Overview of Storage and Indexing

Chapter 8

Why Is This Important?

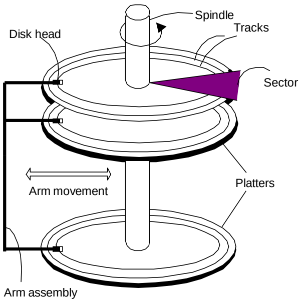
- DB performance depends on time it takes to get the data from storage system and time to process
- Choosing the right index for faster access can speed up queries significantly
- Understanding why a query is slow helps finding a remedy
- Warning: DBMS is a complex system
  - Cannot understand every little detail
  - Our focus: Most important aspects, abstracted enough to make them “digestible”

Data on External Storage

- Disks: Can retrieve random page at fixed cost
  - But reading several consecutive pages is much cheaper than reading them in random order
- Tapes: Can only read pages in sequence
  - Cheaper than disks; used for archival storage
- Flash memory: Starting to replace disks due to much faster random access
  - Writes still slow, size often too small for DB applications
- File organization: Method of arranging a file of records on external storage.
  - Record id (rid) is sufficient to physically locate record
  - Index: data structure for finding the ids of records with given values faster
- Architecture: Buffer manager stages pages from external storage to main memory buffer pool. File and index layers make calls to the buffer manager.

Components of a Disk

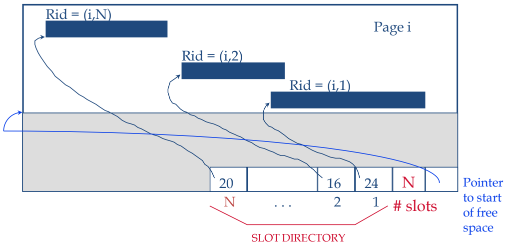
- Platters spin
  - E.g., 10K rpm
- Arm assembly is moved in or out to position a head on a desired track.
- Tracks under heads make a cylinder.
- Only one head reads or writes at any one time.
- Block size is a multiple of sector size (which is fixed).
  - 512 bytes (old), 4096 bytes (new)



Accessing a Disk Page

- Time to access (read/write) a disk block:
  - Seek time (moving arms to position disk head on track)
  - Rotational delay (waiting for block to rotate under head)
  - Transfer time (actually moving data to/from disk surface)
- Seek time and rotational delay dominate.
  - Seek time typically a little below 9msec (consumer disks)
  - Rotational delay around 4msec on average (7.2K rpm disk)
  - Transfer rate disk-to-buffer of 70MB/sec (sustained)
- Key to lower I/O cost: reduce seek/rotation delays.
  - Hardware vs. software solutions?

Records on a Disk Page



- Rid = <page#, slot#>
- Can move records on page without changing rid.

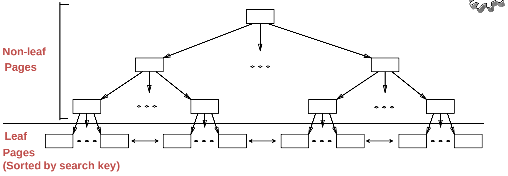
Possible File Organizations

- Heap (random order) files
  - Suitable when typical access is a file scan retrieving all records.
- Sorted Files
  - Best if records must be retrieved in some order, or only a `range' of records is needed.
- Indexes = data structures to organize records via trees or hashing.
  - Like sorted files, they speed up searches for a subset of records, based on values in certain (“search key”) fields
  - Updates are much faster than in sorted files.

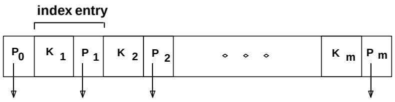
Indexes

- An index on a file 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 (minimal set of fields that uniquely identify a record in a relation).
- An index contains a collection of data entries, and supports efficient retrieval of all data entries k* with a given key value k.
  - Given data entry k*, we can find record with key k in at most one disk I/O. (Details soon…)

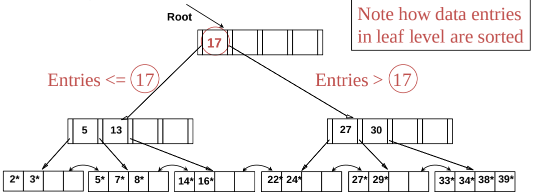
B+ Tree Indexes



- Balanced index: all root-to-leaf paths have same length
  - For n data entries, tree has height log n
- Leaf pages contain data entries, and are chained (prev & next)
- Non-leaf pages have index entries; only used to direct searches:



Example B+ Tree



Note how data entries in leaf level are sorted

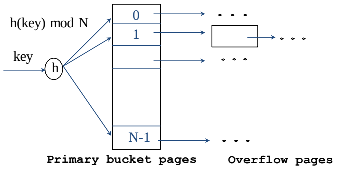
- Find 28*? 29*? All > 15* and < 30*
- Insert/delete: Find data entry in leaf, then change it. Need to adjust parent sometimes.
  - And change sometimes propagates up the tree

Hash-Based Indexes

- Good for equality selections.
- Index is a collection of buckets.
  - Bucket = primary page plus zero or more overflow pages.
  - Buckets contain data entries.
- Hashing function h: h(r) = bucket in which (data entry for) record r belongs.
  - h looks at the search key fields of r.
  - No need for “index entries” in this scheme.

Static Hashing

- # primary pages fixed, allocated sequentially, never de-allocated; overflow pages if needed.
- h(k) mod N = bucket to which data entry with key k belongs. (N = # of buckets)
  - h(key) = (a * key + b) usually works well



Alternatives for Data Entry *k** in Index

- In a data entry k* we can store:
  1. Data record with key value k, or
  2. <k, rid of data record with search key value k>, or
  3. <k, list of rids of data records with search key k>
- Choice of alternative for data entries is orthogonal to the indexing technique used to locate data entries with a given key value k.
  - Typically, index contains auxiliary information that directs searches to the desired data entries

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Alternative 1 for Data Entries

- Actual data record stored in index
  - Index structure is a file organization for data records (instead of a Heap file or sorted file).
- At most one index on a given collection of data records can use Alternative 1.
  - Otherwise, data records are duplicated, leading to redundant storage and potential inconsistency.
- If data records are very large, # of pages containing data entries is high. Implies size of auxiliary information in the index is also large, typically.

Alternatives 2 and 3 for Data Entries

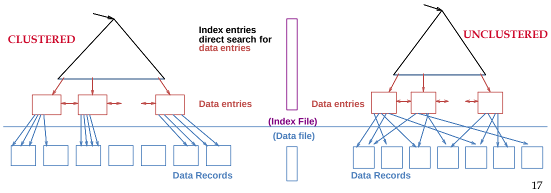
- Data entries typically much smaller than data records. So, better than Alternative 1 with large data records, especially if search keys are small.
  - Portion of index structure used to direct search, which depends on size of data entries, is much smaller than with Alternative 1.
- Alternative 3 more compact than Alternative 2, but leads to variable-sized data entries even if search keys are of fixed length.
- Extra cost for accessing data records in another file
  - Index only return rids

Index Classification

- Primary vs. secondary: If search key contains primary key, then called primary index.
  - Unique index: Search key contains a candidate key.
- Clustered vs. unclustered: If order of data records is the same as, or `close to', order of data entries, then called clustered index.
  - Alternative 1 implies clustered
    - In practice, clustered also implies Alternative 1 (since sorted files are rare).
  - 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.

Clustered vs. Unclustered Index

- Suppose 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 page for future inserts).
  - Overflow pages may be needed for inserts. (Thus, order of data records is `close to', but not identical to, the sort order.)



Cost Model for Our Analysis

- We ignore CPU costs, for simplicity:
  - B: The number of data pages ("blocks")
  - R: Number of records per page
  - D: (Average) time to read or write a single disk page
- Measuring number of page I/O's ignores gains of pre-fetching a sequence of pages; thus, even I/O cost is only approximated.
- Average-case analysis; based on several simplifying assumptions.

Good enough to show the overall trends!

Comparing File Organizations

- Heap files (random order; insert at eof)
- Sorted files, sorted on attributes <age, sal>
- Clustered B+ tree file, Alternative 1, search key <age, sal>
- Heap file with unclustered B + tree index on search key <age, sal>
- Heap file with unclustered hash index on search key <age, sal>

Operations to Compare

- Scan: Fetch all records from disk
- Equality search
- Range selection
- Insert a record
- Delete a record

Assumptions in Our Analysis

- Heap Files:
  - Equality selection on key; exactly one match.
- Sorted Files:
  - Files compacted after deletions.
- Indexes:
  - Alternatives 2, 3: data entry size = 10% of record size
  - Tree: 67% occupancy (this is typical).
    - Implies file size = 1.5 data size
  - Hash: No overflow buckets.
    - 80% page occupancy => File size = 1.25 data size

Assumptions (contd.)

- Scans:
  - Leaf levels of a tree-index are chained.
  - Index data-entries plus actual file scanned for unclustered indexes.
- Range searches:
  - We use tree indexes to restrict the set of data records fetched, but ignore hash indexes.

I/O Cost of Operations

	Scan	**Equality**	**Range**	**Insert**	**Delete**
Heap file	BD	0.5BD	BD	2D	Search + D
Sorted file	BD	D $\log_2 B$	D($\log_2 B$ + #pgs w. match recs)	Search + BD	Search + BD
Clustered index	1.5BD	D$\log_F 1.5B$	D($\log_F$ 1.5B + #pgs w. match recs)	Search + D	Search + D
Unclustered tree index + Heap file	BD(R+0.15)	D(1+$\log_F$ 0.15B)	D(logF 0.15B + #pgs w. match recs)	Search + 3D	Search + 3D
Unclustered hash index + Heap file	BD(R+0.125)	2D	BD	4D	4D

Several assumptions underlie these (rough) estimates!

Choice of Indexes

- What indexes should we create?
  - Which relations should have indexes?
  - What field(s) should be the search key?
  - Should we build several indexes?
- For each index, what kind of an index should it be?
  - Clustered?
  - Hash or tree?

Choice of Indexes (Contd.)

- One approach: Consider the most important queries in turn. Consider the best plan using the current indexes, and see if a better plan is possible with an additional index. If so, create it.
  - Must understand how a DBMS evaluates queries and creates query evaluation plans.
- Before creating an index, must also consider the impact on updates in the workload.
  - Trade-off: Indexes can make queries go faster, updates slower. Require disk space, too.

Index Selection Guidelines

- Attributes in WHERE clause are candidates for index keys.
  - Exact match condition suggests hash index.
  - Range query suggests tree index.
    - Clustering is especially useful for range queries; can also help on equality queries if there are many duplicates.
- Multi-attribute search keys should be considered when a WHERE clause contains several conditions.
  - Order of attributes is important for range queries.
  - Such indexes can sometimes enable index-only strategies for important queries: when only indexed attributes are needed.
    - For index-only strategies, clustering is not important.
- Try to choose indexes that benefit many queries.
- Since only one index can be clustered per relation, choose it based on important queries that would benefit the most from clustering.

Examples of Clustered Indexes

- B+ tree index on E.age can be used to get qualifying tuples.
  - How selective is the condition?
  - Is the index clustered?
- Consider the GROUP BY query.
  - If many tuples have E.age > 10, using E.age index and sorting the retrieved tuples may be costly.
  - Clustered E.dno index may be better!
- Equality queries and duplicates:
  - Clustering on E.hobby helps!

```
SELECT E.dno
FROM Emp E
WHERE E.age>40
```

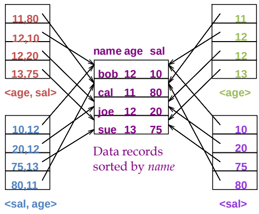
```
SELECT E.dno, COUNT (*)
FROM Emp E
WHERE E.age>10
GROUP BY E.dno
```

```
SELECT E.dno
FROM Emp E
WHERE E.hobby=Stamps
```

Indexes with Composite Search Keys

- Composite Search Keys: Search on a combination of fields.
  - Equality query: **Every** field value is equal to a constant. E.g. wrt <sal,age> 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, or
  - Spatial order.

Examples of composite key indexes using lexicographic order.



Data records sorted by *name*

Data entries in index sorted by <*sal,age*>

Data entries sorted by <*sal*>

Composite Search Keys

- To retrieve Emp records with age=30 AND sal=4000, an index on <age,sal> would be better than an index on age alone or an index on sal.
  - Choice of index key orthogonal to clustering etc.
- If condition is 20<age<30 AND 3000<sal<5000:
  - Clustered tree index on <age,sal> or <sal,age> is best.
- If condition is age=30 AND 3000<sal<5000:
  - Clustered <age,sal> index much better than <sal,age> index.
- Composite indexes are larger, updated more often.

Index-Only Plans

- Some queries can be answered without retrieving any tuples from one or more of the relations involved, if a suitable index is available.

<E.dno>

```
SELECT E.dno, COUNT(*)
FROM Emp E
GROUP BY E.dno
```

<E.dno,E.sal>
Tree index!

```
SELECT E.dno, MIN(E.sal)
FROM Emp E
GROUP BY E.dno
```

<E.age,E.sal>
or
<E.sal,E.age>
Tree index!

```
SELECT AVG(E.sal)
FROM Emp E
WHERE E.age=25 AND
 E.sal BETWEEN 3000 AND 5000
```

Summary

- 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 can be actual data records, <key, rid> pairs, or <key, rid-list> pairs.
  - Choice orthogonal to indexing technique used to locate data entries with a given key value.
- Can have several indexes on a given file of data records, each with a different search key.
- Indexes can be classified as clustered vs. unclustered and primary vs. secondary.
  - Differences have important consequences for utility/performance.

Summary (Contd.)

- Understanding the nature of the workload and performance goals essential to developing a good design.
  - What are the important queries and updates?
  - What attributes and relations are involved?
- Indexes must be chosen to speed up important queries (and perhaps some updates).
  - Index maintenance overhead on updates to key fields.
  - Choose indexes that can help many queries, if possible.
  - Build indexes to support index-only strategies.
  - Clustering is an important decision; only one index on a given relation can be clustered!
  - Order of fields in composite index key can be important.