An Event-Based Approach to Spatial Information

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Abstract

The notion of the location of an object at a moment of time is relatively straightforward, it is the region of space occupied by the object at that time. However, we are often concerned with the location of something over an extended period of time, as in *Alice was in the room for ten minutes.* Conceptualizing the location of an object in this case is much more difficult because changes of a spatial nature, i.e., changes in position, size or shape, can occur to any or all of the objects being related. Motion of course always involves changes in the location of at least one of the related objects. In this paper we propose an event-based approach to the representation of spatial information in natural language. The essential idea is to treat spatial relations as event types. The utility of this proposal is illustrated through examples of representations of locative events, various types of motion events, spatial deixis and spatial anaphora. Finally, we show how the atemporal spatial axioms of Randell, Cui & Cohn (1992) can be translated into event-based axioms for time-aware spatial reasoning.

1 Introduction

The notion of the location of an object at an instant of time is relatively straightforward, it is the region of space occupied by the object at that time. However, we are often concerned with the location of something over an extended period of time, as in *Alice was in the room for ten minutes.* Conceptualizing the location of an object in such a case is a much more difficult problem because changes of a spatial nature, i.e., changes in position, size or shape, can occur to any or all of the objects being related. For example, Alice may walk about the room, or the room may be on a moving train, or, more fancifully, Alice or the room may grow or shrink or change shape, etc. Motion of course always involves changes in the location of at least one of the related objects. In this paper we propose an event-based approach to the representation of spatial information in natural language which is capable of handling these complexities, as well as providing the benefits of the event-centered representational approach in general. Essentially, we propose to treat spatial relations as stative event types.

Although the idea that events should be included as part of the meanings of sentences has a long history (for a discussion see Parsons, 1990), the earliest detailed proposal as to how this could be done is that of Davidson (1967). For example, Davidson gives as the representation for the sentence *Shem kicked Shaun*: (∃x)(Kicked(Shem,Shaun,x)), where x is an event "such that x is a kicking of Shaun by Shem" (p.118).

The increasingly popular "event-centered" style of representation that forms the basis of our approach is a development of Davidson's original proposal, and is based on the following three premises. First, that events (or what are sometimes called eventualities or situations) understood as concrete spatio-temporal particulars constitute a part of the ontology presupposed by natural language. Second, that many sentences make an implicit reference to an event even when they lack an explicit event-referring expression. And third, that the other entities referred to in the sentence are related to this implicit event assertionally rather than structurally, that is, the links between the event and the entities that play roles in that event are in the form of propositions. These propositions are most often composed of two-place predicates one of whose arguments is the event. Thus, the event is the "center" around which the other entities of the sentence are arranged. It is the third premise which distinguishes these representations from Davidson's. Some other names which have been used for this variant of Davidson's approach are *slot-assertion notation* (Charniak & McDermott, 1985), *aspectualized representations* (Wilensky, 1991), and *representations with underlying events* (Parsons, 1990). Parsons (1990) and Wilensky (1991) offer many compelling arguments in favor of this style of representation.

2 Spatial and Temporal Ontology

In our temporal ontology we assume the existence of both time points and time intervals. In this we follow the proposals of Galton (1990), who argues against a purely interval-based approach to time, and of Allen & Hayes (1987), who also add time points to an initially interval-based ontology.

Two major candidates in the area of commonsense spatial ontologies are the proposals of Randell, Cui & Cohn (1992) and of Asher & Vieu (1995). Both theories are based on the mereotopological calculus of Clarke (1981, 1985). All of these theories take regions (as opposed to points) of space as primitive. We will use the theory of Randell et al. (1992) because of its relative simplicity. The fifteen relations between regions of space defined in their theory (p.167) are:

(1) C(x,y) - region x is connected to region y. The notion of connection between two regions of space is taken as primitive with the other relations being defined in terms of it. Randell et al. define that C(x,y) holds if the topological closures of x and y have at least one point in common.

(2) region x is disconnected from region y:

$DC(x,y) \equiv_{def} \neg C(x,y)$

(3) region x is part of region y:

$P(x,y) \equiv_{def} \forall z \,.\, C(z,x) \rightarrow C(z,y)$

(4) region x is a proper part of region y:

$PP(x,y) \equiv_{def} P(x,y) \wedge \neg P(y,x)$

(5) region x is equal to region y:

$EQ(x, y) \equiv_{def} P(x,y) \wedge P(y,x)$

(6) region x overlaps region y:

$O(x,y) \equiv_{def} \exists z \,.\, P(z,x) \wedge P(z,y)$

(7) region x partially overlaps region y:

$PO(x,y) \equiv_{def} O(x,y) \wedge \neg P(x,y) \wedge \neg P(y,x)$

(8) region x is discrete from region y:

$DR(x,y) \equiv_{def} \neg O(x,y)$

(9) region x is a tangential proper part of region y:

$TPP(x,y) \equiv_{def} PP(x,y) \wedge \exists z . EC(z,x) \wedge EC(z,y)$

(10) region x is externally connected to region y:

$EC(x,y) \equiv_{def} C(x,y) \wedge \neg O(x,y)$

(11) region x is a nontangential proper part of region y:

$NTPP(x,y) \equiv_{def} PP(x,y) \wedge \neg\exists z . EC(z,x) \wedge EC(z,y)$

(12) the inverse of P:

$P^{-1}(x,y) \equiv_{def} P(y,x)$

(13) the inverse of PP:

$PP^{-1}(x,y) \equiv_{def} PP(y,x)$

(14) the inverse of TPP:

$TPP^{-1}(x,y) \equiv_{def} TPP(y,x)$

(15) the inverse of NTPP:

$NTPP^{-1}(x,y) \equiv_{def} NTPP(y,x)$

The basic relations are DC, EC, PO, EQ, TPP, NTPP, TPP^{-1}, and $NTPP^{-1}$. These relations are mutually exhaustive and pairwise disjoint. The remaining seven relations are related to the basic relations as follows:

$C(x,y) \leftrightarrow O(x,y) \vee EC(x,y)$

$P(x,y) \leftrightarrow PP(x,y) \vee EQ(x,y)$

$PP(x,y) \leftrightarrow TPP(x,y) \vee NTPP(x,y)$

$O(x,y) \leftrightarrow P(x,y) \vee P^{-1}(x,y) \vee PO(x,y)$

$DR(x,y) \leftrightarrow DC(x,y) \vee EC(x,y)$

$P^{-1}(x,y) \leftrightarrow PP^{-1}(x,y) \vee EQ(x,y)$

$PP^{-1}(x,y) \leftrightarrow TPP^{-1}(x,y) \vee NTPP^{-1}(x,y)$

In addition to these relations, various functions from regions of space to regions of space can be usefully defined. Jackendoff (1983), Herskovits (1986) and Zelinsky-Wibbelt (1993), as well as Randell et al. (1992), contain many examples of such functions. For example, Herskovits (1986, p.65) represents *she is under the tree* as follows:

$\exists t$. under(place(she,t), underside(outline(branchpart(place(tree, t)))))

In this formula, ‘under’ is a predicate, ‘place’ is a function from objects and instants of time to regions of space, and ‘underside’, ‘outline’ and ‘branchpart’ are all functions from regions of space to regions of space. We will introduce such functions as they are needed.

3 Representing Locative Events

Our proposed representation for the durative locative state/event expressed by *Alice was in the room for ten minutes* is:

$$\text{inst}(e1, P) \wedge \text{arg1}(e1) = \text{loc}(\text{alice1}) \wedge \text{arg2}(e1) = \text{interior}(\text{loc}(\text{room1})) \wedge \text{duration}(\text{time}(e1), \text{ten-minutes}) \wedge \text{before}(\text{time}(e1), ST)$$

In this formula, *e1* denotes the locative event described by the sentence, an instance of the spatially-part-of (P) event type. That is, we propose that spatial relations, such as those of Randell et al. (1992), be construed as stative event types. The functions *arg1(e1)* and *arg2(e1)* denote the two spatial regions being related; in this case arg1(e1) is a spatial part of arg2(e1). The spatial regions serving as arguments in these events will generally be denoted through the use of the fluent *loc*, which gives the spatial position of its argument for each instant of time occupied by the event (see Davis (1990) for a detailed discussion of fluents). Galton's (1995) analysis of motion is also based on such a fluent. Most of our spatial functions, such as *interior* above, are also fluents. The interval of time occupied by the event is denoted by the function *time(e1)*. The time of e1 has a duration of ten minutes and is in the past, i.e., before the speech time ST.

A major motivation for the approach taken in this paper comes from sentences involving perception of spatial configurations, such as *John saw Alice in the room.* In this sentence, what is being seen is an individual locative event—Alice being in the room. We can represent this sentence as follows:

$$\text{inst}(e2, \text{seeing}) \wedge \text{experiencer}(e2) = \text{john1} \wedge \text{object}(e2) = e3 \wedge \text{before}(\text{time}(e2), ST) \wedge \text{inst}(e3, P) \wedge \text{arg1}(e3) = \text{loc}(\text{alice1}) \wedge \text{arg2}(e3) = \text{interior}(\text{loc}(\text{room1})) \wedge \text{time}(e3) = \text{time}(e2)$$

Significantly, we can also perceive negative locative events, as in for example, *John saw Alice not in the room.* We can represent this sentence as follows:

$$\text{inst}(e4, \text{seeing}) \wedge \text{experiencer}(e4) = \text{john1} \wedge \text{object}(e4) = e5 \wedge \text{before}(\text{time}(e4), ST) \wedge \text{inst}(e5, \text{not}(P)) \wedge \text{arg1}(e5) = \text{loc}(\text{alice1}) \wedge \text{arg2}(e5) = \text{interior}(\text{loc}(\text{room1})) \wedge \text{time}(e5) = \text{time}(e4)$$

where not(P) is the event type generated by applying the property negation operator *not* to the event type P. Therefore e5 is an event of the type not being in the room. Given the homogeneity of the locative event types and the inconsistency between types R and not(R), the meaning of the *not* operator is expressed by the following two axioms:

(1) $\forall e,R.\ \text{inst}(e, \text{not}(R)) \rightarrow \neg\exists e'.\ \text{subevent}(e', e) \wedge \text{inst}(e', R)$

(2) $\forall e,R.\ \text{inst}(e, R) \rightarrow \neg\exists e'.\ \text{subevent}(e', e) \wedge \text{inst}(e', \text{not}(R))$

A spatially located event such as *John practiced the piano in this room* can be represented as follows:

$$\text{inst}(e6, \text{practicing}) \wedge \text{agent}(e6) = \text{john1} \wedge \text{patient}(e6) = \text{piano1} \wedge \text{before}(\text{time}(e6), ST) \wedge \text{inst}(e7, P) \wedge \text{arg1}(e7) = \text{loc}(e6) \wedge \text{arg2}(e1) = \text{interior}(\text{loc}(\text{room2})) \wedge \text{time}(e7) = \text{time}(e6)$$

Examples such as this one bring up the question of the relationship between the location of an event and the locations of the objects that play roles in that event. In this sentence, it appears that if the event of John practicing the piano is located in a room, then both John and the piano are also located in that room. This inference will generally be true for the examples used in this paper, but we would not want to claim that it is always true. At any rate, although it is not a direct concern of this paper, rules roughly the form of the following will eventually need to be defined for the various event roles:

$$\forall e \,.\, inst(e, event\text{-}type) \rightarrow \exists e' \,.\, inst(e', P) \wedge arg1(e') = loc(agent(e)) \wedge arg2(e') = loc(e)$$

That is, the location of the agent of an event is part of the location of the event.

4 Representing Motion Events

The most basic motion events are instances of motion types such as *walking, running, driving,* and *sliding.* As an example, the representation of *John ran* is simply:

$$inst(e1, running) \wedge agent(e1) = john1 \wedge before(time(e1), ST)$$

If we add an indication of length, as in *John ran a mile,* we get:

$$inst(e1, running) \wedge agent(e1, john1) \wedge length(path(e1), one\text{-}mile) \wedge before(time(e1), ST)$$

Unlike location events, motion events contain spatial paths as part of their meaning. The defining properties of paths are (1) regions on a path may be visited repeatedly, as can happen in, for example, running around a circular track, and (2) paths are given lengths using purely spatial measures, e.g., five miles. Therefore, paths cannot be understood simply as the join or the sum of the instantaneous locations of the event, nor can they be analyzed as four-dimensional spatio-temporal objects. Instead paths need to be conceptualized as the types of objects known in mathematics as parametric curves. Parametric curves can keep track of repeated visits to the same locations, while at the same time being purely spatial in nature.

Motion is always relative to some frame of reference, so, for example, the event of walking down the aisle of a moving airplane has different paths depending on whether we use the airplane or the earth as the frame of reference. However, for the purposes of this paper we will assume a uniform frame of reference for all events, and so we can omit the reference frame role from our representations.

An event is *continually-moving* if the moving object(s) of the event, and equivalently the event itself, never stands still over the interval of the event. This is defined as:

$$\forall e.\, continually\text{-}moving(e) \leftrightarrow \neg\exists i \,.\, \{during(i, time(e)) \wedge interval(i) \wedge \forall t, t'.\, [t \in i \wedge t' \in i] \rightarrow loc(e,t) = loc(e,t')\}$$

If an event is continually-moving, then we have that:

$\forall$e, e´ . proper-subevent(e´, e) $\wedge$ continually-moving(e)
  $\rightarrow$ proper-subpath(path(e´), path(e))

That is, if e´ is a proper subevent of e and e is continually-moving, then the path of e´ is a proper subpath of that of e.

We can take a motion event and give it a location, as in *John ran a mile in the park.* This can be represented as:

inst(e1, running) $\wedge$ agent(e1) = john1 $\wedge$ length(path(e1), one-mile)
 $\wedge$ before(time(e1), ST)
 $\wedge$ inst(e2, P) $\wedge$ arg1(e2) = loc(e1) $\wedge$ arg2(e2) = interior(loc(park1))
 $\wedge$ time(e2) = time(e1)

Jackendoff (1983) proposes a classification of paths as they are expressed by prepositional phrases. All of these paths are oriented according to reference objects or places. There are three major types depending on the nature of the path's relationship to its reference object: bounded paths, directions and routes. Here we offer analyses of events containing paths of these three different types as a way of illustrating the utility of our event-based representational approach.

Bounded paths include *source paths,* in which the reference object occupies the initial position in the path, and *goal paths,* in which the reference object occupies the final position in the path. Source path expressions usually use the preposition *from,* as in *from the house,* and goal path expressions often use *to,* as in *to the store.* The analyses of bounded paths that underlie these representations are based on ideas of Galton (1995) and Asher & Sablayrolles (1995). The general source path, *from X,* has the representation:

inst(E, motion-type)
 $\wedge$ inst(E´, TPP) $\wedge$ arg1(E´) = loc(E) $\wedge$ arg2(E´) = proximity(loc(X))
  $\wedge$ time(E´) = initial-pt(time(E))
 $\wedge$ inst(E´´, not(P)) $\wedge$ arg1(E´´) = loc(E) $\wedge$ arg2(E´´) = proximity(loc(X))
  $\wedge$ time(E´´) = minus-initial-pt(time(E))

In this formula, E is the event of moving from X and E´ is the locative event for the source X. The tangential part relation TPP used here assumes continuous motion, the more general part relation P is used if we allow for the possibility of discontinuous jumps. *Proximity(L)* is the function which denotes the immediate neighborhood of a spatial region L, including its interior. Therefore, you have gone to the store if you arrive either in the immediate vicinity of the store or in the store itself. This function is based on one of the same name defined by Asher & Sablayrolles (1995) which generates the "outer-halo" or exterior neighborhood of an object, but also includes the interior region of its argument. As they also point out, the notion of proximity may depend not only on the reference object itself but also on the nature of the theme/agent object, as well as on the context.

The following temporal functions are often helpful:

initial-pt(T) $=_{def}$ the initial instant of time T. Initial-pt(T) may or may not be a part of T.

final-pt(T) $=_{def}$ the final instant of time T. Final-pt(T) may or may not be a part of T.
minus-initial-pt(T) $=_{def}$ T minus initial-pt(T).
minus-final-pt(T) $=_{def}$ T minus final-pt(T).
middle(T) $=_{def}$ T minus initial-pt(T) and final-pt(T).

The goal path, *to Y*, has the representation:

inst(E, motion-type)
∧ inst(E´, TPP) ∧ arg1(E´) = loc(E) ∧ arg2(E´) = proximity(loc(Y))
∧ time(E´) = final-pt(time(E))
∧ inst(E´´, not(P)) ∧ arg1(E´´) = loc(E) ∧ arg2(E´´) = proximity(loc(Y))
∧ time(E´´) = minus-final-pt(time(E))

An event with a composite bounded path, such as *John walked from the house to the store,* can therefore be represented as follows:

inst(e3, walking) ∧ agent(e3) = john1
∧ inst(e4, TPP) ∧ arg1(e4) = loc(e3) ∧ arg2(e4) = proximity(loc(house1))
∧ time(e4) = initial-pt(time(e3))
∧ inst(e5, not(P)) ∧ arg1(e5) = loc(e3) ∧ arg2(e5) = proximity(loc(house1))
∧ time(e5) = minus-initial-pt(time(e3))
∧ inst(e6, TPP) ∧ arg1(e6) = loc(e3) ∧ arg2(e6) = proximity(loc(store1))
∧ time(e6) = final-pt(time(e3))
∧ inst(e7, not(P)) ∧ arg1(e7) = loc(e3) ∧ arg2(e7) = proximity(loc(store1))
∧ time(e7) = minus-final-pt(time(e3))

Bounded paths are also present in event types such as *enter*, *arrive* and *leave*, analyses of which are proposed in Asher & Sablayrolles (1995)

In Jackendoff's second class of paths, called *directions*, "the reference object or place does not fall on the path, but would if the path were extended some unspecified distance" (Jackendoff, 1983, p.165). Such paths may either be in the direction of the reference object, as in *toward the house* or *in the direction of the village*, or in a direction away from the reference object, as in *away from the store.* In general, *toward X* can be represented as:

inst(E, motion-type)
∧ inst(E´, toward) ∧ arg1(E´) = direction(loc(E), path(E)) ∧ arg2(E´) = loc(X)

Direction(L,P) is a function which gives the direction of the first derivative of the path P at the given location L. Similarly, *away from X* can be represented as:

inst(E, motion-type)
∧ inst(E´, away-from) ∧ arg1(E´) = direction(loc(E), path(E)) ∧ arg2(E´) = loc(X)

As an example, *the missile flew toward the jet* could be represented as:

inst(e6, flying) ∧ theme(e6) = missile1
∧ inst(e7, toward) ∧ arg1(e7) = direction(loc(e6), path(e6)) ∧ arg2(e7) = loc(jet1)

In this example it is probable that the missile and the jet are moving simultaneously, and so there must be the possibility of continual adjustments in the direction of the missile.

The third class of paths, called *routes*, is characterized by having the reference object or place be related to an interior point on the path. Some route expressions are *by the school, along the river, through the tunnel,* and *across the field.* The truth conditions for routes can be quite complex. As an example, we represent *through X* as follows:

inst(E, motion-type)
∧ inst(E1, TPP) ∧ arg1(E1) = loc(E) ∧ arg2(E1) = proximity(loc(end1(X)))
∧ time(E1) = initial-pt(time(E))
∧ inst(E2, not(P)) ∧ arg1(E2) = loc(E) ∧ arg2(E2) = proximity(loc(X))
∧ time(E2) = minus-initial-pt(time(E))
∧ inst(E3, TPP) ∧ arg1(E3) = loc(E) ∧ arg2(E3) = proximity(loc(end2(X)))
∧ time(E3) = final-pt(time(E))
∧ inst(E4, not(P)) ∧ arg1(E4) = loc(E) ∧ arg2(E4) = proximity(loc(end2(X)))
∧ time(E4) = minus-final-pt(time(E))
∧ inst(E5, P) ∧ arg1(E5) = loc(E) ∧ arg2(E5) = interior(loc(X))
∧ time(E5) = time(E)

Therefore we can represent *Mary ran through the tunnel* as:

inst(e14, running) ∧ agent(e14) = mary1 ∧ before(time(e14), ST)
∧ inst(e15, TPP) ∧ arg1(e15) = loc(e14) ∧ arg2(e15) = proximity(loc(end1(tunnel1)))
∧ time(e15) = initial-pt(time(e14))
∧ inst(e16, not(P)) ∧ arg1(e16) = loc(e14) ∧ arg2(e16) = proximity(loc(tunnel1))
∧ time(e16) = minus-initial-pt(time(e14))
∧ inst(e17, TPP) ∧ arg1(e17) = loc(e14) ∧ arg2(e17) = proximity(loc(end2(tunnel1)))
∧ time(e17) = final-pt(time(e14))
∧ inst(e18, not(P)) ∧ arg1(e18) = loc(e14)
∧ arg2(e18) = proximity(loc(end2(tunnel1)))
∧ time(e18) = minus-final-pt(time(e14))
∧ inst(e19, P) ∧ arg1(e19) = loc(e14) ∧ arg2(e19) = interior(loc(tunnel1))
∧ time(e19) = time(e14)

Essentially, what this formula says is that Mary ran from one end of the tunnel to the other end by way of the interior of the tunnel.

5 Spatial Deixis and Anaphora

In spatial deixis, regions of space are indicated through pointing. One possibility is to treat these regions as constants. For example, *John lives here* can be represented as:

$$
\begin{aligned}
&\text{indicated-region(region1)} \\
&\quad \wedge \text{inst(e15, living-state)} \wedge \text{theme(e15)} = \text{john1} \wedge \text{during(ST, time(e15))} \\
&\quad \wedge \text{inst(e16, P)} \wedge \text{arg1(e16)} = \text{loc(e15)} \wedge \text{arg2(e16)} = \text{interior(region1)} \\
&\quad \wedge \text{time(e16)} = \text{time(e15)}
\end{aligned}
$$

Here and *there* can also be used for spatial anaphora. For example, *Al lives on the Ohio in Kentucky and Ed works there* can be represented as:

$$
\begin{aligned}
&\text{inst(e20, living-state)} \wedge \text{theme(e20)} = \text{al1} \wedge \text{during(ST, time(e20))} \\
&\quad \wedge \text{inst(e21, P)} \wedge \text{arg1(e21)} = \text{loc(e20)} \\
&\qquad \wedge \text{arg2(e21)} = \cap\text{(proximity(loc(Ohio-River)), interior(loc(Kentucky)))} \\
&\quad \wedge \text{inst(e22, working-state)} \wedge \text{theme(e22)} = \text{ed1} \wedge \text{during(ST, time(e22))} \\
&\quad \wedge \text{inst(e23, P)} \wedge \text{arg1(e23)} = \text{loc(e22)} \\
&\qquad \wedge \text{arg2(e23)} = \cap\text{(proximity(loc(Ohio-River)), interior(loc(Kentucky)))}
\end{aligned}
$$

In this example, the referent of *there* is the spatial function:

$$\cap\text{(proximity(loc(Ohio-River)), interior(loc(Kentucky)))}$$

where $\leftrightarrow$ gives us the spatial intersection of the two regions. As discussed in Creary et al. (1989, p.45), in this sentence *there* may be understood as referring to the intersection of the complete regions ‘on the Ohio’ and ‘in Kentucky’, but not to the particular subpart where Al lives. Therefore, a simple conjunction of the two relations will not provide the region we need to serve as the referent of *there.*

Another interesting example of spatial anaphora from Creary et al. (p.45) is *Bill sang everywhere Mary sang.* Our proposed representation for this sentence is:

$$
\begin{aligned}
&\forall\, e, e', x\ .\ \text{inst(e, singing)} \wedge \text{agent(e)} = \text{mary1} \wedge \text{before(time(e), ST)} \\
&\qquad\qquad \wedge \text{inst(e}', \text{P)} \wedge \text{arg1(e}') = \text{loc(e}') \wedge \text{arg2(e}') = \text{loc(x)} \\
&\qquad\qquad \wedge \text{time(e}') = \text{time(e)} \\
&\qquad \rightarrow \exists\, e'', e'''\ .\ \text{inst(e}'', \text{singing)} \wedge \text{agent(e}'') = \text{bill1} \wedge \text{before(time(e}''), \text{ST)} \\
&\qquad\qquad\qquad\qquad \wedge \text{inst(e}''', \text{P)} \wedge \text{arg1(e}''') = \text{loc(e}'') \wedge \text{arg2(e}''') = \text{loc(x)} \\
&\qquad\qquad\qquad\qquad \wedge \text{time(e}''') = \text{time(e}'')
\end{aligned}
$$

6 Time-Aware Reasoning about Spatial Relations

The atemporal definitions of the spatial relations of Randell et al. (1992) given above can now be written in terms of locative events for time-aware spatial reasoning.

(1) To start with, the lattice of spatial relations in Randell et al. (p.168), can now be understood as a lattice of locative event types:

$$\text{subtype}(O, C) \wedge \text{subtype}(EC, C) \wedge \text{subtype}(P, O) \wedge \text{subtype}(P^{-1}, O) \wedge \text{subtype}(PO, O)$$
$$\wedge\ \text{subtype}(PP, P) \wedge \text{subtype}(EQ, P) \wedge \text{subtype}(EQ, P^{-1}) \wedge \text{subtype}(PP^{-1}, P^{-1})$$
$$\wedge\ \text{subtype}(TPP, PP) \wedge \text{subtype}(NTPP, PP) \wedge \text{subtype}(NTPP^{-1}, PP^{-1})$$
$$\wedge\ \text{subtype}(TPP^{-1}, PP^{-1}) \wedge \text{subtype}(DC, DR) \wedge \text{subtype}(EC, DR)$$

Assuming ordinary inheritance rules, such as those given here, a number of needed inferences are provided directly by this type lattice.

$$\text{inst}(e, R) \wedge \text{subtype}(R, R') \rightarrow \text{inst}(e, R')$$
$$\text{subtype}(R, R') \wedge \text{subtype}(R', R'') \rightarrow \text{subtype}(R, R'')$$

The definitions of the other locative event types in terms of the connectivity (C) event type are as follows:

(2) region x is disconnected from region y:

$$\text{inst}(e, DC) \leftrightarrow \text{inst}(e, \text{not}(C))$$

(3) region x is part of region y:

$$[\text{inst}(e, P) \wedge \text{arg1}(e) = x \wedge \text{arg2}(e) = y \wedge \text{time}(e) = i]$$
$$\leftrightarrow$$
$$[\forall z, e'. (\text{inst}(e', C) \wedge \text{arg1}(e') = z \wedge \text{arg2}(e') = x \wedge \text{time}(e') = i)$$
$$\rightarrow \exists e''. \text{inst}(e'', C) \wedge \text{arg1}(e'') = z \wedge \text{arg2}(e'') = y \wedge \text{time}(e'') = i]$$

(4) region x is a proper part of region y:

$$[\exists e''. \text{inst}(e'', PP) \wedge \text{arg1}(e'') = x \wedge \text{arg2}(e'') = y \wedge \text{time}(e'') = i]$$
$$\leftrightarrow$$
$$[\exists e,e'. \text{inst}(e, P) \wedge \text{arg1}(e) = x \wedge \text{arg2}(e) = y$$
$$\wedge\ \text{inst}(e', \text{not}(P)) \wedge \text{arg1}(e') = y \wedge \text{arg2}(e') = x$$
$$\wedge\ i = \cap(\text{time}(e),\text{time}(e'))]$$

(5) region x is equal to region y:

$$[\exists e''. \text{inst}(e'', EQ) \wedge \text{arg1}(e'') = x \wedge \text{arg2}(e'') = y \wedge \text{time}(e'') = i]$$
$$\leftrightarrow$$
$$[\exists e,e'. \text{inst}(e, P) \wedge \text{arg1}(e) = x \wedge \text{arg2}(e) = y$$
$$\wedge\ \text{inst}(e', P) \wedge \text{arg1}(e') = y \wedge \text{arg2}(e') = x$$
$$\wedge\ i = \cap(\text{time}(e),\text{time}(e'))]$$

(6) region x overlaps region y:

$$[\exists e. \text{inst}(e, O) \wedge \text{arg1}(e) = x \wedge \text{arg2}(e) = y \wedge \text{time}(e) = i]$$
$$\leftrightarrow$$

$$[\exists e',e'',z.\ inst(e', P) \wedge arg1(e') = z \wedge arg2(e') = x$$
$$\wedge\ inst(e'', P) \wedge arg1(e'') = z \wedge arg2(e'') = y$$
$$\wedge\ i = \cap(time(e'),time(e''))]$$

(7) region x partially overlaps region y:

$$[\exists e.\ inst(e, PO) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$$
$$\leftrightarrow$$
$$[\exists e',e'',e'''.\ inst(e', O) \wedge arg1(e') = x \wedge arg2(e') = y$$
$$\wedge\ inst(e'', not(P)) \wedge arg1(e'') = x \wedge arg2(e'') = y$$
$$\wedge\ inst(e''', not(P)) \wedge arg1(e''') = y \wedge arg2(e''') = x$$
$$\wedge\ i = \cap(time(e'),time(e''),time(e'''))]$$

(8) region x is discrete from region y:

$$inst(e, DR) \leftrightarrow inst(e, not(O))$$

(9) region x is a tangential proper part of region y:

$$[\exists e.\ inst(e, TPP) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$$
$$\leftrightarrow$$
$$[\exists e',e'',e''',z.\ inst(e', PP) \wedge arg1(e') = x \wedge arg2(e') = y$$
$$\wedge\ inst(e'', EC) \wedge arg1(e'') = z \wedge arg2(e'') = x$$
$$\wedge\ inst(e''', EC) \wedge arg1(e''') = z \wedge arg2(e''') = y$$
$$\wedge\ i = \cap(time(e'),time(e''),time(e'''))]$$

(10) region x is externally connected to region y:

$$[\exists e''.\ inst(e'', EC) \wedge arg1(e'') = x \wedge arg2(e'') = y \wedge time(e'') = i]$$
$$\leftrightarrow$$
$$[\exists e,e'.\ inst(e, C) \wedge arg1(e) = x \wedge arg2(e) = y$$
$$\wedge\ inst(e', not(O)) \wedge arg1(e') = x \wedge arg2(e') = y$$
$$\wedge\ i = \cap(time(e),time(e'))]$$

(11) region x is a nontangential proper part of region y:

$$[\exists e.\ inst(e, NTPP) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$$
$$\leftrightarrow$$
$$[[\exists e'.\ inst(e', PP) \wedge arg1(e') = x \wedge arg2(e') = y \wedge time(e') = i]$$

$$[\neg\exists e'',e''',z.\ inst(e'', EC) \wedge arg1(e'') = z \wedge arg2(e'') = x$$
$$\wedge\ inst(e''', EC) \wedge arg1(e''') = z \wedge arg2(e''') = y$$
$$\wedge\ during(\leftrightarrow(time(e''),time(e''')), i)]]$$

(12) the inverse of P:

$$[\exists e.\ inst(e, P) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$$

$\leftrightarrow$

$[\exists e'.\ inst(e', P^{-1}) \wedge arg1(e') = y \wedge arg2(e') = x \wedge time(e') = i]$

(13) the inverse of PP:

$[\exists e.\ inst(e, PP) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$

$\leftrightarrow$

$[\exists e'\ .\ inst(e', PP^{-1}) \wedge arg1(e') = y \wedge arg2(e') = x \wedge time(e') = i]$

(14) the inverse of TPP:

$[\exists e.\ inst(e, TPP) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$

$\leftrightarrow$

$[\exists e'\ .\ inst(e', TPP^{-1}) \wedge arg1(e') = y \wedge arg2(e') = x \wedge time(e') = i]$

(15) the inverse of NTPP:

$[\exists e.\ inst(e, NTPP) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$

$\leftrightarrow$

$[\exists e'.\ inst(e', NTPP^{-1}) \wedge arg1(e') = y \wedge arg2(e') = x \wedge time(e') = i]$

The seven nonbasic relations are related to the basic relations as follows:

(1) connected to:

$[\exists e.\ inst(e, C) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$

$\leftrightarrow$

$[\exists e'.\ [inst(e', O) \vee inst(e', EC)] \wedge arg1(e') = x \wedge arg2(e') = y \wedge time(e') = i]$

(2) part of:

$[\exists e.\ inst(e, P) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$

$\leftrightarrow$

$[\exists e'.\ [inst(e', PP) \vee inst(e', EQ)] \wedge arg1(e') = x \wedge arg2(e') = y \wedge time(e') = i]$

(3) proper-part of:

$[\exists e.\ inst(e, PP) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$

$\leftrightarrow$

$[\exists e'.\ [inst(e', TPP) \vee inst(e', NTPP)] \wedge arg1(e') = x \wedge arg2(e') = y \wedge time(e') = i]$

(4) overlaps:

$[\exists e.\ inst(e, O) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$

$\leftrightarrow$

$[\exists e'.\ [inst(e', P) \vee inst(e', P^{-1}) \vee inst(e', PO)] \wedge arg1(e') = x \wedge arg2(e') = y$
$\wedge\ time(e') = i]$

(5) discrete from:

$[\exists e.\ inst(e, DR) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$

$\leftrightarrow$

$[\exists e'. [inst(e', DC) \vee inst(e', EC)] \wedge arg1(e') = x \wedge arg2(e') = y \wedge time(e') = i]$

(6) the inverse of part of:

$[\exists e. inst(e, P^{-1}) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$

$\leftrightarrow$

$[\exists e'. [inst(e', PP^{-1}) \vee inst(e', EQ)] \wedge arg1(e') = x \wedge arg2(e') = y \wedge time(e') = i]$

(7) the inverse of proper-part of:

$[\exists e. inst(e, PP^{-1}) \wedge arg1(e) = x \wedge arg2(e) = y \wedge time(e) = i]$

$\leftrightarrow$

$[\exists e'. [inst(e', TPP^{-1}) \vee inst(e', NTPP^{-1})] \wedge arg1(e') = x \wedge arg2(e') = y \wedge time(e') = i]$

The symmetric spatial relations are C, DC, EQ, O, PO, DR and EC. The axiom schema for symmetric relations, R, is as follows:

$$inst(e, R) \rightarrow \exists e'. inst(e', R) \wedge arg1(e') = arg2(e) \wedge arg2(e') = arg1(e) \wedge time(e') = time(e)$$

The transitive spatial relations are P, PP, EQ, NTPP, P^{-1}, PP^{-1} and $NTPP^{-1}$. The axiom schema for transitive relations, R, is as follows:

$$inst(e, R) \wedge arg1(e) = x \wedge arg2(e) = y \wedge inst(e', R) \wedge arg1(e') = y \wedge arg2(e') = z \rightarrow \exists e''. inst(e'', R) \wedge arg1(e'') = x \wedge arg2(e'') = z \wedge time(e'') = \cap(time(e),time(e'))$$

The subinterval (or homogeneity) property as applied to spatial relations, R, is expressed by:

$$subevent(e, e') \wedge inst(e', R) \rightarrow inst(e, R)$$

$$inst(e', R) \wedge during(t, time(e')) \rightarrow \exists e. subevent(e, e') \wedge time(e) = t$$

7 Conclusion

In this paper, we have proposed an event-based approach to the representation of spatial information. The essential idea is to treat spatial relations as stative event types. This approach is able to accommodate any complications due to spatial changes in one or more of the related objects, as well as providing the benefits of the event-centered representational approach, particularly with respect to perception and inference. The utility of this proposal was illustrated through examples of representations of locative events, various types of motion events, spatial deixis and spatial anaphora. Finally, the atemporal spatial axioms of Randell et al. (1992) were translated into event-based axioms for time-aware spatial reasoning.

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