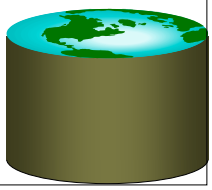
File Organizations and Indexing

Lecture 4

R&G Chapter 8

"If you don't find it in the index, look very carefully through the entire catalogue."

-- Sears, Roebuck, and Co., Consumer's Guide, 1897



Indexes

- Sometimes, we want to retrieve records by specifying the *values in one or more fields*, e.g.,
  - Find all students in the "CS" department
  - Find all students with a gpa > 3
- An *index* on a file is a disk-based data structure that speeds up selections on the *search key fields* for the index.
  - Any subset of the fields of a relation can be the search key for an index on the relation.
  - *Search key* is not the same as *key* (e.g. doesn't have to be unique ID).
- An index contains a collection of *data entries*, and supports efficient retrieval of all records with a given search key value **k**.

First Question to Ask About Indexes

- What kinds of selections do they support?
  - Selections of form field <op> constant
  - Equality selections (op is =)
  - Range selections (op is one of <, >, <=, >=, BETWEEN)
  - More exotic selections:
    - 2-dimensional ranges ("east of Berkeley and west of Truckee and North of Fresno and South of Eureka")
      - Or n-dimensional
    - 2-dimensional distances ("within 2 miles of Soda Hall")
      - Or n-dimensional
    - Ranking queries ("10 restaurants closest to Berkeley")
    - Regular expression matches, genome string matches, etc.
    - One common n-dimensional index: R-tree
      - Supported in Oracle and Informix
      - See http://gist.cs.berkeley.edu for research on this topic

Index Breakdown

- What selections does the index support
- Representation of data entries in index
  - i.e., what kind of info is the index actually storing?
  - 3 alternatives here
- Clustered vs. Unclustered Indexes
- Single Key vs. Composite Indexes
- Tree-based, hash-based, other

Alternatives for Data Entry **k*** in Index

- Three alternatives:
  - Actual data record (with key value **k**)
  - <**k**, rid of matching data record>
  - <**k**, list of rids of matching data records>
- Choice is orthogonal to the indexing technique.
  - Examples of indexing techniques: B+ trees, hash-based structures, R trees, …
  - Typically, index contains auxiliary information that directs searches to the desired data entries
- Can have multiple (different) indexes per file.
  - E.g. file sorted by *age*, with a hash index on *salary* and a B+tree index on *name*.

Alternatives for Data Entries (Contd.)

- Alternative 1:
  Actual data record (with key value **k**)
  - If this is used, index structure is a file organization for data records (like Heap files or sorted files).
  - At most one index on a given collection of data records can use Alternative 1.
  - This alternative saves pointer lookups but can be expensive to maintain with insertions and deletions.

Alternatives for Data Entries (Contd.)

Alternative 2
<**k**, rid of matching data record>
and Alternative 3
<**k**, list of rids of matching data records>

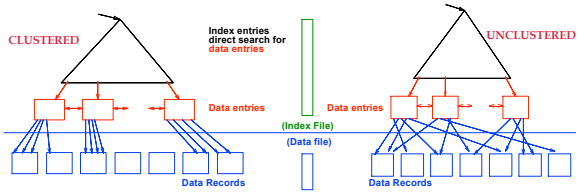
- Easier to maintain than Alt 1.
- If more than one index is required on a given file, at most one index can use Alternative 1; rest must use Alternatives 2 or 3.
- Alternative 3 more compact than Alternative 2, but leads to *variable sized data entries* even if search keys are of fixed length.
- Even worse, for large rid lists the data entry would have to span multiple blocks!

Index Classification

- *Clustered* vs. *unclustered*: If order of data records is the same as, or `close to', order of index data entries, then called *clustered index*.
  - A file can be clustered on at most one search key.
  - Cost of retrieving data records through index varies *greatly* based on whether index is clustered or not!
  - Alternative 1 implies clustered, *but not vice-versa*.

Clustered vs. Unclustered Index

- Suppose that Alternative (2) is used for data entries, and that the data records are stored in a Heap file.
  - To build clustered index, first sort the Heap file (with some free space on each block for future inserts).
  - Overflow blocks may be needed for inserts. (Thus, order of data recs is `close to', but not identical to, the sort order.)



Unclustered vs. Clustered Indexes

- What are the tradeoffs????
- Clustered Pros
  - Efficient for range searches
  - May be able to do some types of compression
  - Possible locality benefits (related data?)
  - ???
- Clustered Cons
  - Expensive to maintain (on the fly or sloppy with reorganization)

Cost of Operations

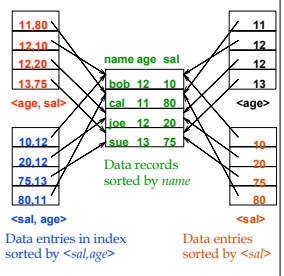
B: The number of data pages
R: Number of records per page
D: (Average) time to read or write disk page

	Heap File	Sorted File	Clustered File
Scan all records	BD	BD	1.5 BD
Equality Search	0.5 BD	$(\log_2 B) * D$	$(\log_F 1.5B) * D$
Range Search	BD	$[(\log_2 B) +$ #match pg$]*D$	$[(\log_F 1.5B) +$ #match pg$]*D$
Insert	2D	$((\log_2 B)+B)D$	$((\log_F 1.5B)+1) * D$
Delete	0.5BD + D	$((\log_2 B)+B)D$ *(because R,W 0.5)*	$((\log_F 1.5B)+1) * D$

Composite Search Keys

- Search on a combination of fields.
  - Equality query: Every field value is equal to a constant value. E.g. wrt <age,sal> index:
    - age=20 and sal =75
  - Range query: Some field value is not a constant. E.g.:
    - age > 20; or age=20 and sal > 10
- Data entries in index sorted by search key to support range queries.
  - Lexicographic order
  - Like the dictionary, but on fields, not letters!

Examples of composite key indexes using lexicographic order.



Summary

- File Layer manages access to records in pages.
  - Record and page formats depend on fixed vs. variable-length.
  - Free space management an important issue.
  - Slotted page format supports variable length records and allows records to move on page.
- Many alternative file organizations exist, each appropriate in some situation.
- If selection queries are frequent, sorting the file or building an *index* is important.
  - Hash-based indexes only good for equality search.
  - Sorted files and tree-based indexes best for range search; also good for equality search. (Files rarely kept sorted in practice; B+ tree index is better.)
- Index is a collection of data entries plus a way to quickly find entries with given key values.

Summary (Contd.)

- Data entries in index can be actual data records, <key, rid> pairs, or <key, rid-list> pairs.
  - Choice orthogonal to *indexing structure (i.e., tree, hash, etc.).*
- Usually have several indexes on a given file of data records, each with a different search key.
- Indexes can be classified as *clustered* vs. *unclustered*
- Differences have important consequences for utility/performance.
- Catalog relations store information about relations, indexes and views.

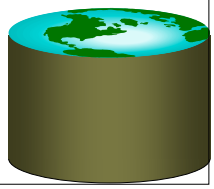
Tree-Structured Indexes

Lecture 5

R & G Chapter 10

"If I had eight hours to chop down a tree, I'd spend six sharpening my ax."

Abraham Lincoln



Review: Files, Pages, Records

- Abstraction of stored data is "files" of "records".
  - Records live on *pages*
  - Physical Record ID (RID) = <page#, slot#>
- *Variable length* data requires more sophisticated structures for records and pages. (why?)
  - Records: offset array in header
  - Pages: Slotted pages w/internal offsets & free space area
- Often best to be "lazy" about issues such as free space management, exact ordering, etc. (why?)
- Files can be unordered (heap), sorted, or kinda sorted (i.e., "clustered") on a *search key.*
  - Tradeoffs are update/maintenance cost vs. speed of accesses via the search key.
  - Files can be clustered (sorted) at most one way.
- Indexes can be used to speed up many kinds of accesses. (i.e., "access paths")

Tree-Structured Indexes: Introduction

- Selections of form field <op> constant
- Equality selections (op is =)
  - Either "tree" or "hash" indexes help here.
- Range selections (op is one of <, >, <=, >=, BETWEEN)
  - "Hash" indexes don't work for these.

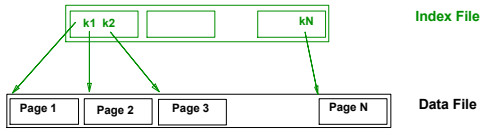
- Tree-structured indexing techniques support both *range selections* and *equality selections*.
- *ISAM*: static structure; early index technology.
- *B+ tree*: dynamic, adjusts gracefully under inserts and deletes.
- ISAM =Indexed Sequential Access Method

A Note of Caution

- ISAM is an old-fashioned idea
  - B+-trees are usually better, as we'll see
    - Though not *always*
- But, it's a good place to start
  - Simpler than B+-tree, but many of the same ideas
- Upshot
  - **Don't** brag about being an ISAM expert on your resume
  - **Do** understand how they work, and tradeoffs with B+-trees

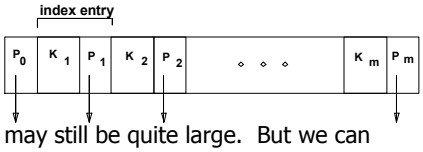
Range Searches

- ``*Find all students with gpa > 3.0*''
  - If data is in sorted file, do binary search to find first such student, then scan to find others.
  - Cost of binary search in a database can be quite high. Q: Why???
- Simple idea: Create an `index' file.

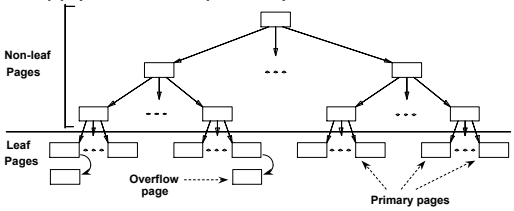


☛ *Can do binary search on (smaller) index file!*

ISAM



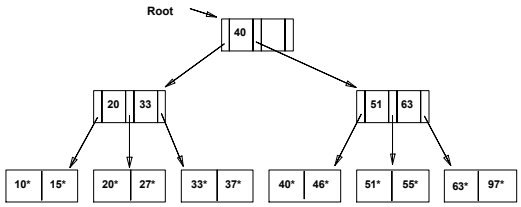
- Index file may still be quite large. But we can apply the idea repeatedly!



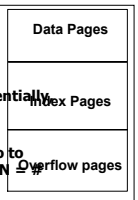
☛ *Leaf pages contain data entries.*

Example ISAM Tree

- ***Index entries*:<search key value, page id>**
  they direct search for data entries *in leaves.*
- **Example where each node can hold 2 entries;**



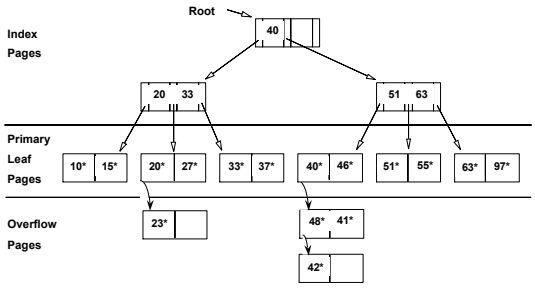
ISAM is a STATIC Structure



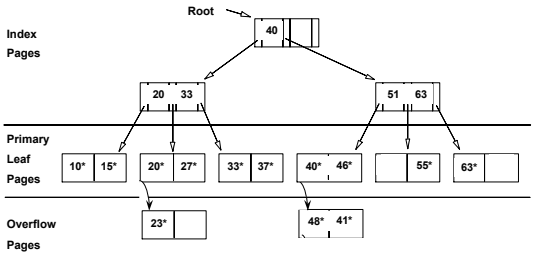
- ***File creation*: Leaf (data) pages allocated sequentially, sorted by search key; then index pages allocated, then overflow pgs.**
- ***Search*: Start at root; use key comparisons to go to leaf. Cost = $\log_F N$; F = # entries/pg (i.e., fanout), N = # leaf pgs**
  - no need for `next-leaf-page' pointers. (Why?)
- ***Insert*: Find leaf that data entry belongs to, and put it there. Overflow page if necessary.**
- ***Delete*: Find and remove from leaf; if empty page, de-allocate.**

Static tree structure: *inserts/deletes affect only leaf pages.*

Example: Insert 23*, 48*, 41*, 42*



... then Deleting 42*, 51*, 97*



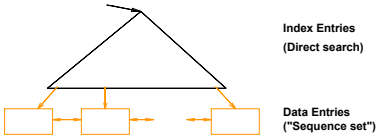
☛ *Note that 51* appears in index levels, but not in leaf!*

ISAM ---- Issues?

- Pros
  - ????
- Cons
  - ????

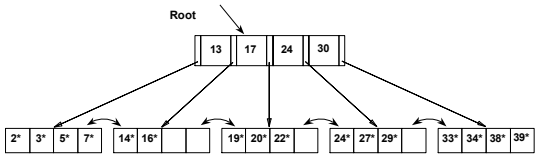
B+ Tree: The Most Widely Used Index

- **Insert/delete at log $_F$ N cost; keep tree *height-balanced*.**
  - F = fanout, N = # leaf pages
- **Minimum 50% occupancy (except for root). Each node contains *m entries where* d <= *m* <= 2d entries. "d" is called the *order* of the tree.**
- **Supports equality and range-searches efficiently.**
- **As in ISAM, all searches go from root to leaves, but structure is dynamic.**



Example B+ Tree

- Search begins at root, and key comparisons direct it to a leaf (as in ISAM).
- Search for 5*, 15*, all data entries >= 24* ...



☛ *Based on the search for 15*, we know it is not in the tree!*

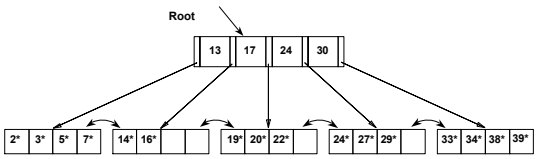
B+ Trees in Practice

- Typical order: 100. Typical fill-factor: 67%.
  - average fanout = 133
- Typical capacities:
  - Height 2: 133^3 = 2,352,637 entries
  - Height 3: 133^4 = 312,900,700 entries
- Can often hold top levels in buffer pool:
  - Level 1 = 1 page = 8 Kbytes
  - Level 2 = 133 pages = 1 Mbyte
  - Level 3 = 17,689 pages = 133 MBytes

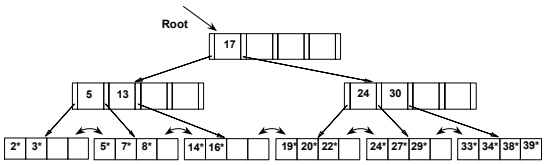
Inserting a Data Entry into a B+ Tree

- Find correct leaf *L*.
- Put data entry onto *L*.
  - If *L* has enough space, *done*!
  - Else, must *split* *L (into L and a new node L2)*
    - Redistribute entries evenly, **copy up** middle key.
    - Insert index entry pointing to *L2* into parent of *L*.
- This can happen recursively
  - To split index node, redistribute entries evenly, but **push up** middle key. (Contrast with leaf splits.)
- Splits "grow" tree; root split increases height.
  - Tree growth: gets *wider* or *one level taller at top.*

Example B+ Tree – Inserting 8*



Example B+ Tree - Inserting 8*

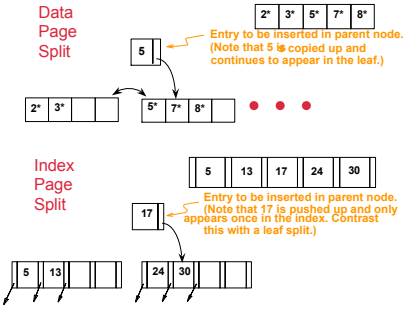


❖ Notice that root was split, leading to increase in height.

❖ In this example, we can avoid split by re-distributing entries; however, this is usually not done in practice.

Data vs. Index Page Split
(from previous example of inserting "8*")

- Observe how minimum occupancy is guaranteed in both leaf and index pg splits.
- Note difference between *copy-up* and *push-up*; be sure you understand the reasons for this.

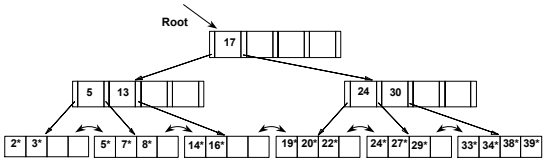


Deleting a Data Entry from a B+ Tree

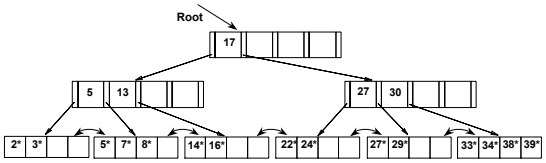
- Start at root, find leaf *L* where entry belongs.
- Remove the entry.
  - If L is at least half-full, *done!*
  - If L has only **d-1** entries,
    - Try to re-distribute, borrowing from *sibling (adjacent node with same parent as L).*
    - If re-distribution fails, *merge* L and sibling.
- If merge occurred, must delete entry (pointing to *L* or sibling) from parent of *L*.
- Merge could propagate to root, decreasing height.

In practice, many systems do not worry about ensuring half-full pages. Just let page slowly go empty; if it's truly empty, easy to delete from tree.

Example Tree (including 8*)
Delete 19* and 20* ...



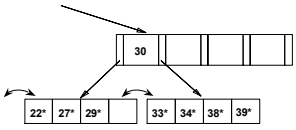
Example Tree (including 8*)
Delete 19* and 20* ...

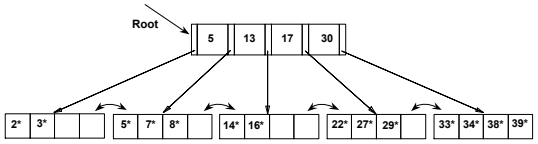


- Deleting 19* is easy.
- Deleting 20* is done with re-distribution. Notice how middle key is *copied up*.

... And Then Deleting 24*

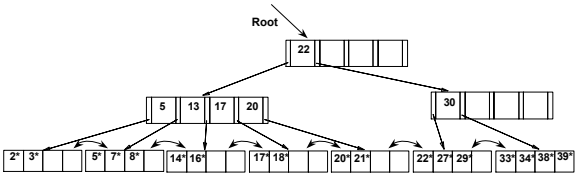
- Must merge.
- Observe `*toss*' of index entry (on right), and `*pull down*' of index entry (below).





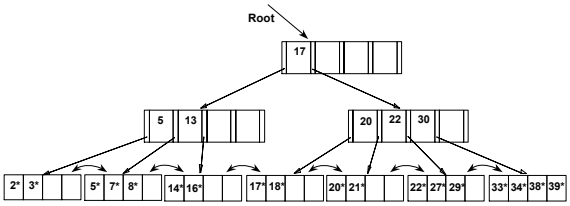
Example of Non-leaf Re-distribution

- Tree is shown below *during deletion* of 24*. (What could be a possible initial tree?)
- In contrast to previous example, can re-distribute entry from left child of root to right child.



After Re-distribution

- Intuitively, entries are re-distributed by `*pushing through*' the splitting entry in the parent node.
- It suffices to re-distribute index entry with key 20; we've re-distributed 17 as well for illustration.



Prefix Key Compression

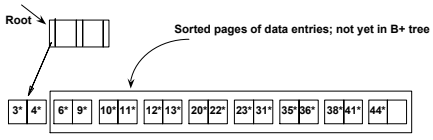
- Important to increase fan-out. (Why?)
- Key values in index entries only `direct traffic'; can often compress them.
  - E.g., If we have adjacent index entries with search key values *Dannon Yogurt*, *David Smith* and *Devarakonda Murthy*, we can abbreviate *David Smith* to *Dav*. (The other keys can be compressed too ...)
    - Is this correct? Not quite! What if there is a data entry *Davey Jones*? (Can only compress *David Smith* to *Davi*)
    - In general, while compressing, must leave each index entry greater than every key value (in any subtree) to its left.
- Insert/delete must be suitably modified.

Suffix Key Compression

- If many index entries share a common prefix
  - E.g. MacDonald, MacEnroe, MacFeeley
  - Store the common prefix "Mac" at a well known location on the page, use suffixes as split keys
- Particularly useful for composite keys
  - Why?

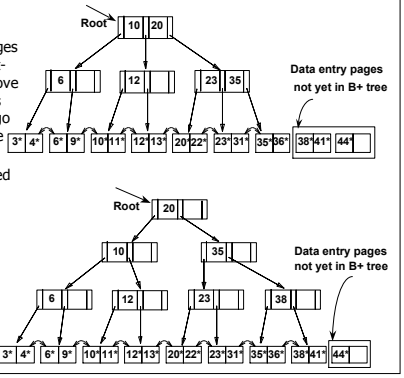
Bulk Loading of a B+ Tree

- If we have a large collection of records, and we want to create a B+ tree on some field, doing so by repeatedly inserting records is very slow.
  - Also leads to minimal leaf utilization --- why?
- *Bulk Loading* can be done much more efficiently.
- *Initialization*: Sort all data entries, insert pointer to first (leaf) page in a new (root) page.



Bulk Loading (Contd.)

- Index entries for leaf pages always entered into right-most index page just above leaf level. When this fills up, it splits. (Split may go up right-most path to the root.)
- Much faster than repeated inserts, especially when one considers locking!



Summary of Bulk Loading

- Option 1: multiple inserts.
  - Slow.
  - Does not give sequential storage of leaves.
- Option 2: *Bulk Loading*
  - Has advantages for concurrency control.
  - Fewer I/Os during build.
  - Leaves will be stored sequentially (and linked, of course).
  - Can control "fill factor" on pages.

A Note on `Order'

- *Order* (**d**) concept replaced by physical space criterion in practice (`*at least half-full*').
  - Index pages can typically hold many more entries than leaf pages.
  - Variable sized records and search keys mean different nodes will contain different numbers of entries.
  - Even with fixed length fields, multiple records with the same search key value (*duplicates*) can lead to variable-sized data entries (if we use Alternative (3)).
- Many real systems are even sloppier than this --- only reclaim space when a page is *completely* empty.

Summary

- Tree-structured indexes are ideal for range-searches, also good for equality searches.
- ISAM is a static structure.
  - Only leaf pages modified; overflow pages needed.
  - Overflow chains can degrade performance unless size of data set and data distribution stay constant.
- B+ tree is a dynamic structure.
  - Inserts/deletes leave tree height-balanced; $\log_F N$ cost.
  - High fanout (**F**) means depth rarely more than 3 or 4.
  - Almost always better than maintaining a sorted file.

Summary (Contd.)

  - Typically, 67% occupancy on average.
  - Usually preferable to ISAM, modulo *locking* considerations; adjusts to growth gracefully.
  - If data entries are data records, splits can change rids!
- Key compression increases fanout, reduces height.
- Bulk loading can be much faster than repeated inserts for creating a B+ tree on a large data set.
- Most widely used index in database management systems because of its versatility. One of the most optimized components of a DBMS.