

## Spatial Reasoning for Information Brokering

H. Stuckenschmidt, C. Schlieder, U. Visser, T. Vögele, H. Neumann

Intelligent Systems Group  
Center for Computing Technologies  
University of Bremen  
P.O.B.: 33 04 40, D-28334 Bremen  
Tel.: +49 421 218 7090, Fax: +49 421 218 7196  
E-Mail: {heiner, cs, visser, vögele, neumann}@tzi.de

### Abstract

The World Wide Web provides new opportunities for collecting information from distributed, multiple, and heterogeneous data sources. Information brokering can be used to provide coordinated access to these sources if they are structured or semi-structured. The BUSTER (Bremen University Semantic Translator for Enhanced Retrieval) approach provides enabling technologies for information search and integration and can be seen as an information broker. However, it is not possible to represent and reason about spatial objects. In this paper, we motivate the need for the integration of spatial representation and reasoning and propose an extension of the approach. We discuss approaches for spatial representations. We conclude with a new concept for an extension of BUSTER with explicit representations of spatial concepts and reasoning mechanisms that can be applied in order to support spatial information brokering.

**Keywords:** Spatial Representation and Reasoning, Spatial Queries, Metadata, Information Brokering

### Introduction

The rapid growth of the World Wide Web and its information sources too frequently the finding and accessing of information sources is difficult and time-consuming. This leads to a situation where technical, structural and semantic problems arise from the fact that the information is distributed, multiple, and heterogeneous and often without structure. Furthermore, even semi-structured data such as HTML pages and structured data such as relational bases raise computational difficulties (i.e. context-dependency).

### The Need for Information Brokering

An information brokering system can be used to provide coordinated access to heterogeneous, structured and semi-structured sources. Levine (Levine 1995) gives an overview of information brokering which tracks the modern origin to a French organization supplying "information on demand" per phone in 1935. Modern

opinions redefine the term information brokering and refer to the process of collecting and re-distribution of information (i.e. (Levy, Srivastava, & Kirk 1995); (Fikes, Farquhar, & Pratt 1996); (Martin *et al.* 1997)). However, our problem of finding information that include the appropriate sources relevant to the user, terming and formulating queries understandable to source, interpreting the retrieved information and then integrating the collected information into a coherent answer still exists.

In systems with a large number of available data sources, it is often not trivial to find the right set of data for a given task. If, for example, an information request is submitted to an information broker, the broker has to decide which of the registered sources it should use to answer the request. The BUSTER approach addresses this problem by providing a common interface to heterogeneous information sources in terms of an intelligent information broker (<http://www.semantic-translation.de>). A user can submit a query request to the network of integrated data sources. In this query phase several components of different levels interact.

Metadata, i.e. data describing a data source, are often used to organize and manage large collections of data sources. Typically, such metadata catalogues are based on standardized meta data formats like the Dublin Core. In the BUSTER approach, each data source is represented by a specific ontology, the so-called source ontology (Visser *et al.* 2001). It contains an explicit description of the concepts covered by the data source, together with information about the structural and syntactic details of the data source. User queries are matched against different source ontologies. If the matching succeeds, the broker establishes a connection to the actual information source. If the matching fails, the broker decides that there is no valuable information available and tries different information sources (Vögele, Stuckenschmidt, & Visser 2000)

In this paper we will concentrate on the process of

Copyright © 2001, American Association for Artificial Intelligence (www.aaai.org). All rights reserved.

finding information. We start with a description of the current implementation of the BUSTER system and its abilities in terms of locating information and performing information integration on the structural level. We argue for the need of complex spatial queries and briefly review general approach to spatial representation. Based on this description we develop a framework for the representation of spatial knowledge that allows to process complex queries for spatial objects and sketch the reasoning process using a didactic example. We conclude with summarizing the proposed solution and pointing out to areas of further research.

## Querying Spatially Related Objects

In its current state, the BUSTER system allows us to retrieve information in terms of concept descriptions that are matched against an explicit model of information contained in an information source. The OIL language (Fensel *et al.* 2000) that is used in the system can be used to state complex concept expressions containing logical operators and restrictions on the properties of a concept to be retrieved. If we are only concerned with thematic information this matching process is a powerful tool for information retrieval. Concerning spatially related concepts, however, things become difficult.

When concerned with spatially related data, we are not only interested in the type of an information item that can be defined using OIL, but we also want to restrict the spatial dimension. A straightforward way to include the spatial dimension is to ask for instances of a certain type that can be found at a certain location. Such queries have the following structure:

concept @ location

As already mentioned above, the OIL language allows us to describe and reason about indirect notions of concepts in terms of concept expressions that are matched against descriptions of information sources. We claim that we also need the possibility to refer to locations in terms of spatial expressions that reduce the set of possible locations without restricting the search to a single location. Current approaches for retrieving location (i.e. gazeteers) are not able to reason about complex spatial expressions (compare (Schlieder, Vögele, & Visser 2001)).

## Levels of spatial abstraction

Techniques for representing spatial information have been studied thoroughly by AI research on qualitative spatial reasoning (see (Cohn 1997) for an overview). A basic insight from this line of research is that efficient spatial problem-solving relies on abstracting from spatial detail. Three levels of spatial abstraction can be distinguished according to the degree by which the spatial position is determined: topological, ordinal and metrical information.

**Topological information** Spatial properties that stay invariant under the most general group of spatial transformations, namely homomorphisms (intuitively: rubber-sheet distortions), convey topological information. A connected region, for instance, remains connected under these transformations. In other words: connectedness constitutes a topological property of regions. Among the different systems of spatial relations proposed for encoding topological information, the most widely used in GIS applications is a system of eight relations which was described in (Egenhofer 1991) and given a logical formalization by Randell, Cui and Cohn (Randell, Cui, & Cohn 1992). It is known as the region connection calculus RCC-8 and can express facts such as "region A touches region B", or "region A lies within region B".

**Ordinal information** The fact that a region is convex constitutes a piece of ordinal information about the regions shape. Convexity is neither preserved under topological transformations nor does it imply any metrical properties. In other words, ordinal information provides an intermediate level of abstraction between topological and metrical information. Systems of ordinal relations describe the location of points with respect to reference systems consisting of directed lines. A typical example is the system of cardinal directions north-west-south-east which locates a point with respect to another point by means of an absolute reference system (Frank 1992). Often, a relative reference system is needed which yields descriptions of spatial positions that are rotation-invariant. Examples of such systems are the line segment relations (Schlieder 1995) or the panorama representation (Rougemont & Schlieder 1997).

**Metrical information** Distances or angles are metrical invariants. Generally, metrical invariants are measures, i.e. they can be expressed by real numbers that obey certain mathematical criteria. Nevertheless, it is often necessary to abstract qualitatively even from metrical information. In natural language, adverbs such as "close" or "far" are frequently used to express distance information. Several systems of qualitative distance relations have been proposed which can be used to represent the semantics of linguistic expressions (e.g. (Clementini, Felice, & Hernandez 1997)).

## Improving the BUSTER System

As we have seen above, to build truly expressive spatial queries as well as to annotate data sources in an intuitive way, we need constructs to describe

- partonomic relations,
- topological relations,
- relations of direction, and
- relations of distance

between spatial objects as well as Boolean combinations over these relations. In the following we introduce an approach to reasoning about these concepts. We evaluate our approach using the following example query that could be stated in connection with the planning of a holiday trip:

```
(and capital historic-place)
@
  (and (part-of western-europe)
    (or (connected-to mediterranean-sea)
      (connected-to north-sea))
    (not (north-of belgium))
    (next-to germany))
```

Intuitively, we search for information about historically interesting places that are capitals of a country. We further claim that these places have to be in a location (i.e. a country) that is part of western Europe either connected to the Atlantic Ocean or the North Sea. Further the location should not be north of Belgium. Of all these objects, we want to have the one that is next to Germany.

The conceptual part of the query can already be handled by the BUSTER system. Using a small ontology of cities and their attractions, we retrieve the following five cities: Amsterdam, Madrid, Paris, Rome and Lisbon. We have different options for implementing the retrieval process for the spatial part. A straightforward approach would be to encode spatial relations in the ontology and use the a reasoner for the spatial part. However, the language supported by this reasoner is not expressive enough to cover the axioms of a theory of space. In particular, it can only reason about general subset-relations without a notion of connectedness. The use of a more expressive logic, on the other hand, will lead to a reasoning complexity that is not acceptable for the retrieval process. Constraint-based approaches that are prominent in spatial reasoning also have problems with respect to this specific application. We argued (Schlieder, Vögele, & Visser 2001) that RCC-8 fails to capture relevant two-dimensional inferences, because the formalism does not encode spatial dimensions. We concluded that a diagrammatic reasoning approach (Glasgow, Narayanan, & Chandrasekaran 1995) is the most suitable for this kind of reasoning task. We therefore use a graph-based representation of space that can be derived from actual polygon data using computational geometry and apply graph algorithms for selecting interesting locations. In the following we present representation for the relations mentioned above and describe the reasoning process. Thereby we follow and extend the ideas described in (Schlieder, Vögele, & Visser 2001).

## Partonomies

In order to find a type of abstraction for describing partonomies, we take a look at different geometrical arrangement of polygons. In the following, polygons

are closed sets of points, i.e. edges and vertices belong to the polygon.

We consider polygons  $P_1, \dots, P_n$  that are contained in a part of the plane bounded by a polygon  $P$ . Two special types of arrangements of the polygons within the containing polygon  $P$  can be distinguished:

- In a *polygonal covering*  $P_1 \cup \dots \cup P_n = P$ . The polygons cover the containing polygon. In general, they will overlap.
- In a *polygonal patchwork* for all  $i \neq j$  from  $\{1, \dots, n\}$   $\text{interior}(P_i \cap P_j) = \emptyset$ . The polygons are either disjoint or intersect only in edges and/or vertices.
- A *polygonal tessellation* is a polygonal covering which also forms a polygonal patchwork.

Polygonal tessellations occur frequently: in a map of Germany, for instance, the federal states constitute a tessellation. Because of their importance, we will pay more attention to tessellations than to any other arrangement of spatial parts.

Partonomies are the result of recursively applying the standard part-of relation to describe parts of parts. Similarly, the polygons of a covering, patchwork or tessellation can contain other polygons. In analogy to partonomies we introduce decompositions which are defined recursively as hierarchical data structures for encoding the spatial part-of relation together with the type of arrangement of the parts.

By abstraction from the type of spatial arrangement one obtains the partonomy that underlies a decomposition. This partonomy is encoded by the *decomposition tree* which has the same nodes as the decomposition and whose edges denote the binary part-of relation between polygons (compare fig. 1).

In order to process the first part of the spatial expression, we have to check which of the cities that match the concept expressions lies in countries that belong to Western Europe. We decide this by consulting the decomposition graph which represents the tessellation. Figure 1 shows such a decomposition tree that shows the distinction between countries assumed to belong to Western Europe: Portugal (P), Spain (E), France (F), Luxembourg (L), Belgium (B) and the Netherlands (N). The other countries on the map are belong to Central Europe: Germany (G), Switzerland (S), Austria (A), Denmark (D) and Italy (I).

By simply following the arcs in the tree downwards starting at the node representing Western Europe, we find all countries that fulfill the requirements. As Rome lies in Italy that is defined to belong to Central Europe, we can exclude this city from the collection of possible solutions.

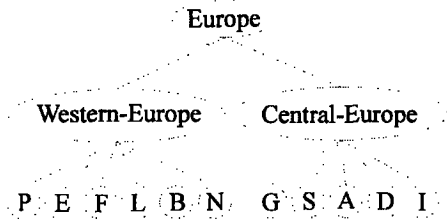


Figure 1: A decomposition tree for the tessellation

### Topology

A common way of representing the topology of a collection of polygons in a tessellation is a neighborhood graph. The neighborhood graph of a homogeneous decomposition by tessellation is a graph  $\mathcal{N} = (V, E)$  with the set of undecomposed polygons as nodes  $V$  and all pairs of neighboring polygons as edges  $E$ . If only the neighborhood graph is used, then the two arrangements of polygons shown below cannot be distinguished (fig. 2). Both have the same neighboring graph but they differ fundamentally with respect to neighborhood: neighbors of  $P_1$  and  $P_3$  can never be neighbors of  $P_2$  if the polygons are arranged as in (a) while they can be in the arrangement (b). The problem is linked to multiple neighborhoods, that is, the fact that in (a)  $P_1$  and  $P_3$  have two disconnected edges in common. Therefore, the qualitative representation of the decomposition should be able to encode multiple neighborhood relations between two polygons.

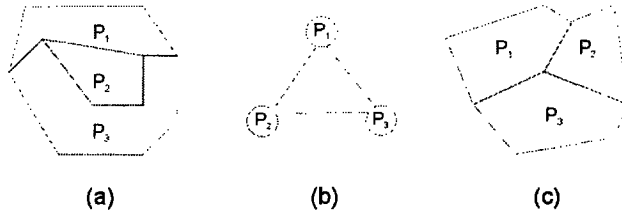


Figure 2: Multiple neighborhood relations

As solution to the problem of finding an adequate abstraction for a decomposition we propose to represent it by a connection graph. Figure 3 shows the connection graph  $Cof$  a homogeneous decomposition by tessellation  $D$ . Each polygon from  $D$  is represented by a vertex from  $C$ . In addition there is the node 1 representing the external polygonal region. The edges from  $C$  which are incident with a vertex are easily obtained together with their circular ordering by scanning the contour of the corresponding polygon. As the example shows, the connection graph is a multi-graph in which several edges can join the same pair of vertices, i.e. Spain has two connections with the Atlantic Ocean.

The connection graph can be used to process the

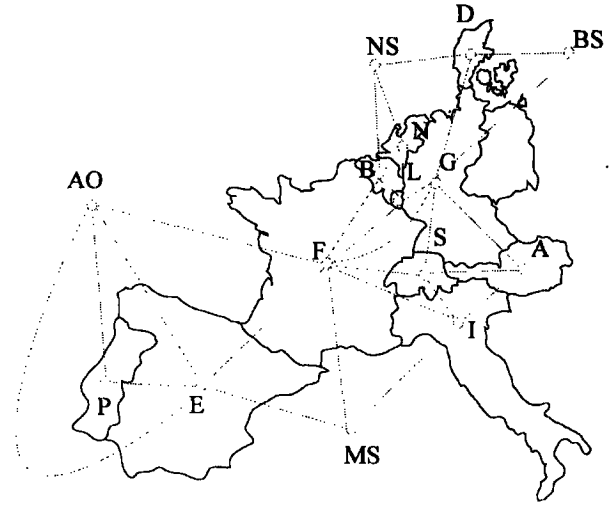


Figure 3: Connection graph representation of a decomposition by tessellation

second part of the spatial expression stating that the polygons we are looking for have either to be connected with the Mediterranean or to the North Sea. Again, this can easily be decided by following all edges in the connection graph starting at the nodes that representing the Mediterranean and the North Sea, respectively.

Looking at the connection graph in figure 3, we can see that this criterion is met by the cities Madrid, Paris and Amsterdam, because the countries they lie in, i.e. Spain, France and The Netherlands are connected to one of these seas. Lisbon is excluded from the collection of possible solutions, because Portugal does not have this connection.

### Directions

We argued that the representation of a tessellation in terms of a connection graph preserves the topological relations. The problem with this representation concerning directional information is the fact that topological information is rotation-invariant by nature. Therefore it is not possible to encode directions in the connection graph. In order to include directions, we assign special direction labels to edges in the graph. These labels are described by the following function:

$$DIR : E \rightarrow 2\{N, NO, O, SO, S, SW, W, NW\}$$

The functions assigns a set of qualitative directions according to points of the compass. We use the qualitative description N to refer to direction between 315 and 45, NW for 0 to 90, W for 45 to 115 degree and so on. An edge is labeled with a set of these descriptions because connected polygons often fall into more than one of these angle sections

due to their spatial extension. Figure 4 shows the connection graph of the example together with the labeling for the edges between France and its neighbors.

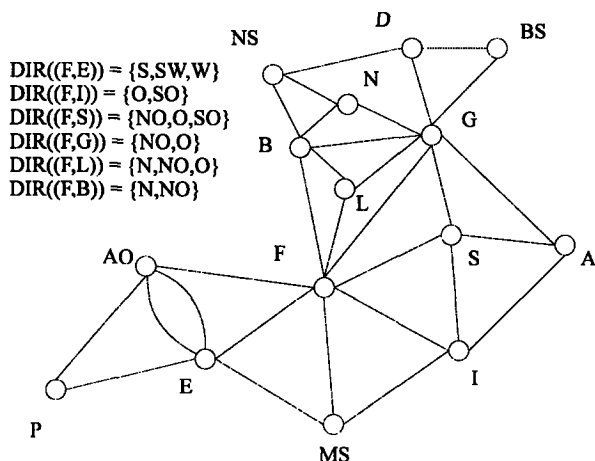


Figure 4: Direction labels used to describe direction of France's neighbors

This kind of labeling allows us to reason directly about directional information of connected polygons. Reasoning about directions of polygons which are not directly connected, however, is more complicated. In this case, we have to extract labels of the transitive closure of the connection graph. The advantage of this approach is the ability to refer to complete directional information in the course of the reasoning process. However, a larger representation that contains redundant information is needed in this case because we know that directional relations are transitive. Another approach is to use an additional calculus on direction labels. This approach preserves the minimality of the representation, but we cannot assume that such a calculus will be correct and complete.

In the example query, we restricted interesting locations to those that are not north of Belgium. This means that the labels NW, N and NO must not be contained in the label of the edge between Belgium and the location we seek. Applying this criterion to the locations of the remaining cities (Amsterdam, Paris and Madrid) we can decide that the Netherlands do not meet this criterion because they are directly connected to Belgium and the edge contains all three forbidden labels. France (directly) and Spain (by transitivity) can be proven to meet the criterion. Therefore, Amsterdam is excluded from the set of possible solutions.

## Distances

Concerning distance information we find a situation similar to the one we observed concerning directions. The connection graph does only imply a very weak

notion of distance. It allows to compute the shortest path between two nodes (i.e. the graph-theoretic distance) but it does not capture the real distances between polygons. Figure ?? shows an example that illustrates the problems that occur if only the connection graph is used. We consider the distance between Luxembourg and The Netherlands on one hand, and Luxembourg and Spain on the other hand. While the graph-theoretic distance is the same, figure 5 clearly shows that Spain is much further away from Luxembourg than the Netherlands.

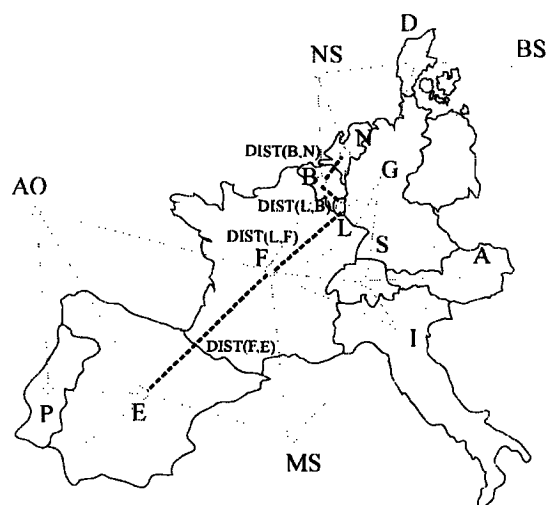


Figure 5: Using Distance Information

In order to overcome this problem we use additional distance labels for edges. Again we have to decide whether to choose a local or a global assignment of distances. In order to avoid redundant information, we prefer a local assignment. There are many options for defining these labels. First of all, we have to decide whether to use a qualitative or a quantitative notions of distance. A quantitative approach again requires a suitable calculus while a quantitative measure allows the application of standard algebra. The next problem is how to derive distance information from the actual data. Again there are various options. The mean distance between connected polygons should be a good approximation. A possibility of computing this distance is to determine the centroids of two polygons and use Euclidian distance between them.

Regardless of the kind of distance measure we choose, we get a result for our example query, because France lies on the shortest path from Germany to Spain. This implies that Madrid which lies in Spain is definitely further away from Germany than Paris which lies in France. As a consequence, this last criterion restricts the set of solutions for our query to exactly one city,

namely Paris. Looking at the actual situation, we see that the result meets the intuitive expectations.

## Discussion

We argued for the need of spatial reasoning in information brokering. Starting from a system capable of processing conceptual queries, we underlined the need to process spatial expressions, i.e. Boolean combinations of spatial relations over location names that refer to polygons in two-dimensional space. We argued that diagrammatic reasoning is the technique of choice for our purposes and sketched the reasoning process triggered by a complex query that contains all logical operators and types of relations.

Though the approach is promising, there are still many open questions to be answered. First of all, large scale diagrammatic representations (i.e. connection graphs) have to exist in order to make this approach possible. In order to avoid a tremendous modeling effort, there is a need for mechanisms that are able of producing a diagrammatic representation on the basis of real data. Once the models have been extracted, they have to be represented. On one hand, the representation has to support efficient reasoning, on the other hand, these models constitute valuable knowledge that should be exchanged. A reuse of these models in other contexts can also be considered interesting. As discussed in the previous section, partonomic and topological information could be directly derived from the representation while direction and distance required additional reasoning. In this paper, we did not address the problem of developing calculi for local reasoning about distances and directions. The development of correct calculi with efficient implementations is a task for the future. Finally, the whole approach was based on a strict separation of conceptual and spatial reasoning. Therefore a wide range of queries cannot be stated. For example, the search for locations which are connected to some kind of ocean, mixes spatial concepts (connectedness) with conceptual information (locations of type ocean). The development of an integrated reasoning approach can be seen as a long-term research goal.

## References

- Clementini, E.; Felice, P. D.; and Hernandez, D. 1997. Qualitative representation of positional information. *Artificial Intelligence* 95:317–356.
- Cohn, A. 1997. Qualitative spatial representation and reasoning techniques. In Brewka, G., ed., *KI-97 Advances in Artificial Intelligence*, 1–30. Berlin: Springer.
- Egenhofer, M. 1991. Reasoning about binary topological relations. In *roc. Advances in Spatial Databases*, 143–160.
- Fensel, D.; Horrocks, I.; Harmelen, F. V.; Decker, S.; Erdmann, M.; and Klein, M. 2000. Oil in a nutshell. In Dieng, R., ed., *Proceedings of the 12th European Workshop on Knowledge Acquisition, Modeling, and Management (EKAW'00)*, Lecture Notes in Artificial Intelligence. Springer-Verlag.
- Fikes, R.; Farquhar, A.; and Pratt, W. 1996. Information brokers: Gathering information from heterogeneous information sources. In Stewman, J. H., ed., *Proceedings of the Ninth Florida Artificial Intelligence Research Symposium (FLAIRS '96)*, 192–197. Eckerd College, Key West, Florida.
- Frank, A. 1992. Qualitative spatial reasoning about distances and directions in geographic space. *Journal of Visual Languages and Computing* 3:343–371.
- Glasgow, J.; Narayanan, H.; and Chandrasekaran, B. 1995. *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Cambridge, MA: MIT Press.
- Levine, M. M. 1995. A brief history of information brokering. *Bulletin of the American Society for Information Science* 21(3).
- Levy, A. Y.; Srivastava, D.; and Kirk, T. 1995. Data model and query evaluation in global information systems. *Journal of Intelligent Information Systems (JIIS)* 5(2):121–143.
- Martin, D.; Oohama, H.; Moran, D.; and Cheyer, A. 1997. Information brokering in an agent architecture. In *Proceedings of The Practical Application of Intelligent Agents and Multi-Agent Technology (PAAM 97)*.
- Randell, D.; Cui, Z.; and Cohn, A. 1992. A spatial logic based on regions and connection. In *Proc. Conference on Knowledge Representation and Reasoning (KR-92)*, 165–176.
- Rougemont, M. D., and Schlieder, C. 1997. Spatial navigation with uncertain navigation. In *Proc. 14th National Conference on Artificial Intelligence (AAAI'97)*, 649–554.
- Schlieder, C.; Vögele, T.; and Visser, U. 2001. Qualitative spatial representation for information retrieval by gazeteers. Working Paper, AI Group, University of Bremen, <http://www.tzi.de/buster/papers/COSIT01.pdf>.
- Schlieder, C. 1995. Reasoning about ordering. In Frank, A., and Kuhn, W., eds., *Proc. Conference on Spatial Information Theory*, 341–350. Berlin: Springer.
- Vögele, T.; Stuckenschmidt, H.; and Visser, U. 2000. Towards intelligent brokering of geo-information. In *Symposium on Urban and Rural Data Management UDMS*.
- Visser, U.; Stuckenschmidt, H.; Schuster, G.; and Vögele, T. 2001. Ontologies for geographic information processing. *Computers & Geosciences*. to appear.