CMSC724: Access Methods; Indexes[1]; GiST

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[1] Partially based on notes from Joe Hellerstein

Outline

Access Methods: Why ?

- Most queries have predicates in them
  - Accessing only the needed records key in performance
- How relations are stored ?
  - Heap files: sequential scans, very very fast
  - Index structures: random accesses to the needed data
  - Scan performance increasing much faster than seeks
    - Must perform *much better* than Scan
    - No point in building indexes on small relations
- Note the emphasis on "queries"
  - Utility depends more on query workload than data
- Why not use in-memory indexes ?
  - Data exchange with disks in units of "blocks"

Access Methods

- Support iterator interface:
  - open (possibly with selection condition)
  - get_next, close, insert, delete, update_field
- Performance goals:
  - Disk I/O (or time) for lookups, inserts, deletes
  - cold vs hot lookups
  - Compare to sequential (seek times improving much slower)

Access Methods

- At a high level:
  - *partition:* partition a dataset or domain into buckets
  - *label:* provide a label for each bucket
  - Sometimes hierarchically (trees), sometimes not (hashing)
- Key Differentiating Factors
  - Data (1-d vs 2-d vs n-d, points vs intervals vs spatial objects vs images etc...)
  - Query types (equality, range, nearest-neighbor etc..)
  - Balanced (B+-tre, R-Tree) vs Unbalanced (Quad-tree)
    - Balanced $\rightarrow$ predictable, uniform performance, but hard to guarantee
    - Typically requires rearranging of labels, splits etc..

Access Methods

- Key Differentiating Factors
  - Data- vs Space-partitioning
  - Data-partitioning: the buckets are disjoint, but the labels may not be
    - May have to follow down the tree along multiple paths (e.g. R*-tree)
  - Space-partitioniing: the labels are disjoint, buckets may not be
    - e.g. Quad-trees, K-D-B trees
    - May have to duplicate pointers to data items in the leaves (e.g. R+-tree)
- B+-trees: disjoint buckets and disjoint labels

Access Methods

- Imagine:
  - The data is already stored on disk in some arbitrary order and you are not allowed to change it
  - How would you best build a hierarchical index structure on top for equality queries ?
    - Use BloomFilters ?
    - No option is going to work well if the data is really arbitrary and you can't find something to order by
  - But an interesting thought exercise
    - E.g. you might discover the third byte is different across blocks, but same within a block
  - Clustering of data is critical
    - Obvious for 1-d data, not so clear otherwise
- Not academic question: Imagine building an index over a distributed Grid/P2P data

Access Methods

- Implementation Issues:
  - Concurrency & recovery
    - Very important issue
    - Intertwined to a very complex degree
    - Can't build access methods in vacuum for just querying
  - Cost estimation
    - Query optimizer needs this information
  - Bulk loading
    - Important – have to be done very often

Outline

B+-Tree

- Balanced, 50% utilization
  - In practice, allow getting lower when doing deletes
  - Inserts are more common, something will get inserted there soon
- $O(\log_d(n))$ search, update, delete costs
  - d = order of the tree (number of keys per page)
- Optimizations
  - Key compression
  - Bulk loading algorithms
  - Faster count queries
    - Maintain counts of tuples in the subtrees at the inner nodes

B+-Tree

- Concurrency: not 2PL - too slow
  - Release locks on upper-level nodes as soon as possible
    - Too many queries want to access them
  - Tricky when doing inserts
    - Higher-level pages may have to be split
  - One Solution: Do “preparatory” splits when inserting
  - Much work of engineering nature, few research papers
- B-Trees ?
  - The inner nodes store pointers to data
  - B+-Tree – all pointers to data are at the leaves
  - B+-Trees make many things significantly easier
    - E.g. Can do a “scan” on the leaves for range queries

Outline

Indexes

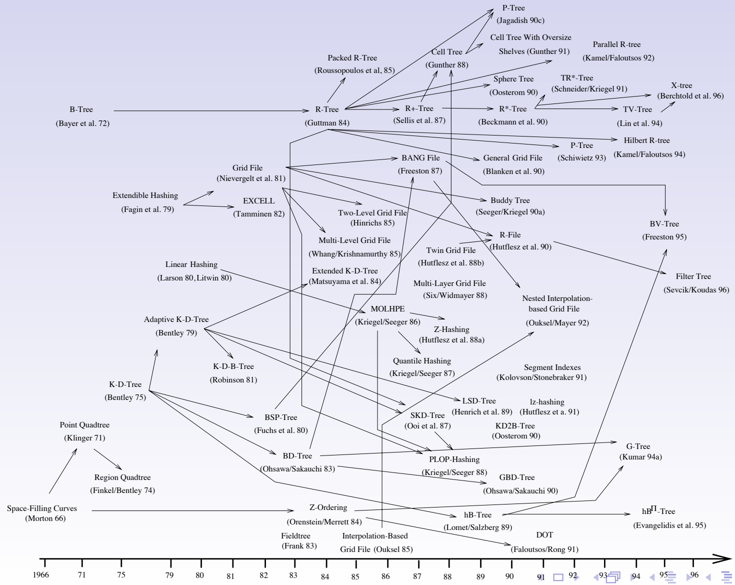
- B+-tree: Optimal for one-dimensional data (for range/equality queries)
- Linear hashing, extensible hashing: Only equality queries
- Multi-dimensional point data
  - Range queries: $(20 < \mathit{age} < 30) \wedge (10,000 < \mathit{salary})$
    - Space-filling curves: Impose a linear order on the multi-d data (limited applicability)
    - Grid-files, Quad-trees, K-D-B trees etc. . .
  - Nearest-Neighbor queries/similarity searches (very common)
    - Many indexing structures designed, no real consensus
    - Golden rule: Must beat sequential scans

Indexes

- Multi-dimensional spatial data (*regions, areas etc.*)
  - Queries: find all objects that contain this point, find objects that overlap this object
  - R-Tree and variants
- Intervals (e.g. time periods associated with events)
  - Queries: Find intervals containing this point, find overlapping intervals etc...
  - Several optimality results exists (see work by Lars Arge, Jeff Vitter et al.)
- XML ?
  - Some work, but generally considered very hard
- GiST: Generalized Search Tree

Indexes: A Timeline

Multidimensional Access Methods; Gaede, Gunther; ACM Surveys 1998



Indexes

- Much work since then as well
- When reading these papers, ask yourself:
  - Does it beat sequential scan sufficiently ?
  - Is the data/workload realistic ?
  - Are there other natural workloads on which it may not do well ?
- Little rigor in this area
- Some theoretical work, but problems not easy
  - “Curse of Dimensionality”

Outline

R-Tree

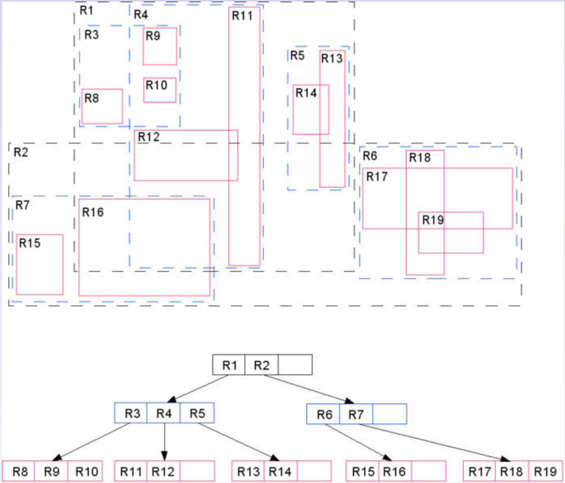


Figure: R-Tree

R-Tree

- Multi-dimensional, spatial data (points, rectangles)
- Queries: point in polygon, polygon in polygon, overlaps polygon, contains polygon
- *labels*: bounding rectangles
- Bulk loading ? Hard...
- Search: Follow all paths.
- Insert: Driven by minimizing *area enlargement*
- Split algorithms: exhaustive, quadratic, linear
- Delete: re-insert if too small (why ?)

R*-Tree

- R*-Tree: An improvement over R-Tree
- Analysis: four optimization metrics ?
  - Minimize area covered by a directory rectangle.
  - Minimize overlap
  - Minimize margin
  - Maximize storage *utilization*
- Conflict with each other
  - E.g., minimizing area covered conflicts with maximizing storage utilization.

R*-Tree

- Changes:
  - Insertion algorithm slightly different (minimizes "overlap" at leaf level)
  - Aggressive re-insertion (30% entries re-inserted at the same level)
    - Causes headaches with concurrency
- Lots of heuristics. . . backed by experimental analysis. . .
- Shown to outperform R-Trees in many experimental studies

R+-Tree

- R+-Tree
  - Space-partitioning version of R*-Tree
  - Forces non-overlapping keys
    - So same data item must be inserted into multiple leaf nodes
  - BUT don't need to follow all paths down to the leaves

Outline

GiST

- Motivation: Extensibility
  - New applications: GIS, multimedia (e.g. pictures), CAD, libraries, sequence datasets (Bioinformatics) etc...
  - OR systems (next class) allow defining new data types
  - What about querying over them ?
- Two proposed solutions:
  - Option 1: Design new index structures
  - Option 2: Try to use an existing index structure
    - E.g. Can use space-filling curves and B+-Trees to support querying multi-dimensional data
    - Limited applicability (only equality/range queries)
    - What if the app needs new type of query ?
- Postgres paper had an initial discussion

GiST

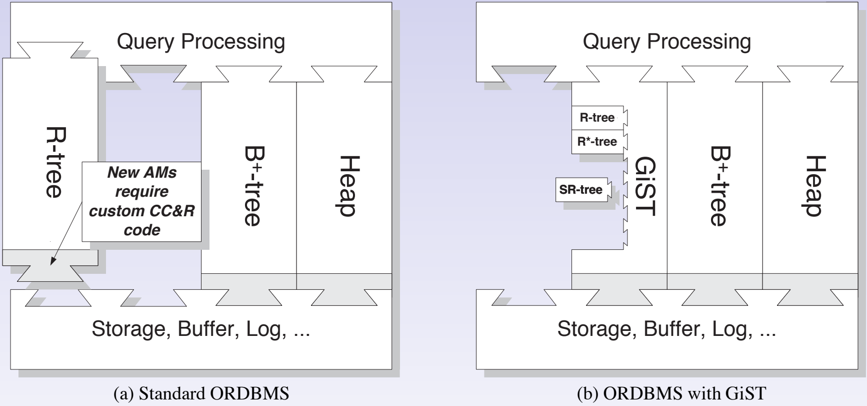


Figure 1: Access method interfaces – the database extender's perspective.

Figure: From: High-Performance Extensible Indexing; Kornacker; VLDB 1999

GiST

- Generalized Search Tree
  - Allows extending data types as well as queries
  - A single data structure that can handle many different index structures
    - So a single code-base
  - How to use ?
    - Register six methods with the database system
    - Start inserting/deleting/querying
- Allows indexing arbitrary types of data
- Question: *Is it always a good idea to use a GiST ?*
  - No
  - Some data and query workloads not amenable to indexing (scan preferred)
  - Ideas later further developed in Theory of Indexability

GiST

- Key insight:
  - An index structure partitions the input data hierarchically
  - GiST associates a “predicate” with each subtree, that is true for all data items in the subtree
    - Predicates on a single path from root to a leaf may not agree with each other, but must agree with the leaf
  - Nodes contain between 2 to M entries (except root)
  - Leaf nodes: *(p, ptr)*
    - *ptr*: pointer to actual record
    - *p*: predicate satisfied by the record
  - Non-leaf nodes: *(p, ptr)*
    - *ptr*: pointer to another node
    - *p*: predicate satisfied by all records in the subtree below

GiST

- Need to define 6 functions for a new search tree
  - Consistent(E, q): given a $E = (ptr, p)$, might q be satisfied by some tuple in the subtree below *ptr*
    - search/querying (search also done when inserting)
  - Union: Find new keys
    - inserts (when add a new E to a page)
  - Compress, Decompress: used for compressing the keys
    - Required to implement common optimizations
  - Penalty, PickSplit: Used for deciding where to insert a new object, and how to split a page if needed
- Very similar to R-Tree in many regards

GiST Algorithms

- Search: Query *q*
  - Find all pairs *E = (p, ptr)* such that $consistent(E, q)$
  - Follow down all the pointers
  - Somewhat inefficient, can do better for linear orders
- Insert/Delete: Keep the tree balanced
  - Use the methods Penalty, PickSplit etc, to decide where to insert/delete, how to rearrange
- Discussion of how to support R*-Tree illustrates the difficulties simulating an index precisely
  - But as with all generalized/extensible approaches, you gain in simplicity what you sacrifice in performance

GiST: Analysis

- Why an index might perform poorly ?
  - Predicates at inner nodes not effective → traverse down unnecessarily
    - Reason 1: Too much overlap between the data items themselves (e.g. spatial data)
    - Reason 2: Key compression not good, ie., the predicates can't approximate the subtree well (e.g. homework question)
  - Predicates too large in size in number of bytes
    - If predicates are allowed to be large, then search will be more efficient (fewer paths travelled)
    - BUT large predicates → tree height increases
    - Trade-off between key compression and search effectiveness

GiST: Analysis;

- Why an index might perform poorly ?
  - Poor storage utilization (too much wasted space)
    - Trade-off between this and above factors
    - Better storage utilization increases key overlap
    - Since we may have to force items together that shouldn't be
  - BUT poor storage utilization → tree height increases
- Complex trade-offs that can only be answered given a dataset and a query workload

GiST: Using Bloom Filters as Predicates

- The predicates are Bloom filters of the items in the subtree (as in homework)
  - Only supports equality queries
- Consistent(E, q): Check if “q” $\in$ the Bloom filter
- Union: Bit-wise union etc...
- Why bad ?
  - If the Bloom Filter size is small (say 10 bits):
    - Too much key overlap
    - All bits in the higher level nodes likely to be set to 1
    - Many predicates will satisy $Consistent(E, q)$
  - If the Bloom Filter size large (say 1000 bits):
    - Number of keys per page too low
    - The height of the tree will be large
- Not sure if anybody has formally analyzed this

GiST: Other issues

- Much later work at Berkeley: GiST Project Website
  - Indexability theory
  - Formalisms for analysis: different types of inefficiencies
- AmDB: A visual debugger and profiler
- Concurrency, recovery etc: Not addressed in this paper
  - See High-Performance Extensible Indexing

GiST: How extensible is it ?

- Generalizes many ideas, but some limitations
  - Recall the discussion of R*-Trees in the paper
- From: Generalizing "Search"...; P. Aoki; ICDE 98
- SS-Tree: Similarity search tree
  - For nearest-neighbor queries
  - Records organized in hierarchical clusters
    - For each cluster: *store centroid, bounding sphere radius*
  - Search: Traverse down the tree looking for the sphere closest to the query point
- Several Issues: e.g. Search is not depth-first
- Need a few modifications (see the paper above)

SS-Tree

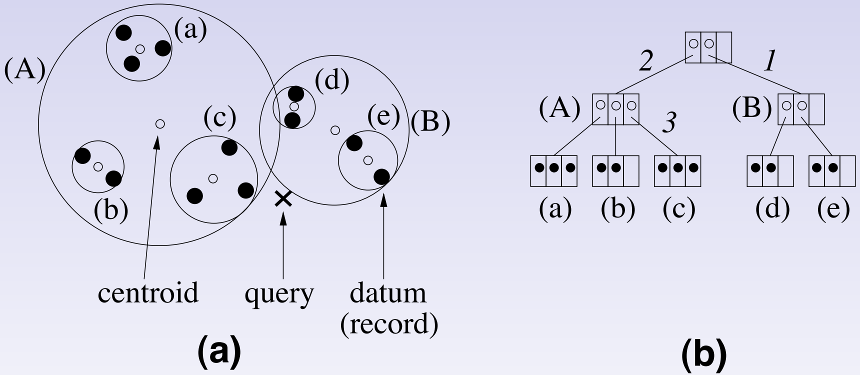


Figure 1. Similarity search using an SS-tree.
(a) Spatial coverage diagram.
(b) Tree structure diagram.