Extended Spatiotemporal UML: Motivations, Requirements, and Constructs

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This paper presents a conceptual modeling language for spatiotemporal applications that offers built-in support for capturing spatially referenced, time-varying information. More specifically, the well-known object-oriented Unified Modeling Language (UML) is extended to capture the semantics of spatiotemporal data. The extension, Extended Spatiotemporal UML, maintains language clarity and simplicity by introducing a small base set of fundamental modeling constructs: spatial, temporal, and thematic. These constructs can then be combined and applied at attribute, attribute group, association, and/or class levels of the object-oriented model; where the attribute group is an additional construct introduced for attributes with the same spatiotemporal properties. A formal functional specification of the semantic modeling constructs and their symbolic combinations is given and an example is used to illustrate the simplicity and flexibility of this approach.

INTRODUCTION

Spatiotemporal applications have been the focus of considerable attention recently. The need for a temporal dimension in traditional spatial information systems and for high-level models useful for the conceptual design of the resulting spatiotemporal systems has become clear. Although having in common a need to manage spatial data and their changes over time, various spatiotemporal applications may manage different types of spatiotemporal data and may be based on very different models of space, time, and change. For example, the term spatiotemporal data is used to refer both to temporal changes in spatial extents, such as redrawing the boundaries of a voting precinct or land deed, and to changes in the value of thematic (i.e., alphanumeric) data across time or space, such as variation in soil acidity measurements depending on the measurement location and date. A spatiotemporal application may be concerned with either or both types of data. This, in turn, is likely to influence the underlying model of space employed, e.g., the two types of spatiotemporal data generally correspond to an object- versus a field-based spatial model. For either type of spatiotemporal data, change may occur in discrete steps, e.g., changes in land deed boundaries, or in a continuous process, e.g., changes in the position of a moving object such as a car. Another type of spatiotemporal data is composite data whose components vary depending on time or location. An example is the minimum combination of equipment and wards required in a certain category of hospital (e.g., general, maternity, psychiatric), where the relevant regulations determining the applicable base standards vary by locality and time period.

A conceptual data modeling language for such applications should provide a clear, simple, and consistent notation to capture alternative semantics for time, space, and change processes. These include point- and interval-based time semantics; object- and field-based spatial models; and instantaneous, discrete, and continuous views of change processes. Multiple dimensions for time (e.g., valid, transaction) and space should also be supported.

Although there has been considerable work in conceptual data models for time and space separately, interest in providing an integrated spatiotemporal model is much more recent. Spatiotemporal data models are surveyed in Abraham (1999), including lower-level logical models (Claramunt, 1995; Langran, 1993; Pequet, 1995). Those models that deal with the integration of spatial, temporal, and thematic data at the conceptual level are the most relevant to this work and are reviewed here. Several conceptual frameworks have been designed to integrate spatial, temporal, and thematic data based on Object-Oriented (OO) or Entity-Relationship (ER) data models.
that include a high-level query language capable of specifying spatiotemporal entity types. The data definition component of these query languages thus has some potential for use in modeling spatiotemporal applications.

Becker (1996) and Faria (1998) propose OO models based on extensions of ObjectStore and O2 respectively. Becker (1996) considers both object- and field-based spatial models, defining a hierarchy of elementary spatial classes with both geometric and parameterized thematic attributes. Temporal properties are incorporated by adding instant and interval timestamp keywords to the query language. In Faria (1998), spatial and temporal properties are added to an object class definition by associating it with pre-defined temporal and spatial object classes. This solution is not suitable for representing temporal or spatial variation at the attribute level, as the timestamp and spatial locations are defined only at the object component level. In addition, both Becker (1996) and Faria (1998) offer text-based query languages; the non-graphical query languages of these models reduce their suitability as conceptual modeling languages.

A few papers specifically address the need for a graphical modeling language to support conceptual design of applications dealing with space and time. The MADS model (Parent, 1999) extends an object-based model with predefined hierarchies of spatial and temporal abstract data types and special complex data types to describe all of an attribute’s properties, i.e., name, cardinality, domain, and temporal or spatial dimensions. The use of a non-standard, hybrid ER/OO model and the definition of new composite data structures for spatiotemporal properties, rather than exploiting existing features of the ER or OO models, increases the complexity of the model syntax. A thematic attribute value can be associated with a spatial extent describing where it is valid; however, there is no provision for attributes having a spatial domain. This reduces the flexibility of the model since any data element associated directly with several different spatial extents must be modeled as an association of spatial objects rather than as a single object with several spatial attributes.

Tryfona (1999) proposes the SpatioTemporal ER model (STER) that adds temporal and spatial icons to entities, attributes, and relationships to support timestamped spatial objects and layers. Composite data whose components vary over space and relationships associated with spatial extents are not considered. Instead, spatial relationships are used to represent explicit geometric or topological relationships between associated spatial objects, which could otherwise be derived on demand. Therefore, temporal relationships describe model structure (i.e., timestamps), whereas spatial relationships describe model integrity (i.e., constraints).

None of the models described above provide explicit support for modeling a group of thematic properties measured at the same time and locations, consider interpolation, or support alternative time models (i.e., periodic versus aperiodic recording of data values). An earlier spatiotemporal extension to the Unified Modeling Language (UML) proposed in Price (1999) defines an attribute group within the OO model and then defines constructs that provide support for modeling spatiotemporal properties at the object, association, attribute, and attribute group levels. However, neither the syntax nor the semantics of the symbols introduced in Price (1999) are presented formally.

In this paper, we propose an extension of UML intended to address the goals outlined earlier, i.e., to support a range of spatiotemporal models and data types using a clear, simple, and consistent notation. Extending the OMG standard for OO modeling was selected as the best approach given its high level of acceptance, tool support, understandability, and extensibility. Although the applicability of the proposed model is not necessarily limited to the Geographic Information System (GIS) domain, the focus is primarily on GIS concerns and application examples in this paper. We introduce a small base set of modeling constructs for spatiotemporal data that can be combined and applied to different levels of the object-oriented model in a consistent manner, guided by the same simple principles. The result is the Extended Spatiotemporal UML. A formal functional specification of the semantic modeling constructs and symbolic combinations is given.

The rest of the paper is organized as follows. The next section illustrates the problems with using UML to model spatiotemporal data and considers possible solutions. Then we describe the syntax and semantics of the fundamental new constructs introduced—the spatial, temporal, and thematic symbols—for the solution (i.e., UML extension) proposed in this paper. This is followed by a section that discusses three other symbols: the attribute group symbol, the existence-dependent symbol, and the specification box (used to specify the details of the spatiotemporal semantics). The section "Using Extended Spatiotemporal UML" shows how the previous example presented would be modeled using the proposed UML extension. Finally, conclusions and future directions are presented.

**USING UML FOR SPATIOTEMPORAL DATA**

In this section, we evaluate the core constructs and extension mechanisms defined in UML (Booch, 1999; Rumbaugh, 1999; OMG 1999) in terms of their suitability for modeling spatiotemporal data and defining a UML extension to facilitate such modeling respectively. The UML usage and notation used is based on Rumbaugh (1999), except that we use informal textual descriptions for complex attribute domains and constraints for the sake of readability. We use Backus-Naur Form (BNF) for specific explanations of syntax or terminology. The next section uses an application example to demonstrate some of the problems associated with modeling spatiotemporal data using only the core model of UML. We then evaluate alternative approaches to extending a conceptual modeling language and evaluate UML’s extension mechanisms.