Spatial Data Management

Chapter 28
Types of Spatial Data

- **Point Data**
  - Points in a multidimensional space
  - E.g., *Raster data* such as satellite imagery, where each pixel stores a measured value
  - E.g., Feature vectors extracted from text

- **Region Data**
  - Objects have spatial extent with location and boundary
  - DB typically uses geometric approximations constructed using line segments, polygons, etc., called *vector data*. 
Types of Spatial Queries

- **Spatial Range Queries**
  - *Find all cities within 50 miles of Madison*
  - Query has associated region (location, boundary)
  - Answer includes overlapping or contained data regions

- **Nearest-Neighbor Queries**
  - *Find the 10 cities nearest to Madison*
  - Results must be ordered by proximity

- **Spatial Join Queries**
  - *Find all cities near a lake*
  - Expensive, join condition involves regions and proximity
Applications of Spatial Data

- Geographic Information Systems (GIS)
  - E.g., ESRI’s ArcInfo; OpenGIS Consortium
  - Geospatial information
  - All classes of spatial queries and data are common

- Computer-Aided Design/Manufacturing
  - Store spatial objects such as surface of airplane fuselage
  - Range queries and spatial join queries are common

- Multimedia Databases
  - Images, video, text, etc. stored and retrieved by content
  - First converted to feature vector form; high dimensionality
  - Nearest-neighbor queries are the most common
Single-Dimensional Indexes

- B+ trees are fundamentally single-dimensional indexes.
- When we create a composite search key B+ tree, e.g., an index on \(<age, sal>\), we effectively linearize the 2-dimensional space since we sort entries first by age and then by sal.

Consider entries:
\(<11, 80>, <12, 10>, <12, 20>, <13, 75>\)
Multidimensional Indexes

- A multidimensional index **clusters** entries so as to exploit “nearness” in multidimensional space.
- Keeping track of entries and maintaining a balanced index structure presents a challenge!

Consider entries:
- `<11, 80>`, `<12, 10>`
- `<12, 20>`, `<13, 75>`

Spatial clusters
B+ tree order

Diagram: A 2D space with points at `(11, 80)`, `(12, 10)`, `(12, 20)`, `(13, 75)` and corresponding B+ tree order.
Motivation for Multidimensional Indexes

- Spatial queries (GIS, CAD).
  - Find all hotels within a radius of 5 miles from the conference venue.
  - Find the city with population 500,000 or more that is nearest to Kalamazoo, MI.
  - Find all cities that lie on the Nile in Egypt.
  - Find all parts that touch the fuselage (in a plane design).

- Similarity queries (content-based retrieval).
  - Given a face, find the five most similar faces.

- Multidimensional range queries.
  - $50 < \text{age} < 55 \ \text{AND} \ 80K < \text{sal} < 90K$

- Partial match queries.
  - look up all points (records) matching in one or more dimensions (attributes).
What’s the difficulty?

- An index based on spatial location needed.
  - One-dimensional indexes don’t support multidimensional searching efficiently. (Why?)
  - Hash indexes only support point queries; want to support range queries as well.
  - Must support inserts and deletes gracefully.
- Ideally, want to support non-point data as well (e.g., lines, shapes).
- The R-tree meets these requirements, and variants are widely used today.
Geometric index structures

Hash-like indexes
- Grid files
- Partitioned hash functions

Tree-based indexes
- Multiple-key indexes
- kd-trees
- Quad trees
- R-trees

These indexes are *heuristic*, i.e., they are not (proved to be) worst case efficient.
Grid files

- Simple idea:
  - Split each dimension into intervals.
  - Put each point into a bucket corresponding to the intervals it lies in.
- Overflow handling as in hash tables.
- Supports partial match queries, range queries, and nearest neighbor queries (how?)
- Bad case: All data along "diagonal" - need many grid lines (in internal memory) to avoid large buckets.
kd-trees

- Short for "k-dimensional search tree".
- Change from ordinary search trees:
  - Each node is associated with a dimension.
  - An internal node partitions the points of its subtree along its dimension.
  - Dimensions rotate down the tree: 1, 2, ..., k, 1, 2, ..., k, 1, 2, ...
  - Supports partial match queries, range queries and nearest neighbor queries.
- Bad case: Many points with same value in some dimension makes it impossible to split points well along this dimension.
R Trees (Guttman 84)

- "Region trees" – multidimensional indices
  - Any number of dimensions
  - Generally uses containment of bounding boxes, not full polygons, for efficiency

- Must deal with two issues vs. a B+ Tree:
  - Is there a complete ordering?
  - Can items overlap without being identical?

- Basic idea of the R Tree:
  - Create a tree based on containment of polygons/"rectangles" – child polygons are contained within parent polygons
The R-Tree

- The R-tree is a tree-structured index that remains balanced on inserts and deletes.
- Each key stored in a leaf entry is intuitively a box, or collection of intervals, with one interval per dimension.
- Example in 2-D:
R-Tree Properties

- Leaf entry = \(<\text{n-dimensional box, rid}>\)
  - This is Alternative (2), with *key value* being a box.
  - Box is the tightest bounding box for a data object.

- Non-leaf entry = \(<\text{n-dim box, ptr to child node}>\)
  - Box covers all boxes in child node (in fact, subtree).

- All leaves at same distance from root.

- Nodes can be kept 50% full (except root).
  - Can choose a parameter \(m\) that is \(\leq 50\%\), and ensure that every node is at least \(m\%\) full.
Example of an R-Tree

- Leaf entry
- Index entry
- Spatial object approximated by bounding box R8
Example R-Tree (Contd.)
Search for Objects Overlapping Box Q

Start at root.
1. If current node is non-leaf, for each entry \(<E, \text{ptr}>\), if box $E$ overlaps $Q$, search subtree identified by $\text{ptr}$.
2. If current node is leaf, for each entry \(<E, \text{rid}>\), if $E$ overlaps $Q$, $\text{rid}$ identifies an object that might overlap $Q$.

Note: May have to search several subtrees at each node! (In contrast, a B-tree equality search goes to just one leaf.)
Improving Search Using Constraints

- It is convenient to store boxes in the R-tree as approximations of arbitrary regions, because boxes can be represented compactly.
- But why not use convex polygons to approximate query regions more accurately?
  - Will reduce overlap with nodes in tree, and reduce the number of nodes fetched by avoiding some branches altogether.
  - Cost of overlap test is higher than bounding box intersection, but it is a main-memory cost, and can actually be done quite efficiently. Generally a win.
**Insert Entry \(<B, \text{ptr}>\)**

- Start at root and go down to “best-fit” leaf L.
  - Go to child whose box needs least enlargement to cover B; resolve ties by going to smallest area child.
- If best-fit leaf L has space, insert entry and stop. Otherwise, split L into L1 and L2.
  - Adjust entry for L in its parent so that the box now covers (only) L1.
  - Add an entry (in the parent node of L) for L2. (This could cause the parent node to recursively split.)
Splitting a Node During Insertion

- The entries in node L plus the newly inserted entry must be distributed between L1 and L2.
- Goal is to reduce likelihood of both L1 and L2 being searched on subsequent queries.
- **Idea:** Redistribute so as to minimize area of L1 plus area of L2.

Exhaustive algorithm is too slow; quadratic and linear heuristics are described in the paper.

GOOD SPLIT!  
BAD!
R-Tree Variants

- The R* tree uses the concept of forced reinserts to reduce overlap in tree nodes. When a node overflows, instead of splitting:
  - Remove some (say, 30% of the) entries and reinsert them into the tree.
  - Could result in all reinserted entries fitting on some existing pages, avoiding a split.

- R* trees also use a different heuristic, minimizing box perimeters rather than box areas during insertion.

- Another variant, the R+ tree, avoids overlap by inserting an object into multiple leaves if necessary.
  - Searches now take a single path to a leaf, at cost of redundancy.
Comments on R-Trees

- Deletion consists of searching for the entry to be deleted, removing it, and if the node becomes under-full, deleting the node and then re-inserting the remaining entries.
- Overall, works quite well for 2 and 3 D datasets. Several variants (notably, R+ and R* trees) have been proposed; widely used.
- Can improve search performance by using a convex polygon to approximate query shape (instead of a bounding box) and testing for polygon-box intersection.
R Trees in Practice

- One of many (dozens of!) multidimensional index structures
  - Perhaps the most popular, though not as ubiquitous as the B+ Tree
  - Implemented in a few DBMSs, such as Oracle, Illustra (Stonebraker startup, acquired by Informix, then IBM) and MySQL
Generalizing B+ Trees and R Trees: GiST

- The Generalized Search Tree (GiST) abstracts the “tree” nature of a class of indexes including B+ trees and R-tree variants.
  - Striking similarities in insert/delete/search and even concurrency control algorithms make it possible to provide “templates” for these algorithms that can be customized to obtain the many different tree index structures.
  - B+ trees are so important (and simple enough to allow further specialization) that they are implemented specially in all DBMSs.
  - GiST provides an alternative for implementing other tree indexes in an ORDBS.
Indexing High-Dimensional Data

- Typically, high-dimensional datasets are collections of points, not regions.
  - E.g., Feature vectors in multimedia applications.
  - Very sparse

- Nearest neighbor queries are common.
  - R-tree becomes worse than sequential scan for most datasets with more than a dozen dimensions.

- As dimensionality increases contrast (ratio of distances between nearest and farthest points) usually decreases; “nearest neighbor” is not meaningful.
  - In any given data set, advisable to empirically test contrast.
Summary

- Spatial data management has many applications, including GIS, CAD/CAM, multimedia indexing.
  - Point and region data
  - Overlap/containment and nearest-neighbor queries

- Many approaches to indexing spatial data
  - R-tree approach is widely used in GIS systems
  - Other approaches include Grid Files, Quad trees, and techniques based on “space-filling” curves.
  - For high-dimensional datasets, unless data has good “contrast”, nearest-neighbor may not be well-separated