Temporal and Spatial Database
2014/2015 2nd semester

Spatial Databases
SL06

- Introduction
- Modeling spatial concepts
- Organizing the underlying space
- Spatial data types, algebras, and relationships
- Integrating geometry into DBMS data model
- Querying spatial databases
- Spatial indexes
- System architecture
The slides were developed in a collaboration between Michael Böhlen from the University of Zurich and Johann Gamper from the Free University of Bozen-Bolzano and are based on the following material:

Introduction/1

- The **goal** of spatial database research is to extend DBMS data models and query languages to be able to manage geometries/geometric objects.
  - Data structures for geometric shapes
  - Algorithms for performing geometric computations
  - Indexing techniques for multi-dimensional space
  - Extensions of query optimizers

- The main **motivation** for spatial databases in the past was to support geographic information systems (GIS)
  - Early GIS made limited use of DBMS technology
    - Only non-spatial data were stored in a DB; geometries were managed in separate files
  - Modern GIS systems are built on top of DBMS
    - All major commercial systems offer spatial extensions (e.g., Oracle, IBM DB2, Informix)
Spatial databases have a **wider scope** and are able to represent other spaces (beside geographical spaces in GIS systems)

- The layout of a VLSI design
- A 3D model of the human body
- A protein structure studied in molecular biology

An important distinction has to be made between **image databases** and **spatial databases**

- Image databases manage raster images of space
- Spatial databases manage objects (with clear location and extent) in space
- Feature extraction can be used to identify spatial entities within an image that can be stored in a spatial database.
Definition: A spatial DBMS

- is a DBMS with additional capabilities for handling spatial data
- offers **spatial data types** in its data model and query language
  - Structure in space, e.g., point, line, region
  - Relationships among them, e.g., intersection
- supports spatial data types in its implementation
  - Providing at least **spatial indexing** (retrieving objects in particular area without scanning the whole space)
  - Efficient algorithms for **spatial join** (not simply filtering the Cartesian product)
The entities to be represented in a spatial database include anything that might appear on a paper map.

Two alternative views about what needs to be represented:

- **Objects in space**: Distinct entities arranged in space, each of which has its own geometric description.
  - e.g., cities, rivers, highway networks, forests, etc.

- **Space**: Space itself, i.e., to say something about every point in space.
  - e.g., thematic maps, land use, partition of a country into districts.

To model these diverse entities the following classes of concepts are distinguished:

- Single objects
- Spatially related collections of objects
Modeling Spatial Concepts/2

- Three fundamental abstractions of **single objects**
  - **Point**: An object for which only its location but not its extent is relevant
    - e.g., cities on a large-scale map, hospitals, subway stations
  - **Line (curve)**: An entity moving through space or a connection in space
    - e.g., rivers, highways, telephone cables
  - **Region**: An entity that has an extent in the 2D space
    - e.g., countries, forests, lakes
    - May in general have holes and consist of several disjoint pieces
Spatial Data in PostgreSQL

- PostgreSQL offers various geometric types:
  - point: \((x,y)\)
  - lseg: \(((x_1,y_1),(x_2,y_2))\)
  - box: \(((x_1,y_1),(x_2,y_2))\)
  - path: \([((x_1,y_1),...)]\)
  - polygon: \(((x_1,y_1),...)\)
  - circle: \(<(x,y),r>\)

```
CREATE TABLE cities (  
  name VARCHAR(80),  
  location point );

INSERT INTO cities  
VALUES ('San Francisco', '(-194.0, 53.0)');

CREATE TABLE t (id INT,  
area polygon);

INSERT INTO t  
VALUES (1, '(((2,2),(3,4),(3,6),(1,1))');
```
PostGIS is a spatial database extender for PostgreSQL.
PostGIS adds support for geographic objects.
PostGIS adds a universal geometry data type.
Do not mix PostgreSQL and PostGIS.

```sql
CREATE TABLE shapes (name VARCHAR, geom geometry);

INSERT INTO shapes VALUES
('Point', 'POINT(0 0)'),
('Linestring', 'LINESTRING(0 0, 1 1, 2 2)'),
('Polygon', 'POLYGON((0 0, 1 0, 1 1, 0 0))'),
('PolyHole', 'POLYGON((0 0, 10 0, 10 10, 0 0),
(1 1, 1 2, 2 2, 1 1))');
```
Spatial Data in Oracle

- Oracle Spatial allows to store, index and query spatial data.
- Oracle provides a SDO_GEOMETRY object type for all spatial objects.

```sql
CREATE TABLE cola_markets (
    mkt_id NUMBER PRIMARY KEY,
    name VARCHAR2(32),
    shape SDO_GEOMETRY);

INSERT INTO cola_markets VALUES (1, 'cola_a',
    SDO_GEOMETRY(2003, -- 2D polygon
        NULL, NULL,
        SDO_ELEM_INFO_ARRAY(1,1003,3),
        -- rectangle (1003 = exterior)
        SDO_ORDINATE_ARRAY(1,1, 5,7)
        -- LL and UR corner ));

CREATE INDEX cola_spatial_idx
    ON cola_markets(shape)
    INDEXTYPE IS MDSYS.Spatial_index;
```
The two most important abstractions for spatially related collections of objects

**Partition:** A set of region objects that are required to be disjoint
- The adjacency relationship is of particular interest, i.e., common boundary of region objects
- e.g., land use, districts, land ownership

**Network:** A graph embedded into the plane, consisting of a set of point objects forming its nodes and a set of line objects describing the geometry of the edges
- e.g., highways, public transport, power supply lines

Other interesting abstractions include **nested partition**, e.g., a country partitioned into provinces partitioned into districts, etc.
Organizing the Underlying Space/1

- Euclidean geometry is not suitable as a basis for modeling in spatial databases
  - Euclidean space is **continuous**, i.e., points are represented by a pair of real numbers $p = (x, y) \in \mathbb{R}^2$
  - But computer numbers are **discrete**
    - $\Rightarrow$ space is represented by a discrete raster

- **Example**: Intersection of two lines
  - Intersection point is rounded to the nearest grid point
  - A subsequent test to determine whether the intersection point is on one of the lines yields a false result

![Diagram of intersecting lines with rounded intersection point and subsequent test yielding a false result.]
Organizing the Underlying Space/2

► Experiment by Cotelo-Lema and Luaces (cf. paper *DualgridFF: a Robust, Consistent and Efficient Physical Data Model for Spatial Databases*, in ACMGIS 2010)

► Evaluation of correctness of set operations in Postgis v1.0.2 (v1.5.1.1).

► N/A indicates a topological exception (Postgis v1.0.2)

<table>
<thead>
<tr>
<th>Test</th>
<th>% Wrong answers (Original Postgis)</th>
</tr>
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<tbody>
<tr>
<td>1  ((A \cap B) - A = \emptyset)</td>
<td>N/A (2.25%)</td>
</tr>
<tr>
<td>2  ((A \cap B) - B = \emptyset)</td>
<td>N/A (2.37%)</td>
</tr>
<tr>
<td>3  ((A \cap B) \subseteq A)</td>
<td>5.66%</td>
</tr>
<tr>
<td>4  ((A \cap B) \subseteq B)</td>
<td>5.97%</td>
</tr>
<tr>
<td>5  (A \cup (A \cap B) = A)</td>
<td>N/A (2.25%)</td>
</tr>
<tr>
<td>6  (B \cup (A \cap B) = B)</td>
<td>N/A (2.37%)</td>
</tr>
<tr>
<td>7  ((A \cap B) \subseteq (A \cup B))</td>
<td>0%</td>
</tr>
<tr>
<td>8  (A \subseteq (A \cup B))</td>
<td>2.31%</td>
</tr>
<tr>
<td>9  (B \subseteq (A \cup B))</td>
<td>2.31%</td>
</tr>
<tr>
<td>10 (\text{disjoint}((A - B), (A \cap B)))</td>
<td>0%</td>
</tr>
<tr>
<td>11 (\text{disjoint}((B - A), (A \cap B)))</td>
<td>0%</td>
</tr>
<tr>
<td>12 (\text{disjoint}((A - B), B))</td>
<td>3.48%</td>
</tr>
<tr>
<td>13 (\text{disjoint}((B - A), A))</td>
<td>2.31%</td>
</tr>
<tr>
<td>14 ((A \cup B) - B = (A - B))</td>
<td>N/A (3.48%)</td>
</tr>
<tr>
<td>15 ((A \cup B) - A = (B - A))</td>
<td>N/A (2.31%)</td>
</tr>
<tr>
<td>16 ((A - B) \subseteq A)</td>
<td>3.08%</td>
</tr>
<tr>
<td>17 (B - A \subseteq B)</td>
<td>2.31%</td>
</tr>
<tr>
<td>18 ((A \cup B) - (A \cap B) = \text{symdiff}(A, B))</td>
<td>0%</td>
</tr>
<tr>
<td>19 ((A - B) \cup (B - A) = \text{symdiff}(A, B))</td>
<td>0%</td>
</tr>
</tbody>
</table>
Organizing the Underlying Space/3

- Approach 1: Definition of a **discrete geometric basis** for modeling as well as for implementation.
  - The goal is to not compute new intersection points within geometric operations.
  - Two approaches for a geometric basis:
    - **Simplicial complexes** (based on combinatorial topology) (Frank & Kuhn 86, Egenhofer, Frank & Jackson 89)
    - **Realms** (Güting & Schneider 93, Schneider 97)

- Approach 2: Deal with numeric imprecision in applications and/or in spatial operations.
  - Rewrite equality on points to distance comparisons with threshold.
  - Oracle uses a tolerance with many spatial operators.
Spatial Data Types and Algebras

- The basic spatial abstractions can be embedded into an existing DBMS data model by using abstract data types

- **Spatial (abstract) data types** encapsulate
  - the structure of a spatial object, e.g., region
  - and operations on it, e.g., predicates, functions, construction operators

- **Spatial algebra**: A collection of spatial data types with related operations.
  - Important properties of an algebra are **closure** under operations and **completeness**.
Spatial Queries in PostgreSQL

- Operators and functions in PostgreSQL:
  - +, translation, box '((0,0),(1,1))' + point '(2.0,0)'
  - #, intersection, '((1,-1),(-1,1))' # '((1,1),(-1,-1))'
  - @>, contains?, circle '((0,0),2)' @> point '(1,1)'
  - #, number of points, # '((1,0),(0,1),(-1,0))'
  - @@, center, @@ circle '((0,0),10)'
  - area(object), area, area(box '((0,0),(1,1))')
  - center(object), point center, center(box '((0,0),(1,2))')
  - circle(box), box to circle, circle(box '((0,0),(1,1))')

```
SELECT * FROM r WHERE poly @> '(2, 8)';
SELECT point(area) FROM t;
```
Spatial Queries in PostGIS

```sql
SELECT id, ST_AsText(poly)
FROM r
WHERE ST_Contains(poly, ST_GeomFromText('POINT(9 2)'));

SELECT ST_Contains(
    ST_GeomFromText('POLYGON((0 0, 10 10, 10 0, 0 0))'),
    ST_GeomFromText('POINT(0 0)'));

SELECT name, beer_price,
    distance(location,
        GeometryFromText('POINT(1195722 383854)',2167))
FROM pubs;

SELECT COUNT(*) AS cnt, p.id AS id
FROM polys p JOIN circles c
ON ST_Contains(c.geom, ST_PointOnSurface(p.geom))
GROUP BY p.id
```
Spatial Queries in Oracle

```sql
SELECT SDO_GEOMETRY('POINT(-79 37)') FROM DUAL;

SELECT name, SDO_GEOM.SDO_AREA(shape, 0.005) FROM cola_markets;

SELECT SDO_GEOM.SDO_DISTANCE(b.shape, d.shape, 0.005) FROM cola_markets b, cola_markets d WHERE b.name = 'cola_b' AND d.name = 'cola_d';

SELECT SDO_GEOM.RELATE(b.shape, 'anyinteract', d.shape, 0.005) FROM cola_markets b, cola_markets d WHERE b.name = 'cola_b' AND d.name = 'cola_d';

SELECT * FROM cola_markets WHERE SDO_OVERLAPS(shape, SDO_GEOMETRY('POINT(-79 37)')) = 'TRUE';

SELECT c.shape.Get_Dims() FROM cola_markets c WHERE c.name = 'cola_b';
```
- **ROSE Algebra** *(RObust Spatial Extension, Güting & Schneider 95)*
  - A spatial algebra with realm-based spatial data types (i.e., objects composed from realm elements)
- **ROSE data types**: points, lines, regions
ROSE Algebra/2

- **ROSE operations**: ROSE provides precisely defined operations
  - Let $GEO = \{\text{points, lines, regions}\}$, $EXT = \{\text{lines, regions}\}$ and $geo \in GEO$, $ext \in EXT$
  - Spatial predicates for topological relationships
    - $\text{inside}: \quad geo \times \text{regions} \rightarrow \text{bool}$
    - $\text{intersect, meets}: \quad ext \times ext \rightarrow \text{bool}$
    - $\text{adjacent, encloses}: \quad \text{regions} \times \text{regions} \rightarrow \text{bool}$
  - Operations returning atomic spatial data types
    - $\text{intersection}: \quad \text{lines} \times \text{lines} \rightarrow \text{points}$
    - $\text{intersection}: \quad \text{regions} \times \text{regions} \rightarrow \text{regions}$
    - $\text{plus, minus}: \quad geo \times geo \rightarrow geo$
    - $\text{contour}: \quad \text{regions} \rightarrow \text{lines}$
Spatial operators returning numbers

\[ \text{dist} : \text{geo} \times \text{geo} \to \text{real} \]
\[ \text{perimeter, area} : \text{regions} \to \text{real} \]

Spatial operations on set of objects

\[ \text{sum} : \text{set}(\text{obj}) \times (\text{obj} \to \text{geo}) \to \text{geo} \]

- \text{sum} is a spatial aggregate function: Takes a set of objects together with a spatial attribute of the objects of type \text{geo} and returns the geometric union of all attribute values
- e.g., form the union of a set of provinces to determine the area of a country

\[ \text{closest} : \text{set}(\text{obj}) \times (\text{obj} \to \text{geo}) \times \text{geo} \to \text{set}(\text{obj}) \]

- The \text{closest} operator determines within a set of objects those whose spatial attribute value has minimal distance from some other geometric object
Integrating Geometry into the DBMS Data Model

▶ Spatial datatypes can be embedded in any data model, e.g., the relational data model.
▶ DBMS data model must be extended with SDTs at the level of atomic data types (integer, string).
▶ Basic idea
  ▶ Represent **spatial objects** by objects (of the DBMS data model) with at least one SDT attribute.
    ▶ Relational data model: spatial objects are tuples with at least one SDT attribute.
    ▶ **Example:** Relational tables to store cities, rivers, and countries:
      cities(name: string, pop: int, loc: points)
      rivers(name: string, route: line)
      highways(name: string, route: line)
      states(name: string, area: region)
▶ Representation of **spatially related collections of objects** (e.g., partitions) as a set of objects with a region attribute.
  ▶ Loses some information, e.g., regions are disjoint.
Connect operations of a spatial algebra to the facilities of a DBMS query language

Two main issues must be considered

- Fundamental operations for manipulating sets of database objects
  - spatial selection, spatial join, etc.
- Graphical input and output
Spatial selection: Select those objects that satisfy a spatial predicate with the query object

- All cities in Bavaria?
  ```sql
  select sname
  from cities c
  where c.center inside Bavaria.area
  ```

- All rivers intersecting a query window?
  ```sql
  select *
  from rivers r
  where r.route intersects Qwindow
  ```

- All big cities no more than 100 km from Hagen?
  ```sql
  select cname
  from cities c
  where dist(c.center,Hagen.center) < 100
  and c.pop > 500k
  ```
Spatial join: Compares any two joined objects based on a predicate on their spatial attribute values.

For each river passing through Bavaria, cities within less than 50 km?
```sql
select r.rname, c.cname
from rivers as r, cities as c
where r.route intersects Bavaria.area and
dist(r.route,c.area) < 50 km
```

Make a list, showing for each country the number of its neighbor countries?
```sql
select s.name, count(*)
from states as s, states as t
where s.area adjacent t.area
group by s.name
```
Spatial function application: Apply (spatial) functions to each member of a set.

Return the part of river Rhine that is within Germany?

```sql
select intersection(r.route, s.area)
from rivers as r, states as s
where r.name = 'Rhine'
and s.name = 'Germany'
```
Graphical input and output

While traditional DBMS deal with alphanumerical data (types), some data (types) in spatial DBMS require a graphical representation

- Input: How to determine “Qwindow” or “Bavaria” in the previous examples?
- Output: How to show “intersection(route,Bavaria.area)” or “r.route”?

The final information to be retrieved is often the result of several queries, the result of which should be graphically overlayed on top of a map

- Graphical combination of several query results (e.g., add/remove layers, change order of layers)
- Display of context (e.g., show background such as a raster image or boundary of states)
Spatial Indexing/1

- Mainly used to support spatial selection
  - but supports also other operations, e.g., spatial join or finding the closest object
- A spatial index 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:
  - Map spatial objects to a 1-D space and utilize standard indexing techniques, e.g., B-tree
  - Dedicated spatial index data structures, e.g., R-tree
Spatial Indexing/2

- A fundamental idea of spatial indexing is the use of approximations
  - Bounding box approximation
  - Grid approximation

- Leads to a filter and refine strategy for query processing
  1. Filter: Returns a set of candidate objects which is a superset of the objects fulfilling a predicate
  2. Refine: For each candidate, the exact geometry is checked
Most spatial index structures are designed to either store **points** (for point values) or **rectangles** (for line and region values).

Operations on those structures: insert, delete, check membership.

Typical 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

- **for rectangles:**
  - *Intersection query*
  - *Containment query*
Spatial Index Structures for Points/1

- **Spatial index structures for points**
  - Data structures for representing points in \( k \) dimensions (multi-attribute) have a long tradition, e.g., a tuple \( t = (x_1, \ldots, x_k) \)
  - Can be used to store geometrical points
  - Problem: index must cluster points that are close to each other

- **1-D embedding: basic idea**
  1. Find a linear order for points such that points close together in space are also close to each other in the linear order
     - Maintains locality
  2. Define this order recursively for a hierarchical subdivision of the space at different granularities.
Spatial Index Structures for Points/2

- **Bit-interleaving** is the most popular such order (Morton 1966)
  - Later also called **z-order** (Orenstein and Manola, 1988)

![Diagram of bit-interleaving](image)

- Each cell at each level of the hierarchy has an associated bit string whose length corresponds to the level to which the cell belongs.
  - e.g., the top-right cell in the left diagram has bit string 11, on the right-side cell 1110 is shown.
  - The bit-string 1110 is obtained by choosing 11 at the top level, and then 10 within the top level quadrant.
- The order which is imposed on all cells of a hierarchical subdivision is given by the **lexicographical order of the bit strings**.
GRID index: Spatial index structure for points (Nievergelt, Hinterberger, and Sevcik 84)

- The following example partitions the data space into *cells* by an irregular grid.

The directory is a *k*-dimensional array whose entries are logical pointers to buckets.

All points in a cell are stored in the bucket pointed to by the corresponding directory entry.

The scales are small and are kept in main memory; the directory is on the disk.
Spatial Index Structures for Points/4

- **kd-Tree** (Bentley 75)
  - Binary tree where each internal node contains a key drawn from one of the $k$ dimensions
  - The key in the root node (level 0) divides the data space with respect to dimension 0, the keys in its children (level 1) divide the two subspaces with respect to dimension 1, and so forth, up to dimension $k - 1$, after which cycling through the dimensions restarts.
  - Leaves contain the points to be stored
The **R-tree** (Guttmann 84) groups objects and encloses them into minimum bounding rectangles (MBRs).

- MBRs are organized hierarchically (as a tree) and may overlap.
- Advantage: Spatial object (or key) is in a single bucket.
- Disadvantage: Multiple search paths due to overlapping bucket regions.
Spatial Index Structures for Rectangles/2

**Transformation approach**

- Idea: Consider simple geometric shapes as points in higher dimensional space (the parameter space)
- $k$-dimensional rectangles are transformed into $2k$-dimensional points, and a point data structure is used.
- Rectangle $(x_l, x_r, y_b, y_t)$ can be viewed as a point in 4-D space

**Example:** Interval $i = [i_1, i_2]$ is mapped to a point $(x, y)$ in 2-D:

- An intersection query with an interval $q = [q_1, q_2]$ translates to a condition: Find all points $(x', y')$ s.t. $x' < q_2$ and $y' > q_1$.
- All intervals intersecting $q$ are in the shaded area
Spatial Join/1

- Very active research area in the last few years
- Traditional join methods such as hash join or sort/merge join are not applicable
- Filtering Cartesian product is expensive
- Proposed methods can be classified along the following criteria:
  - Grid approximation/bounding box
  - None/one/both operands are represented in a spatial index structure
- **Grid approximations** with an overlap predicate
  - A parallel scan of two sets of z-elements corresponding to two sets of spatial objects is performed
  - Similar to a merge join
Spatial Join/2

- **Bounding boxes**: For two sets of rectangles $R$ and $S$ all pairs $(r, s)$, $r \in R$ and $s \in S$ such that $r$ intersects $s$:
  - *No spatial index on $R$ and $S$*: rectangle intersection algorithm uses a computational geometry algorithm to detect rectangle intersection; external divide and conquer algorithm that is similar to external merge sorting
  - *Spatial index on either $R$ or $S$*: index join scans 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 (efficient if non-indexed operand is not too big)
  - *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.
Requirements

- Representations for the data types of a spatial algebra
- Procedures for atomic operations (e.g., overlap)
- Spatial index structures
- Access operations for spatial indices
- 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
- Spatial data types and operations within data definition and query language
- User interface extensions to handle graphical representation and input of SDT values
GIS architectures using a closed DBMS

- First generation systems: built on top of file system
  - no high level data definition
  - no flexible querying
  - no transaction management
  - ...
- Using a standard (mostly relational) DBMS
  - Layered architecture
  - Dual architecture
Layered architecture

- Representation of SDT values:
  - Decompose SDT value into a set of tuples, one tuple per point or line segment
  - Obviously a terrible solution

<table>
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</tbody>
</table>

- Represent SDT values in “long fields” of DBMS
  - DBMS handles geometries only as uninterpreted byte strings
Dual architecture

SDT representation broken into two pieces:

- Advantage: Freedom to use efficient data structures and algorithms in the spatial subsystem
- Problems: Query must also be decomposed into two parts
  - Complex query processing
  - No global query optimization possible
Integrated spatial DBMS architecture

- Using an Extensible DBMS
- The only clean way to accommodate the requirements for spatial databases
- Leads to an integrated architecture such that
  - No difference in principle between a standard data type (STRING) and a spatial data type (REGION); same for operations
  - No difference in principle between index for standard attribute (e.g., B-tree) and for spatial attribute (R-tree)
  - Mechanisms for query optimization do not distinguish spatial or other operations
Spatial DBMS prototypes built on extensible systems

- SECONDO (Güting 04)
- PostgreSQL with PostGIS
- MONET (Boncz et al. 96)
- PROBE (Orenstein 86)

Commercial extensible DBMS with spatial extensions

- Oracle Spatial
- IBM DB2 (with Spatial Extender)
- Informix Universal Server (with Geodetic DataBlade)
- SQL Server Spatial
Summary

- A spatial DBMS offers capabilities for dealing with spatial data, it offers spatial data types, and it supports spatial data types in its implementation (spatial indexing and spatial join).
- The most important spatial data types are points, lines and regions.
- The issues that arise from the precision of geometric operations must be handled in a principled way.
- Along with spatial data types comes a spatial algebra (i.e., operations on spatial data types) and spatial relationships.
- Spatial indexes are a crucial part of any database systems that supports geographical information: mapping to lower dimensional space, grid file, kd tree, R* tree.
- Spatial data types must be integrated into the DBMS at the level of standard data types. This is best achieved with an extensible DBMS.
- In order to query spatial databases we need support for graphical input and output.