \( x \) and \( z \) as follows. From rule 1 we have,

- \( y_0 \) intersections:
  \[
  \{x_0, x_1, x_2, x_3\} \supseteq y_0 \quad \land \quad y_0 \subseteq \{z_0\}
  \rightarrow
  x_0 \cap z_0 \neq \phi \land x_1 \cap z_0 \neq \phi
  \land
  x_2 \cap z_0 \neq \phi \land x_3 \cap z_0 \neq \phi
  \]
• $y_1$ intersections:

$$\{x_0, x_3\} \supseteq y_1 \wedge y_1 \subseteq \{z_0\} \rightarrow x_1 \cap z_0 \neq \emptyset \wedge x_3 \cap z_0 \neq \emptyset$$

• $y_2$ intersections:

$$\begin{align*}
\{x_0, x_3\} &\supseteq y_2 \wedge y_2 \subseteq \{z_0, z_1, z_2\} \\
&\rightarrow x_0 \cap (z_0 \cup z_1 \cup z_2) \neq \emptyset \\
&\wedge x_3 \cap (z_0 \cup z_1 \cup z_2) \neq \emptyset
\end{align*}$$

• $y_3$ intersections:

$$\begin{align*}
\{x_3\} &\supseteq y_3 \wedge y_3 \subseteq \{z_0, z_1\} \\
&\rightarrow x_3 \cap z_0 \neq \emptyset \wedge x_3 \cap z_1 \neq \emptyset
\end{align*}$$

• $y_4$ intersections:

$$\begin{align*}
\{x_3\} &\supseteq y_4 \wedge y_4 \subseteq \{z_0\} \\
&\rightarrow x_3 \cap z_0 \neq \emptyset
\end{align*}$$

Applying rule 2 we get the following,

• $x_0 \subseteq \{y_0, y_1, y_2\} \wedge \{y_0, y_1, y_2\} \subseteq \{z_0, z_1, z_2\}$

$x_0$ has no empty intersections with components in $Z$.

• $x_1 \subseteq y_0 \wedge y_0 \subseteq \{z_0\} \rightarrow x_1 \cap z_1 = \emptyset \wedge x_1 \cap z_2 = \emptyset$

• $x_2 \subseteq y_0 \wedge y_0 \subseteq \{z_0\} \rightarrow x_2 \cap z_1 = \emptyset \wedge x_2 \cap z_2 = \emptyset$

• $x_3 \subseteq \{y_0, y_1, y_2, y_3, y_4\} \wedge \{y_0, y_1, y_2, y_3, y_4\} \subseteq \{z_0, z_1, z_2\}$

$x_3$ has no empty intersections with components in $Z$.

Refining the above constraints, we get the following intersection matrix.

<table>
<thead>
<tr>
<th></th>
<th>$z_0$</th>
<th>$z_1$</th>
<th>$z_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_0$</td>
<td>1</td>
<td>-</td>
<td>$a_1$</td>
</tr>
<tr>
<td>$x_1$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$x_2$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$x_3$</td>
<td>1</td>
<td>1</td>
<td>$a_2$</td>
</tr>
</tbody>
</table>

Comparing the resulting matrix above with the matrices in figure 5, it can be seen that the result matrix corresponds to two possible relationships between objects $x$ and $z$, namely the relationships $R_3$ and $R_5$.

A different conclusion is obtained if the relationship between objects $y$ and $z$ is as shown in figure 7(a). The composition of the relationships between $x$, $y$ and $z$ in this case will result in the definite matrix in figure 7(b) which corresponds to $R_5$ in figure 5.

2.4. Reasoning between Object with Different Dimensions

Spatial reasoning is needed between spatial objects of different dimension and not only between objects with similar dimension. The set of valid relations between
Figure 7: Given the relationship between objects $x$ and $y$ as in figure 6(a) and (c) and the relation between the objects $y$ and $z$ as defined in (a) in this figure the composition shall result in the definite intersection matrix between $x$ and $z$ shown in (b).

Figure 8: Relationships between object with different dimension.
regions and between lines and regions have been identified\textsuperscript{11}. As an example of reasoning between regions and lines is shown in figure 8. The matrices for the relations in the figure are as follows.

\[
R(x, z) = \begin{bmatrix}
y_0 & y_1 & y_2 \\
x_0 & 1 & 1 & 1 \\
x_1 & 0 & 0 & 1 \\
x_2 & 0 & 0 & 1
\end{bmatrix} \quad \circ \quad \begin{bmatrix}
z_0 & z_1 & z_2 & z_3 \\
y_0 & 0 & 0 & 0 \\
y_1 & 1 & 1 & 1 \\
y_2 & 1 & 0 & 0 & 1
\end{bmatrix}
\]

From rule 1 we have,

- \(y_0\) intersections:

\[
\{x_0\} \sqsupseteq y_0 \quad \land \quad y_0 \sqsubseteq \{z_3\} \\
\Rightarrow x_0 \cap z_3 \neq \phi
\]

- \(y_1\) intersections:

\[
\{x_0\} \sqsupseteq y_1 \quad \land \quad y_1 \sqsubseteq \{z_0, z_1, z_2, z_3\} \\
\Rightarrow x_0 \cap z_0 \neq \phi \land x_0 \cap z_1 \neq \phi \\
\land \quad x_0 \cap z_2 \neq \phi \land x_0 \cap z_3 \neq \phi
\]

- \(y_2\) intersections:

\[
\{x_0, x_1, x_2\} \sqsupseteq y_2 \quad \land \quad y_2 \sqsubseteq \{z_0, z_1\} \\
\Rightarrow x_0 \cap (z_0 \cup z_3) \neq \phi \\
\land \quad x_1 \cap (z_0 \cup z_3) \neq \phi \\
\land \quad x_2 \cap (z_0 \cup z_3) \neq \phi
\]

Applying rule 2 we get the following,

- \(x_1 \sqsubseteq \{y_2\} \quad \land \quad \{y_2\} \sqsubseteq \{z_0, z_3\} \Rightarrow x_1 \cap \{z_1 \cap z_2\} = \phi\)

- \(x_2 \sqsubseteq y_2 \quad \land \quad y_2 \sqsubseteq \{z_0, z_1\} \Rightarrow x_2 \cap \{z_1 \cap z_2\} = \phi\)

Refining the above constraints, we get the following intersection matrix.

\[
\begin{array}{cccc}
z_0 & z_1 & z_2 & z_3 \\
x_0 & 1 & 1 & 1 & 1 \\
x_1 & 0 & 0 & a_2 \\
x_2 & b_1 & 0 & 0 & b_2
\end{array}
\]

The matrix represents the possible relations in figure 9. The formalism was used to derive the full composition table between two regions and a region and a non-directed line. The full table is given in the appendix. The table shows the conceptual neighbourhood phenomenon observed by Freksa\textsuperscript{12}, namely that in the case of indefinite composition the disjunctive set of relations are conceptual neighbours.

Note that in the above example a directed line is used, with two different end points in this case, the result of the reasoning are the same if a non-directed line
Figure 9: Possible relations resulting from the composition in figure 8.

was used. This is due to that the components $z_1$ and $z_2$ always have a non-empty intersection with $x_0$ only.

3. Applications

In this section the generality of the formalism is demonstrated by using it to offer explanations to some aspects in qualitative reasoning and by applying it to the order domain.

3.1. Definite and Indefinite Compositions

As seen from the previous example and from the composition table in the appendix, indefinite compositions are those where the the result of the spatial reasoning problem is a set of disjunctive spatial relations as opposed to one definite relation. On the other hand definite compositions result in only one relation. In fact in composition tables, which hold the results of reasoning between all the possible set of relations between the concerned objects, many of the entries are disjunctive sets of spatial relations. If $m'$ and $n'$ are the number of components of the sets $x'$ and $z'$ respectively and $m$ and $n$ are the total number of components of the spaces $X$ and $Z$ respectively and $x' \subseteq X$ and $z' \subseteq Z$. Using Rule 1 ($(x' \supseteq y_j) \land (y_j \subseteq z') \rightarrow (x' \cap z' \neq \phi)$), the composition of relations can be classified into the following.

I. If $(m' = 1 \lor n' = 1)$, then the rule shall propagate a definite set of intersections. For example, if $y_j$ intersects the only element of $x'$, then this element of $x'$ must have a non-empty intersection with every element from the set $z'$. Also, if $y_j$ intersects with the only element of $z'$, then this element of $z'$ must have a non-empty intersection with every element from the set $x'$. If this property holds for every component of the intermediate space $Y$ then the composition must result in a definite relation. An example of this case is the composition of the inside relationship between two simple convex polygons: $inside(A, B) \land inside(B, C) \rightarrow inside(A, C)$

II. If $(m' > 1 \land n' > 1)$, for at least one $y_j$ of the space $Y$ no definite intersections are propagated (i.e. $x' \cap z' \neq \phi$). If after the application of the reasoning rules this result still holds, then the composition shall produce a non-definite set of disjunctive relations.
III. If \((m' = m \land n' = n)\), i.e. \((X \sqsupseteq y_j) \land (y_j \sqsubseteq Z)\), no distinguishing constraints can be propagated from the component \(y_j\), as this case is an expression of the first general constraint in section . Also since the implication of such constraint is that every component of one space may intersect with all the components of the other space no empty intersection will be propagated (using rule 2) for any component.

IV. If \((m' = 1 \land n' = 1 \land x' = \{x_0\} \land z' = \{z_0\})\), i.e. \(x'\) is the infinite component and \(z'\) is the infinite component, then the rule becomes an expression of the second general constraint in section , i.e. no distinguishing constraint will be propagated.

V. If all the propagated intersections for the set of components of the intermediate space are either of type 3 or 4 above then the composition results in the universal relation (disjunction of set of all possible relationships) - since the only constraints propagated are the general ones, i.e no specific constraint propagated. An example is the compositions: \(\text{overlap}(A, B) \land \text{overlap}(B, C)\) and \(\text{disjoint}(A, B) \land \text{disjoint}(B, C)\) for two simple convex polygons.

### 3.2. Conceptual Neighbourhood

An observation made by Freksa \(^{14}\) on the temporal composition table derived by Allen \(^5\) is that the table entries which are a disjunctive set of relations are always sets of relations which are conceptual neighbors. “Two relations between pairs of events are conceptual neighbors if they can be directly transformed into one another by continuous deformation (i.e., shortening or lengthening) of the events \(^{12}\)”. The same observation was made for the composition tables derived in the spatial domain \(^{12}\) and this property was utilized in making the reasoning process more efficient.

However, there was no explanation on why this phenomenon occurs \(^3\).

In this section the reasoning formalism developed shall be used to give an explanation on phenomenon of the conceptual neighbourhood. The main condition for conceptual neighbourhood relations can be defined in terms of component intersection. Conceptual neighbour relations are created by continuous deformation of one object (shortening or lengthening) \(^{12}\). When an object is deformed while in contact with another object one or more of its components moves into neighbouring (adjacent) components of the other object. In a dense connected space if a component \(x_1\) of object \(x\) has a non-empty intersection with a component \(y_1\) from object \(y\), when object \(x\) is deformed (or moved) and if such deformation involves the component \(x_1\), then \(x_1\) has to intersect with other components of \(y\), for example \(y_2\), such that \(y_2\) is connected to \(y_1\). Thus, conceptual neighbourhood are characterized as follows: the union of the components that a specific component intersect with in both relations from the same object will be connected as defined by the adjacency matrix or else the continuity of the deformation is lost (i.e. non conceptual neighbours). I.e. if \(R_1(x, y)\) and \(R_2(x, y)\) are conceptual neighbours then if in \(R_1\), \(x_1 \cap y_1 = 1\) and in \(R_2\), \(x_1 \cap y_2 = 1\) then \(y_1\) and \(y_2\) must be connected in the adjacency matrix.
The initial assumptions of our formalism states that all the components of the objects and the space are dense and connected. From rule 1, if \( y_j \subseteq x' \) and \( x' = (x_1 \cup x_2) \) then \( x'_1 \subseteq x_1 \) and \( x'_2 \subseteq x_2 \) are the two sets of points that intersect with the point set \( y_j \), i.e. \( y_j = (x'_1 \cup x'_2) \).

In 15 connectedness is defined as follows: a topological space is separated if it is the union of two disjoint non-empty open sets and a space is connected it is is not separated. From the above if \( x'_1 \) does not connect to \( x'_2 \) then \( x'_1 \cup x'_2 \) is separated, i.e. \( y_j \) is separated. Since \( y_j \) is connected (by assumption) then \( x'_1 \) and \( x'_2 \) are connected, and hence \( x_1 \) and \( x_2 \) are also connected. The same applies to \( y_j \subseteq z' \), and hence the elements of \( z' \) are connected. Since \( x' \supseteq y_j \land y_j \subseteq z' \rightarrow x' \cap z' \neq \emptyset \), then any element of \( x' \) can intersect with connected elements of \( z' \) and vice versa. For example, if \( x' = x_1 \cup x_2 \) and \( z' = z_1 \cup z_2 \) then \((x_1 \cap z_1 \neq \emptyset \lor x_1 \cap z_2 \neq \emptyset)\), i.e. \( x_1 \) may intersect with connected components, which will result in a disjunctive set of conceptual neighbourhood relations.

The following example illustrates the above argument. Consider the composition of the relationships between simple convex regions in Figure 10. By applying the reasoning rules we have that \( x_1 \cap (z_1 \cup z_2) \neq \emptyset \) \( z_1 \) is connected to \( z_2 \) and thus the possible relationships from this composition are conceptual neighbors as shown in the figure.

Thus if any component of the intermediate space \( (y_j) \) is not connected the composition does not guarantee that the resulting relations from the composition are conceptual neighbours. Bennett 3 gave an example for a discontinuous composition.

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Figure 10: (a) \( x \) covers \( y \) and \( y \) covers \( z \), (b) Result of the composition.
Figure 11: Discontinuous composition due to disconnected components [Bennet-94].

\[
\begin{array}{ccc}
  & f & \\
0 & 1 & f \\
1 & 0 & t \\
0 & 0 & s \\
0 & 0 & 0 & p_0 \\
\end{array}
\]

Figure 12: a) An event, b) representation of the event by adjacency matrix.

which falls into the last category, see figure 11. In the figure, the two concave cavities in the intermediate space $B$ are not connected, yet are treated implicitly as one component. If we consider the two cavities as two components, then the relation between $C$ and $B$ ($c_1 \lor c_2$) will then become a disjunctive set of disjoint relations. This is the only other possibility for discontinuous composition. As can be easily recognized, the two possibilities can be mapped into one another by changing object composition. Note that if the three objects $A$, $B$ and $C$ were three dimensional objects with the two cavities now forming one connected path (for example, object $B$ represents two wheels connected by a shaft) it can be intuitively seen that the discontinuity in the resulting composition no longer exist since no separated component is considered.

3.3. Applying the Reasoning Formalism to Temporal Relations

The reasoning formalism can be applied to order relations by considering a 1D space where the object (or value) divides that space into two semi-infinite lines, one representing all objects (values) with the relation $<$ and the other for values $>$. In the temporal domain (an order domain), consider an event $e$ in an event space $E$ as shown in figure 12. $e$ can be decomposed into the following components: $s$: its start, $f$: its finish, $t$: its duration. The event space $E$ is composed of $e$ and $p_0$: a semi-infinite line representing the past of $e$ and $f_0$: a semi infinite line representing the future of $e$. The connectivity matrix for $E$ is as shown in figure 12(b).

Relationship between two events can be represented by an intersection matrix. For example the overlap relationship in figure 13 can be represented by the matrix in the same figure. Both the general space constraints in section are also applicable in the temporal domain. In the above example, $f_{01} \cap f_{02} \neq \emptyset$ and $p_{01} \cap p_{02} \neq \emptyset$, i.e.
the future as well as the past of any two events must intersect. The analysis of indefinite and definite intersections given earlier is also applicable here. For example, if during(A, B) and during(C, B), then all the components of B either intersect only with the futures or pasts of both A and C or with every component in A and C, i.e. propagates only the two general constraints and hence result in the universal relation. The explanation of conceptual neighbourhood is also applicable in the temporal domain. The two reasoning rules proposed are also applicable in the temporal domain. For example, consider the composition of the two relationships: overlap(e1, e2) and overlap(e2, e3) as shown in figure 13. Applying the two reasoning rules over the above matrices as in section, we get the result matrix in figure 14 which can corresponds to one of the three relations shown in the figure.

4. Approaches to Spatial Reasoning

The formalism proposed in this paper was shown to be applicable to reasoning over topological as well as order relations between complex objects. Approaches to spatial reasoning in the literature can generally be classified into a) using transitive propagation and b) using theorem proving.

- Transitive propagation: In this approach the transitive property of some spatial relations is utilized to carry out the required reasoning. This applies to the order relations, such as before, after and (<, =, >) (for example, a < b ∧ b < c → a < c), and to the subset relations such as contain and inside (for example, inside(A, B) ∧ inside(B, C) → inside(A, C), east(A, B) ∧ east(B, C) → east(A, C)).

Transitive property of the subset relations was employed by Egenhofer for reasoning over topological relationships. Transitive property of the order rela-

\[\begin{array}{cccccc}
\text{f}_{01} & \text{f}_1 & t_1 & s_1 & p_{01} \\
\text{f}_{02} & 1 & 0 & 0 & 0 & 0 \\
\text{f}_2 & 1 & 0 & 0 & 0 & 0 \\
s_2 & 1 & 1 & 1 & 0 & 0 \\
p_{02} & 0 & 0 & 1 & 1 & 1 \\
\text{f}_{03} & 1 & 0 & 0 & 0 & 0 \\
\text{f}_3 & 1 & 0 & 0 & 0 & 0 \\
t_3 & 1 & 1 & 1 & 0 & 0 \\
s_3 & 0 & 0 & 1 & 0 & 0 \\
p_{03} & 0 & 0 & 1 & 1 & 1 \\
\end{array}\]
Figure 14: Result of the composition in figure 13 is a set of disjunctive relations \( \text{before}(e_1, e_3) \lor \text{meet}(e_1, e_3) \lor \text{overlap}(e_1, e_3) \).

Order in Space...

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Tions has been utilized by Mukerjee & Joe\(^{17}\), Guesgen\(^4\), Chang & Lu\(^{18}\), Lee & Hsu\(^{19}\) and Papadias & Sellis\(^{20}\). Although order relations can be utilized in reasoning over point-shaped objects, they cannot be directly applied when the actual shapes and proximity of objects are considered.

- Theorem proving (elimination): where reasoning can be carried out by checking every relation in the full set of sound relations in the domain to see whether it is a valid consequence of the composition considered (theorems to be proved) and eliminating the ones which are not consistent with the composition\(^21\).

Bennett\(^{16}\) have proposed a propositional calculus for the derivation of the composition of topological relations between simple regions using this method. However, checking each relation in the composition table to prove or eliminate is not possible in general cases and is considered a challenge for theorem provers\(^2\).

In general the limitation of all the methods in the above two approaches are as follows:

- Spatial reasoning is studied only between objects of similar types, e.g. between two lines or two simple areas. Spatial relations exist between objects of any type and it is limiting to consider the composition of only specific object shapes.

- Spatial reasoning was carried out only between objects with the same dimension as the space they are embedded in, e.g. between two lines in 1D, between
two regions in 2D, etc.

- Spatial reasoning is studied mainly between simple object shapes or objects with controlled complexity, for example, regions with holes treated as concentric simple regions. No method has yet been presented for spatial reasoning between objects with arbitrary complexity.

The method proposed here is simple and general - only two rules are used to derive composition between objects of random complexity and is applicable to different types of spatial relations (topological and order).

5. Conclusions

A general approach for spatial reasoning is proposed. The approach consists of a set of two general constraints to govern the spatial relationships between objects in space, and two general rules to propagate relationships between objects in space. The following conclusions may be drawn:

- The reasoning process is general and can be applied on any types of objects with random complexity.

- The approach is simple and is based on the application of two rules for the propagation of empty and non-empty intersections between object components.

- The approach is based on a uniform representation of the topology of the space as a connected set of components. A structure called adjacency matrix is proposed to capture the topology of objects of different complexity in any space dimension.

A classification is given of the conditions where definite and indefinite compositions result. The reasoning method was used to explain the phenomenon of the conceptual neighbourhood. The approach was shown to be applicable to the representation and reasoning over events in the temporal domain. Finally, the method is applied in a finite known number of steps (equal to the number of components of the intermediate objects) which allows its implementation in spatial information systems.

References


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Table 1: The composition table between two regions and a region and a line. The numbers in the table correspond to relations $R_1$ to $R_{19}$ between a region and a line.