INTRODUCTION

During the past several years, traditional databases have been enhanced to include spatially referenced data. Spatial database management (SDBM) systems aim at providing models for the efficient manipulation of data related to space. Such type of manipulation is useful for any type of applications based on large spatial data sets, such as computer-aided design (CAD), very large scale integration (VLSI), robotics, navigation systems, and image processing.

Spatial data applications, (in particular, geospatial applications) differ from traditional data applications for the following reasons (Voisard & David, 2002):

- spatial information deals with spatial and nonspatial data, which implies that the definition of spatial data types be closed under the operations applicable to them;
- many spatial data are inherently uncertain or vague, which may lead to conflicting data (e.g., the exact boundary of a lake or pollution area is often unclear);
- topological and other spatial relations are very important and are usually implicitly represented;
- data are highly structured by the notion of object aggregation;
- user-defined operations require an extensible underlying model; and
- functions exist at both a low level of abstraction (e.g., points, lines, polylines) and a high level of abstraction (e.g., maps, thematic layers, configurations).

Spatial databases often deal with different kinds of data imperfections, which can be classified into uncertainty, imprecision/vagueness, incompleteness, and inconsistency (Pason, 1996). Whereas uncertainty, imprecision, vagueness, and incompleteness are usually seen as different types of data inaccuracy that arise from problems in data collection, inconsistency is the kind of data imperfection that results from the existence of contradictory data.

Contradictory data in spatial databases arise from different forms of errors (Cockcroft, 1997). A primary source of errors that can give rise to contradictions is the inconsistency generated by conflicting descriptions of locations or the characteristics and qualities of spatial features. This kind of inconsistency is commonly associated with problems of positional or data inaccuracy. A secondary source of errors that can result in contradictions is the mismatch between stored data and structural or semantic consistency rules underlying the model of reality (e.g., a region that is represented by a polyline that is not closed). Database designers usually attempt to avoid this second kind of error by enforcing integrity constraints.

Research progress on consistency in spatial databases has been the result of an interdisciplinary effort. This effort has dealt with ontological issues (Frank, 2001) concerning the definition of semantic and topological consistency. It has also considered the appropriate conceptual frameworks for analyzing spatial consistency, the specification language of integrity constraints, and the design of computational-geometry algorithms to implement consistency checkers.

The following section describes models for defining consistency of spatial data that focus on topological consistency in the presence of multiple representation levels or in the integration of heterogeneous databases. Subsequently, the specification of integrity constraints in spatial databases is discussed to complete the background for presenting challenges and future trends in the treatment of consistency in spatial databases.

BACKGROUND

The conceptual bases for modeling consistency are topological and other geometric characteristics of spatial objects. In particular, spatial primitives and spatial relations are fundamental in the definition of consistency rules that enforce a particular model of space. Spatial primitives depend on the classical distinction between field-based and entity-based models (Shekhar, Coyle, Goyal, Liu, & Sakar, 1997). Each of these approaches to modeling space implies spatial primitives with their own definitions and rules. For example, the field-based approach to space includes the definition of tessellations, isolines, and triangular irregular network, with their corresponding definition rules. Likewise, the
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entity-based approach includes definitions rules for lines and polygons.

In addition to spatial primitives, spatial relations play an important role in spatial information systems, because such relations describe spatial information and are used as the spatial criteria for querying spatial databases. Even though positional information is often a basis for specifying the spatial component of objects, spatial relations such as adjacency and containment do not require absolute positional data. Common spatial relations are typically grouped into three kinds: topological, orientation, and distance. Topological relations deal mainly with the concept of connectivity and are invariant under topological transformations, such as rotation, translation, and scaling. Orientation relations presuppose the existence of a vector space and are subject to change under rotation, while they are invariant under translation and scaling. Distance relations express spatial properties that reflect the concept of a metric and, therefore, change under scaling, but are invariant under translation and rotation.

Models for each kind of spatial relation exist, which have led to a productive research area referred as qualitative reasoning (Stock, 1997). Such models give definition rules for each type of spatial relations as well as consistency in the combination of spatial relations. In particular, there is a comprehensive method for analyzing the topological consistency of spatial configurations based on the logical consistency expressed by the composition of relations (Egenhofer & Sharma, 1993). For example, given that a spatial object A is inside of a second object B, and B is disjoint to a third object C, to keep the topological consistency, A must also be disjoint to C.

Two important cases that have been addressed in the modeling of consistency that differ from basic definition rules are consistency at multiple representations and consistency for data integration. The problem of multiple representations consists of data changing their geometric and topological structures due to changes in scale. Conceptually, multiple representations may be considered as different data sets that cover the same area with different levels of detail. Within the context of assessing consistency at multiple representation levels, topological relations are considered as first-class information, which must prevail in case of conflict (Egenhofer & Clementini, 1994. Kuipers, Paredaens, & den Bussche, 1997). Multiple representation levels in spatial databases may not imply inconsistent information, but rather, merely different levels of detail or scale. In such cases, topological consistency at the level of objects and objects’ interrelations must be enforced.

The modeling of topological consistency at multiple representation levels has been based on the definition of topological invariants across multiple representations (Tryfona & Egenhofer, 1997). Examples of topological invariants are the set intersections of boundaries and interiors as well as the sequence, dimension, type, and boundedness of boundary-boundary intersections. The comparison of topological invariants is used to define the topological consistency of objects and topological relations at multiple representation levels. In addition, topological invariants and consistency-checking of topological configurations have been basis for defining consistency of composite objects at multiple representations (Egenhofer, Clementini, & Di Felice, 1994).

Spatial data sets to be integrated are assumed to contain the same features or objects that can be extracted from several sources at different times. These data may vary in reliability, accuracy and scale of representation. Thus, integrating spatial information may create conflicts due to the different representations for the same features concerning, for example, shape, dimension, and positional accuracy. In this context, different types of consistency can be distinguished (Abdelmoty & Jones, 1997): total consistency, which occurs when two data sets are identical; partial consistency, which occurs when certain subsets of two data sets are identical; conditional consistency, which occurs when by applying a set of functions over a data set it becomes totally consistent with respect to another data set; and inconsistency level, which occurs when there is nothing in common between data sets.

The common approach to integrating different representations has assumed that, when no further information exists about the origin of data, both representations are adopted. The idea is to merge both representations such that the resulting representation is modeled as a vague or unclear one. In modeling these unclear boundaries, three alternatives are found: fuzzy models (Schneider, 2000; Usery, 1996), which are based on the theory of fuzzy sets and have been applied to spatial uncertainty; probabilistic models (Burrough, 1996; Finn, 1993), which are based on probability theory to model positional and measurement uncertainty; and exact models (Clementini & Di Felice, 1996, 1997; Erwing & Schneider, 1997), which map data models for spatial objects with sharp boundaries onto spatial objects with broad boundaries.

INTEGRITY CONSTRAINTS IN SPATIAL DATABASES

Integrity constraints enforce consistency in spatial databases. Integrity constraints must be taken into account when updating a database such that the semantics and quality of data are preserved. In the spatial domain,