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MOBR

► Minimum Bounding Rectangle

Model Driven Architecture

► Modeling with Enriched Model Driven Architecture

Model Driven Development

► Modeling with Enriched Model Driven Architecture

Model Driven Engineering

► Modeling with Enriched Model Driven Architecture

Model Generalization

► Abstraction of GeoDatabases

Modeling and Multiple Perceptions

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Synonyms

Data modeling; Multiscale databases; Multirepresentation

Definition

Multirepresentation generalizes known concepts such as database views and geographic multiscale databases. This chapter describes the handling of multi-representation in the MADS (Modeling Application Data with Spatio-temporal features) data modeling approach. MADS builds on the concept of orthogonality to support multiple modeling dimensions. The structural basis of the MADS model is based on extended entity-relationship (ER) constructs. This is complemented with three other modeling dimensions: space, time, and representation. The latter allows the specification of multiple perceptions of the real world and modeling of the multiple representations of real-world elements that are needed to materialize these perceptions.

Historical Background

Traditional database design organizes the data of interest into a database schema, which describes objects and their relationships, as well as their attributes. At the conceptual level, the design task relies on well-known modeling approaches such as the ER model [1] and Unified Modeling Language (UML) [2]. These approaches only deal with classical alphanumeric data. The idea of using conceptual spatial and spatiotemporal data models emerged in the 1990s. Most proposals were extensions of either the ER (e. g., [3,4,5]), UML (e. g., [6,7]), or object-oriented data models (e. g., [8]). Spatiotemporal data models are the current focus of research and development, both in academia and in industry: They allow the representation of the past and future evolution of geographic objects as well as moving and deforming objects. Both features are essential for complex development issues such as environmental management and city planning.

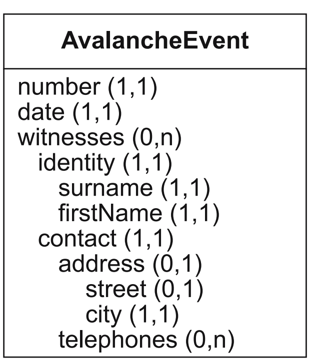
Most geographic applications confronted with a variety of user categories showing different requirements of the same data (e. g., different administrations involved in city management) also need another modeling dimension: multiple representations. Multiple representations allow, for example, the spatial feature of a city being described as a point and as an area, the former for use in statewide maps, the latter in local maps. Interest in supporting this functionality has emerged recently [5,9] and the concept of multi-representation is now popular in the research community and with user groups. The MADS proposal is playing an important role in establishing and advancing this trend.

Scientific Fundamentals

Definition 1: *conceptual data model.* A data model is conceptual if it enables a direct mapping between the perceived real world and its representation with the concepts of the model. In particular, a conceptual model does not have implementation-related concerns.

Definition 2: *data modeling dimension.* A data modeling dimension is a domain of representation of the real world that focuses on a specific class of phenomena. Examples of modeling dimensions include: data structure, space, time, and multirepresentation.

Definition 3: *orthogonality.* Modeling dimensions are said to be orthogonal if, when designing a database schema, choices in a given dimension do not depend on the choices in other dimensions. For example, it should be possible to record the location of a reservoir on a river (a spatial feature in the space dimension) irrespective of whether the reservoir, in the data structure dimension, has been modeled as an independent object or as an attribute of the river object. Orthogonality greatly simplifies the data model and its use, while enhancing its expressive power, i. e., its ability to represent all phenomena of interest. The orthogonality of multiple modeling dimensions is an essential characteristic of MADS. A detailed presentation of the model can be found in [5,10].



Modeling and Multiple Perceptions, Figure 1 A diagram of an object type with its attributes

Thematic Data Structure Modeling

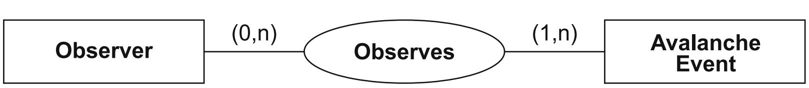
Definitions 4, 5, and 6: Object Types, Attributes, and Methods Database *objects* represent real-world entities of interest to applications. An *object type* defines the properties of interest for a set of objects that, from the application viewpoint, are considered as similar. Properties are either attributes or methods. An *attribute* is a property that is represented by a value in each object of the type. A *method* is a behavioral property common to all objects of the type.

Figure 1 illustrates an object type AvalancheEvent and its attributes. These may be *simple*, e. g., number for AvalancheEvent, or *complex* (i. e., composed of other attributes), e. g., witnesses.

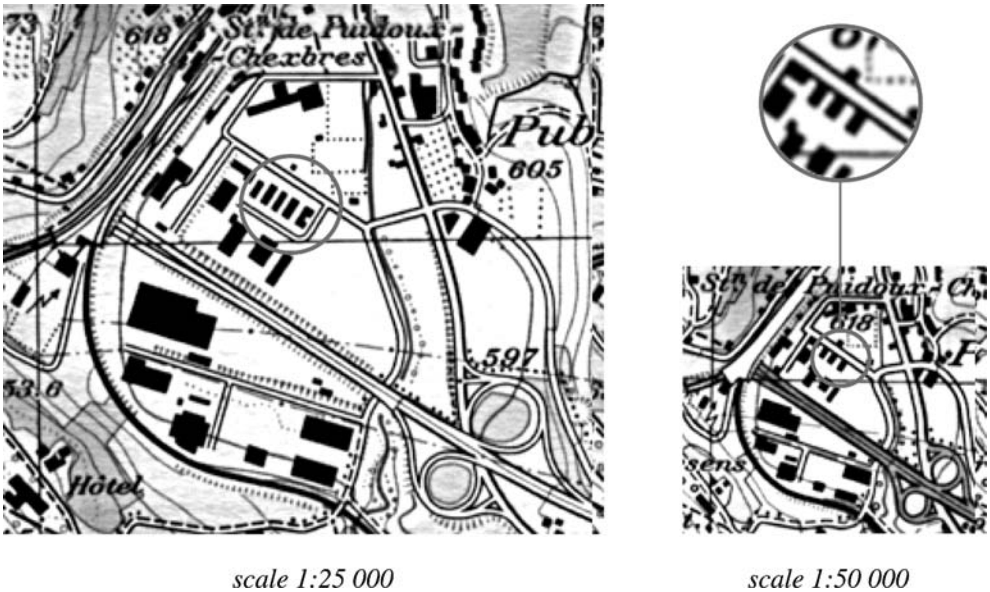
Definition 7: Cardinality *Attribute cardinality*, defined by two numbers (min, max), denotes the minimum and maximum number of values that an attribute may hold within an object. The maximum cardinality determines whether an attribute is *monovalued* or *multivalued*, i. e., whether it holds at most one or several values. The minimum cardinality determines whether an attribute is *optional* (min $= 0$) or *mandatory* (min > 0), i. e., whether an object may hold no value or must hold at least one value.

Definitions 8 and 9: Relationship Types and Roles Relationships represent real-world links between objects that are of interest to the application. Relationships that, from the application perspective, have the same characteristics are grouped in relationship types. Roles represent the involvement of an object type into a relationship type. A relationship type defines two or more roles: They are *n*-ary, *n* being the number of roles. Figure 2 shows an example of a binary relationship of the type Observes.

Cardinality constraints define the minimum and maximum number of relationships that may link an object in a role. For example, in Fig. 2 the (0,*n*) cardinalities on the role associated to the Observer object type express that an observer may have never observed an avalanche, and that an observer may have observed any number of avalanches. As object types, relationship types may be described by properties (attributes and methods). The generic term *instance* denotes either an object or a relationship: an object (relationship) is an instance of the object (relationship) type it belongs to. MADS identifies two basic kinds of relationship types, association and multiassociation, described next.



Modeling and Multiple Perceptions, Figure 2 A diagram showing a relationship type linking two object types



Modeling and Multiple Perceptions, Figure 3 An example situation calling for a multiassociation relationship

Modeling and Multiple Perceptions, Figure 4 An example of a multiassociation type

Definition 10: Association Types An *association type* is a relationship type such that each role links exactly one instance of the linked object type.

Associations are the usual kind of relationships. However, in some situations the association relationship does not allow accurate representation of real-world links existing between objects. Figure 3 shows two maps of the same area at different scales. Focusing on the area within the superimposed circles, the left-hand, more detailed, map shows five aligned buildings whereas at the same location the right-hand map shows only three. Suppose that the application stores the five buildings in the left-hand map as instances of the BuildingScale15’000 object type, and the three buildings in the right-hand map as instances of the BuildingScale25’000 object type. If the application requires the correlation of cartographic representations, at different scales, of the same real-world entities, some link must relate the five instances of BuildingScale15’000 to the three instances of BuildingScale25’000. The multiassociation construct allows directly representation of such a link.

Definition 11: Multiassociation Types A *multiassociation type* is a relationship type such that each role links a nonempty collection of instances of the linked object type.

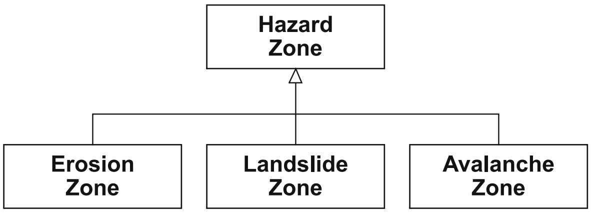
Consequently, each role in a multiassociation type bears two pairs of (min, max) cardinalities. A first pair is the conventional one, defining for each object instance how many relationship instances it can be linked to via the role. The second pair defines for each relationship instance how many object instances it can link with this role. Its value for minimum is at least 1. Using a multiassociation type, the above correspondence between cartographic buildings can be modeled as shown in Fig. 4.

Apart from the additional cardinality constraints, multiassociation types share the same features as association types.

Definition 12: is-a Links The *is-a* (or generalization/specialization) link relates two object or two relationship types, a generic one (the *supertype*) and a specific one (the *subtype*). It states that the subtype describes a subset of the real-world instances described by the supertype, and this description is a more precise one.

Figure 5 shows a generalization hierarchy of object types with three is-a links. The generic object type representing hazard zones is specialized in subtypes representing landslide, erosion, and avalanche zones.

A well-known characteristic of is-a links is *property inheritance*: All properties and links defined for the supertype also hold for the subtype. An immediate benefit of inher-



Modeling and Multiple Perceptions, Figure 5 Object types connected by is-a links

itance is *type substitutability*, i. e., enforcing the fact that wherever an instance of a type can be used in some data manipulation, an instance of any of its subtypes can be used instead.

Describing Space and Time Using the Discrete View

In MADS, space and time description is orthogonal to data structure description, which means that the description of a phenomenon may be enhanced by spatial and temporal features whatever data structure (i. e., object, relationship, attribute) has been chosen to represent it.

Definition 13: Discrete View The *discrete* (or *object*) *view* of space and time defines the spatial and temporal extents of the phenomena of interest. The *spatial extent* is the set of points that the phenomenon occupies in space, while the *temporal extent* is the set of instants that it occupies in time.

Specific data types support the manipulation of spatial and temporal values, like a point, a surface, or a time instant. MADS supports a hierarchy of spatial data types and another hierarchy of temporal data types. Generic data types allow the description of object types whose instances may have different types of spatial or temporal extents. For example, a **River** object type may contain large rivers with an extent of type **Surface** and small rivers with an extent of type **Line**. Examples of spatial data types are: **Geo** ( ), the most generic spatial data type, **Surface** ( ), and **SurfaceBag** ( ). The latter is useful for describing objects with a nonconnected surface, like an archipelago. Examples of temporal data types are: **Instant** ( ), **TimeInterval** ( ), and **IntervalBag** ( ). The latter is useful for describing the periods of activity of noncontinuous phenomena.

In MADS, temporality associated to object/relationship types or to attributes corresponds to *valid time*, which conveys information on when a given fact of the database is considered valid from the application viewpoint.

Definition 14: Spatial, Temporal, Spatiotemporal Objects and Relationships A *spatial* (and/or *temporal*) *object type* is an object type that holds spatial (and/or temporal) information pertaining to the object as a whole.

For example, in Fig. 6a both object types are spatial as shown by the **Surface** ( ) icon, while only **LandPlot** is temporal as shown by the **TimeInterval** ( ) icon. Following common practice, an object type is called *spatiotemporal* if either it has both a spatial and a temporal extent, separately, or has a time-varying spatial extent (i. e., its spatial extent changes over time and the history of extent values is recorded).

Similarly, *spatial*, *temporal*, and *spatiotemporal relationship types* hold spatial and/or temporal information pertaining to the relationship as a whole, as for an object type. For example, in Fig. 2, the **Observes** relationship type can be defined as temporal, of the type **Instant**, to record when observations are made.

Spatial and temporal information at the object- or relationship-type level is kept in dedicated system-defined attributes: *geometry* for space and *lifecycle* for time. Geometry is a spatial attribute (see below) with any spatial data type as domain. When representing a moving object, geometry is a time-varying spatial attribute. On the other hand, the lifecycle allows users to record when an object (or link) was (or is planned to be) created and deleted. It may also support recording that an object is temporarily suspended, like an employee who is on temporary leave. Therefore the lifecycle of an instance says for each instant what is the status of the corresponding real-world object (or link) at this instant: scheduled (its creation is planned later), active, suspended (it is temporarily inactive), disabled (definitively inactive).

Definition 15: Spatial, Temporal, Spatiotemporal Attributes A *spatial* (*temporal*) *attribute* is a simple attribute whose domain of values is one of the spatial (temporal) data types. A *spatiotemporal attribute* is a time-

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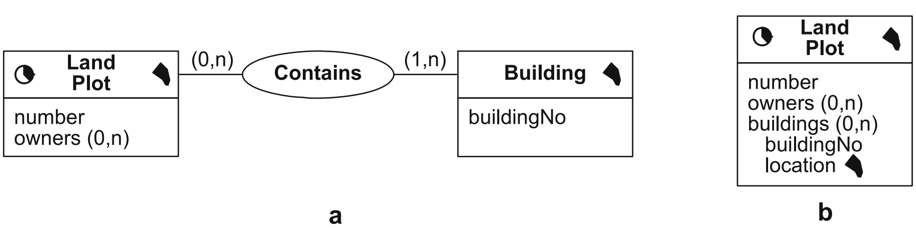
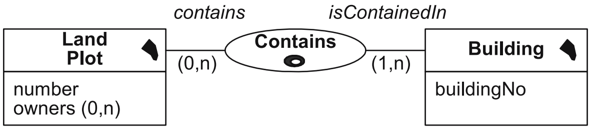


Modeling and Multiple Perceptions, Figure 6 **a**, **b** Alternative schemas for land plots and buildings



Modeling and Multiple Perceptions, Figure 7 A topological relationship of the type **Inclusion** ( )

varying spatial attribute, i. e., a spatial attribute whose value changes over time and the history of its values is recorded (see Definition 17).

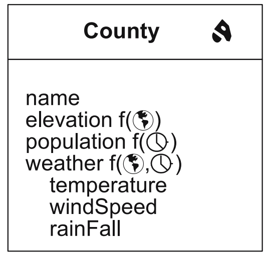
Each object and relationship type, whether spatiotemporal or not, may have spatial, temporal, and spatiotemporal attributes. For example, in Fig. 6b the **LandPlot** object type includes, in addition to its spatial extent, a complex and multivalued attribute **buildings** whose second component attribute, **location**, is a spatial attribute describing, for each building, its spatial extent.

Constraining Relationships with Space and Time Predicates

The links among spatial (temporal) object types often describe a spatial (temporal) constraint on the spatial (temporal) extents of the linked objects. For example, designers may want to enforce each **Contains** relationship of Fig. 6a to link a pair of objects provided that the spatial extent of the land plot contains the spatial extent of the building. In MADS, this can be done by defining **Contains** as a constraining relationship of the type topological inclusion, as shown in Fig. 7 by the icon.

Definition 16: Constraining Relationships *Constraining relationships* are binary relationships enforcing the geometries or lifecycles of the linked objects types to comply with a topological or synchronization constraint.

Figure 8 shows a temporal synchronization relationship of the type **During**, stating that observers can observe avalanche events only while they are on duty. Relationship types may simultaneously bear multiple constraining semantics. For example, the **Intersects** relationship type shown in Fig. 9 enforces both a topological overlapping and a synchronization overlapping constraint.



Modeling and Multiple Perceptions, Figure 10 An object type with varying attributes

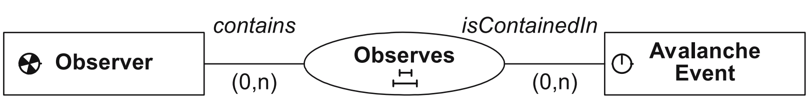
Describing Space and Time Using the Continuous View

Beyond the discrete view, there is a need to support another perception of space and time, the *continuous* (or *field*) *view*.

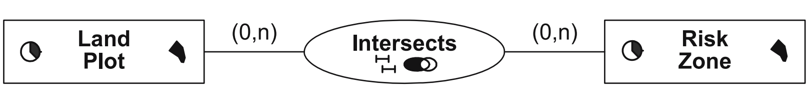
Definition 17: Continuous View, Varying Attribute In the *continuous view*, a phenomenon is perceived as a function associating to each point (instant) of a spatial (temporal) extent a value. In the MADS model the continuous view is supported by space (and/or time) *varying attributes*, which are attributes whose value is a function. The domain of the function is a spatial (and/or temporal) extent. Its range can be a set of simple values (e. g., **Real** for temperature, **Integer** for rainfall, **Point** for a moving car), or a set of composite values if the attribute is complex as, in Fig. 10, **weather**. If the attribute is multivalued, the range is a powerset of values.

Figure 10 shows examples of varying attributes and their visual notation in MADS. For instance, **elevation** is a space-varying attribute defined over the geometry of the county. It provides for each geographic point of the county its elevation. An example of a time-varying attribute is **population**, which is defined over a time interval, e. g., [1900, 2008]. Then, **weather** is a space and time-varying attribute which gives for each point of the spatial extent of the county and each instant of a time interval a composite value describing the weather at this location and this instant. Attributes that are space and time-varying are also called *spatiotemporal attributes*.

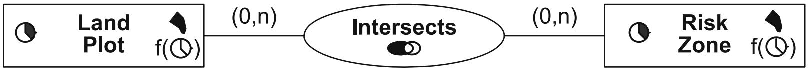
A constraining topological relationship may link moving or deforming objects, i. e., spatial objects whose geome-



Modeling and Multiple Perceptions, Figure 8 A synchronization relationship type of the **During** kind ( )



Modeling and Multiple Perceptions, Figure 9 A topological **Overlap** ( ) and synchronization **Overlap** ( ) relationship type



Modeling and Multiple Perceptions, Figure 11 An example of a topological relationship that links spatial object types with deforming geometries

tries are time-varying. Figure 11 shows an example. In this case two possible interpretations can be given to the topological predicate, depending on whether it must be satisfied either in at least one instant or in every instant belonging to both time extents of the varying geometries [11]. Applied to the example of Fig. 11, the two interpretations result in accepting in the relationship **Intersects** only instances that link a land plot and a risk zone such that their geometries intersect for at least one instant or for every instant belonging to both life spans. When defining the relationship type, the designer has to specify which interpretation holds.

Supporting Multiple Perceptions and Multiple Representations

Databases store representations of real-world phenomena that are of interest to a given set of applications. However, while the real world is supposed to be unique, its representation depends on the intended purpose.

Definition 18: Perceptions and Representations Each application has a peculiar *perception* of the real world of interest. These perceptions may vary both in terms of what information is to be kept and in terms of how the information is to be represented. Fully coping with such diversity entails that any database element may have several descriptions, or *representations*, each one associated to the perceptions it belongs to. Both metadata (descriptions of objects, relationships, attributes, is-a links) and data (instances and attribute values) may have multiple representations. There is a bidirectional mapping between the set of perceptions and the set of representations. This mapping links each perception to the representations perceived through this perception.

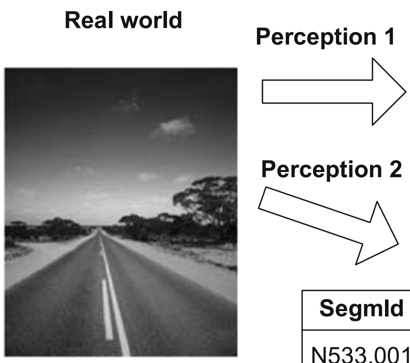
Classic databases do not support the mapping between perceptions and representations. They usually store for each real-world entity or link a unique, generic representation, hosting whatever is needed to globally comply with all application perceptions. An exception exists for databases supporting generalization hierarchies, which allow the storage of several representations of the same entity in increasing levels of specificity. These classic databases have no knowledge of perceptions. Hence the system cannot provide any service related to perception-dependent data management. Applications have to resort to the view mechanism to define and extract data sets that correspond to their own perception of the database. But still, each view is a relational table or object class. They cannot make up a whole perception, which is a subset of the database containing several object types related by relationship types and is-a links. Instead, MADS explicitly supports multiple perceptions for the same database.

Definition 19: Multiperception Databases A *multiperception database* is a database where designers and users have the ability to define and manipulate several perceptions of the database. A multiperception database stores one or several representations for each database element, and records for each perception the representations it is made up.

Geographical applications have strong requirements in terms of multiple representations. For example, cartographic applications need to keep multiple geometries for each object, each geometry corresponding to a representation of the extent of the object at a given *spatial resolution*. The resolution of a spatial database is the minimum size of any spatial extent stored in the database. Resolution is closely related to the scale of the maps that are produced from the database. The scale of a printed map is the amount of reduction between the real world and its graphic representation in the map. Multiscale representations are needed as there is still no complete set of algorithms for *cartographic generalization* [12], i. e., the process to automatically derive a representation at a less-detailed resolution from a representation at a more precise resolution.

Geographical databases are also subject to classical semantic resolution differences. For example, an application may see a road as a single object, while another one may see it in more detail as a sequence of road sections, each one represented as an object, as in Fig. 12. As another example, geographical databases need to support *hierarchical value domains* for attributes, where values are chosen depending on the level of detail. In the hierarchical domain for **land use**, Fig. 13, **orchard** and **rural area** are two representations of the same value at different resolutions.

In MADS, each perception has a user-defined identifier, called its *perception stamp*, or just *stamp*. In the sequel, perception stamps are denoted as s1, s2, ..., sn. From data definitions (metadata) to data values, anything in a database (object type, relationship type, attribute, role, instance, value) belongs to one or several perceptions. Stamping an element of the schema or of the database defines for which perceptions the element is relevant. In



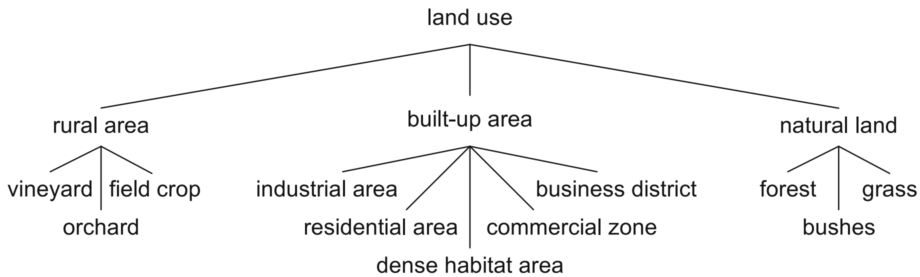
Road

Name	Extent	Length
Napoléon		358.550

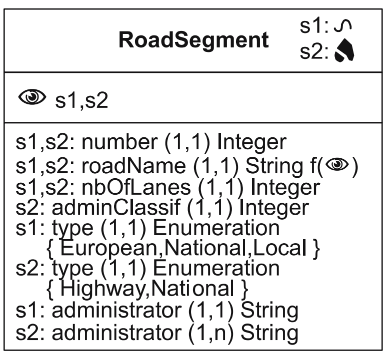
RoadSegment

SegmId	RoadName	Extent	NbLanes
N533.001	Napoléon		3
N533.002	Napoléon		2
N533.003	Napoléon		4

Modeling and Multiple Perceptions, Figure 12 Two different perceptions of the same reality, leading to different representations



Modeling and Multiple Perceptions, Figure 13 An example of a hierarchical domain



Modeling and Multiple Perceptions, Figure 14 An illustration of a birepresentation type, defined for perceptions s1 and s2

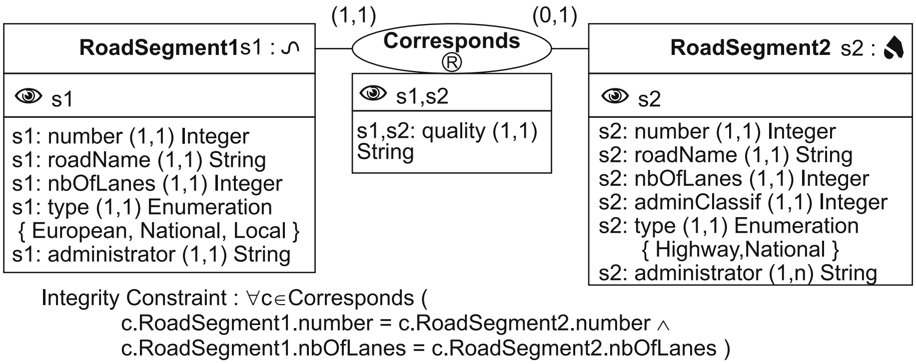
the diagrams, e. g., Fig. 14, the box identified by the icon defines the set of perceptions for which this type is valid. Similarly, the specification of the relevant stamps is attached to each attribute and method definition.

There are two complementary techniques to organize multiple representations. One solution is to build a single object type containing several representations, the knowledge of "which representation belongs to which perception" being provided by the stamps of the properties of the type. Following this approach, in Fig. 14 the designer has defined a single object type **RoadSegment**, grouping two representations, one for perception s1 and one for perception s2.

Definition 20: Multirepresentation Object/Relationship Types An object or relationship type is *multirepresentation* if at least one of its characteristics has at least two different representations. The characteristic may be at the schema level (e. g., an attribute with different definitions) or at the instance level (i. e., different sets of instances or an instance with two different values).

The alternative solution to organize multiple representations is to define two separate object types, each one bearing the corresponding stamp(s) (cf. Fig. 15). The knowledge that the two representations describe the same entities is then conveyed by linking the object types with a relationship type that holds an *interrepresentation* semantics (indicated by the Ⓡ icon). In the example of Fig. 15, the same real-world road segment is materialized in the database as two object instances, one in **RoadSegment1** and one in **RoadSegment2**. Instances of the relationship type **Corresponds** tell which object instances represent the same road segment.

The actual representation of instances of multirepresentation object types changes from one perception to another.



Modeling and Multiple Perceptions, Figure 15 The RoadSegment type (from Fig. 14) split into two monorepresentation object types and an interrepresentation relationship type

Consider the object type **RoadSegment** of Fig. 14. The spatial extent of the type is represented either as a surface (the more precise description, perception s2) or as a line (the less precise description, perception s1) depending on resolution. Furthermore, perception s1 needs the attributes **number**, **roadName**, **numberOfLanes**, **type**, and **administrator** (denoting the maintenance firm in charge). Perception s2 needs the attributes **number**, **roadName**, **numberOfLanes**, **adminClassification**, **type**, and **administrator**. While the road segment number and the number of lanes are the same for s1 and s2, the name of the road is different, although a string in both cases. For instance, the same road may have name "RN85" in perception s1 and name "Route Napoléon" in s2. We call this a *perception-varying attribute* (see below), identified as such by the **f**(👁) notation. The **type** attribute takes its values from predefined sets of values, the sets being different for s1 and s2. Several administrators for a road segment may be recorded for s2, while s1 records only one.

Definition 21: Perception-Varying Attribute An attribute is perception-varying if its value in an instance may change from one perception to another. A perception-varying attribute is a function whose domain is the set of perceptions of the object (or relationship) type and whose range is the value domain defined for this attribute. These attributes are the counterpart of space-varying and time-varying attributes in the space and time modeling dimensions.

Stamps may also be specified at the instance level. This allows the defining of different subsets of instances that are visible for different perceptions. For example, as the object type **RoadSegment** in Fig. 14 has two stamps, it is possible to define instances that are only visible to s1, instances that are only visible to s2, and instances that are visible to both s1 and s2.

Relationship types can be in multirepresentation, like object types. Their structure (roles and association/multiassociation kind) and semantics (e. g., topology, synchronization) may also have different definitions depending on the perception. Figure 16 shows an example of different semantics, where the designer defined the relationship **GivesAccess** as (1) a topological adjacent relationship type for perception s1, and (2) a plain relationship without any peculiar semantics or constraint for perception s2.

A relationship type may have different roles for different perceptions. For example, Fig. 17 shows that an observation is perceived in s1 as a binary relationship between an observer and an avalanche event, while perception s2 sees the same observation as a ternary relationship, also involving the expert who has validated the observation.

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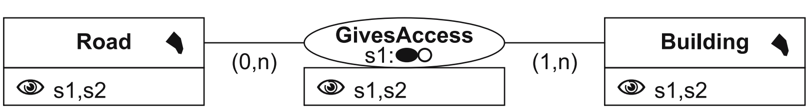
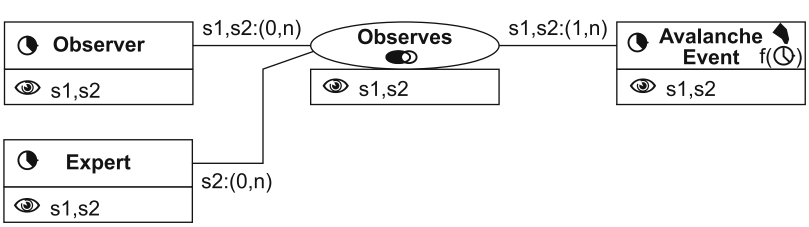


Modeling and Multiple Perceptions, Figure 16 A relationship type with two different semantics: topological adjacency for s1 and plain relationship for s2



Modeling and Multiple Perceptions, Figure 17 A relationship type with a role specific to perception s2

Key Applications

Multirepresentation databases are an essential feature for all applications that need to provide different categories of users with different sets of data, organized in different ways, without imposing a single centralized model of the real world for the whole enterprise. Multirepresentation databases play a key role in guaranteeing and maintaining the consistency of a database with decentralized control and autonomy of updates from different user categories. Multiscale map production applications are one example of a domain where this feature is highly desirable. Management and analysis of municipal, regional, and statewide databases are other examples where the same geographic area is input to a variety of uses. Domain-oriented (e. g., environmental) interorganizational as well as international applications call for integrated databases that provide autonomous usage by the contributing organizations and countries.

Future Directions

Considering the large number of perceptions that some huge databases may have to support, an investigation into how perceptions may be organized and structured (as objects of interest per se) is planned.

Another direction for future research is adding complementary modeling dimensions to the MADS model, such as the multimedia dimension, the precision dimension (supporting, for example, fuzzy, imprecise, and approximate spatial and temporal features), and the trust or data quality dimension.

Finally, spatiotemporal and trajectory data warehousing represent wide-open research domains to develop efficient support for geographically based decision making.

Cross References

► Modeling with ISO 191xx Standards

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Modeling Cycles in Geospatial Domains

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Synonyms

Event, cyclic; Event, recurrent; Event, periodic

Definition

In a geospatial context, cycles can be defined as regularly repeated phenomena or events. According to the distribution of this kind of happening over time, cycles can be classified as *strong periodic*, *near periodic*, or *intermittent*. Strong periodicity refers to cycles in which the duration of every occurrence of the event is the same as