Advanced Data Types and New Applications

These slides are a modified version of the slides of the book "Database System Concepts" (Chapter 24), 5th Ed., McGraw-Hill, by Silberschatz, Korth and Sudarshan.
Original slides are available at www.db-book.com

Temporal Databases

Time In Databases

- Databases model the current state of the world, reality at the current time.
- Temporal databases model the states of the real world across time.
- In many applications it is important to store and retrieve information about past states (patient data base: medical history of a patient, factory monitoring system: past and current reading from sensors)
- Databases that store information about states of the real world across time are called **temporal databases**.
- Facts in temporal relations have associated times
- **Valid time**: denotes the time period during which a fact is true with respect to the real world
- The **transaction time** for a fact is the time interval during which the fact is stored within the database system.
- In a **temporal relation**, each tuple has an associated time when it is true; the time may be either valid time or transaction time.
- **A bi-temporal relation** stores both valid and transaction time.

We record not only changes in what happened at different times, but also changes in what was officially recorded at different times.

- Only the transaction time is system dependent and is generated by the database system.

Oracle, DB2, ..

Time In Databases (Cont.)

- Example of a temporal relation:

account-number	*branch-name*	*balance*	*from*	*to*
A-101	Downtown	500	1999/1/1 9:00	1999/1/24 11:30
A-101	Downtown	100	1999/1/24 11:30	*
A-215	Mianus	700	2000/6/2 15:30	2000/8/8 10:00
A-215	Mianus	900	2000/8/8 10:00	2000/9/5 8:00
A-215	Mianus	700	2000/9/5 8:00	*
A-217	Brighton	750	1999/7/5 11:00	2000/5/1 16:00

- A tuple has only one time interval. A tuple is represented once for every disjoint time interval in which it is true.
- * in the *to* column means the tuple is true until the time in the column is changed
- Temporal query languages have been proposed to simplify modeling of time as well as time related queries.

Account table

Account-number	branch-name	balance
A-101	Downtown	100
B-215	Mianus	700

BiTemporal Account table

Account-number	branch-name	balance	VT_from	VT_to	TT_from	TT_to
A-101	Downtown	500	1999/1/1	1999/1/24	1999/1/1	1999/2/1
A-101	Downtown	100	1999/1/25	*	1999/3/1	*
A-215	Mianus	700	2000/6/2	2000/8/8	2000/6/5	2000/8/2
A-215	Mianus	900	2000/8/8	2000/9/5	2000/8/2	2000/9/5
A-215	Mianus	700	2000/9/5	*	2000/9/9	*

- Suppose we consider our sample bank database to be bi-temporal. Only the concept of valid time allows the system to answer queries such as - “What was Smith’s balance two days ago?”.

- On the other hand, queries such as - “What did we record as Smith’s balance two days ago?” can be answered based on the transaction time.

- The difference between the two times is important. For example, suppose, three days ago the teller made a mistake in entering Smith’s balance and corrected the error only yesterday. This error means that there is a difference between the results of the two queries (if both of them are executed today).

Time Specification in SQL-92

- **date**: four digits for the year (1--9999), two digits for the month (1--12), and two digits for the date (1--31).
- **time**: two digits for the hour, two digits for the minute, and two digits for the second, plus optional fractional digits.
- **timestamp**: the fields of **date** and **time**, with six fractional digits for the seconds field.
- **T**imes are specified in the *Universal Coordinated Time*, abbreviated UTC (from the French); supports **time with time zone** (time as local time plus the offset of the local time from UTC).
- **interval**: refers to a period of time (e.g., 2 days and 5 hours), without specifying a particular time when this period starts; could more accurately be termed a *span*.

Temporal Query Languages

- Predicates *on time intervals*
  - *precedes, overlaps,* and *contains*.
  - *Intersect* can be applied on two intervals, to give a single (possibly empty) interval;
  - the *union* of two intervals may or may not be a single interval.

- A **snapshot** of a temporal relation at time t consists of the tuples that are **valid** at time t, with the time-interval attributes projected out.
- **Temporal selection**: involves time attributes
- **Temporal projection**: the tuples in the projection inherit their time-intervals from the tuples in the original relation.
- **Temporal join**: the time-interval of a tuple in the result is the intersection of the time-intervals of the tuples from which it is derived. If intersection is empty, tuple is discarded from join.

	VT_from	VT_to
A-101	1999/1/1	*
A-215		
A-215		

	VT_from	VT_to
A-101	1990/1/1	1990/1/21
A-215	….	….
A-215		

Temporal join

A-101 not belongs to the output

Temporal Query Languages (Cont.)

- Functional dependencies must be used with care: adding a time field may invalidate functional dependency
- A **temporal functional dependency** $\mathbf{x} \xrightarrow{\tau} \mathbf{Y}$ holds on a relation schema R if, all snapshots of r satisfy the functional dependency $X \rightarrow Y$.

- SQL:1999 Part 7 (SQL/Temporal) is a proposed extension to SQL:1999 to improve support of temporal data.

Impossibile visualizzare l'immagine.

Spatial and Geographic Data

Spatial Databases

- Spatial databases store information related to spatial locations, and support efficient storage, indexing and querying of spatial data.
- Special purpose index structures are important for accessing spatial data, and for processing spatial join queries.
- **Computer Aided Design (CAD)** databases store design information about how objects are constructed

  E.g.: designs of buildings, aircraft, layouts of integrated-circuits
- Geographic databases store geographic information (e.g., maps). Database for **geographic information systems (GIS).**

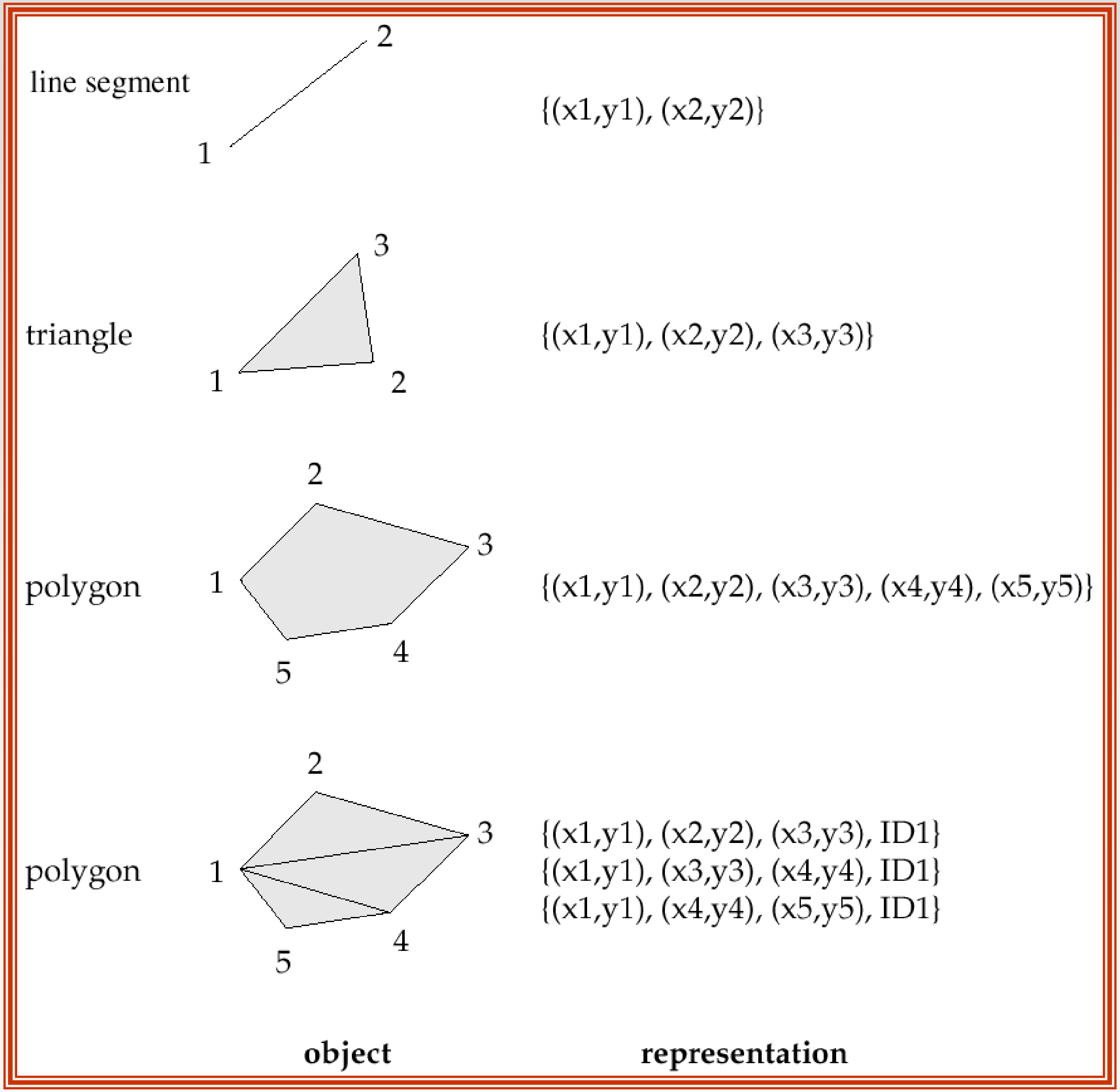
(INITIALLY store & retrieve data as files in the file system)

(Ability to store and query large amount of data efficiently)

Represented of Geometric Information

- Various geometric constructs can be represented in a database in a normalized fashion.
- Represent a line segment by the coordinates of its endpoints.
- Approximate a curve by partitioning it into a sequence of segments
  - Create a list of vertices in order, or
  - Represent each segment as a separate tuple that also carries with it the identifier of the curve (2D features such as roads).
- Closed polygons
  - List of vertices in order, starting vertex is the same as the ending vertex, or
  - Represent boundary edges as separate tuples, with each containing identifier of the polygon, or
  - Use **triangulation** — divide polygon into triangles
    - Note the polygon identifier with each of its triangles.

Representation of Geometric Constructs



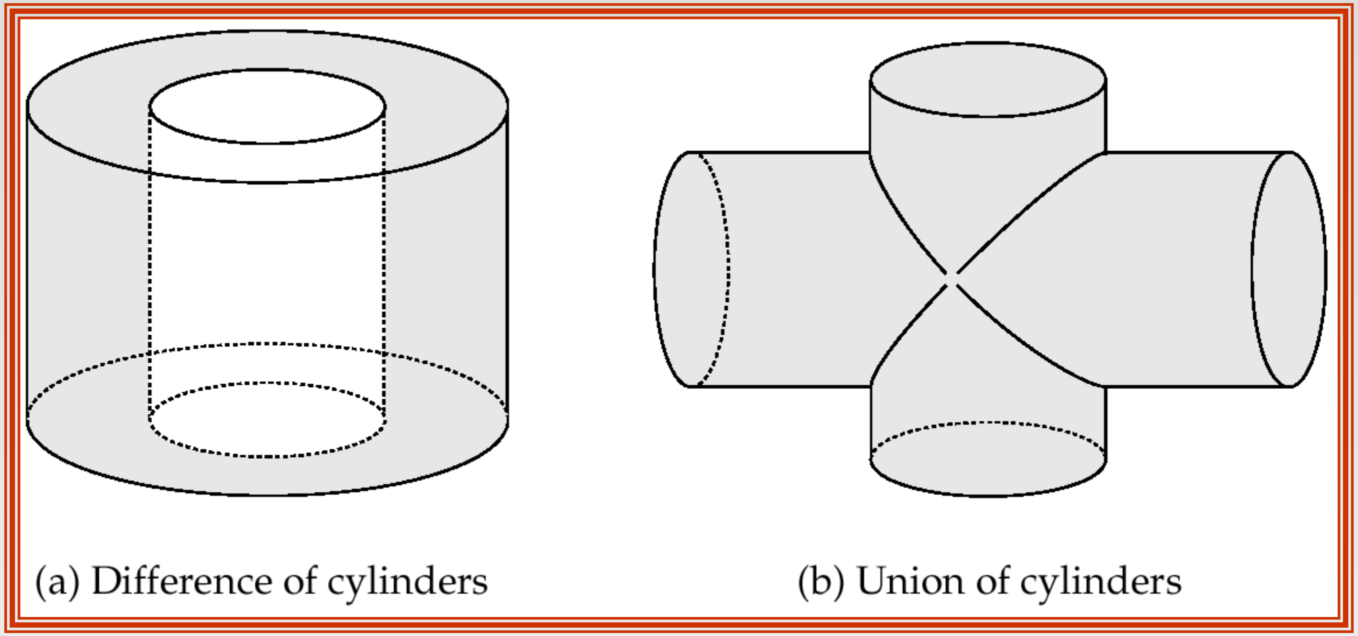
Representation of Geometric Information (Cont.)

- 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: ……

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.
  Wireframing is one of the method of geometric modelling system. A wireframe model represents shape of solid object by its characteristics links and points

Representation of Geometric Constructs



(a) Difference of cylinders (b) Union of cylinders

- 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.

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Geographic Data

Applications of Geographic Data

- Geographic data
  Examples of geographic data
  - map data for vehicle navigation
  - distribution network information for power, telephones, water supply, and sewage

- Vehicle navigation systems store information about roads and services for the use of drivers:
  - **Spatial data**: e.g, road/restaurant/gas-station coordinates
  - **Non-spatial data**: e.g., one-way streets, speed limits, traffic congestion
- **Global Positioning System (GPS)** unit - utilizes information broadcast from GPS satellites to find the current location of user with an accuracy of tens of meters.
  - increasingly used in vehicle navigation systems as well as utility maintenance applications.

Geographic Information System

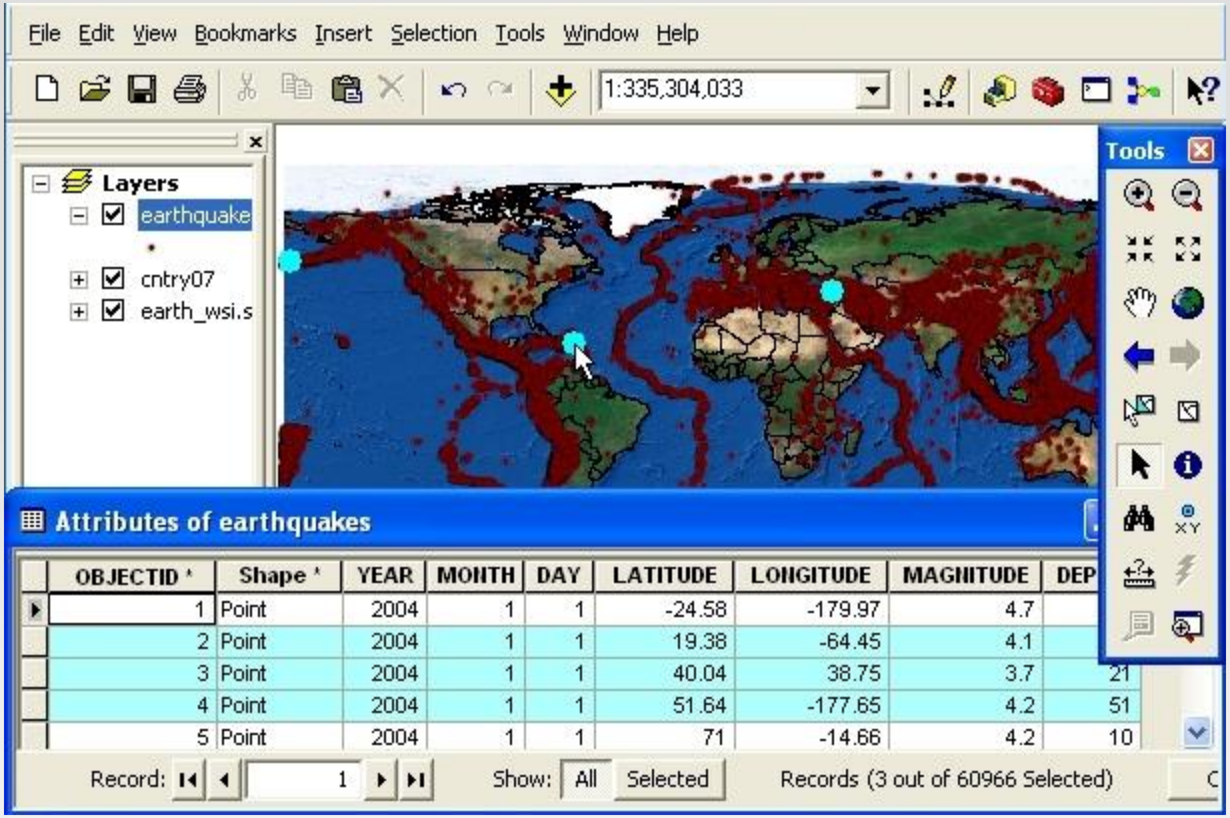
A **geographic information system** (**GIS**) is a system designed to capture, store, manipulate, analyze, manage, and present all types of geographic information for decision making

In developing a digital topographic data base for a GIS, topographical maps are the main source, and aerial photography and satellite images are extra sources for collecting data and identifying attributes which can be mapped in layers.

GIS applications are tools that allow users to create interactive queries (user-created searches), analyze spatial information, edit data in maps, and present the results of all these operations.

Example

Geographical distribution of earthquakes

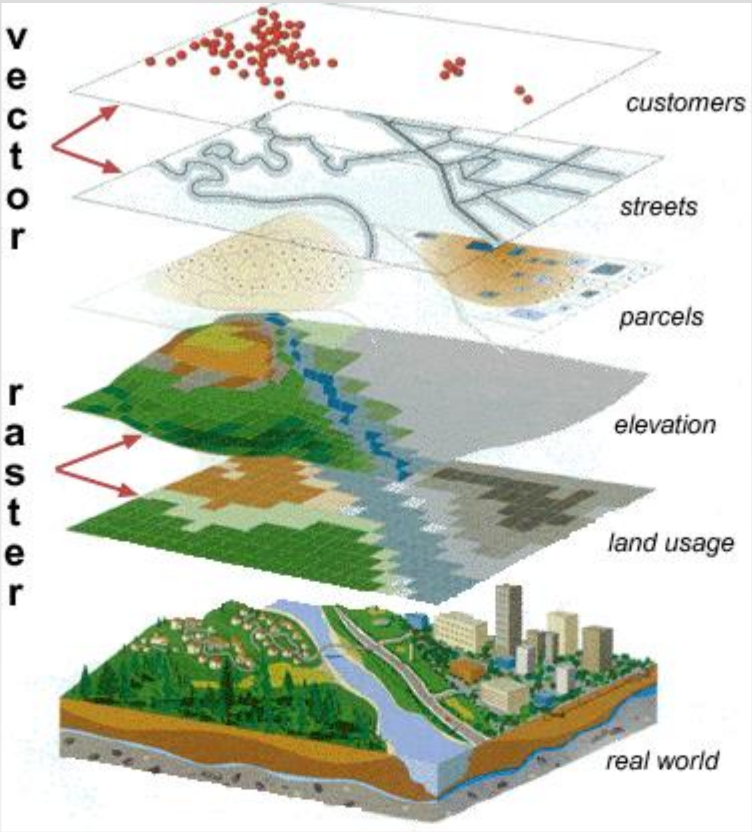


Each point is an earthquake area

Each point is a record in tha table with different attributes:

- earthquake deph
- earthquake magnitude
- some attributes that denote properties of the object: colour, shape, symbol

Sometimes table analysis not allow to find correlations between phisycal phenomena



Thematic layers

GIS organize information in individual data **themes** that describe the distribution of a phenomenon across a geographic extent.

This organizing principle of geographic layers became one of the universal GIS principles that provided the foundation for how GIS systems represent, operate on, manage, and apply geographic information.

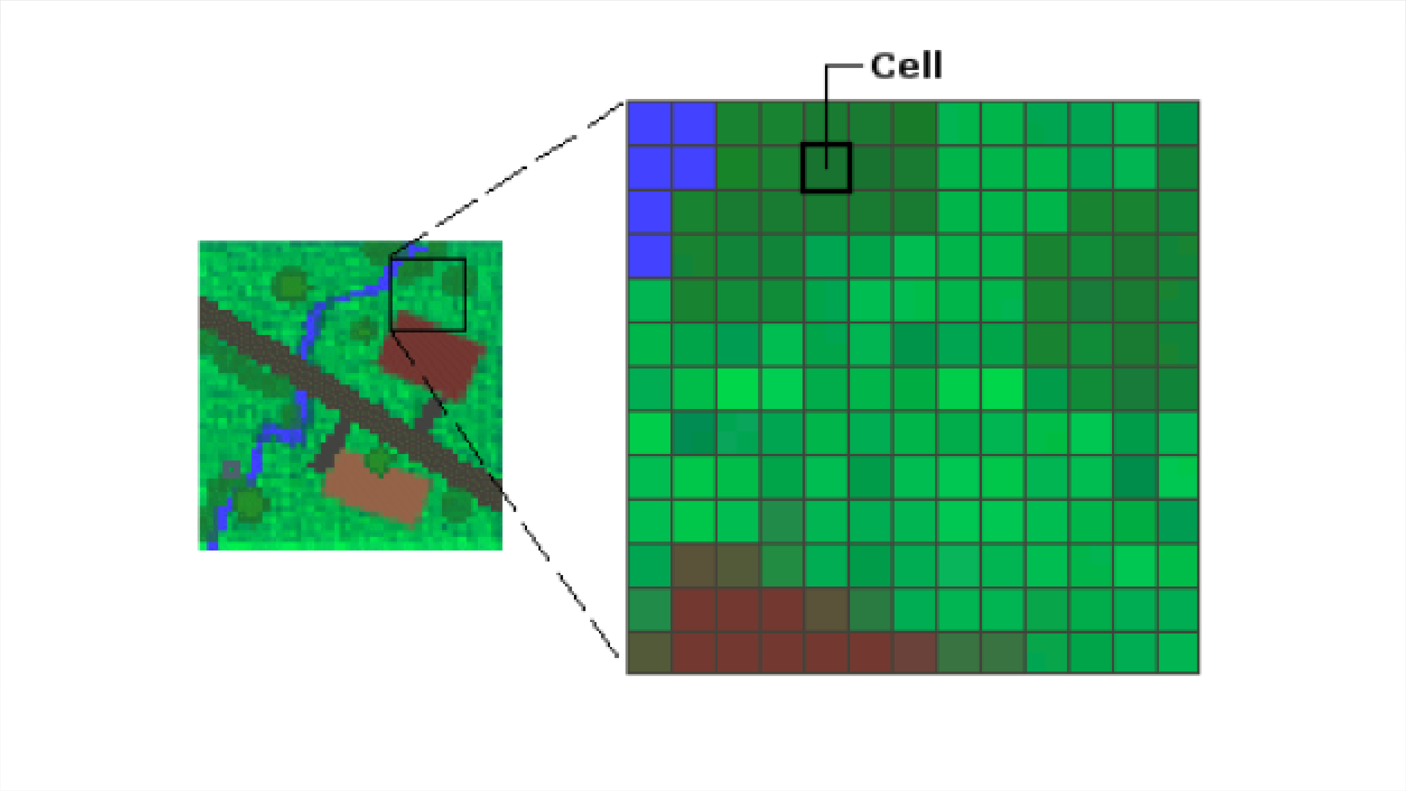
There are two broad methods used to store data in a GIS : raster images and vectors.

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.

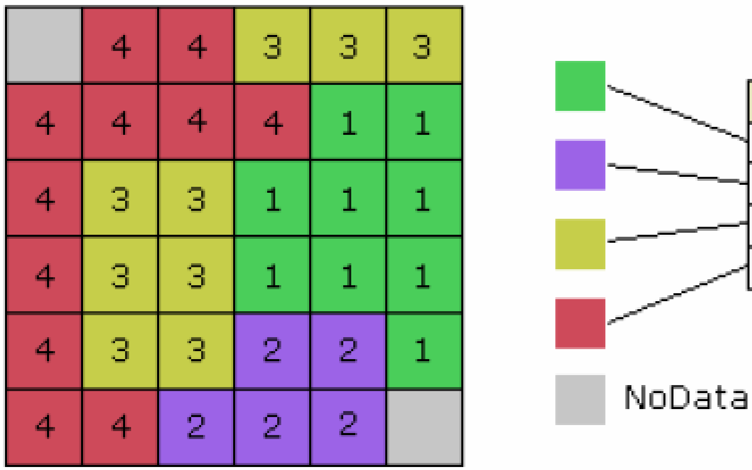
Raster data

- a matrix of cells (or pixels) organized into rows and columns (a grid), as shown in the graphic below, where each cell contains a value representing information of the geographic feature at the cell location, such as land-use.



Raster image: digital aerial photographs, imagery from satellites, digital pictures, or even scanned maps.

Raster data set



Raster attribute table

OID	VALUE	COUNT	TYPE	AREA	CODE
0	1	9	Forest land	8100	FL010
1	2	5	Wetland	4500	WL001
2	3	9	Crop land	8100	CL301
3	4	11	Urban	9900	UL040

There is a row for each distinct value in the data set.
A column contains the count of the number of cells with each value.
This table may also have a column that provides a textual description of each of the values in the data set.

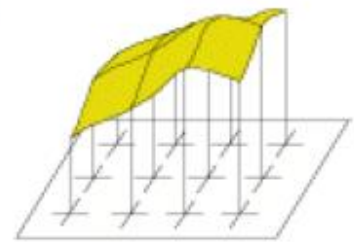
There are three default fields created in the table:
- ObjectID (OID) is a unique system-defined object identifier number for each row
- VALUE is a value in the raster data set.
- COUNT represents the number of cells in the raster data set with the cell value in the VALUE column.

Cell values represented by NoData are not in the raster attribute table.

Value applies to the center point of the cell

For certain types of data, the cell value represents a measured value at the center point of the cell. An example is a raster of elevation

+ 315	+ 319	+ 321	+ 323
+ 317	+ 323	+ 328	+ 326
+ 313	+ 318	+ 325	+ 323

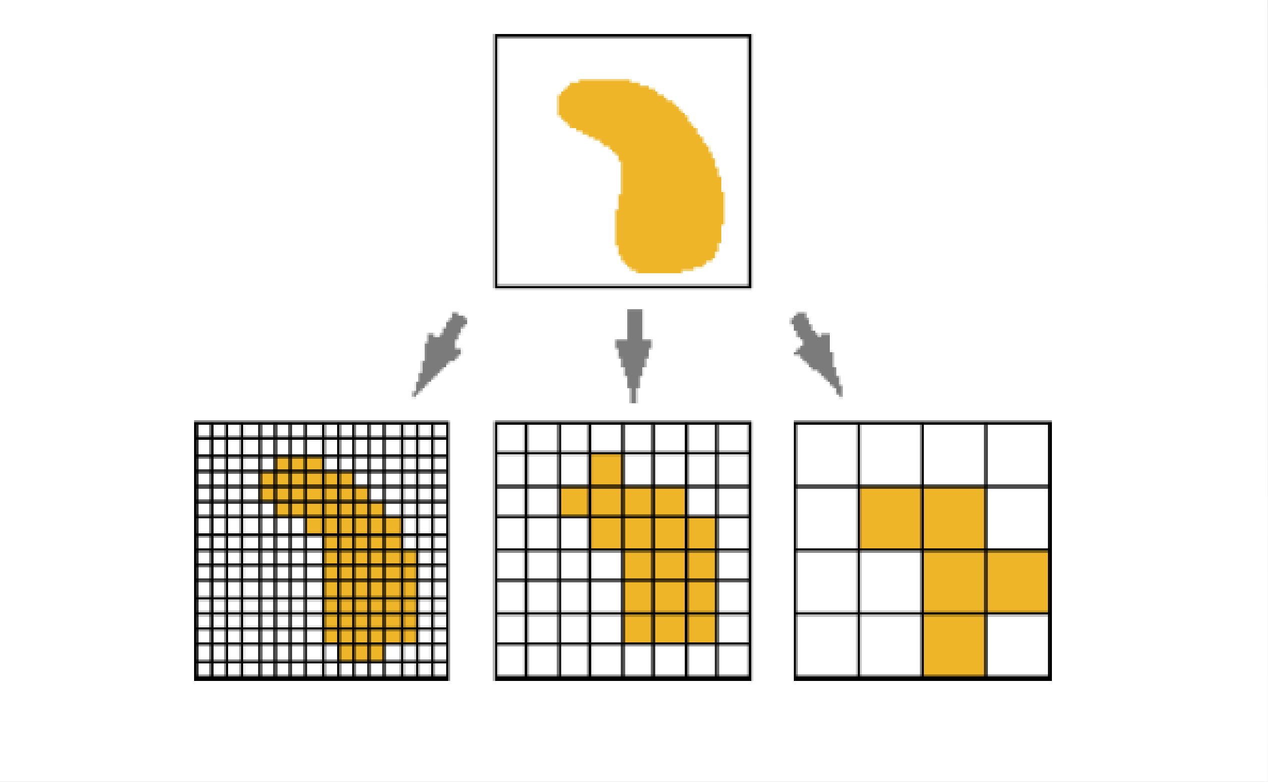


Value applies to the whole area of the cell

For most data, the cell value represents a sampling of a phenomenon, and the value is presumed to represent the whole cell square.

50	45	40	35
35	40	35	25
20	25	30	20

- The cell size determines how coarse or fine the patterns or features in the raster will appear. The smaller the cell size, the smoother or more detailed the raster will be. However, the greater the number of cells, the longer it will take to process, and it will increase the demand for storage space. If a cell size is too large, information may be lost or subtle patterns may be obscured.



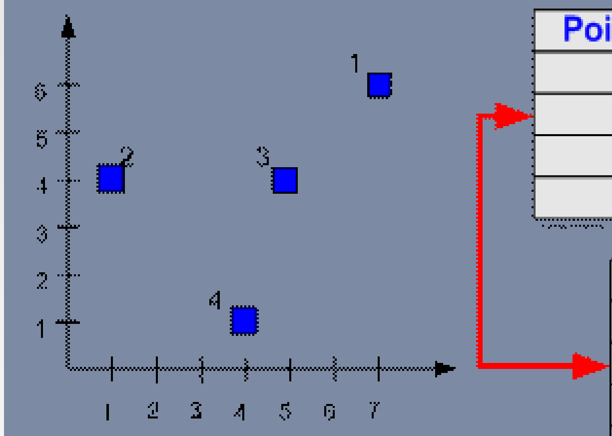
Geographic Data (Cont.)

- **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 are often used to represent map data.
  - **Roads** can be considered as two-dimensional and represented by lines and curves (multiple line segments).
  - 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.
  - **Topological information** , such as height, may be represented by a surface divided into polygons covering regions of equal height (a height value associated with each polygon)

Vector data

- **Point**

Each point is stored by its location (X, Y) together with the table attribute of this point. For example, 4 points below have their coordinate location in (X, Y) and each point has attributes of deep and amount of **water contamination**.

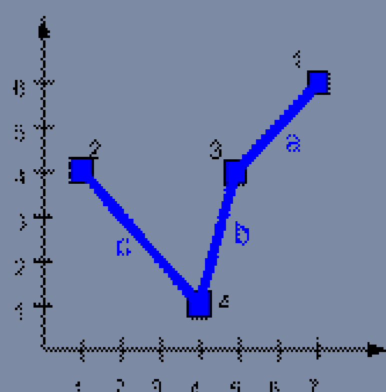


Point No	X	Y
1	7	6
2	1	4
3	5	4
4	4	1

Point No	deep	amount
1	12.35	63.45
2	25.79	79.83
3	3.50	24.34
4	17.52	69.23

- **Line**

Each line is stored by the sequence of first and last point together with the associated table attribute of this line. For example, three lines below (a, b and c) have their first and last node to distinguish their location and each line has attributes of flow and capacity of the **sewerage pipe**. Notice that each node has coordinate (X, Y) that is stored in another table.



Node No	X	Y
1	7	6
2	1	4
3	5	4
4	4	1

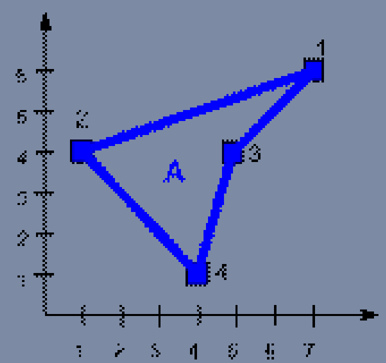
Line	First Node	Last Node
a	1	3
b	3	4
c	4	2

Line	Flow	Capacity
a	960	2200
b	1250	2000
c	1100	2000

- **Polygon**

Polygon is represented by a *closed* sequence of lines. Unlike line or poly-line (sequence of line), polygon always closed. That is, the first point is equal to the last point. A polygon can be represented by a sequence of nodes where the last node is equal to the first node. For example, polygon A below has its first and last node in node number 1 to settle its location. Aside from location attributes, the polygon has associated attributes of **area and population**.

- Notice that each node has coordinate (X, Y) that is stored in another table.



Node No	X	Y
1	7	6
2	1	4
3	5	4
4	4	1

Polygon	Node sequence
A	1,3,4,2,1

Polygon	Area	Population
A	15.23	12.35

Spatial Queries

A number of types of query involve spatial locations

- Nearness queries request objects that lie near a specified location.
  Find all restaurants that lie within a given distance
- Nearest neighbor queries, given a point or an object, find the nearest object that satisfies given conditions.
  The nearest gasoline station
- Region queries deal with spatial regions. e.g., ask for objects that lie partially or fully inside a specified region.
  All markets within the boundaries of a given town.
- Queries that compute intersections or unions of regions.
  All regions with a low annual rainfall and a high population density.
  They use
  - Spatial join of two spatial relations with the location playing the role of join attribute (one relation representing rainfall, the other relation population density).

Spatial Queries (Cont.)

- Spatial data is typically queried using a graphical query language; results are also displayed in a graphical manner.
- Graphical interface constitutes the front-end
- Extensions of SQL with abstract data types, such as lines, polygons and bit maps, have been proposed to interface with back-end.
  - allows relational databases to store and retrieve spatial information
  - Queries can use spatial conditions (e.g. contains or overlaps).
  - queries can mix spatial and nonspatial conditions (the nearest restaurant that has vegetarian selection and that charges less than $10 for a meal)

- Indices are required for efficient access to spatial data.
- Queries often access data in a region of the space
- The problem is: how the space can be partitioned into regions such that all records in the region can be stored in a block?

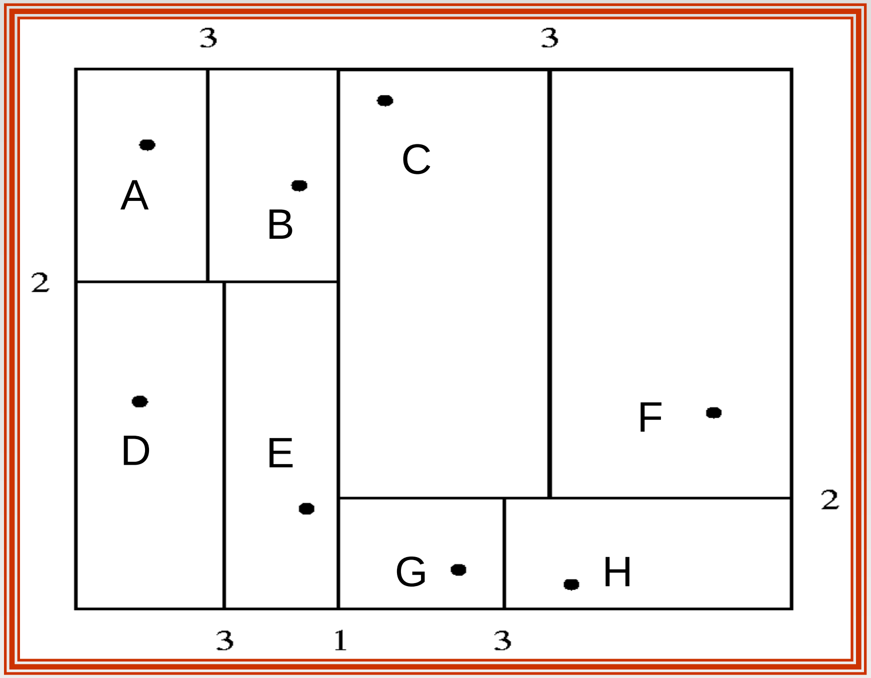
Traditional index structures such as hash indices and B-trees are not suitable, since they deal only with one-dimensional data, where spatial data are typically of two or more dimensions

Indexing of Spatial Data

- **k-d tree** - early structure used for indexing in multiple dimensions (balanced binary tree).
- Each level of a *k-d* tree partitions the space into two.
  - choose one dimension for partitioning at the root level of the tree.
  - choose another dimensions for partitioning in nodes at the next level and so on, cycling through the dimensions.
- In each node, approximately **half of the points stored in the sub-tree fall on one side and half on the other**.
- Partitioning stops when a node has less than a given maximum number of points.
- The **k-d-B tree** extends the *k-d* tree to allow **multiple child nodes** for each internal node; well-suited for secondary storage.

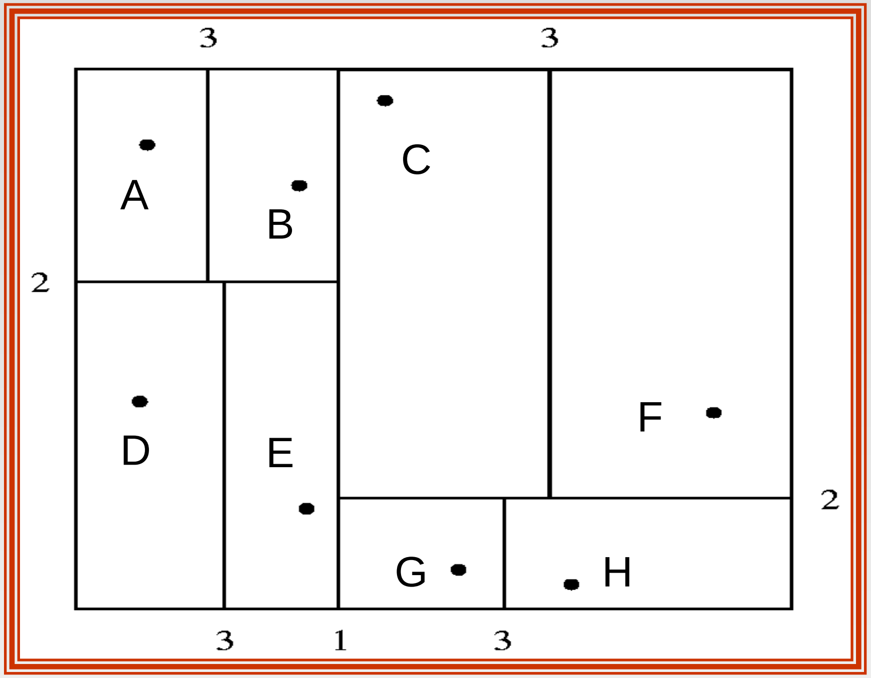
Division of Space by a k-d Tree

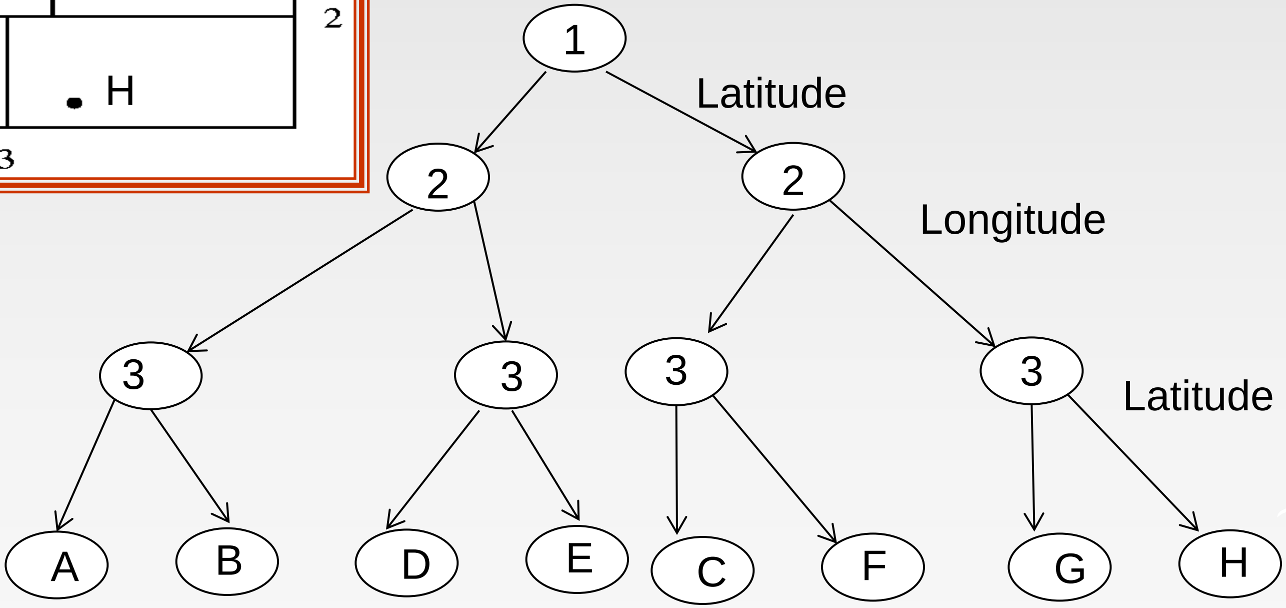
Cities (Name, Latitude, Longitude)		
A	…	…
B	…	…
C	…	…
D	…	…
E	…	…
F	…	…
G	…	…
H	…	…



- Each line in the figure (other than the outside box) corresponds to a node in the *k-d* tree
  - the maximum number of points in a leaf node has been set to 1.
- The numbering of the lines in the figure indicates the level of the tree at which the corresponding node appears.
- K-d-B tree extends the number of children (to reduce the high of the tree) of internal nodes

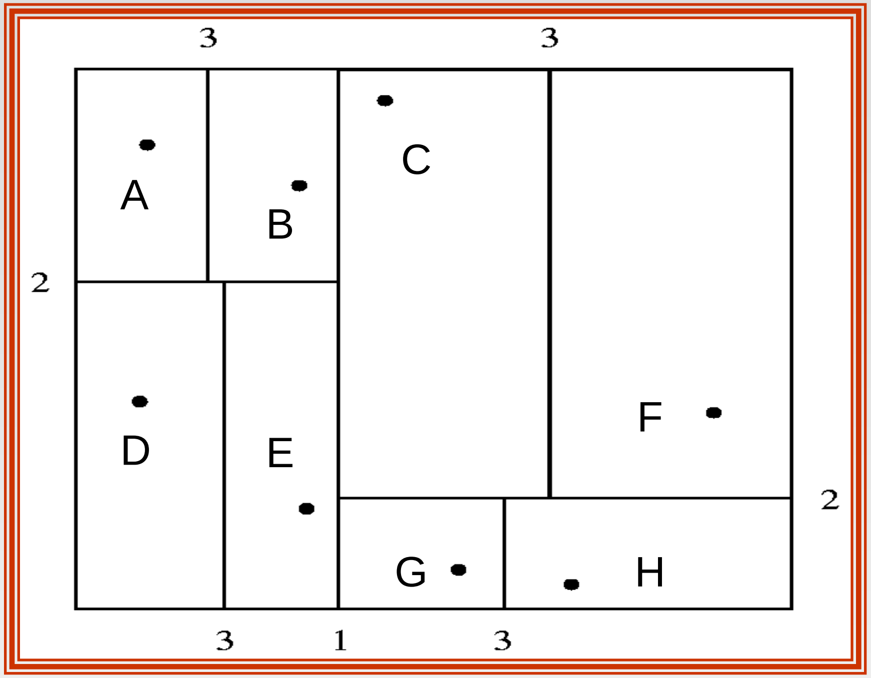
Division of Space by a k-d Tree





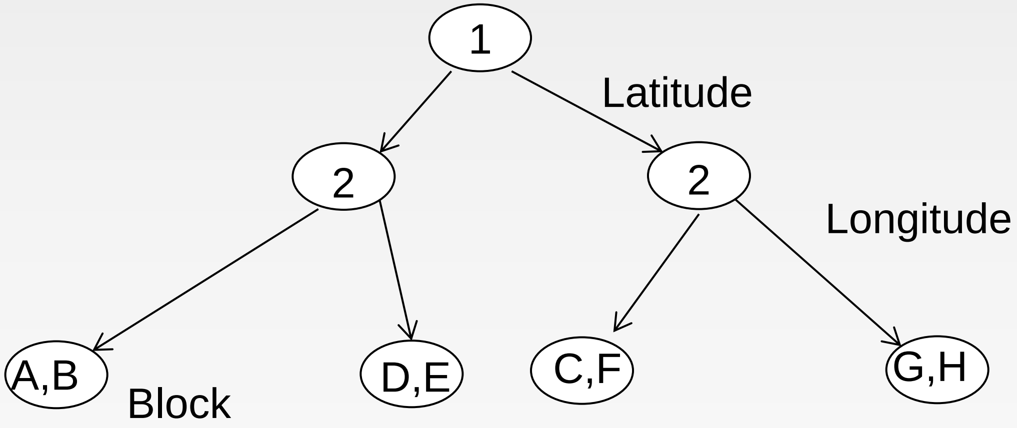
- number of cities in a block set to 1
- half of the cities on one side and half on the other

Division of Space by a k-d Tree



- number of cities in a block set to 2

- half of the cities on one side and half on the other



Cities located in the same region are stored in the same block

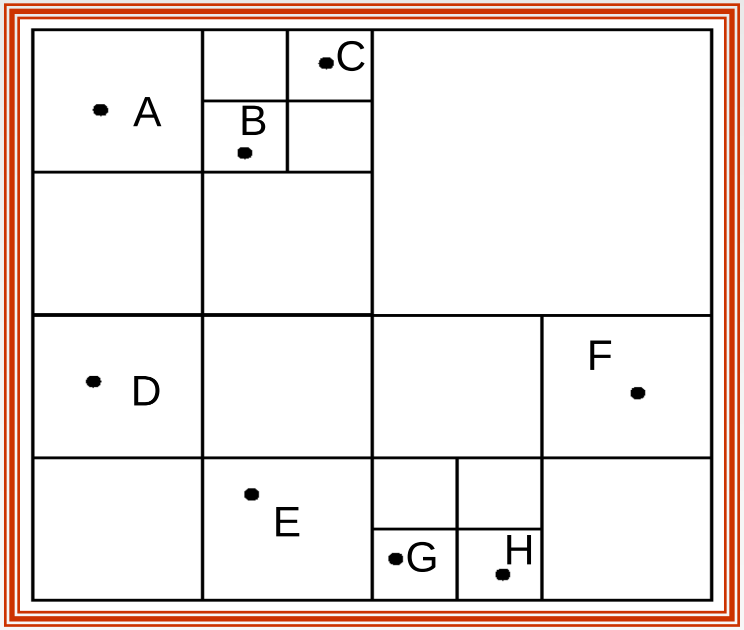
Division of Space by Quadtrees

Quadtrees

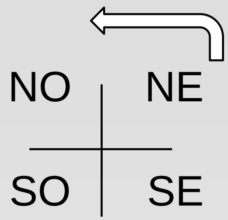
- Each node of a quadtree is associated with a **rectangular region of space**; the top node is associated with the entire target space.
- Each non-leaf nodes divides its region into **four equal sized quadrants**
  - correspondingly each such node has four child nodes corresponding to the four quadrants and so on
- Leaf nodes have between zero and some fixed maximum number of points (set to 1 in example).

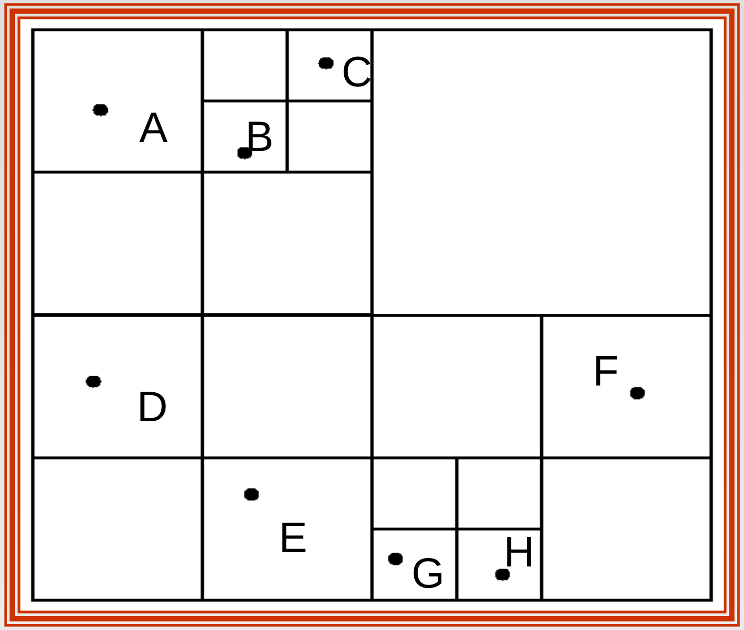
This type of quadtree is called
Point Region quadtree (PR quadtree)

PR quadtree: stores points; space is divided based on regions, rather than on the actual set of points stored (**four equal sized quadrants)**.



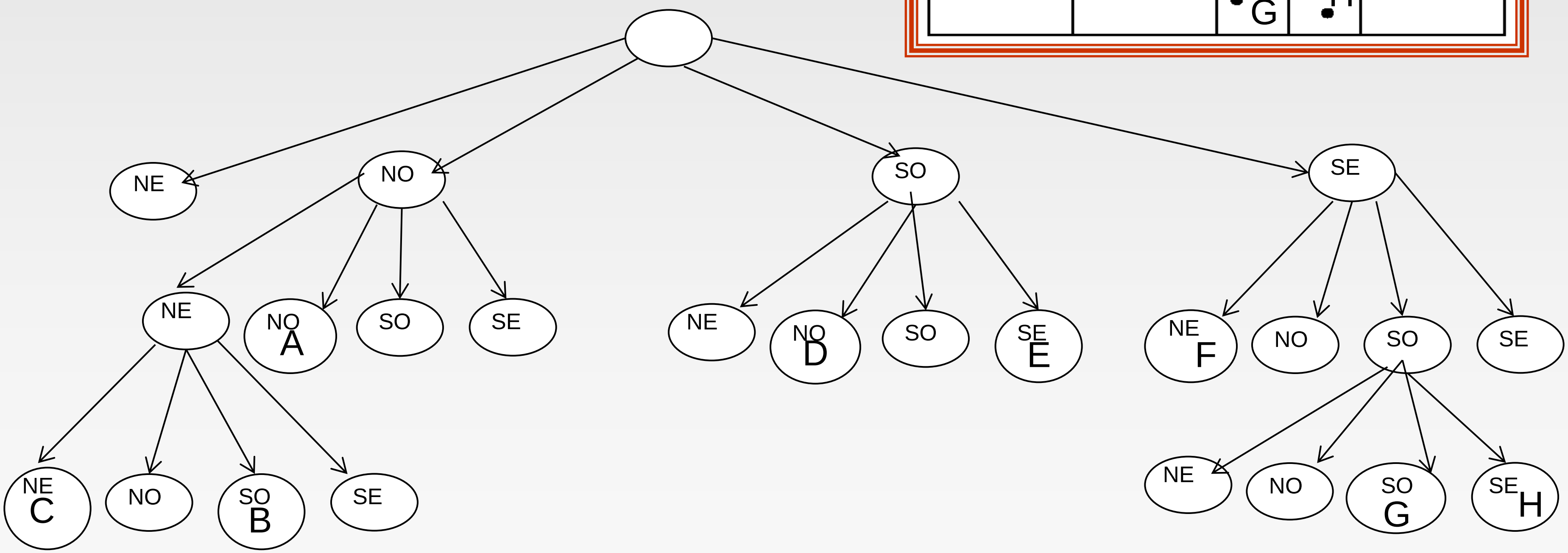
PR quadtree





quadrants are named according to the geographycal position and are listed in the order NE, NO, SO and SE

PR quadtree

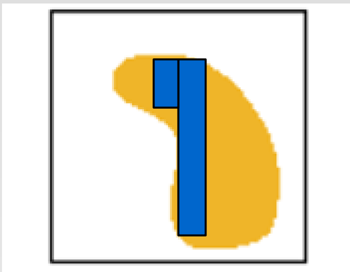


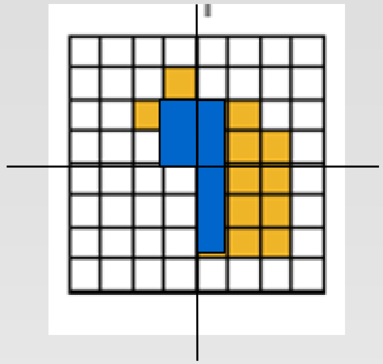
Quadtrees (Cont.)

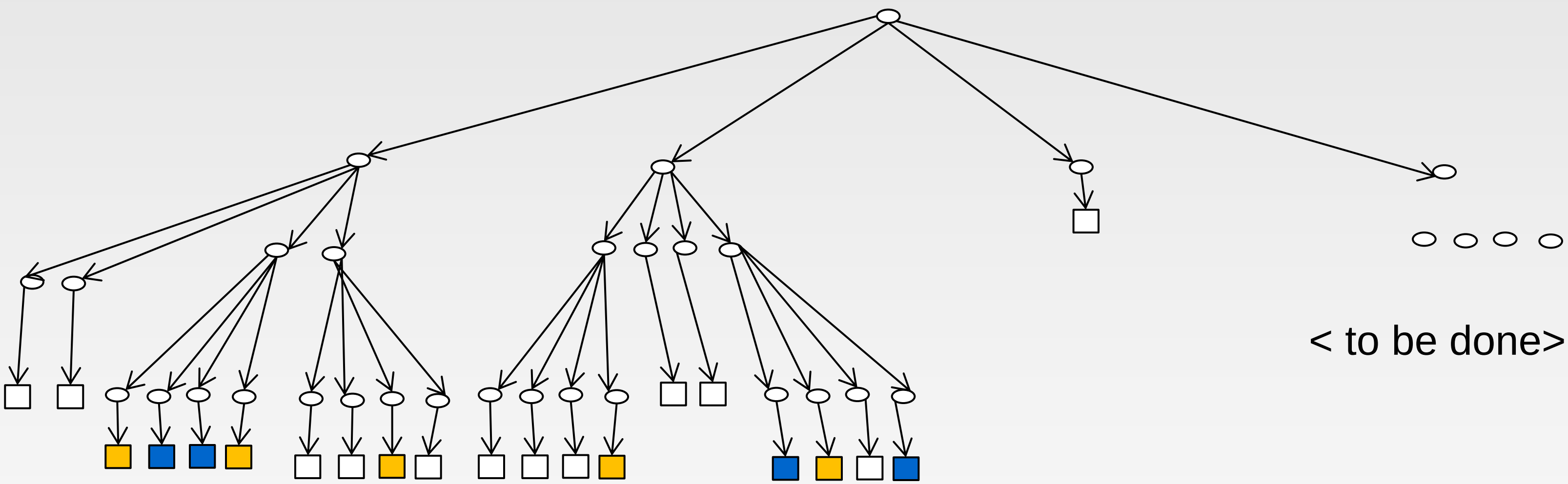
We can use Region quadtree to store raster information

- **Region quadtrees** store raster information.
  - A node is a leaf node if all the values in the cells that it covers are the same. Otherwise, it is subdivided further into four children of equal area, and is therefore an internal node.
  - Each node corresponds to a matrix of cells.
  - The matrix corresponding to leaves either contain just a single element (cell), or have multiple elements (cells), all of which have the same value.

Raster data







Quadtrees (Cont.)

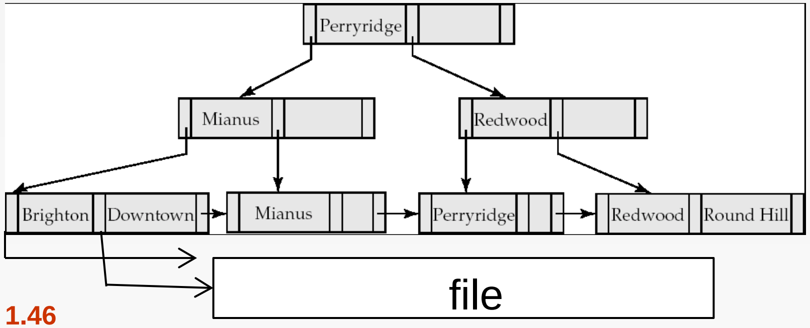
- Indexing of line segments and polygons presents new problems
- Extensions of *k-d* trees and PR quadtrees have been proposed to index line segments and polygons
- However, a line segment or polygon may cross a partitioning line
  - This requires splitting segments/polygons into pieces at partitioning boundaries and they must be represented in each of the sub-trees in which its pieces occur.
    - Same segment/polygon may be represented at several leaf nodes-> inefficiencies in storage and inefficiencies in queries

R-Trees

Indexing of objects such as line segments, rectangles, and other polygons

- **R-trees** (Rectangle-trees) are a N-dimensional extension of B^+-trees.
- Basic idea: generalize the notion of a one-dimensional interval associated with each B+ -tree node to an N-dimensional interval, that is, an N-dimensional rectangle.
- Balanced tree structure with indexed objects in leaf nodes.
- The storage efficiency of R-trees is better than that of k-d trees or quadtrees since a polygon is stored only once
- Will consider only the two-dimensional case (N = 2)
  - generalization for N > 2 is straightforward, although R-trees work well only for relatively small N

Example of B+-tree



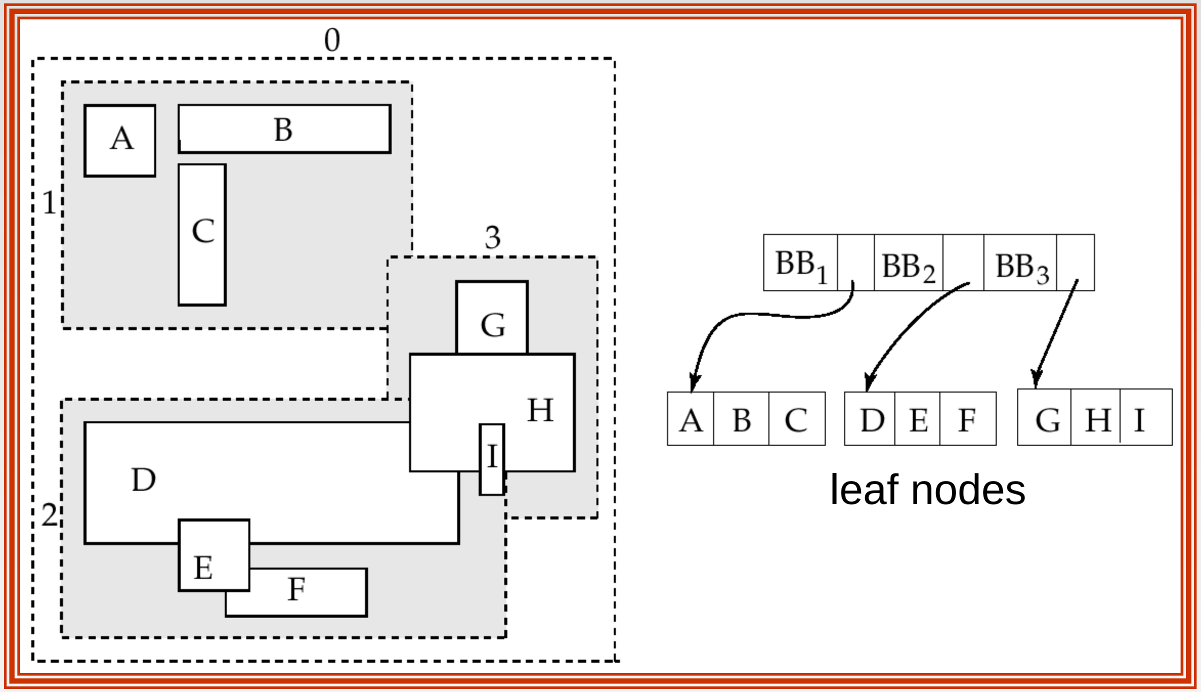
R Trees (Cont.)

- A rectangular **bounding box** is associated with each tree node.
  - Bounding box of a leaf node is a minimum sized rectangle parallel to the axes that contains all objects (lines, rectangles, polygons) associated with the leaf node.
  - The bounding box associated with a non-leaf node is the smallest rectangle parallel to the axes that contains the bounding box associated with all its children.
  - Bounding box of a node serves as its **key** in its parent node (if any)
  - *Bounding boxes of children of a node are allowed to overlap*

- A polygon is stored only in one node, and the bounding box of the node must contain the polygon

Example R-Tree

- A set of rectangles (solid line) and the bounding boxes (dashed line) of the nodes of an R-tree for a set of rectangles.
  The R-tree is shown on the right.



Bounding boxes are shown with extra space inside them, to make them stand out

We shall see how to implement search, insert and delete operations on an R-tree

If indexed objects are not rectangles, we can store bounding boxes of objects in leaves. This helps to speed up checks for overlaps in a query.

Queries

- Point queries
  - select * from ...
    where latitude = ... AND longitude = ...
- Region queries
  - select * from ...
    where v1 <= latitude <= v2 AND w1 <= longitude <= w2
- Nearest-neighbor queries
  - nearest point to a specific location
- Partial match queries
  - select * from ...
    where v1 <= latitude <= v2

Search in R-Trees

A search for objects containing a point has to follow all child nodes whose associated bounding boxes contain the point.

- To find data items (rectangles/polygons) intersecting (overlaps) a given query object (point/region), do the following, starting from the root node:
  - If the node is a leaf node, output the data items whose keys intersect the given query object (point/region).
  - Else, for each child of the current node whose bounding box overlaps the query object (point/region), recursively search the child
- Can be very inefficient in worst case since multiple paths may need to be searched
  - but works acceptably in practice.

Insertion in R-Trees

- To insert a data item (single traversal down from the root):
  - Find a leaf to store it, and add it to the leaf
    - To find leaf, follow a child (if any) whose bounding box contains bounding box of data item
      - At each internal node, we may find multiple children whose bounding boxes contain the bounding box of the object
      - The R-tree algorithm chooses one of them arbitrarily
    - In none of the children satisfy this condition, chooses a child whose overlap with data item bounding box is maximum for continuing the traversal of the tree
  - Once the leaf node has been reached, if the node is already full, the algorithm performs node splitting

Insertion in R-Trees

- Handle overflows by splitting and propagates splitting upwards if required (as in B+ -trees)
  - The R-tree insertion ensures that the tree remains balanced
- Adjust bounding boxes such that they remain consistent: bounding boxes of leaves contains all the bounding boxes of the objects stored at the leaf;
  bounding boxes of internal nodes contain all bounding boxes of the children nodes

The main difference with B+-tree is in how the node is split:

in B+-tree it is possible to find a value such that half entries are less and half entries are greater than the value.

in two dimensions, it is not always possible to split the entries into two sets so that their bounding boxes do not overlap

Split procedure

- Split procedure:
  - Goal: divide the set S of entries of an overfull node into two sets S1 and S2 such that the bounding boxes of S1 and S2 have minimum total area. This is a heuristic.
  - Alternative: divide the set S of entries of an overfull node into two sets S1 and S2 such that the bounding boxes of S1 and S2 have the minimum overlap
- Finding the “best” split (minimum total area or minimum overlap) is expensive
- Cheaper heuristics such as quadratic split are used

Splitting an R-Tree Node

- **Quadratic split** divides the entries in a node as follows
  1. Find pair of entries in S with "**maximum separation**"
     - that is, the pair such that the bounding box of the two would has the maximum wasted space (area of bounding box – sum of areas of two entries)
  2. Place these entries in the two new sets S1 and S2, respectively
  3. Then to add the remaining entries: repeatedly find the entry with "**maximum preference**" for one of the two new sets, and assign the entry to that set.
     For each entry e, let e1 be the increase in size of the bounding box of S1 and e2 the increase in size of the bounding box of S2 if e is added to S1 or S2; choose one of the entries with maximum difference of e1 and e2 and add it to S1 if e1 is less than e2
  4. Stop when half the entries have been added to one set
     - Then assign remaining entries to the other set
  - Nodes are constructed from S1 and S2

Deleting in R-Trees

- Deletion of an entry in an R-tree done much like a B^+-tree deletion.
  - In case of underfull node, borrow entries from a sibling if possible, else merging sibling nodes
  - Alternative approach removes all entries from the underfull node, deletes the node, then reinserts all entries
  - Each node at least half full.

R-Trees

R-trees are supported in many modern database systems, along with variants like R^+ -trees and R*-trees