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 ovelapping 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

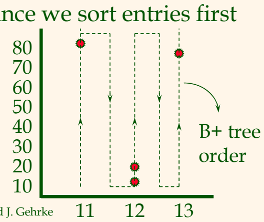
Applications of Spatial Data

- 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.

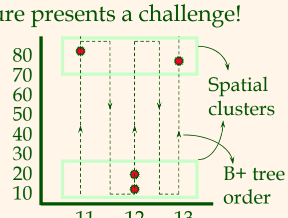
Consider entries:
<11, 80>, <12, 10>
<12, 20>, <13, 75>



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>



Motivation for Multidimensional Indexes

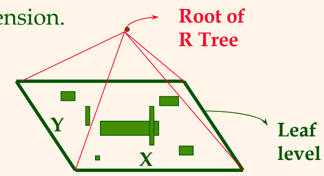
- Spatial queries (GIS, CAD).
  - Find all hotels within a radius of 5 miles from the conference venue.
  - Find the city with population 500,000 or more that is nearest to Kalamazoo, MI.
  - Find all cities that lie on the Nile in Egypt.
  - Find all parts that touch the fuselage (in a plane design).
- Similarity queries (content-based retrieval).
  - Given a face, find the five most similar faces.
- Multidimensional range queries.
  - 50 < age < 55 AND 80K < sal < 90K

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.

The R-Tree

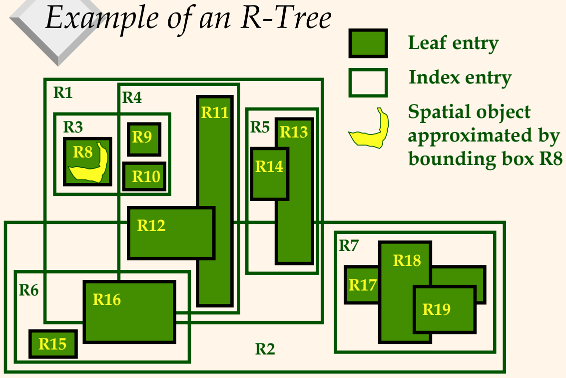
- The R-tree is a tree-structured index that remains balanced on inserts and deletes.
- Each key stored in a leaf entry is intuitively a box, or collection of intervals, with one interval per dimension.
- Example in 2-D:



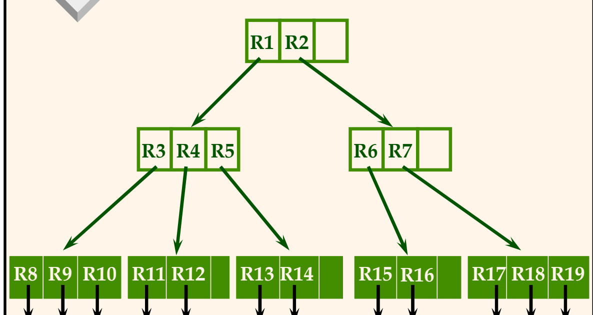
R-Tree Properties

- Leaf entry = < 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 = < 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 <= 50%, and ensure that every node is at least *m*% full.

Example of an R-Tree



Example R-Tree (Contd.)



Search for Objects Overlapping Box Q

Start at root.
1. If current node is non-leaf, for each entry <E, ptr>, if ***box*** E overlaps Q, search subtree identified by ptr.
2. If current node is leaf, for each entry <E, rid>, if E overlaps Q, 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.

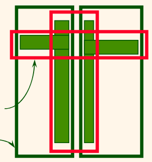
Insert Entry <B, ptr>

- 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.



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.

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

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.