Specifications For Interoperability: Formalizing Spatial Relations 'In', 'Auf' and 'An' and the Corresponding Image Schemata ' Container', 'Surface' and 'Link'

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Abstract

The formal specification of spatial objects and spatial relations is at the core of geographic data exchange and interoperability for GIS. Spatial image schemata are good candidates for important relations. The paper reviews methods for the formal description of spatial relations, integrates them in a categorical view, and applies the methods arrived at to describe three important spatial image schemata for small-scale (tabletop) space.

1. Introduction

Standardization of technical terms and the fundamental concepts necessary to make computer interact is mostly achieved or can be achieved with the current tools. The economically important and scientifically challenging question is to describe the meaning of GIS data in terms of the real world. What does it mean that "P 271" is a point, that building 'A1' is on parcel "343a", A is on the B-River etc.? Specification of spatial relations is of great practical interest to define spatial relations in spatial query languages unambiguously (Egenhofer 1992). Kuhn has pointed out the importance of image schemata as a tool to build 'natural' (i.e., cognitively sound) user interfaces for GIS (Kuhn and Frank 1991; Kuhn 1993).

2. Formalizing Spatial Meaning

Topological relations between simply connected regions were treated in (Egenhofer 1989; Egenhofer, Clementini et al. 1994) Metric relations between point-like objects, especially cardinal directions (Frank 1991; Freksa 1991; Hernández 1991) and approximate distances (Frank 1992; Hernández, Clementini et al. 1995; Frank 1996) were discussed. Other efforts dealt with ordering among configurations of points, and (Schlieder 1995) linguists made systematic efforts to clarify the meaning of spatial prepositions (Herskovits 1986)

3. Specification of Image Schemata

Johnson presented a list of 'image schemata', which represent highly abstract structures of human experience - mostly spatial experience (Johnson 1987) (Table 1). It is assumed that they are fundamental structures which are used in human cognition (Lakoff 1987). Spatial image schemata are, for example, closely related to spatial prepositions (Mark 1989). Despite all efforts, there has been limited success in formalizing spatial image schemata.

Container	Balance	Full-Empty	Iteration	Compulsion
Blockage	Counterforce	Process	Surface	Restraint Removal
Enablement	Attraction	Matching	Part-Whole	Mass-Count
Path	Link	Collection	Contact	Center-Periphery
Cycle	Splitting	Merging	Object	Scale
Near-Far	Superimposition.			

Table 1. Partial list of image schemata (from (Johnson 1987))

4. Difficulty with Specifying Image Schemata

If a topic has been on the research agenda for nearly 10 years and little progress is made, it might be useful to consider the reasons for the lack of progress:

4.1 Definition of Image Schemata

Researchers in the past have used a working definition, which implied that image schemata describe spatial (and similarly physical) relations between objects, but most have concentrated more on spatial prepositions like 'in', 'above' etc. and assumed that these relate directly to the image schemata (often following (Lakoff and Johnson 1980; Johnson 1987; Lakoff 1987).

The single image schema is not a precise, well-defined quantity, but 'prototype effects' as described by (Rosch 1973; Rosch 1973; Rosch 1978) apply. To make progress, a very specific environment must be fixed (Rodriguez and Egenhofer 1997,) and we and others have used small-scale space (tabletop space).

4.2 Language Dependence

Most treatments are motivated with spatial prepositions from a particular language. Here the German spatial prepositions 'in', 'auf' and 'an' are used as target, and the rules deduced justified with German language examples. It is assumed that there are universals in the semantics, and different languages may combine the primes differently (Wierzbicka 1996). This helps to build a set of query primitives from which language-specific expressions are combined. The Egenhofer relations have been used in this way to define more complex topological relations (Mark, Comas et al. 1995).

4.3 Polysemy

A single word may have multiple meanings. It may be useful to assume that multiple different meanings exist and define one after the other. For example, I restrict 'in' here to mean 'directly in' and differentiate it from 'in*' which generalized ‘in’ to include indirect containment.

Die Münze ist im Beutel und der Beutel ist in der Tasche. Die Münze ist in* der Tasche.

The coin is in the purse and the purse is in the pocket. The coin is in* the pocket.

4.4 Default Values

Multiple levels of detail are considered for image schemata. Should 'move in' consider the size of the moved object with respect to the container? Should the amount of free space on a tabletop be taken into account when something is moved onto it? It seems necessary today to structure the specifications of image schemata in layers (or a hierarchy), which consider increasingly more properties.

5. Difficulties with the Formalization of Descriptions

Image schemata cannot be defined in isolation, but require objects which they relate and an environment in which the statements can be interpreted. This causes complication for the formalization as a review of methods used shows:

5.1 Predicate Calculus

Lakoff gives a definition of a CONTAINER using predicate calculus (Lakoff 1987). This is justified by the fundamental expressive power of predicate calculus (Hayes 1977; McCarthy 1985), but it is limited by the 'frame problem'.

5.2 Relations

The behaviour of topological relations (Egenhofer, Clementini et al. 1994; Papadias and Sellis 1994), but also cardinal directions and approximate distances (Frank 1992; Frank 1996) have been analyzed using the relation calculus and described as the outcome of 'relation composition' (";"). *R;S = aRb and bSc.* For example, *a North b and b East c => a NorthEast c,* is written as *North;East => NorthEast.*

Relation calculus leads to easy-to-read tables, where the outcome of the combination of two relations is given. Such tables show patterns. Their disadvantage is their size; relational tables grow with the square of the number of relations involved.

5.3 Functions

The use of functions in lieu of relations is often referred to as a functional style. Relation composition is replaced by function composition ("."), defined as $f \,.\, g\,(x) = f\,(g\,(x))$.

Compositions can be tabulated similarly to the tables often used for relation composition. Function composition tables quickly become very large, because the arguments passed are not fixed as in relation calculus, but pair-wise agreement of arguments must be differentiated.

5.4 Model-Based

An abstract model is constructed with a fundamental set of operations and a sufficient number of observed operations to differentiate all possible states. New and more complex operations can be constructed using the given operations.

Model-based specifications have the advantage that the difference between the ontology incorporated in the model and the epistemology of the observers can be clarified. On top of the same ontology, multiple epistemologies may be constructed. For example, it is possible to use the English prepositions 'in' and 'on' in lieu of the German 'in', 'auf' and 'an'.

6. Formal Definition of the Image Schemata for 'In', 'Auf', 'An'

We consider the common-sense spatial reasoning conclusions from the relations 'in', 'auf' and 'an' between an object and a relatum, and the operations to establish such relations (*moveIn, moveAuf, moveAn*). For each relation we have a converse. *(a (conv Rel) b = b Rel a).* The spatial relations and their converses are interpreted as Boolean functions *Rel (a,b) -> Bool*, or functions which return for an object the relatum *fRel a -> b = a Rel b*. We say that an object *participates* in a spatial relation *Rel* if the corresponding *fRel* returns an object (this is equivalent to *Exist b: a Rel b*).

6.1 Ontology

The scene is a tabletop of unspecified objects, which are moved from the outside. The following complete list of assumptions holds:

1. In this world objects can be moved, unless the move is blocked by the relation the object participates in.
2. An object can be moved to (in, auf, an) a target, unless access to this target is blocked by a relation this target participates in.
3. Every object can enter in any relation with any other object, i.e., all objects can serve as containers or support; objects are not differentiated.

This is a closed world: Moves are not blocked by other considerations, for example:

4. No other objects exist.
5. The number or size of other objects which can be related to an object is not limited. Moves are not blocked by size considerations (for example, objects too large for container, surface completely covered, etc.).

6.2 'In' Blocks Target of Movement

An object cannot be moved to a target if this is already in another object. This is justified by situations as:

x 'in' y (in scene) => blocked (move z into x (in scene))

Du mußt den Beutel zuerst aus der Tasche nehmen, bevor du die Münze hineingeben kannst.
You must take the purse out of the pocket to put the coin in.

6.3 Converse of 'auf' Blocks Object of Movement:

'Auf' blocks the movement of the supporting object. It cannot be moved unless the object 'auf' it is removed.

x 'auf' y (in scene) => blocked (move y in scene)

Teller und Gläser sind auf dem Tisch. Wir müssen den Tisch zuerst abräumen,
bevor wir ihn auf die andere Seite des Zimmers bringen können.
Plates and glasses are on the table. We have to remove all objects from the table,
before we can move it to the other side of the room.

6.4 'In', 'an': Block Movement of Object

'In' and 'an' create a link between the object and the relatum which resists movement (a particular 'break link' operation would be required to break it: unglue, takeOut etc.).

'In' does restrict the movement of the object.

x 'in' y (in scene) => blocked (horizontal move x in scene)

Der Apfel kann nicht aus der Schale rollen, aber du kannst ihn dir herausheben.
The apple cannot roll out of the bowl, but you can take it out (lift it out).

x 'in' y and 'closed' y (in scene) => blocked (move x in scene)

Du mußt die Büchse öffnen, dann kannst du die Würfel herausnehmen.
You must open the box. Then you can take out the dice.

'An' presupposes a physical connection between the object and the relatum (stronger and more permanent than gravity support) which is typically established intentionally (verbs like to nail, to glue, to stick, etc. and not just plain 'to put'). 'An' with this definition could be seen as a 'Link' image schema. Movement is restricted unless the link is broken.

x 'an' y (in scene) => blocked (move x)

Ich habe das Papier auf das Buch gelegt, jetzt klebt es dar**an**.
Wenn du das Papier mitnehmen willst, mußt du es sorgfältig lösen.
I have put the paper on (auf) the book, now it is glued on (an).
If you want to take it with you, then you have to carefully remove it.

6.5 'In', 'an': Invariance Under Movement of Relatum

Corresponding to the blocked access to the object for 'in' and 'an' relations (rule 6.4), these relations are invariant under movement. If x is 'in' y and y is moved, then x is still 'in' y (and the same for 'an').

x 'in' y (in scene) => x 'in' y (in move y in scene) = True

x 'an' y (in scene) => x 'an' y (in move y in scene) = True

These rules will not be expressed explicitly, as they are subsumed by the 'stable world property' (nothing changes unless specifically indicated).

6.6 Undoes a Previous Relation of Object: 'auf'

'Auf' does not restrict the movement of the object:

x 'auf' y (in scene) => move x in scene

Du kannst das gelbe Buch nehmen, es liegt auf dem Tisch.
You can take the yellow book, it is on top of the table.

The effect is, however, that the previously established relation is false and a new relation is established:

scene2 = move x Rel y (scene1)

a Auf z (in scene1) = True

a Auf z (in scene2) = False

a Rel y (in scene2) = True

6.7 Formal Model

A function composition model can be constructed and the rules listed are directly coded. The central operations 'move' with the arguments: relation type, object, target, scene are shown below; the complete program is only 31 lines of code!

```
move i a b s =
      if fRel In b s   -- rule 6.2 : in blocks target of movement
         then error ("in blocked: already in")
```

```
else
if fRelConv Auf a s -- rule 6.4: (conv auf) blocks movement
   then error ("auf move blocked: already covered")
else
if fRel In a s   -- rule 6.5 (1): in blocks movement of object
   then error ("in move blocked: already in")
else
if fRel An a s   -- rule 6.5 (2): an blocks movement of object
   then error ("an move blocked: obj already an")
else
if fRel Auf a s -- rule 6.6: undoes previous 'auf' of object
   then move i a b (takeOff Auf a s)
else
Move i a b s
```

7. Open Questions

7.1 Methodological

The method used here is borrowed from linguistics. Is a single common-sense reasoning chain as given here sufficient? It documents that at least a situation exists, where the suggested spatial inference is made - thus it demonstrates at least one aspect of a spatial relation in (one human's) cognition.

7.2 Language-Independent Primitives

Can language-independent primitives be identified (in the sense of (Wierzbicka 1996)) and combined? Specifically for English and the example discussed: is 'on' a single word in English or is a polysemous definition better (with the two meanings of German 'an' and 'auf')? Are the indirect forms ('indirekt in' and 'indirekt auf') different from the direct forms (polysemy)? There are cases when the two are differentiated:

> Ich sitze nicht auf dem Boden, ich habe mir eine Zeitung untergelegt.
> (I do not sit on the ground, I have put a newspaper under.)

7.3 Relation between Relations and Functions

For both functions and relations a category can be constructed (Bird and Moor 1997). Certain formalizations seem to be easier in the one, others in the latter. Prolog (Clocksin and Mellish 1981) can be used as a tool to work with relations; functional programming languages, especially Haskell (Peterson, Hammond et al. 1997) and Gofer (Jones 1991; Jones 1994) execute (constructive) functional specifications.

7.4 Are Image Schemata the Atoms of Spatial Cognition?

Are image schemata the atoms of Spatial Cognition or are there smaller semantic units from which image schemata can be composed? One could assume that 'in' and 'an' have in common that a thing contained or attached is moved with the container or support; 'in', 'an' and 'auf' show the common behaviour that a thing can be taken away only if it had been put there.

7.5 Extension to Large-Scale (Geographic) Space and Map Space

To make image schemata really useful for GIS, they must apply to geographic objects or the map objects. It is possible to write descriptions for large-scale (geographic) space (Rodriguez and Egenhofer 1997); it becomes necessary to rethink the defining aspects of an image schema.

I suggest that an independent modelling of a geographic or a map ontology - I think they are different - along the same lines as done here for a tabletop scene should be undertaken. If the resulting spatial relations have the same properties, they can be merged. Because I assume that some geographic objects are conceived as similar to shadows or liquids, I would suggest that an investigation of these be performed first.

8. Conclusions

Formal descriptions of spatial relations as they are encountered in everyday life are very important for GIS. They can be used to formally define query language predicates, to optimize the execution of spatial queries. They are crucial for the specification of spatial data exchange formats and GIS interoperability standards.

Most previous efforts to analyze spatial relations have used relation calculus and have concentrated on spatial relations which are amenable to this treatment (topological relations, cardinal directions, approximate distances etc.). The extension of relation calculus to a function calculus is discussed here, linking two previously unconnected tools. The two tools are not as different and their conceptual merging is in category theory (Barr and Wells 1990; Herring, Egenhofer et al. 1990; Asperti and Longo 1991) (Walters 1991). Function composition tables can be used similarly to relation composition tables; they show patterns which can then be succinctly formulated as rules.

The method has been applied to three spatial image schemata (the German prepositions 'in', 'auf' and 'an' - roughly equivalent to English 'in' and 'on'). Formal definitions are given for a tabletop scene, based on 3 types of rules. Contrary to previous, the differentiation between 'an' and 'auf' in German seems not to be dependent on vertical vs. horizontal surface, but of linkage between the object and the relatum (i.e., gravity vs. physical attachment).

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