Chapter 8: Complex Data Types

Database System Concepts, 7th Ed.

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-> 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.

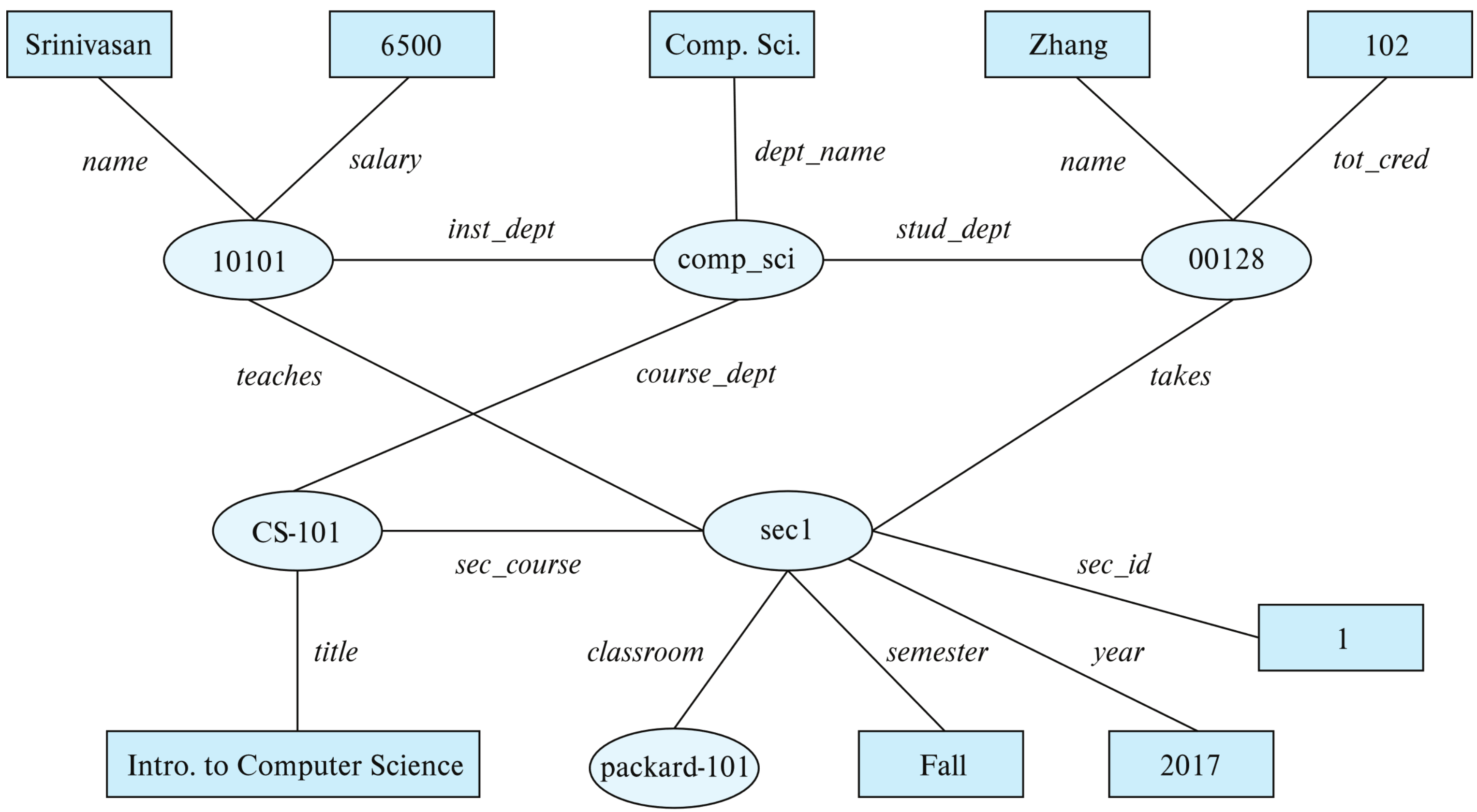
- XQuery language developed to query nested XML structures
  - Not widely used currently
- SQL extensions to support XML
  - Store XML data
  - Generate XML data from relational data
  - Extract data from XML data types
    - Path expressions
- See Chapter 30 (online) for more information

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
    and $n(d)$ = 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 δ 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

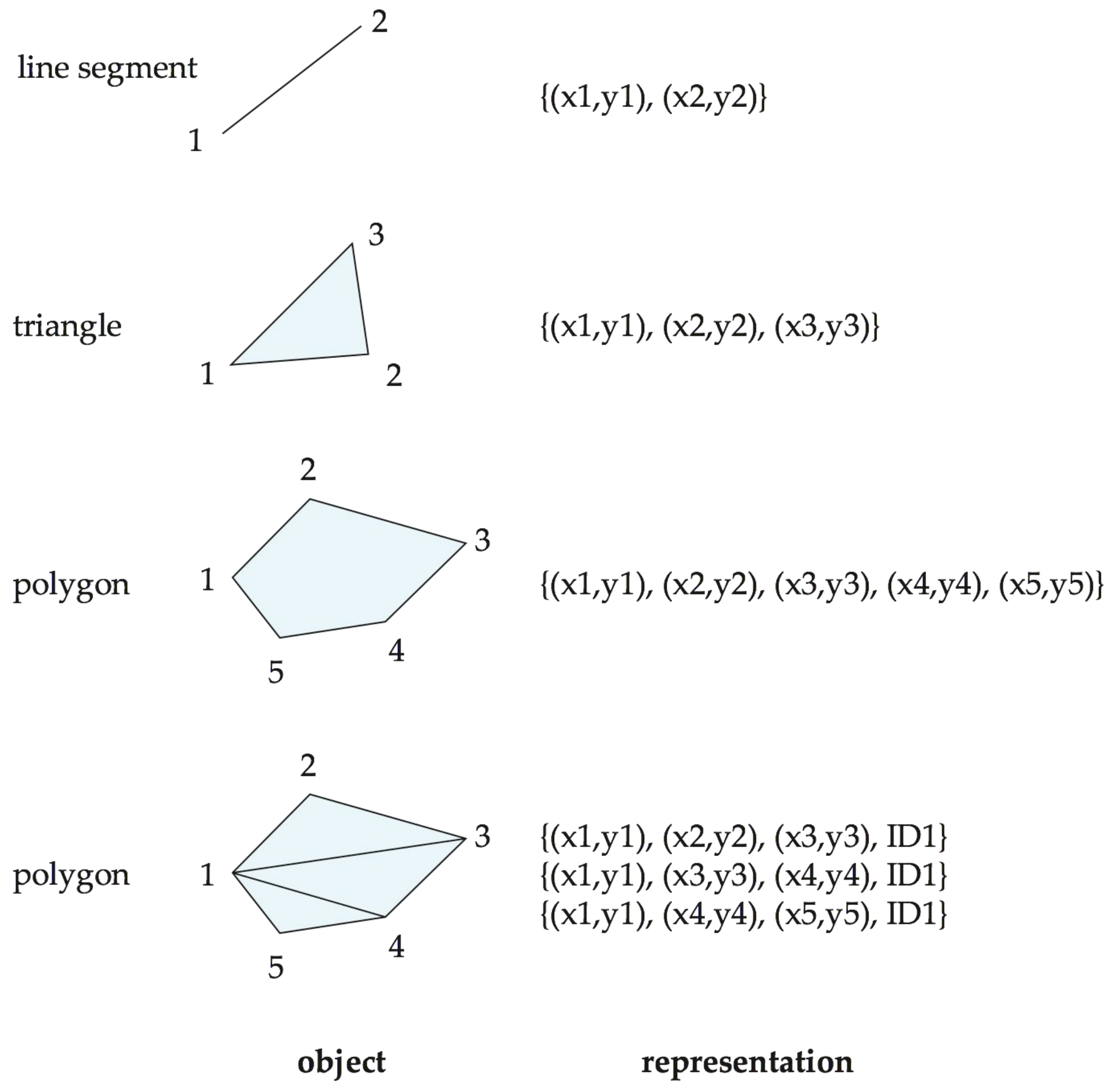
- Spatial databases store information related to spatial locations, and support efficient storage, indexing and querying of spatial data.
  - **Geographic data** -- road maps, land-usage maps, topographic elevation maps, political maps showing boundaries, land-ownership maps, and so on.
    - **Geographic 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



Representation of Geometric Information (Cont.)

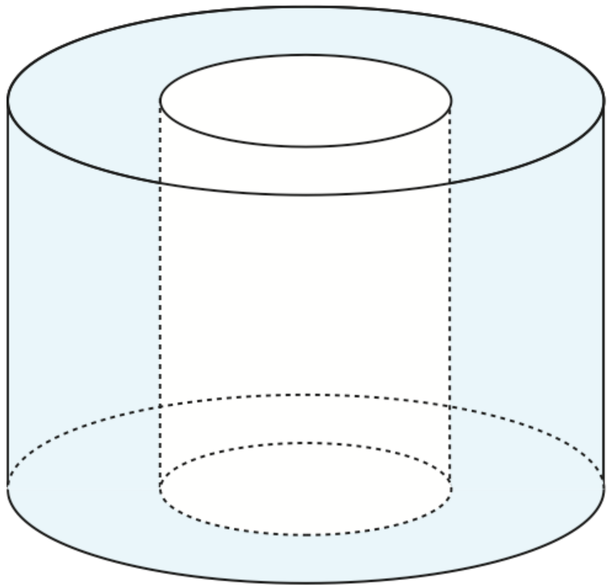
- Representation of points and line segment in 3-D similar to 2-D, except that points have an extra z component
- Represent arbitrary polyhedra by dividing them into tetrahedrons, like triangulating polygons.
- Alternative: List their faces, each of which is a polygon, along with an indication of which 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

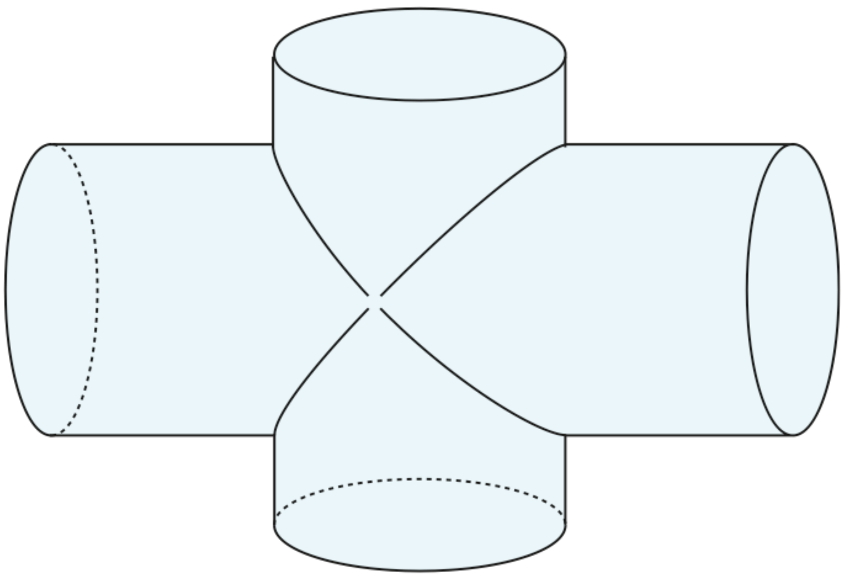
- Represent design components as objects (generally geometric objects); the connections between the objects indicate how the design is structured.
- Simple two-dimensional objects: points, lines, triangles, rectangles, polygons.
- Complex two-dimensional objects: formed from simple objects via union, 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