Accepted for GIScience 2004

From objects to events: GEM, the geospatial event model

Michael Worboys and Kathleen Hornsby

National Center for Geographic Information and Analysis
University of Maine, Orono ME 04469-5711, USA
{worboys, khornsby}@spatial.maine.edu

Abstract

This paper discusses the construction of a modeling approach for dynamic geospatial domains based on the concepts of object and event. The paper shows how such a model extends traditional object-based geospatial models. The focus of the research is the introduction of events into the object-based paradigm, and consequent work on the classification of object-event and event-event relationships. The specific geospatial nature of this model is captured in the concept of a geosetting. The paper also introduces an extension of UML diagrams to incorporate events and their relationship to each other, and to objects. The paper briefly considers an example to show the working of some of the modeling constructs, and concludes with a discussion of further research needed on event aggregation and event-based query languages.

Keywords: event, object, conceptual model

1. Introduction

This paper reports on introductory work on the foundation for the formulation of conceptual models for information systems concerned with dynamic, geospatial domains. Here, the term *conceptual model* refers to a structured representation of part of the world that is to be captured by the information system. Although the representation is structured, it is not yet at the level for direct translation into a form accepted by the database system. In Guarino's terms (Guarino 1998), the paper constructs an *ontology*; "a specific vocabulary used to describe a certain reality, plus a set of explicit assumptions regarding the intended meaning of the vocabulary words." Moreover, the ontology is *upper-level*, as the constructs are general enough to be used in many scenarios involving dynamic, spatial entities. Throughout, we shall use the term *model* to describe this structured collection of upper-level constructs.

From an ontological perspective, an initial distinction can be made between entities existing in the world either as *continuants* or *occurrents.* Continuant entities endure through some extended (although possibly very short) interval of time (e.g., houses, roads, cities, and people). Occurrent entities happen and are then gone (e.g., a house repair job, road construction project, urban expansion, a person's life). There is a difference between a city, whose characteristics are recorded by census and surveyed once each decade, say, and the processes of urban growth and decline, migration, and expansion, that constitute the city in flux. From an information system perspective, continuants and occurrents that have a unique identity in the system are referred to as *objects* and *events*, respectively. In this paper we will not use the term *process*. Events and processes have distinct, although rather elusively definable, shades of meaning, but essentially speak to the same underlying idea. The event of constructing a new ramp from Stillwater Avenue to the I95 highway is clearly related to the process of ramp construction.

Objects and events are both needed to model fully a dynamic system. While continuant entities endure through time, they will usually change some or all of their attributes. Traditionally, such time-varying continuants are represented in information systems as temporally indexed collections of objects or collections of objects, called *snapshots*. The shortcomings of such a representation are that the events that underlie changes are not explicitly represented; indeed the changes are themselves not explicitly represented (Chrisman 1998). Events are needed to capture the mechanisms of change.

Objects and events are fundamentally different, but, as we will see in this paper, from an information modeling perspective, can be treated in many ways as structurally similar. The approach of this paper is to use as much as possible of the methods of object-orientation, designed for modeling static entities, to event modeling. Therefore, we assume a background of basic object-oriented modeling. Our constructions will be framed in a UML-like formalism (Booch *et al.* 1999).

The motivation for this work is a contribution to the development of a general approach to modeling dynamic geospatial phenomena for information system development. Current modeling approaches are limited in that they are capable in only a limited way of expressing dynamic aspects of the world. This work is connected to work (Worboys 2004) concerned with more formal aspects of event specification using process algebras, and to the construction of temporal and event-oriented ontologies (for example, Hobbs 2002, Pan and Hobbs 2004). In (Worboys 2004) a pure event model is developed, in which all entities are modeled as occurrents. In this work we adopt a hybrid approach, allowing three main categories of entities: objects, events, and settings.

The motivation behind this research is that a dynamic model should be capable of formal verification, and should be translatable into a logical model – the next stage of system development. As an example of the kind of capability that this work provides is the ability to specify in what ways events may be aggregated (this is the content of Section 7). An important direction in which this work is leading is to the construction of a query language in which configurations of objects, events, and their relationships, can be framed.

2. Geospatial settings and the situation function

The distinguishing characteristic of a geospatial entity, whether object or event, is its *setting*. Each geospatial object or event is *situated* in a setting. A setting may be either spatial, temporal, or a combination of both. An object or event, however, cannot be situated in more than one setting at the same time. Here, settings do not just refer to point locations, so we allow the possibility of an object or event being situated over an extended location (such as a region, or a time period). Geospatial entities also have the property that their settings are at an appropriate scale, neither too small (e.g., not at the quantum scale) nor too large (not at the cosmic scale).

A setting may be:

1. Purely *spatial* (e.g., point, line, region, or composition thereof). Spatial geosettings have been extensively studied in the GIScience literature (Worboys 1995). Spatial settings may be zero, one, two, or three-dimensional, and are often explicitly or implicitly assumed to be embedded in a space, such as a Euclidean space, a metric space, or a topological space.

2. Purely *temporal* (e.g., instant, interval, period). Temporal settings have also been well researched in the artificial intelligence and temporal database literature (Allen 1983, Snodgrass 1995, 2000). Temporal settings may be zero or one-dimensional, and are explicitly or implicitly assumed to be embedded in a space, such as a linearly ordered set, a partially ordered set, a discrete or continuous set, or a cyclical structure.

3. Mixed *spatio-temporal*. By our constraint that an object or event cannot be situated in more than one setting at the same time, we do not allow the full Cartesian product of space and time here. Formally, spatio-temporal settings are functions from a temporal setting to a spatial setting. Spatio-temporal settings are called *trajectories* (Partsinevelos *et al.* 2001)), *histories* (Griffiths 2002, Galton 2004), or *geospatial lifelines* (Hornsby and Egenhofer 2002).

Just as with objects and events, settings may be abstracted into classes. The classes of all purely spatial and purely temporal settings are denoted **`SpatialSettingClass`** and **`TemporalSettingClass`**, respectively. The class of all spatio-temporal settings is denoted **`STSettingClass.`** Settings may have attributes (e.g., the duration of a time interval, the area of a region). Settings may be organized into subsumption hierarchies (e.g., **`Region`** subsumes **`SimplyConnectedRegion`**). Settings also have spatial, temporal, or spatio-temporal parts, depending upon context, and may be composed into composite entities (e.g., **`Regions`** as a composition of settings in class **`Region`**). However, in the strict sense, settings are not to be considered as objects in the object-oriented sense. A setting does not have an identifier that remains the same when its attributes change. For example, a time interval [3,6], becomes a different interval, when its end-point changes from 6 to 7. In programming language terminology, settings are *literals* or *constants.*

2.1 The Situate function

A function **`Situate`** maps each geospatial object or event to its situation or location in a setting. We will see below that **`Situate`** acts differently, depending on whether the situated entity is an object or an event. However, each geospatial object and event has a unique setting, specified by the action of the **`Situate`** function. If **`GOClass,`** **`GEClass`**, and **`SettingClass,`** denote the classes of geospatial objects, events and settings, respectively, then we have the following definition:

$$\texttt{Situate: GOClass} \cup \texttt{GEClass} \rightarrow \texttt{SettingClass}$$

2.2 Relationships between settings

This section briefly reviews work on setting – setting relationships, in the case where the settings are spatial, temporal, or spatio-temporal. The first remark is that these three kinds of settings do not mix; we do not allow, for example, a spatial setting to stand in relation to a temporal setting.

Spatial settings: Subsumption hierarchies of zero, one and two-dimensional spatial settings are discussed in (Worboys 1995). Part-whole relationships are classically handled by treating a spatial setting as a set of points, and using the subset relationship. Non-classical, mereological approaches that do not assume sets of points stem from the work of Brentano (Simons 1987). Spatial relationships between spatial settings have been investigated by many authors (Egenhofer and Franzosa 1991, Cui *et al.* 1993).

Temporal settings: These have been extensively investigated by the artificial intelligence and temporal database communities. There are three basic classes: **`TemporalInstant`**, **`TemporalInterval`** and **`TemporalPeriod`** (a composition of **`TemporalInterval`**). Reasoning about temporal relationships between temporal settings that are intervals is handled by Allen's interval calculus (Allen 1983) for the linear case and for cycles by Hornsby *et al.* (1999).

Spatio-temporal settings: As discussed above, members of **`STSettingClass`** can considered as functions from temporal to spatial settings, and inherit in this way the properties of their components. Formally,

$$\texttt{STSettingClass} =_{def} [\texttt{TemporalSettingClass} \rightarrow \texttt{SpatialSettingClass}]$$

Thus each member of **`STSettingClass`** assigns to each element of a temporal setting (e.g., each time instant in a temporal interval) an element of a spatial setting (e.g. a point in a spatial region).

Spatio-temporal relations between two spatio-temporal settings may be defined with reference to relations between the domains and codomains of the functions representing them. For example, we can define *disjunction* relations as follows. Let $\texttt{STSet}_1 : \texttt{TS}_1 \rightarrow \texttt{SS}_1$ and $\texttt{STSet}_2 : \texttt{TS}_2 \rightarrow \texttt{SS}_2$ be two instances of **`STSettingClass.`**

$$\texttt{TDisjoint}(\texttt{STSet}_1, \texttt{STSet}_2) =_{def} \texttt{TDisjoint}(\texttt{TS}_1, \texttt{TS}_2)$$

$$\texttt{SDisjoint}(\texttt{STSet}_1, \texttt{STSet}_2) =_{def} \texttt{SDisjoint}(\texttt{Image}(\texttt{STSet}_1), \texttt{Image}(\texttt{STSet}_2))$$

$$\texttt{STDisjoint}(\texttt{STSet}_1, \texttt{STSet}_2) =_{def} \forall \texttt{t} \in \texttt{TS}_1 \cap \texttt{TS}_2 .\ \texttt{STSet}_1(\texttt{t}) \cap \texttt{STSet}_2(\texttt{t}) = \varnothing$$

The first of these equations defines two spatio-temporal settings to be temporally disjoint if and only if their temporal domains are temporally disjoint (note the overloading of the **`TDisjoint`** relation). The second defines two spatio-temporal settings to be spatially disjoint if and only if their spatial images are spatially disjoint (note the overloading of the **SDisjoint** relation). The third defines two spatio-temporal settings to be spatio-temporally disjoint if and only if at each temporal element that they share, their spatial settings are spatially disjoint.

These definitions are not independent. In particular, we have:

$$\mathbf{TDisjoint}(\mathbf{STSet}_1, \mathbf{STSet}_2) \Rightarrow \mathbf{STDisjoint}(\mathbf{STSet}_1, \mathbf{STSet}_2)$$

$$\mathbf{SDisjoint}(\mathbf{STSet}_1, \mathbf{STSet}_2) \Rightarrow \mathbf{STDisjoint}(\mathbf{STSet}_1, \mathbf{STSet}_2)$$

These definitions provide examples of possible relations between settings. There are many others that could be defined similarly.

3. Static geospatial object model

The general conceptual model of static geospatial entities has been thoroughly investigated, both in the object (Egenhofer and Frank 1992, Worboys et al. 1990) and field settings (Tomlin 1990). In this paper, a geospatial object is defined as an object that is situated in a setting (Figure 1). As the diagram shows, geospatial objects can be instances or classes, organized into composition and generalization hierarchies, and related to each other in object-object relationships.

Object situation. Time is abstracted from the static geospatial object model, and **the settings in which geospatial objects are situated are purely spatial**. Purely spatial settings are described in the previous section. We have the following functional restriction of **Situate** to geospatial objects.

$$\mathbf{Situate: GOClass} \rightarrow \mathbf{SpatialSettingClass}$$

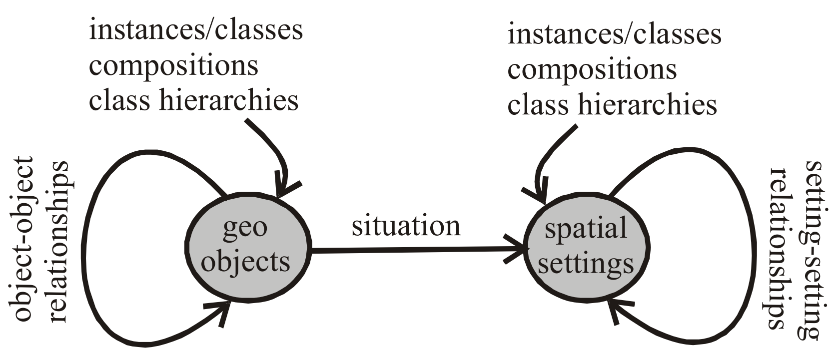

Figure 1. Underlying geospatial object model

A *temporal snapshot* of a collection of geospatial objects is an association of a timestamp to the collection. Object evolution can be modeled as a sequence of temporal snapshots. Within each snapshot, each geospatial object has a purely spatial setting. Temporal snapshot sequences can be represented formally as a function from a purely temporal setting, such as a time interval, to a collection of geospatial objects, as modeled in the previous section. This kind of representation has been discussed by Al-Taha and Barrera

(1994), Worboys (1994), Claramunt (1996), Medak (1999), and Hornsby and Egenhofer (2000).

4. The geospatial event model (GEM)

The principal contribution of this paper and the new aspect of the research is the introduction of geospatial events into the model. Figure 2 shows the scope of the geospatial event model (GEM), which encompasses geospatial objects, events and their geosettings. The gray region in the figure indicates the additional linkages and relations that need to be considered with the addition of events. The GEM, therefore, extends the geospatial object model and consists of the following:

1. Geospatial object instances and classes, their attributes, subsumption and composition hierarchies, and object-object relationships.
2. Geospatial event instances and classes, their attributes, subsumption and composition hierarchies, and event-event relationships.
3. Settings in which geospatial objects and geospatial events are situated, their instances and classes, attributes, subsumption and composition hierarchies.
4. The situation function between geospatial objects and events, and their settings.
5. Geospatial object-event participation relationships, and converse geospatial event-object involvement relationships.

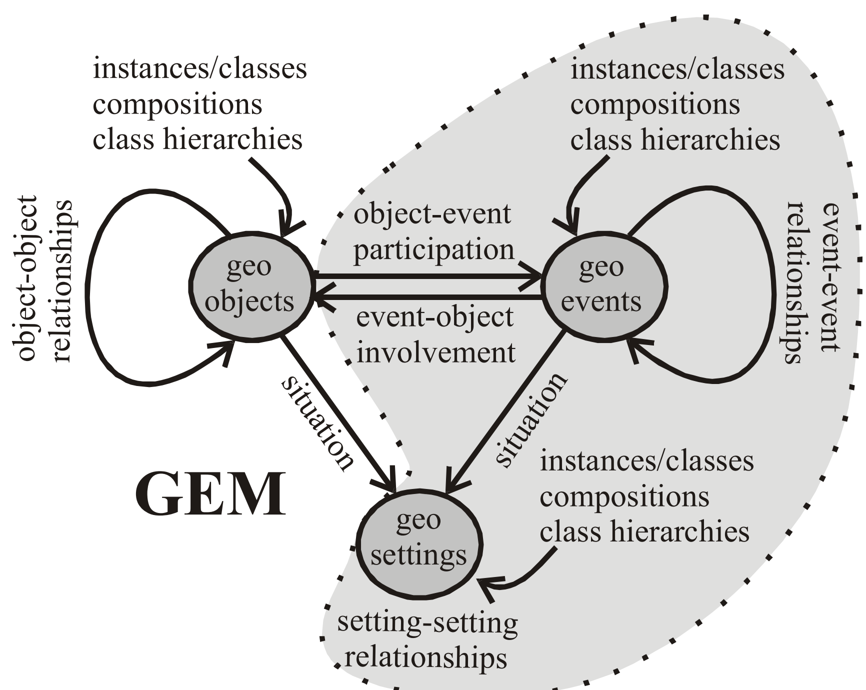

Figure 2: The GEM model: objects, events and their interaction

4.1 Underlying model of events

There are several close structural similarities between objects and events. The following lists some of the parallels:

> *Classification*. It is fundamental to the object-oriented modeling literature that object instances with similar properties and behaviors may be grouped into classes. In the same way, collections of event instances (e.g. the car overturning on Third Avenue at 3.00pm, the traffic signal failure at Main/Fifth at 3.30pm, and the gridlock on the highway at 5.00pm) can be abstracted into classes (e.g., **`TrafficEvent`**). So, events may be modeled as instances or classes.
>
> *Attribution*. As with objects, events can have *attributes* that describe their properties and qualities. So the event class **`TrafficEvent`** might have the attribute **`severity`**, and a specific instance of the class, such as the car overturning on Third Avenue at 3.00pm might have a specific severity level "moderately severe".
>
> *Subsumption* or *generalization.* Classes of both objects and events may be arranged in a hierarchy, based on the relation of subsumption. So, for example, just as object class **`Building`** subsumes object class **`Church`**, so event class **`TrafficEvent`** subsumes event class **`TrafficAccident`**.
>
> *Composition*. Both objects and events may be aggregated into composite entities, and decomposed into parts. However, there is a major distinction between objects and events. Objects may have spatial parts, but events may have temporal or spatio-temporal parts. So, for example, just as object class **`Building`** may be composed of a collection of objects in classes **`Roof`**, **`Window`**, **`Door`**, and so on, so event class **`TrafficAccident`** may be composed of events in classes **`TrafficAccidentReport`**, and **`EmergencyResponse`**. The issue of composition is discussed at greater length below.

Event situation. As with geospatial objects, what makes an event geospatial is its situation in an appropriate setting. The static geospatial object model is timeless and **the settings in which geospatial events are situated are spatio-temporal**. The nature of **`STSettingClass`** has been discussed above. We have the following functional restriction of **`Situate`** to geospatial events.

`Situate: GEClass → STSettingClass`

Note. We are glossing over some issues here. As discussed in (Casati and Varzi 1999), the ways in which an object occupies a region of space and an event occupies a region of spacetime are rather different. In some approaches, a geospatial event might be better thought of as occupying a purely temporal location. Indeed, the distinction has often been made between the spatial parts of a geospatial object, such as the rooms of a house, and the temporal parts of geospatial event, such as the stages of urban decay. Even here there is some looseness, as strictly the adjectives "spatial" and "temporal" should really apply to the settings.

4.2 Geospatial event-event relationships

While there is considerable research in the general data modeling and GIScience literatures on categories of geospatial object-object relationships, there is less work on event-event relationships. Many geospatial event relationships may reduced to relationships between their settings. For example, the issue of whether our trip will take us through the thunderstorm is actually a question of spatio-temporal overlap between the geospatial settings of “trip” and “thunderstorm”. However, there are cases where the relationship is directly between events themselves. This section provides a brief categorization of such relationships.

General kinds of event-event relationships (Grenon and Smith 2004) include, in order of decreasing positive effect:

- *Initiation*: The occurrence of event *A* starts event *B* in progress. E.g., the lights turning green initiates the progress of the vehicle along the road segment.

- *Perpetuation/facilitation*: The occurrence of event *A* plays a positive role in the initiation or continuation of event *B*. E.g., opening the door allows the procession to continue; the opening of a second toll booth facilitated traffic flow in the evening rush hour.

- *Hindrance/blocking*: The occurrence of event *A* plays a positive role in the weakening, temporary stoppage, or termination of event *B*. E.g., the closing of a second toll booth hindered traffic flow in the evening rush hour.

- *Termination*: The occurrence of event *A* allows/forces event *B*, already initiated, to terminate. E.g., running out of fuel terminates the progress of the vehicle along the road segment.

Even though settings have been excluded from this discussion, it is clear that setting-setting relationships will provide constraints on the existence of the above event-event relationship types. For example, the spatio-temporal setting of a traffic light changing to red must be closely related to that of the vehicle journey for the behavior of the lights to impact the journey.

4.3 Geospatial object-event relationships: participation and involvement

Objects and events are closely bound up with each other. Without the occurrence of events (e.g., object creation), objects will not exist. Conversely, without objects many (all?) events will have a vacuity; a traffic jam cannot exist without traffic. This section explores the kinds of relationships can obtain between objects and events, and conversely between events and objects? Again, following Grenon and Smith (2004), these relationships are characterized as *participation* and *involvement* relationships. So, objects participate in events and events involve objects. As with event-event relationships, we are not concerned in this section with relationships between the settings of the objects and events.

A fundamental example of an object-event relationship is the *agentive* relationship, where an object acts to produce a particular event (e.g., a person opens the door). This leads to a subcategory of event, the category of *actions*, in which at least one agent is involved. The dual of the agentive relationship is the *patientive* object-event relationship. Characterizations of objects based on their role with respect to events include the following: *perpetrator objects (initiators*, *perpetuators*, *terminators*), *influencing objects* (*facilitators and hindrances*), and *mediator objects*. The semantics for these categories is similar to the event-event cases above. A new case is *mediation*, where the mediator plays a positive but indirect role in a process involving other participating objects. For example, the building mediates the meeting between John and Mary.

At the object or event class level, in any participation relation, it may be important to know whether participation in an event, or class of events, is mandatory for a particular object, or class of objects. We have already seen in the participation of traffic in a traffic jam, a relationship where the object class traffic is mandatory for an event of class traffic jam to occur. On the other hand, the participation of faulty traffic signals is not mandatory.

The classification of types of involvement of events with objects, following Grenon and Smith, includes:

- *Creation*: An event that results in the creation of an object. For example, a bridge-building event may result in a new bridge.
- *Sustaining in being*: An event that results in the continuation in existence of an object. For example, a bridge-painting event may result in the continued life of the bridge.
- *Reinforcement/degradation*: An event that has positive/negative effects on the existence of an object. For example, plowing snow from a road keeps the road open to traffic; a storm event may result in the loss of some functionality (load-bearing ability) of the bridge.
- *Destruction*: An event that results in the destruction of an object. For example, an explosion event may result in the loss of a bridge.
- *Splitting/merger*: An event that creates/destroys a boundary between objects. For example, the splitting/merging of East and West Germany.

As with participation events, we can categorize involvements as optional or mandatory on the involving events. For example, changing ownership is mandatory upon selling a land parcel, but painting the bridge may only be optional on the continuation of the bridge.

5. GEM as a modeling approach

This analysis offers an approach to modeling information systems that deal with dynamic aspects of the geospatial world. This section considers some aspects of this approach, in particular presenting a diagrammatic notation for representing entities and relationships of the GEM model. We use a notation that extends Unified Modeling Language (UML) constructs (Booch *et al.* 1999). For previous work on spatial visual languages that are UML-based see, for example, Bédard (1999).

From the discussion above, geospatial object and event classes, **`GOClass`** and **`GEClass`**, respectively have the following structure to their definitions:

```
GOClass
     identifier
          GOID
     setting
          Situation:     SpatialSettingClass
     attributes
          Attribute_1:    OClass_1
          ...
          Attribute_m:    OClass_m
     object relationships
          ORel_1          OClass_1
          ...
          ORel_n          OClass_n
     event participation relationships
          PartRel_1       EClass_1
          ...
          PartRel_p       EClass_p

GEClass
     identifier
          GEID
     setting
          Situation:     SpatialSettingClass
     attributes
          Attribute_1:    OClass_1
          ...
          Attribute_m:    OClass_m
     event relationships
          ERel_1          EClass_1
          ...
          ERel_n          EClass_n
     object involvement relationships
          InvRel_1        OClass_1
          ...
          InvRel_p        OClass_p
```

These signatures require an extension of UML's class diagrams where no distinction is typically made concerning the type of class (i.e., object *vs.* event class). A **`GOClass`** diagram is a rectangular icon (Figure 3a) while GEClasses are distinguished from GOClasses through use of a rounded rectangle icon (Figure 3b). Each of these class constructs has four main components, a class name, setting, attributes, and operations.

Settings, as presented in section 3, refer to the spatial, temporal, or spatio-temporal situations that hold for a given class. Spatial settings are either zero, one, or two-dimensional. Temporal settings are either zero or one-dimensional and spatio-temporal settings are described by space-time trajectories, histories, or lifelines. GOClasses are associated with settings that are either spatial or spatio-temporal while spatio-temporal settings hold for GEClasses. Both **GOClass** and **GEClass** diagrams represent settings with a specification in the form, **settingName: settingClass**. Attributes and operations for **GOClass** and **GEClass** are represented in a similar way as UML class diagrams. Any number of attributes and operations may be specified for either **GOClass** or **GEClass.** The signature for attributes is **attributeName: Oclass** while operations are described through an operation name with an optional return class specified.

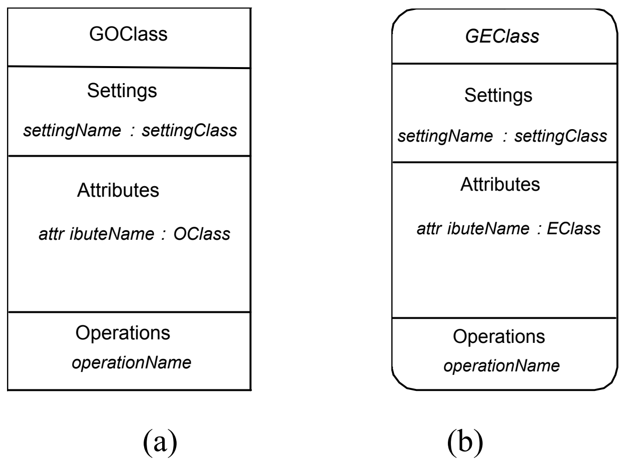

Figure 3: Class diagrams for (a) **GOClass** and (b) **GEClass**.

6. Case Study: Object and event detection

We apply the GEM to a case study that illustrates how entities and events may be modeled for a specific domain. The example scenario is an airport, where entities include airport terminals, plane hangars, various other buildings, and planes. At any given time, an airport also contains pedestrians, passenger and visitor vehicles, and other miscellaneous object entities (e.g., runways, roads, traffic signs, etc.). These entities and the relationships that hold between them can be modeled using subclasses of **GOClass**. For example, Figure 4 shows entities **Plane**, **Runway**, **Hangar**, and **People** GOClasses are associated with an **Airport GOClass** through a composition relation that models the case where these classes are *part-of* an **Airport** (aggregations are considered in more detail in the next section). Multiplicities that describe the constraints of the relationships (e.g., 1: 1..*, read as one to one or more), are attached to the class diagrams. These multiplicities are useful for detailing, for example, whether an object class has a mandatory relationship with another object class (e.g., an airport has at least one runway, and perhaps more).

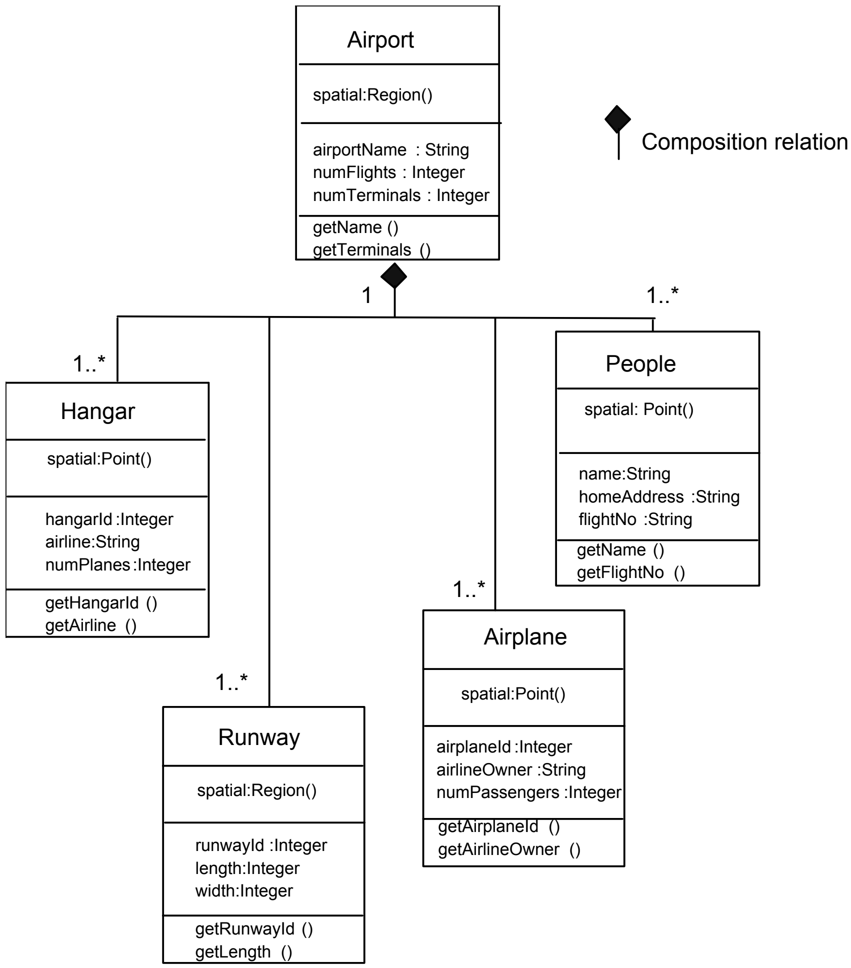

Figure 4: Airport classes

The GEM model also incorporates events that are related to these object classes, for example, **`PlaneTakeOff`** and **`PassengerBoarding`** events (Figure 5). Relating object and event classes allows an investigation of the kinds of possible relationships between object and events, (i.e., object-event participation relationships and event-object involvement relationships). The diagrammatic representation of the model depicts these dual relations through a unidirectional arrow that may be read in either direction. In the same way that certain object classes are mandatory for particular relationships, certain object-event relationships have mandatory components, for example, a **`PlaneTakeOff`** event cannot occur without a plane. This event, however, does not always have to occur on a runway, as other scenarios such as a takeoff from a lake or road (i.e., not an airport) may be possible. Thus evidence from the objects in a given domain ontology (e.g., an airport ontology with runway and plane classes) along with other object indicators (e.g, plane on the runway), contribute to the inferences of particular events.

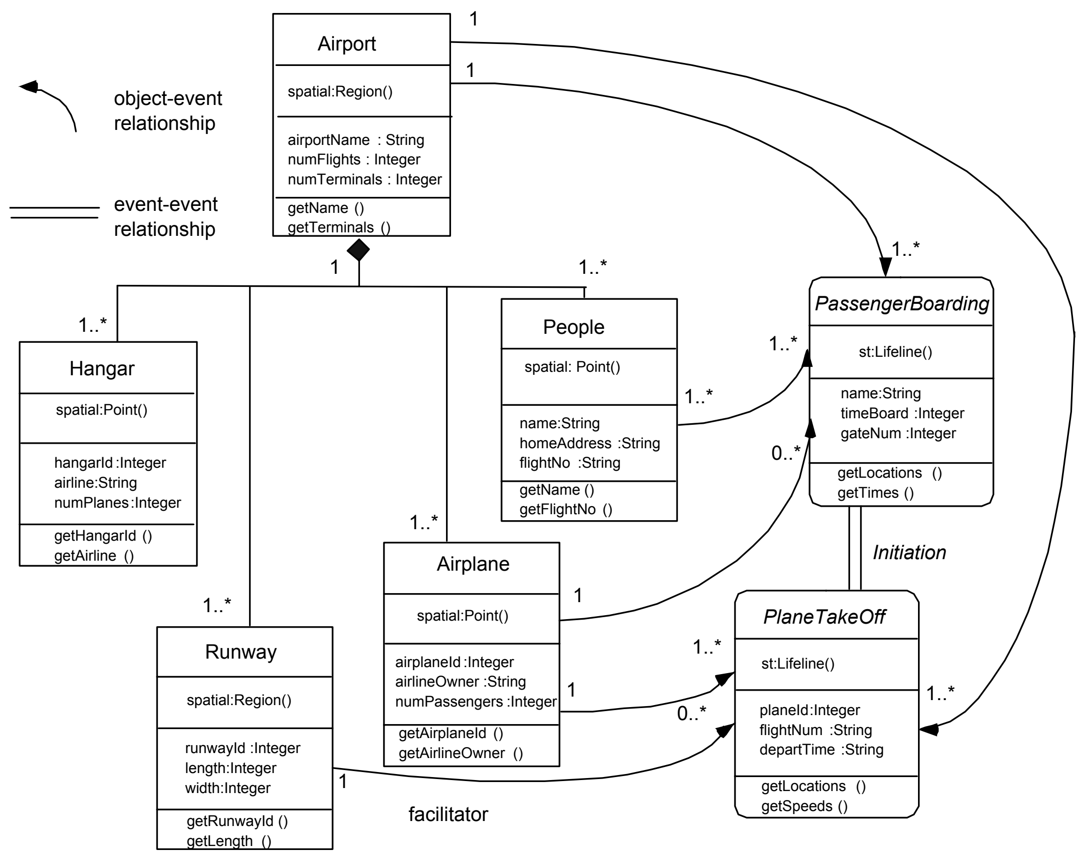

Figure 5: GEM diagram of airport objects and events.

It is possible to label object-event and event-event relations, for example, a **`Runway`** object class serves as a *facilitator* for **`PlaneTakeOff`** events and **`PassengerBoarding`** events *initiate* **`PlaneTakeOff`** events.

7. Conclusions and further work

The motivation for this work is to provide the foundations of a general approach to modeling dynamic geospatial domains. This model is based on the three basic entity types: geospatial object, geospatial event, and geospatial setting. The paper has discussed some of the details of the attributes and relationships between these basic entity types. The constructions of the model were represented diagrammatically by means of extensions to UML. The previous section briefly showed, by means of a case study scenario, how some aspects of the model might be applied. In this conclusion, we examine two further areas of work: extensions of the model to handle aggregate entities and the related issue of granularity, and how the model facilitates the development of query language capability in which events may be explicitly represented. Other ongoing work not described here relates to the translation from this conceptual model to the information system design level.

7.1 Aggregation and granularity

Constructions for object aggregation (composition, grouping, etc.) are a well-understood aspect of the object-oriented approach. This section briefly points to further directions in event aggregation, as well as the possibility of event-object aggregations. Just as objects can have spatial parts, so events can have parts that are spatial (e.g., event **Runway6PlaneTakeOff** is a spatial part of event **PlaneTakeOff**.) Events can more usually have temporal parts (e.g., event **NightPlaneTakeOff** is a temporal part of event **PlaneTakeOff**.). More generally, events can have spatio-temporal parts ((e.g., event **Runway6NightPlaneTakeOff** is a spatio-temporal part of event **PlaneTakeOff**.)

Conversely, events can be combined into *temporal sequence aggregations*. Such sequences can be compared in order to distinguish any spatio-temporal anomalies. For example, if: **PlaneLanding<PlaneTaxiToGate<PassengerDeplaning** is the typical temporal sequence of events that models a plane's arrival, then a sequence of **PlaneLanding<PassengerDeplaning<PlaneTaxiToGate** would signal a possibly unusual or unexpected situation. Sometimes, it is useful to consider the new event as a temporal aggregate. The three events, **PlaneDepartGate**, **PlaneTaxiOnRunway**, and **PlaneTakeOff**, for example, can be aggregated to form a *temporal sequence composite* **PlaneDeparture.**

The relationships between settings of event clusters provide clues as to the appropriate type of event aggregation. We have seen above examples of aggregation based on temporal sequence of settings. It is also clear that spatial proximity might signal useful aggregations. More generally, spatio-temporal relationships between event settings lead to possibilities for event aggregation.

An interesting question is whether hybrid object-event aggregates might be useful modeling constructs in this model. For example, aggregates of the events related to a traffic accident and the vehicles involved. This aggregation would be a closer coupling than the event-object involvement and participation relationships discussed in an earlier section.

An important consideration for modeling geospatial objects and events relates to the *granularity* of events. Granularity refers to the amount of detail (Hobbs 1990, Hornsby and Egenhofer 2002) necessary for a modeling task. Events, like objects, can be treated over multiple granularities. Shifting perspectives from single events to composite events, for example, involves a change in granularity. If, for example, an event, (e.g., a deer is on the runway) occurs during an **PlaneDeparture** event, that granularity may be too coarse to capture whether the event was actually an obstruction event (i.e., the plane was blocked from departing) or that the event occurred during the passenger loading phase of the plane's departure and did not cause a problem for takeoff. Sequences of events may be aggregated based on changes of temporal, spatial, or spatio-temporal granularities.

These, and other issues related to object-event aggregation and granularity, are the subject of ongoing research.

7.2 Query languages for dynamic systems

The GEM model offers a foundation for querying dynamic systems. The addition of GEClasses**,** dual object-event relationships, as well as event-event relationships provides a richer basis and more expressive power for querying. Some of the general kinds of queries supported by this model include:

- What are all the events related to object *X*?
- What are the objects that are related to event *Y*?
- Can event *Y* happen without object *X*?
- What are all the events that are related to event *Y*?
- What events serve as initiator events for event *Y*?
- How many objects serve as event-initiating or facilitating objects?
- What is the spatio-temporal setting for event *Y*?

These queries all involve some dynamic aspect that would not be captured by a strictly object-oriented model. For example, "What events are necessary for a passenger to board a plane?" and "What events could hinder a passenger from getting their checked luggage?" Semantics common in dynamic scenarios, such as initiating, facilitating, and blocking, for example, suggest new predicates for event-based queries. In addition, temporal sequences of events and aggregated events offer even further opportunities for querying. This includes queries, such as "What passenger-related events can hinder a **`PlaneDeparture`** event?" and "What luggage-related events occur between when a passenger checks in at the airline counter and the flight leaves?"

This section has highlighted two key areas of research that relate to event modeling and need further development. It seems clear that the geographic information systems of the future will need the capability to treat dynamic geospatial domains. This paper is a contribution to the development of techniques for conceptual modeling of dynamic geospatial phenomena. We have shown how it is possible to extend object-based approaches to dynamic entities, and seen how this will lead to more powerful modeling representations and query languages.

Acknowledgements

Mike Worboys' work is supported by the National Science Foundation under NSF grant numbers EPS-9983432 and BCS-0327615, the Ordnance Survey of Great Britain, and the UK EPSRC. Kathleen Hornsby's work is supported by the National Geospatial-Intelligence Agency under grant number, NMA201-00-1-200 and the National Institute of Environmental Health Sciences, under grant number 1 R 01 ES09816-01.

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