Introduction to Spatial Database Systems

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Outline

- Introduction & definition
- Modeling
- Querying
- Data structures and algorithms
- System architecture
- Conclusion and summary
Introduction

- Various fields/applications require management of geometric, geographic or spatial data:
  - A geographic space: surface of the earth
  - Man-made space: layout of VLSI design
  - Model of rat brain

Introduction ...

- Common challenge: dealing with large collections of relatively simple geometric objects
- Different from image and pictorial database systems:
  - Containing sets of objects in space rather than images or pictures of a space
Definition

- A spatial database system:
  - Is a database system
    - A DBMS with additional capabilities for handling spatial data
  - Offers spatial data types (SDTs) in its data model and query language
    - Structure in space: e.g., POINT, LINE, REGION
    - Relationships among them: (l intersects r)
  - Supports SDT in its implementation
    - Providing at least spatial indexing (retrieving objects in particular area without scanning the whole space)
    - Efficient algorithm for spatial joins (not simply filtering the cartesian product)

Modeling

- WLOG assume 2-D and GIS application, two basic things need to be represented:
  - Objects in space: cities, forests, or rivers
  - modeling single objects
  - Space: say something about every point in space (e.g., partition of a country into districts)
  - modeling spatially related collections of objects
Modeling …

- Fundamental abstractions for modeling single objects:
  - Point: object represented only by its location in space, e.g., center of a state
  - Line (actually a curve or ployline): representation of moving through or connections in space, e.g., road, river
  - Region: representation of an extent in 2d-space, e.g., lake, city

- Instances of spatially related collections of objects:
  - Partition: set of region objects that are required to be disjoint (adjacency or region objects with common boundaries), e.g., thematic maps
  - Networks: embedded graph in plane consisting of set of points (vertices) and lines (edges) objects, e.g. highways, power supply lines, rivers
Modeling …

A sample (ROSE) spatial type system

EXT={lines, regions}, GEO={points, lines, regions}

- Spatial predicates for topological relationships:
  - inside: \( \text{geo} \times \text{regions} \rightarrow \text{bool} \)
  - intersect, meets: \( \text{ext1} \times \text{ext2} \rightarrow \text{bool} \)
  - adjacent, encloses: \( \text{regions} \times \text{regions} \rightarrow \text{bool} \)

- Operations returning atomic spatial data types:
  - intersection: \( \text{lines} \times \text{lines} \rightarrow \text{points} \)
  - intersection: \( \text{regions} \times \text{regions} \rightarrow \text{regions} \)
  - plus, minus: \( \text{geo} \times \text{geo} \rightarrow \text{geo} \)
  - contour: \( \text{regions} \rightarrow \text{lines} \)

Modeling …

- Spatial operators returning numbers
  - dist: \( \text{geo1} \times \text{geo2} \rightarrow \text{real} \)
  - perimeter, area: \( \text{regions} \rightarrow \text{real} \)

- Spatial operations on set of objects
  - sum: \( \text{set(geo)} \times (\text{obj} \rightarrow \text{geo}) \rightarrow \text{geo} \)
  - A spatial aggregate function, geometric union of all attribute values, e.g., union of set of provinces determine the area of the country
  - closest: \( \text{set(geo)} \times (\text{obj} \rightarrow \text{geo1}) \times \text{geo2} \rightarrow \text{set(obj)} \)
  - Determines within a set of objects those whose spatial attribute value has minimal distance from geometric query object
Modeling …

- **Spatial relationships:**
  - *Topological relationships:* e.g., adjacent, inside, disjoint. Are invariant under topological transformations like translation, scaling, rotation
  - *Direction relationships:* e.g., above, below, or north_of, southwest_of, ...
  - *Metric relationships:* e.g., distance

- **Enumeration of all possible topological relationships between two simple regions (no holes, connected):**
  - Based on comparing two objects boundaries ($\delta A$) and interiors ($A^o$), there are 4 sets each of which be empty or not $= 2^4 = 16$. 8 of these are not valid and 2 symmetric so:

- **6 valid topological relationships:**
  - disjoint, in, touch, equal, cover, overlap

Modeling …

- **DBMS data model must be extended by SDTs at the level of atomic data types (such as integer, string), or better be open for user-defined types (OR-DBMS approach):**

  relation states (sname: STRING; area: REGION; spop: INTEGER)
  relation cities (cname: STRING; center: POINT; ext: REGION; cpop: INTEGER);
  relation rivers (rname: STRING; route: LINE)
Querying

- Two main issues:
  1. Connecting the operations of a spatial algebra (including predicates to express spatial relationships) to the facilities of a DBMS query language.
  2. Providing graphical presentation of spatial data (i.e., results of queries), and graphical input of SDT values used in queries.

Querying …

Fundamental spatial algebra operations:
- Spatial selection: returning those objects satisfying a spatial predicate with the query object
  - “All cities in Bavaria”
    SELECT sname FROM cities c WHERE c.center inside Bavaria.area
  - “All rivers intersecting a query window”
    SELECT * FROM rivers r WHERE r.route intersects Window
  - “All big cities no more than 100 Kms from Hagen”
    SELECT cname FROM cities c WHERE dist(c.center, Hagen.center) < 100 and c.pop > 500k
    (conjunction with other predicates and query optimization)
Querying …

- **Spatial join:** A join which compares any two joined objects based on a predicate on their spatial attribute values.
  
  "For each river pass through Bavaria, find all cities within less than 50 Kms."

  ```sql
  SELECT r.rname, c.cname, length(intersection(r.route, c.area))
  FROM rivers r, cities c
  WHERE r.route intersects Bavaria.area and
  dist(r.route, c.area) < 50 Km
  ```

Querying …

- **Graphical I/O issue:** how to determine “Window” or “Bavaria” in previous examples (input); or how to show “intersection(route, Bavaria.area)” or “r.route” (output) (results are usually a combination of several queries).

- **Requirements for spatial querying** [Egenhofer]:
  
  - Spatial data types
  - Graphical display of query results
  - Graphical combination (overlay) of several query results
    (start a new picture, add/remove layers, change order of layers)
  - Display of context (e.g., show background such as a raster image (satellite image) or boundary of states)
  - Facility to check the content of a display (which query contributed to the content)
Querying ...

- Extended dialog: use pointing device to select objects within a subarea, zooming, ...
- Varying graphical representations: different colors, patterns, intensity, symbols to different objects classes or even objects within a class
- Legend: clarify the assignment of graphical representations to object classes
- Label placement: selecting object attributes (e.g., population) as labels
- Scale selection: determines not only size of the graphical representations but also what kind of symbol be used and whether an object be shown at all
- Subarea for queries: focus attention for follow-up queries

Data Structures & Algorithms

1. Implementation of spatial algebra in an integrated manner with the DBMS query processing.
2. Not just simply implementing atomic operations using computational geometry algorithms, but consider the use of the predicates within set-oriented query processing ➔ Spatial indexing or access methods, and spatial join algorithms
Data Structures …

- Representation of a value of a SDT must be compatible with two different views:
  
  1. DBMS perspective:
     - Same as attribute values of other types with respect to generic operations
     - Can have varying and possibly large size
     - Reside permanently on disk page(s)
     - Can efficiently be loaded into memory
     - Offers a number of type-specific implementations for generic operations needed by the DBMS (e.g., transformation functions from/to ASCII or graphic)

2. Spatial algebra implementation perspective, the representation:
   
   - Is a value of some programming language data type
   - Is some arbitrary data structure which is possibly quite complex
   - Supports efficient computational geometry algorithms for spatial algebra operations
   - Is no geared only to one particular algorithm but is balanced to support many operations well enough
Data Structures …

- From both perspectives, the representation should be mapped by the compiler into a single or perhaps a few contiguous areas (to support DBMS paging). Also supports:
  - Plane sweep sequence: object’s vertices stored in a specific sweep order (e.g., x-order) to expedite plane-sweep operation.
  - Approximations: stores some approximations as well, e.g., MBR
  - Stored unary function values: such as perimeter or area be stored once the object is constructed to eliminate future expensive computations.

Spatial Indexing

- To expedite spatial selection (as well as other operations such as spatial joins, …)
- It organizes space and the objects in it in some way so that only parts of the space and a subset of the objects need to be considered to answer a query.
- Two main approaches:
  1. Dedicated spatial data structures (e.g., R-tree)
  2. Spatial objects mapped to a 1-D space to utilize standard indexing techniques (e.g., B-tree)
Spatial Indexing

- A fundamental idea: use of approximations: 1) continuous (e.g., bounding box), or 2) grid.

- Filter and refine strategy for query processing:
  1. Filter: returns a set of candidate object which is a superset of the objects fulfilling a predicate
  2. Refine: for each candidate, the exact geometry is checked

Spatial Indexing …

- Spatial data structures either store points or rectangles (for line or region values)
- Operations on those structures: insert, delete, member
- Query types for points:
  - Range query: all points within a query rectangle
  - Nearest neighbor: point closest to a query point
  - Distance scan: enumerate points in increasing distance from a query point.
- Query types for rectangles:
  - Intersection query
  - Containment query
Spatial Indexing …

- A spatial index structure organizes points into buckets.
- Each bucket has an associated bucket region, a part of space containing all objects stored in that bucket.
- For point data structures, the regions are disjoint & partition space so that each point belongs into precisely one bucket.
- For rectangle data structures, bucket regions may overlap.

A kd-tree partitioning of 2d-space where each bucket can hold up to 3 points

Spatial Indexing …

- One dimensional embedding: z-order or bit-interleaving
  - Find a linear order for the cells of the grid while maintaining “locality” (i.e., cells close to each other in space are also close to each other in the linear order)
  - Define this order recursively for a grid that is obtained by hierarchical subdivision of space
Spatial Indexing …

- Any shape (approximated as set of cells) over the grid can now be decomposed into a \textit{minimal} number of cells at different levels (using always the highest possible level)

- Hence, for each spatial object, we can obtain a set of “spatial keys”

- Index: can be a B-tree of lexicographically ordered list of the union of these spatial keys

Spatial Indexing …

- Spatial index structures for points:

- Grid-file

- KD-Tree
Spatial Indexing ...

Spatial index structures for rectangles: unlike points, rectangles don’t fall into a unique cell of a partition and might intersect partition boundaries

- Transformation approach: instead of k-dimensional rectangles, 2k-dimensional points are stored using a point data structure
- Overlapping regions: partitioning space is abandoned & bucket regions may overlap (e.g., R-tree & R*-tree)
- Clipping: keep partitioning, a rectangle that intersects partition boundaries is clipped and represented within each intersecting cell (e.g., R*-tree)

A rectangle with 4 coordinates \((X_{\text{left}}, X_{\text{right}}, Y_{\text{bottom}}, Y_{\text{top}})\) can be considered as a point in 4d-space

- For illustration, consider how an interval \(i = (i_1, i_2)\) with 2 coordinates can be mapped to 2d-space (as a point):

Intersection query with interval \(i\):
Find all points \((x, y)\) where:
\[ x < i_2 \text{ and } y > i_1 \]
Spatial Join

- Traditional join methods such as hash join or sort/merge join are not applicable.
- Filtering cartesian product is expensive.
- Two general classes:
  1. Grid approximation/bounding box
  2. None/one/both operands are presented in a spatial index structure
    - Grid approximations and overlap predicate:
      - A parallel scan of two sets of z-elements corresponding to two sets of spatial objects is performed
      - Too fine a grid, too many z-elements per object (inefficient)
      - Too coarse a grid, too many “false hits” in a spatial join

Spatial Join ...

- Bounding boxes: for two sets of rectangles R, S all pairs $(r,s), r \text{ in } R, s \text{ in } S,$ such that $r$ intersects $s$:
  - No spatial index on R and S: `bb_join` which uses a computational geometry algorithm to detect rectangle intersection, similar to external merge sorting
  - Spatial index on either R or S: `index join` scan the non-indexed operand and for each object, the bounding box of its SDT attribute is used as a search argument on the indexed operand (only efficient if non-indexed operand is not too big or else bb-join might be better)
  - Both R and S are indexed: synchronized traversal of both structures so that pairs of cells of their respective partitions covering the same part of space are encountered together.
System Architecture

Extensions required to a standard DBMS architecture:

- Representations for the data types of a spatial algebra
- Procedures for the atomic operations (e.g., overlap)
- Spatial index structures
- Access operations for spatial indices (e.g., insert)
- Filter and refine techniques
- Spatial join algorithms
- Cost functions for all these operations (for query optimizer)
- Statistics for estimating selectivity of spatial selection and join
- Extensions of optimizer to map queries into the specialized query processing method
- Spatial data types & operations within data definition and query language
- User interface extensions to handle graphical representation and input of SDT values

The only clean way to accommodate these extensions is an integrated architecture based on the use of an extensible DBMS.

There is no difference in principle between:

- a standard data type such as a STRING and a spatial data type such as REGION
- same for operations: concatenating two strings or forming intersection of two regions
- clustering and secondary index for standard attribute (e.g., B-tree) & for spatial attribute (R-tree)
- sort/merge join and bounding-box join
- query optimization (only reflected in the cost functions)
System Architecture

Extensibility of the architecture is orthogonal to the data model implemented by that architecture:

- Probe is OO
- DASDBS is nested relational
- POSTGRES, Starbust and Gral extended relational models

- OO is good due to extensibility at the data type level, but lack extensibility at index structures, query processing or query optimization.

- Hence, current commercial solutions are OR-DBMSs:
  - NCR Teradata Object Relational (TOR)
  - IBM DB2 (spatial extenders)
  - Informix Universal Server (spatial datablade)
  - Oracle 8i (spatial cartridges)