



# Database System Concepts, 7<sup>th</sup> Ed.

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## Chapter 8: Complex Data Types

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# Outline

- Semi-Structured Data
- Object Orientation
- Textual Data
- Spatial Data



# Semi-Structured Data

- Many applications require storage of complex data, whose schema changes often
- The relational model's requirement of atomic data types may be an overkill
  - E.g., storing set of interests as a set-valued attribute of a user profile may be simpler than normalizing it
- Data exchange can benefit greatly from semi-structured data
  - Exchange can be between applications, or between back-end and front-end of an application
  - Web-services are widely used today, with complex data fetched to the front-end and displayed using a mobile app or JavaScript
- JSON and XML are widely used semi-structured data models



# Features of Semi-Structured Data Models

## ■ Flexible schema

- **Wide column** representation: allow each tuple to have a different set of attributes, can add new attributes at any time
- **Sparse column** representation: schema has a fixed but large set of attributes, by each tuple may store only a subset

## ■ Multivalued data types

- **Sets, multisets**
  - E.g.,: set of interests {'basketball', 'La Liga', 'cooking', 'anime', 'jazz'}
- **Key-value map** (or just **map** for short)
  - Store a set of key-value pairs
  - E.g., {(brand, Apple), (ID, MacBook Air), (size, 13), (color, silver)}
  - Operations on maps: *put*(key, value), *get*(key), *delete*(key)
- **, Arrays**
  - Widely used for scientific and monitoring applications



# Features of Semi-Structured Data Models

## ■ Arrays

- Widely used for scientific and monitoring applications
- E.g., readings taken at regular intervals can be represented as array of values instead of (time, value) pairs
  - [5, 8, 9, 11] instead of {(1,5), (2, 8), (3, 9), (4, 11)}

## ■ Multi-valued attribute types

- Modeled using *non first-normal-form (NFNF)* data model
- Supported by most database systems today

## ■ **Array database:** a database that provides specialized support for arrays

- E.g., compressed storage, query language extensions etc
- Oracle GeoRaster, PostGIS, SciDB, etc



# Nested Data Types

- Hierarchical data is common in many applications
- JSON: JavaScript Object Notation
  - Widely used today
- XML: Extensible Markup Language
  - Earlier generation notation, still used extensively



# JSON

- Textual representation widely used for data exchange

- Example of JSON data

```
{  
    "ID": "22222",  
    "name": {  
        "firstname": "Albert",  
        "lastname": "Einstein"  
    },  
    "deptname": "Physics",  
    "children": [  
        {"firstname": "Hans", "lastname": "Einstein" },  
        {"firstname": "Eduard", "lastname": "Einstein" }  
    ]  
}
```

- Types: integer, real, string, and
  - *Objects*: are key-value maps, i.e. sets of (attribute name, value) pairs
  - Arrays are also key-value maps (from offset to value)



# JSON

- JSON is ubiquitous in data exchange today
  - Widely used for web services
  - Most modern applications are architected around on web services
- SQL extensions for
  - JSON types for storing JSON data
  - Extracting data from JSON objects using path expressions
    - E.g.  $V \rightarrow ID$ , or  $v.ID$
  - Generating JSON from relational data
    - E.g. `json.build_object('ID', 12345, 'name', 'Einstein')`
  - Creation of JSON collections using aggregation
    - E.g. `json_agg` aggregate function in PostgreSQL
  - Syntax varies greatly across databases
- JSON is verbose
  - Compressed representations such as BSON (Binary JSON) used for efficient data storage





# XML

- XML uses tags to mark up text
- E.g.  
    <course>  
        <course id> CS-101 </course id>  
        <title> Intro. to Computer Science </title>  
        <dept name> Comp. Sci. </dept name>  
        <credits> 4 </credits>  
    </course>
- Tags make the data self-documenting
- Tags can be hierarchical



# Example of Data in XML

```
■ <purchase order>
    <identifier> P-101 </identifier>
    <purchaser>
        <name> Cray Z. Coyote </name>
        <address> Route 66, Mesa Flats, Arizona 86047, USA
    </address>
    </purchaser>
    <supplier>
        <name> Acme Supplies </name>
        <address> 1 Broadway, New York, NY, USA </address>
    </supplier>
    <itemlist>
        <item>
            <identifier> RS1 </identifier>
            <description> Atom powered rocket sled </description>
            <quantity> 2 </quantity>
            <price> 199.95 </price>
        </item>
        <item>...</item>
    </itemlist>
    <total cost> 429.85 </total cost>
    ....
</purchase order>
```



# XML Cont.

- XQuery language developed to query nested XML structures
  - Not widely used currently
- SQL extensions to support XML
  - Store XML data
  - Generate XML data from relational data
  - Extract data from XML data types
    - Path expressions
- See Chapter 30 (online) for more information



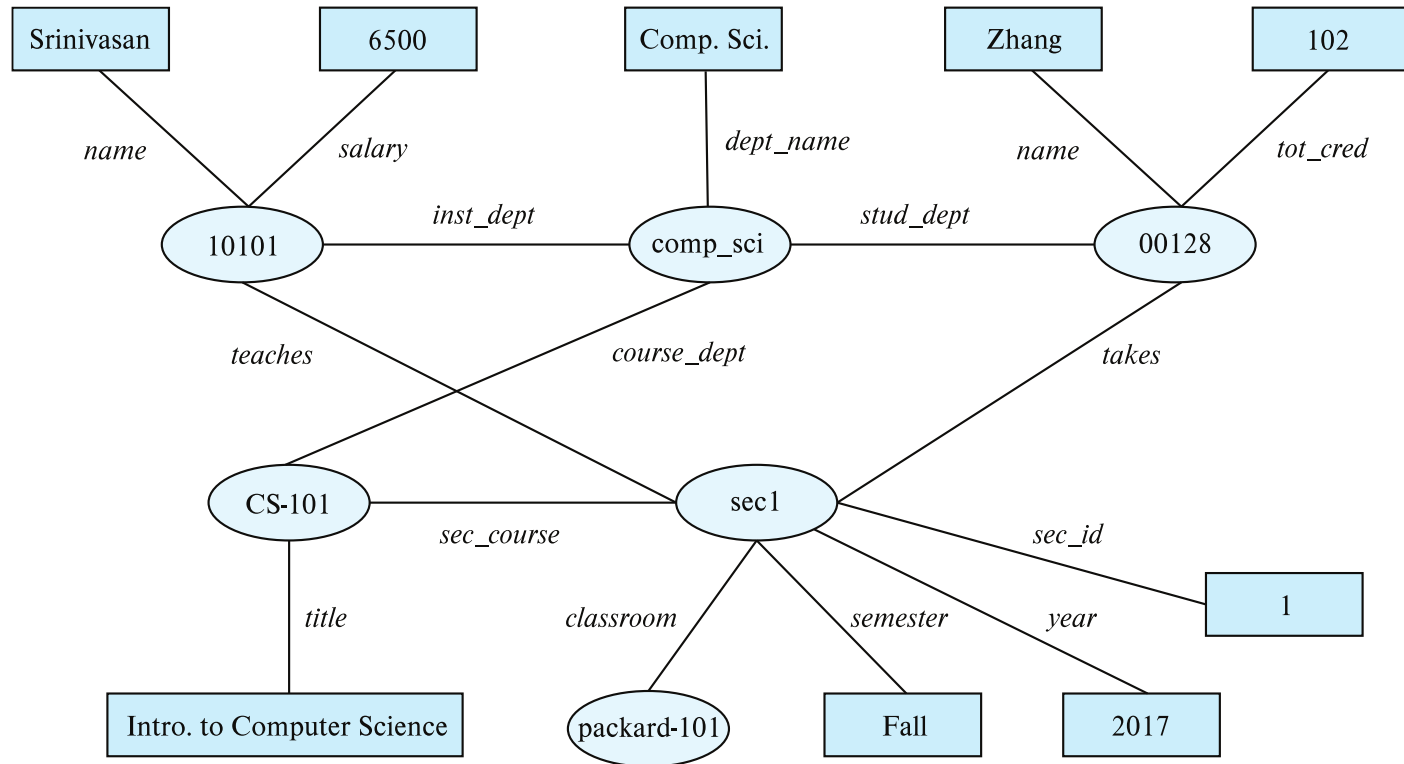
# Knowledge Representation

- Representation of human knowledge is a long-standing goal of AI
  - Various representations of facts and inference rules proposed over time
- **RDF: Resource Description Format**
  - Simplified representation for facts, represented as triples (*subject, predicate, object*)
    - E.g., (NBA-2019, *winner*, Raptors)
    - (Washington-DC, *capital-of*, USA)
    - (Washington-DC, *population*, 6,200,000)
  - Models objects that have attributes, and relationships with other objects
    - Like the ER model, but with a flexible schema
    - (*ID, attribute-name, value*)
    - (*ID1, relationship-name, ID2*)
  - Has a natural graph representation



# Graph View of RDF Data

- Knowledge graph





# Triple View of RDF Data

10101	instance-of	instructor .
10101	name	"Srinivasan" .
10101	salary	"6500" .
00128	instance-of	student .
00128	name	"Zhang" .
00128	tot_cred	"102" .
comp_sci	instance-of	department .
comp_sci	dept_name	"Comp. Sci." .
biology	instance-of	department .
CS-101	instance-of	course .
CS-101	title	"Intro. to Computer Science" .
CS-101	course_dept	comp_sci .
sec1	instance-of	section .
sec1	sec_course	CS-101 .
sec1	sec_id	"1" .
sec1	semester	"Fall" .
sec1	year	"2017" .
sec1	classroom	packard-101 .
sec1	time_slot_id	"H" .
10101	inst_dept	comp_sci .
00128	stud_dept	comp_sci .
00128	takes	sec1 .
10101	teaches	sec1 .



# Querying RDF: SPARQL

- Triple patterns
  - `?cid title "Intro. to Computer Science"`
  - `?cid title "Intro. to Computer Science"`  
`?sid course ?cid`
- SPARQL queries
  - **select** `?name`  
**where** {
    - `?cid title "Intro. to Computer Science" .`
    - `?sid course ?cid .`
    - `?id takes ?sid .`
    - `?id name ?name .`}
  - Also supports
    - Aggregation, Optional joins (similar to outerjoins), Subqueries, etc.
    - Transitive closure on paths



# RDF Representation (Cont.)

- RDF triples represent binary relationships
- How to represent n-ary relationships?
  - Approach 1 (from Section 6.9.4): Create artificial entity, and link to each of the n entities
    - E.g., (Barack Obama, *president-of*, USA, 2008-2016) can be represented as  
(*e1*, *person*, Barack Obama), (*e1*, *country*, USA),  
(*e1*, *president-from*, 2008) (*e1*, *president-till*, 2016)
  - Approach 2: use **quads** instead of triples, with context entity
    - E.g., (Barack Obama, *president-of*, USA, *c1*)  
(*c1*, *president-from*, 2008) (*c1*, *president-till*, 2016)
- RDF widely used as knowledge base representation
  - DBPedia, Yago, Freebase, WikiData, ..
- **Linked open data** project aims to connect different knowledge graphs to allow queries to span databases





# Object Orientation

- **Object-relational data model** provides richer type system
  - with complex data types and object orientation
- Applications are often written in object-oriented programming languages
  - Type system does not match relational type system
  - Switching between imperative language and SQL is troublesome
- Approaches for integrating object-orientation with databases
  - Build an **object-relational database**, adding object-oriented features to a relational database
  - Automatically convert data between programming language model and relational model; data conversion specified by **object-relational mapping**
  - Build an **object-oriented database** that natively supports object-oriented data and direct access from programming language



# Object-Relational Database Systems

- User-defined types
  - **create type** *Person*  
(*ID* **varchar**(20) **primary key**,  
*name* **varchar**(20),  
*address* **varchar**(20)) **ref from**(*ID*); /\* More on this later \*/  
**create table** *people* **of** *Person*;
- Table types
  - **create type** *interest* **as table** (  
*topic* **varchar**(20),  
*degree\_of\_interest* **int**);  
**create table** *users* (  
*ID* **varchar**(20),  
*name* **varchar**(20),  
*interests* *interest*);
- Array, multiset data types also supported by many databases
  - Syntax varies by database



# Type and Table Inheritance

- Type inheritance
  - **create type** *Student* **under** *Person*  
(*degree* **varchar**(20)) ;  
**create type** *Teacher* **under** *Person*  
(*salary* **integer**);
- Table inheritance syntax in PostgreSQL and oracle
  - **create table** *students*  
(*degree* **varchar**(20))  
**inherits** *people*;  
**create table** *teachers*  
(*salary* **integer**)  
**inherits** *people*;
  - **create table** *people* **of** *Person*;  
**create table** *students* **of** *Student*  
**under** *people*;  
**create table** *teachers* **of** *Teacher*  
**under** *people*;



# Reference Types

- Creating reference types
  - **create type** *Person*  
(*ID* **varchar**(20) **primary key**,  
*name* **varchar**(20),  
*address* **varchar**(20))  
**ref from**(*ID*);  
**create table** *people* **of** *Person*;  
**create type** *Department* (  
*dept\_name* **varchar**(20),  
*head* **ref**(*Person*) **scope** *people*);  
**create table** *departments* **of** *Department*  
**insert into** *departments* **values** ('CS', '12345')
  - System generated references can be retrieved using subqueries
    - (**select** **ref**(*p*) **from** *people* **as** *p* **where** *ID* = '12345')
- Using references in **path expressions**
  - **select** *head->name*, *head->address*  
**from** *departments*;



# Object-Relational Mapping

- Object-relational mapping (ORM) systems allow
  - Specification of mapping between programming language objects and database tuples
  - Automatic creation of database tuples upon creation of objects
  - Automatic update/delete of database tuples when objects are update/deleted
  - Interface to retrieve objects satisfying specified conditions
    - Tuples in database are queried, and object created from the tuples
- Details in Section 9.6.2
  - Hibernate ORM for Java
  - Django ORM for Python



# Textual Data

- **Information retrieval:** querying of unstructured data
  - Simple model of keyword queries: given query keywords, retrieve documents containing all the keywords
  - More advanced models rank relevance of documents
  - Today, keyword queries return many types of information as answers
    - E.g., a query “cricket” typically returns information about ongoing cricket matches
- Relevance ranking
  - Essential since there are usually many documents matching keywords



# Ranking using TF-IDF

- Term: keyword occurring in a document/query
- **Term Frequency:**  $TF(d, t)$ , the relevance of a term  $t$  to a document  $d$ 
  - One definition:  $TF(d, t) = \log(1 + n(d, t)/n(d))$   
where
    - $n(d, t)$  = number of occurrences of term  $t$  in document  $d$
    - $n(d)$  = number of terms in document  $d$
- **Inverse document frequency:**  $IDF(t)$ 
  - One definition:  $IDF(t) = 1/n(t)$
- **Relevance** of a document  $d$  to a set of terms  $Q$ 
  - One definition:  $r(d, Q) = \sum_{t \in Q} TF(d, t) * IDF(t)$
  - Other definitions
    - take **proximity** of words into account
    - **Stop words** are often ignored



# Ranking Using Hyperlinks

- Hyperlinks provide very important clues to importance
- Google introduced PageRank, a measure of popularity/importance based on hyperlinks to pages
  - Pages hyperlinked from many pages should have higher PageRank
  - Pages hyperlinked from pages with higher PageRank should have higher PageRank
  - Formalized by **random walk** model
- Let  $T[i, j]$  be the probability that a random walker who is on page  $i$  will click on the link to page  $j$ 
  - Assuming all links are equal,  $T[i, j] = 1/N_i$
- Then PageRank[j] for each page  $j$  can be defined as
  - $P[j] = \delta/N + (1 - \delta) * \sum_{i=1}^N (T[i, j] * P[i])$
  - Where  $N$  = total number of pages, and  $\delta$  a constant usually set to 0.15





# Ranking Using Hyperlinks

- Definition of PageRank is circular, but can be solved as a set of linear equations
  - Simple iterative technique works well
  - Initialize all  $P[i] = 1/N$
  - In each iteration use equation  $P[j] = \delta/N + (1 - \delta) * \sum_{i=1}^N (T[i, j] * P[i])$  to update  $P$
  - Stop iteration when changes are small, or some limit (say 30 iterations) is reached.
- Other measures of relevance are also important. For example:
  - Keywords in anchor text
  - Number of times who ask a query click on a link if it is returned as an answer



# Retrieval Effectiveness

- Measures of effectiveness
  - **Precision**: what percentage of returned results are actually relevant
  - **Recall**: what percentage of relevant results were returned
  - At some number of answers, e.g. precision@10, recall@10
- Keyword querying on structured data and knowledge bases
  - Useful if users don't know schema, or there is no predefined schema
  - Can represent data as graphs
  - Keywords match tuples
  - Keyword search returns closely connected tuples that contain keywords
    - E.g. on our university database given query “Zhang Katz”, Zhang matches a student, Katz an instructor and advisor relationship links them



# Spatial Data



# Spatial Data

- Spatial databases store information related to spatial locations, and support efficient storage, indexing and querying of spatial data.
  - **Geographic data** -- road maps, land-use maps, topographic elevation maps, political maps showing boundaries, land-ownership maps, and so on.
    - **Geographic information systems** are special-purpose databases tailored for storing geographic data.
    - Round-earth coordinate system may be used
      - (Latitude, longitude, elevation)
  - **Geometric data:** design information about how objects are constructed . For example, designs of buildings, aircraft, layouts of integrated-circuits.
    - 2 or 3 dimensional Euclidean space with (X, Y, Z) coordinates



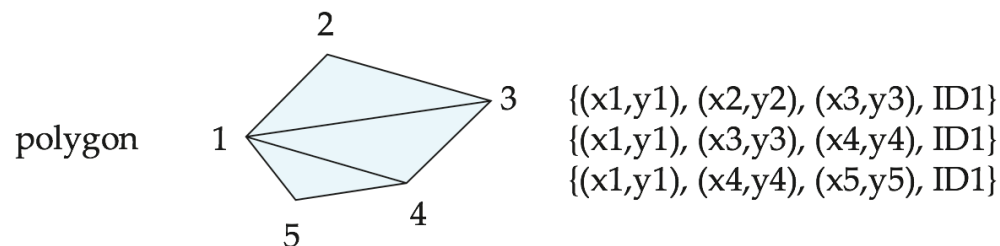
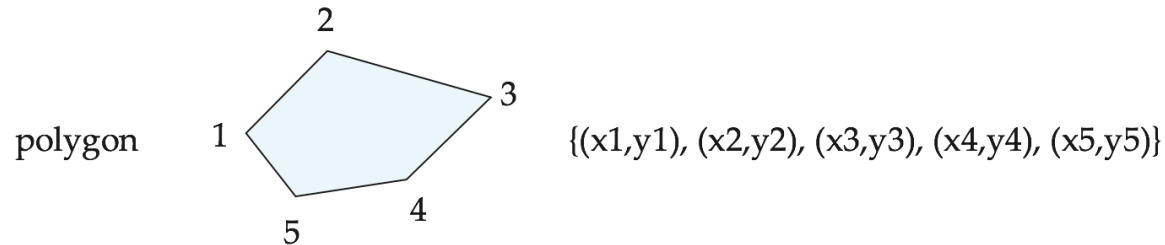
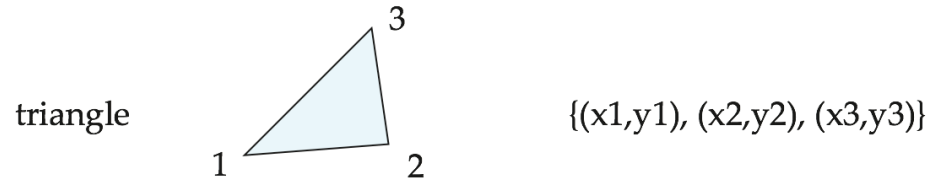
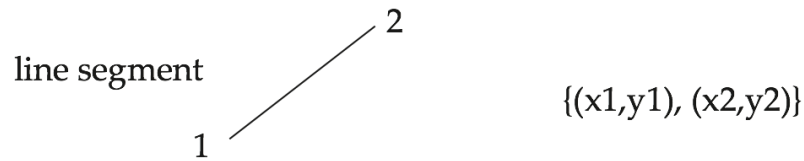
# Represented of Geometric Information

Various geometric constructs can be represented in a database in a normalized fashion (see next slide)

- A **line segment** can be represented by the coordinates of its endpoints.
- A **polyline** or **linestring** consists of a connected sequence of line segments and can be represented by a list containing the coordinates of the endpoints of the segments, in sequence.
  - Approximate a curve by partitioning it into a sequence of segments
    - Useful for two-dimensional features such as roads.
    - Some systems also support *circular arcs* as primitives, allowing curves to be represented as sequences of arc
- **Polygons** is represented by a list of vertices in order.
  - The list of vertices specifies the boundary of a polygonal region.
  - Can also be represented as a set of triangles (**triangulation**)



# Representation of Geometric Constructs



**object**

**representation**



# Representation of Geometric Information (Cont.)

- Representation of points and line segment in 3-D similar to 2-D, except that points have an extra z component
- Represent arbitrary polyhedra by dividing them into tetrahedrons, like triangulating polygons.
- Alternative: List their faces, each of which is a polygon, along with an indication of which side of the face is inside the polyhedron.
- Geometry and geography data types supported by many databases
  - E.g. SQL Server and PostGIS
  - point, linestring, curve, polygons
  - Collections: multipoint, multilinestring, multicurve, multipolygon
  - LINESTRING(1 1, 2 3, 4 4)
  - POLYGON((1 1, 2 3, 4 4, 1 1))
  - Type conversions: *ST GeometryFromText()* and *ST GeographyFromText()*
  - Operations: *ST Union()*, *ST Intersection()*, ...



# Design Databases

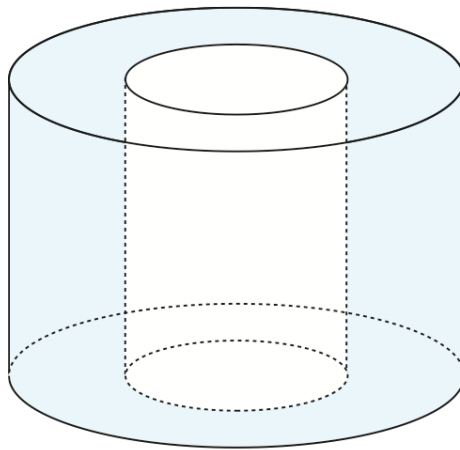
- Represent design components as objects (generally geometric objects); the connections between the objects indicate how the design is structured.
- Simple two-dimensional objects: points, lines, triangles, rectangles, polygons.
- Complex two-dimensional objects: formed from simple objects via union, intersection, and difference operations.
- Complex three-dimensional objects: formed from simpler objects such as spheres, cylinders, and cuboids, by union, intersection, and difference operations.
- Wireframe models represent three-dimensional surfaces as a set of simpler objects.



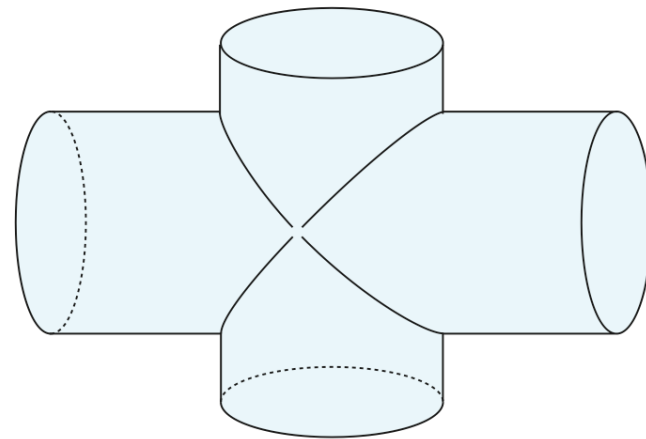


# Representation of Geometric Constructs

- Design databases also store non-spatial information about objects (e.g., construction material, color, etc.)
- Spatial integrity constraints are important.
  - E.g., pipes should not intersect, wires should not be too close to each other, etc.



(a) Difference of cylinders



(b) Union of cylinders



# Geographic Data

- **Raster data** consist of bit maps or pixel maps, in two or more dimensions.
  - Example 2-D raster image: satellite image of cloud cover, where each pixel stores the cloud visibility in a particular area.
  - Additional dimensions might include the temperature at different altitudes at different regions, or measurements taken at different points in time.
- Design databases generally do not store raster data.



# Geographic Data (Cont.)

- **Vector data** are constructed from basic geometric objects: points, line segments, triangles, and other polygons in two dimensions, and cylinders, spheres, cuboids, and other polyhedrons in three dimensions.
- Vector format often used to represent map data.
  - Roads can be considered as two-dimensional and represented by lines and curves.
  - Some features, such as rivers, may be represented either as complex curves or as complex polygons, depending on whether their width is relevant.
  - Features such as regions and lakes can be depicted as polygons.



# Spatial Queries

- **Region queries** deal with spatial regions. e.g., ask for objects that lie partially or fully inside a specified region
  - E.g., PostGIS *ST\_Contains()*, *ST\_Overlaps()*, ...
- **Nearness queries** request objects that lie near a specified location.
- **Nearest neighbor queries**, given a point or an object, find the nearest object that satisfies given conditions.
- **Spatial graph queries** request information based on spatial graphs
  - E.g., shortest path between two points via a road network
- **Spatial join** of two spatial relations with the location playing the role of join attribute.
- Queries that compute intersections or **unions** of regions



# End of Chapter 8