15 Indexing Spatial Data

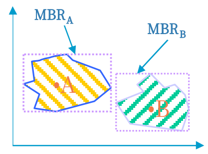
Copyright © 2004, Binnur Kurt

Introduction

- ►Many applications(e.g., CAD, GIS) operate on *spatial data*, which include points, lines, polygons and so on
- ►Conventional DBMSs are unable to support spatial data processing efficiently
  - – First, spatial data are large in quantity, complex in structures and relationships
  - – Second, the retrieval process employs *complex spatial operators* like *intersection*, *adjacency*, and *containment*
  - – Third, it is difficult to define a spatial ordering, so conventional techniques(e.g., sort-merge) cannot be employed for spatial operations
- ►Spatial indexes need!

Query Processing

- ►It is expensive to perform spatial operations (e.g., intersect, contain) on real spatial data
- ►Thus, simpler structure that *approximates* the objects are used: Minimum Bounding Rectangle or circle
- ►Example: intersection



•**Step1**: perform intersection operation between MBR_A and MBR_B

•**Step2**: if MBR_A intersects with MBR_B, then perform intersection operation between A and B

Query Processing (Con't)

- ►Multi-step spatial query processing
  1. The spatial index prunes the search space to a set of candidates
  2. Based on the approximations of candidates, some of the *false hits* can be further filtered away
  3. Finally, the actual objects are examined to identify those that match the query
  - – The multi-step strategy can effectively reduce the number of pages accessed, the number of data to be fetched and tested and the computation time through the approximations
  - – Types of spatial queries
    - • Spatial selection: point query, range(window) query
    - • Spatial join between two or more different entities sets

A Taxonomy of spatial indexes

- ►Classification of spatial indexes
  1. The transformation approach
     - • Parameter space indexing
       - – Objects with *n* vertices in a *k*-dimensional space are mapped into points in a *nk*-dimensional space
       - – e.g.) two-dimensional rectangle described by the two corner (x_1,y_1) and (x_2, y_2) => a point in a four-dimensional space
     - • Mapping to single attribute space
       - – The data space is partitioned into grid cells of the same size, which are then numbered according to some *curve-filling methods*(e.g., hilbert curve, z-ordering, snake-curve)

A Taxonomy of spatial indexes (Con't)

- ►Classification of spatial indexes
  2. The non-overlapping native space indexing approach
     - • Object duplication
     - • Object clipping

A Taxonomy of spatial indexes (Con't)

▶ Classification of spatial indexes

3. The overlapping native space indexing approach
   - Partitioning hierarchically the data space into a manageable number of smaller subspaces
   - Allowing the overlapping between bounding subspaces
   - The overlapping minimization is very important
   - e.g.)
     - binary-tree: kd-tree, LSD-tree, etc.
     - B-tree: k-d-b-tree, R-tree, R*-tree, TV-tree, X-tree, etc.
     - Hashing: Grid-files, BANG files, etc.
     - Space-Filling: Z-ordering, Filter-tree, etc.

Binary-tree based indexing

▶ The characteristics

- A basic data structure for representing data items whose index values are ordered by some linear order
- Repetitively partitioning a data space

▶ Types of binary search trees

- kd-tree
- K-D-B-tree
- hB-tree
- skd-tree
- LSD-tree

Binary-tree based indexing: The *kd*-tree

▶ The kd-tree

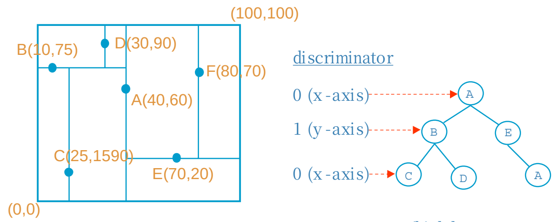
- k-dimensional binary search tree to index multi-attribute data
- A *node* in the tree serves both representation of a actual data point and direction of search
- A *discriminator* is used to indicate the key on which branching decision depends
- A node P has two children, a left son LOSON(P) and a right son HISON(P)
- If discriminator is the j^{th} attribute, then the j^{th} attribute of any node in the LOSON(P) is less than the j^{th} attribute of node P, and the j^{th} attribute of any node in the HISON(P) is greater than or equal to that of node P

Binary-tree based indexing: The *kd*-tree (con't)

▶ The kd-tree

- Complications arise when an internal node(Q) is deleted
  - One of the nodes in the subtree whose root is Q must replace Q
  - To reduce the cost of deletion, a non-homogeneous kd-tree was proposed
- The kd-tree has been the subject of intensive research over the past decade: clustering, searching, storage efficiency and balancing

Binary-tree based indexing: The *kd*-tree (con't)



(a) data space (b) *kd*-tree

Binary-tree based indexing: The *K-D-B*-tree

▶ The K-D-B-tree

- is a combination of a *kd*-tree and B-tree
- consists of a *region page* and a *point page*
  - region page: <region, page-ID> pairs
  - point page: <point, record-ID> pairs
- is perfectly height-balanced
- has poorer storage efficiency, nevertheless

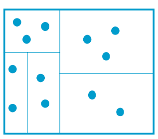
Binary-tree based indexing: The *K-D-B*-tree (Con't)

- Splitting
  - data page splitting
    - A split will occur during insertion of a new point into a *full* point page
    - The two resultant point pages will contain almost the same number of data points
    - The split of a point page may cause the parent region page to split as well, which may propagate upward

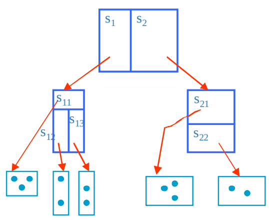
Binary-tree based indexing: The *K-D-B*-tree (Con't)

- Splitting
  - region page splitting
    - A split will occur when a region page is full
    - A region page is partitioned into two region pages such that both have almost the same number of entries
    - The split may propagate downward
    - The downward propagation may cause low storage utilization

Binary-tree based indexing: The *K-D-B*-tree (Con't)



(a) k-space

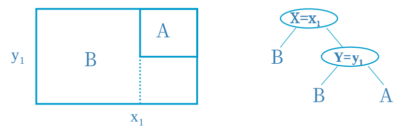


(b) K-D-B Tree

Binary-tree based indexing: The *hB*-tree

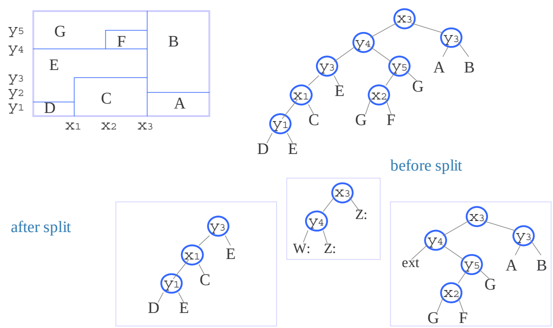
- The hB-tree
  - problem in the K-D-B-tree
    - The split of one index node can cause descendant nodes to be split as well. This may cause sparse index nodes to be created
  - To overcome this problem, the hB-tree (the holey brick B-tree) allows the data space to be holey
  - Based on the K-D-B-tree => height-balanced tree
  - Data nodes + Index nodes
  - Data space may be non-rectangular and kd-tree is used to space representation in internal nodes

Binary-tree based indexing: The *hB*-tree (Con't)



A holey brick is represented via a kd-tree. A holey brick is a brick from which a smaller brick hash been removed. Two leaves of the kd-tree are required to reference the holey brick region denoted by B.

Binary-tree based indexing: The *hB*-tree (Con't)



Binary-tree based indexing: The *hB*-tree (Con't)

- ▶ The advantages
  - – Overcoming the problem of sparse nodes in the K-D-B-tree
  - – The search time and the storage space are reduced because of the use of kd-tree
- ▶ The disadvantages
  - – The cost of node splitting and node deletion are expensive
  - – The multiple references to data nodes may cause a path to be traversed more than once

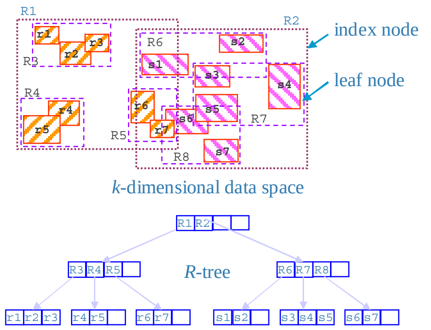
B-tree based indexing: The R-tree

- ▶ The R-tree
  - – A multi-dimensional generalization of the B-tree
  - – A height-balanced tree
  - – Having received a great deal of attention due to its well defined structure
  - – Like the B-tree, node splitting and merging are required

B-tree based indexing: The R-tree (Con't)

- ▶ The structure of the R-tree
  - – Leaf node : a set of entries of <MBR, *object-ID*>
    - • MBR: a bounding rectangle which bounds its data object
    - • object-ID: an object identifier of the data object
  - – Index node : a set of entries of <MBR, *child-pointer*>
    - • MBR: a bounding rectangle which covers all MBRs in the lower node in the subtree
    - • child-pointer: a pointer to a lower level node in the subtree

B-tree based indexing: The R-tree (Con't)



B-tree based indexing: The R-tree (Con't)

- ▶ Search
  - – Query operations: intersect, contain, within, distance, etc.
  - – Query rectangle: a rectangle represented by user
  - – The search algorithm
    - • Recursively traverse down the subtrees of MBR which intersect the query rectangle
    - • When a leaf node is reached, MBRs are tested against the query rectangle and then their objects are tested if they insect the query rectangle
  - – Primary performance factor: minimization of overlaps between MBRs of index nodes => determined by the splitting algorithm(different from other R-tree variants)

B-tree based indexing: The R-tree (Con't)

- ▶ Insertion
  - – Criterion: least coverage
    - • The rectangle that needs *least enlargement* to enclose the new object is selected, the one with the *smallest area* is chosen if more than on rectangle meets the first criterion
- ▶ Deletion
  - – In case that the deletion causes the leaf node to underflow, the node is deleted and all the remaining entries of that node are reinserted from the root

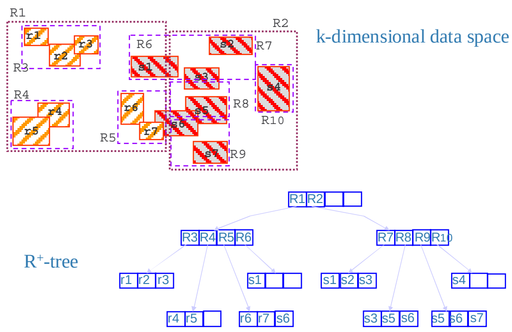
B-tree based indexing: The R*-tree

- The R*-tree
  - Minimization of both coverage and overlap is crucial to the performance of the R-tree. So the near optimal of both minimization was introduced by Beckmann et al.: The criterion that ensures the *quadratic* covering rectangles is used in the insertion and splitting algorithms
  - Dynamic hierarchical spatial indexes are sensitive to the order of the insertion of data: Beckmann proposed a *forced reinsertion* algorithm when a node overflows`

B-tree based indexing: The R^+-tree

- The R^+-tree
  - A compromise between the R-tree and the K-D-B-tree
  - Overcoming the problem of the overlapping of internal nodes of the R-tree
  - The R^+-tree differs from the R-tree:
    - Nodes of an R^+-tree are no guaranteed to be at least half filled
    - The entries of any internal node do not overlap
    - An object identifier may be stored in more than one leaf node
  - The disjoint MBRs avoid the multiple search paths for point queries

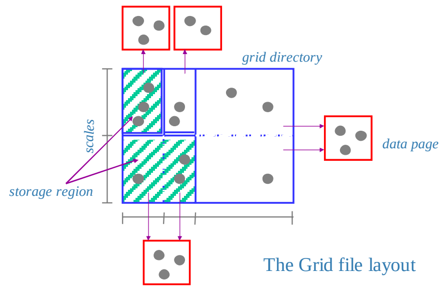
B-tree based indexing: The R^+-tree (Con't)



Cell methods based on dynamic hashing: The grid file

- The grid file
  - Based on dynamic hashing for multi-attribute point data
  - Two basic structures: *k linear scales* + *k-dimensional directory*
  - *grid directory*: k-dimensional array
  - Each grid need not contain at least *m* objects. So a data page is allowed to store objects from several grid cells as long as the union of these cells from a rectangular rectangle, which is known as the *storage region*

Cell methods based on dynamic hashing: The grid file (Con't)

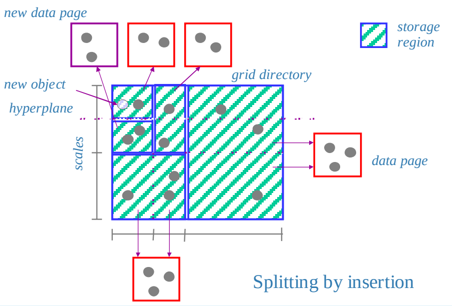


The Grid file layout

Cell methods based on dynamic hashing: The grid file (Con't)

- Splitting by insertion
  - In the case where the data page is *full*, a split is required
    - The split is simple if the storage region covers more than the grid cells
    - Otherwise a new (*k*-1)-dimensional hyperplane partitions the corresponding storage region into two subspaces
      - The corresponding storage region: partition into two regions and distribute objects into the existing page and a new data page
      - Other storage regions: unaffected

Cell methods based on dynamic hashing: The grid file (Con't)



Splitting by insertion

Cell methods based on dynamic hashing: The grid file (Con't)

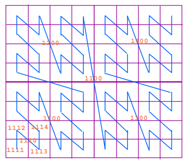
- Merging by deletion
  - Deletion may cause the occupancy of a storage region to fall below an acceptable level, which triggers merging operations
  - If the joint occupancy of two or more adjacent storage regions drops below a threshold, then the data pages are merged into one
  - Two merging approaches: *neighbor* system and *buddy* system

Spatial objects ordering

- The space-filling curves
  - Mapping multi-dimensional objects to one-dimensional values
    - Numbering each grid in a space according to mapping function (e.g., Peano-Hilbert curve, z-ordering, gray-ordering, etc.)
    - one-dimensional locational key is a number
  - A B^+-tree is used to index the objects based on locational keys

Spatial objects ordering (Con't)

e.g.) z-ordering



z-ordering

$$k = \begin{cases} k' + 5^{m-h} & \text{if k is the SW son of k'} \\ k' + 2*5^{m-h} & \text{if k is the NW son of k'} \\ k' + 3*5^{m-h} & \text{if k is the SE son of k'} \\ k' + 4*5^{m-h} & \text{if k is the NE son of k'} \end{cases}$$

mapping function