# Carnegie Mellon Univ.
# Dept. of Computer Science
# 15-415/615 – DB Applications

Faloutsos & Pavlo

Lecture #10 (R&G ch8)

*File Organizations and Indexing*

## Overview

- Review
- Index classification
- Cost estimation



## Alternative File Organizations

Many alternatives exist, *each good for some situations, and not so good in others:*

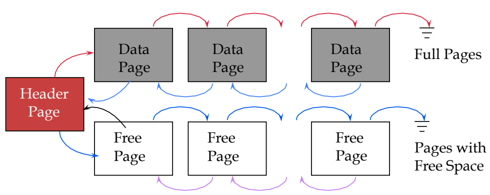
- Heap files: Suitable when typical access is a file scan retrieving all records.
- Sorted Files: Best for retrieval in some order, or for retrieving a `range' of records.
- Index File Organizations: (ISAM, or B+ trees)

## How to find records quickly?

- E.g., student.gpa = '3'

Q: On a heap organization, with *B* blocks, how many disk accesses?

## Heap File Implemented Using Lists




- The header page id and Heap file name must be stored someplace.
- Each page contains 2 `pointers' plus data.

## How to find records quickly?

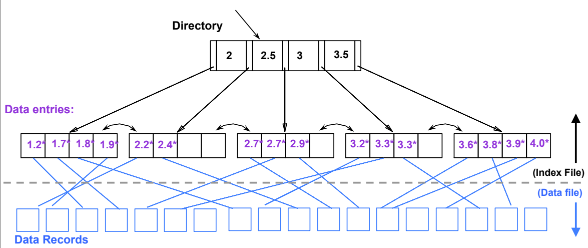
- E.g., student.gpa = '3'

Q: On a heap organization, with *B* blocks, how many disk accesses?
A: *B*

## How to accelerate searches?

- A: Indices, like:

## Example: Simple Index on GPA




An index contains a collection of **data entries**, and supports efficient retrieval of **records** matching a given **search condition**

## 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 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).

## Index Search Conditions

- Search condition = *<search key, comparison operator>*

Examples…

(1) Condition: Department = “CS”
  - Search key: “CS”
  - Comparison operator: equality (=)

(2) Condition: GPA > 3
  - Search key: 3
  - Comparison operator: greater-than (>)

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  - Representation of data entries in index
  - Clustered vs. Unclustered
  - Primary vs. Secondary
  - Dense vs. Sparse
  - Single Key vs. Composite
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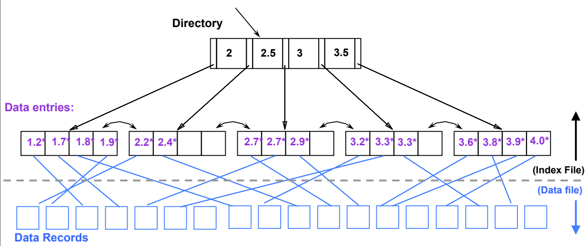
## Details

- ‘data entries’ == what we store at the bottom of the index pages
- what would you use as data entries?
- (3 alternatives here)

## Example: Simple Index on GPA




An index contains a collection of **data entries**, and supports efficient retrieval of **records** matching a given **search condition**

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

1. Actual data record (with key value **k**)

   | 123 | Smith; Main str; 412-999.9999 |

2. <**k**, rid of matching data record>

   | $40 | Rid-1 |
   | $40 | Rid-2 |
   …

3. <**k**, list of rids of matching data records>

   | $40 | Rid-1 | Rid-2 | …

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

1. Actual data record (with key value **k**)
2. <**k**, rid of matching data record>
3. <**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 info that directs searches to the desired data entries
- Can have multiple (different) indexes per file.
  - E.g. file sorted on *age*, with a hash index on *name* and a B+tree index on *salary*.

## Alternatives for Data Entries (Contd.)

Alternative 1:

Actual data record (with key value **k**)

- Then, this is a clustering/sparse index, and constitutes a file organization (like Heap files or sorted files).
- At most one index on a given collection of data records can use Alternative 1.
- 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 Alternative 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 pages!

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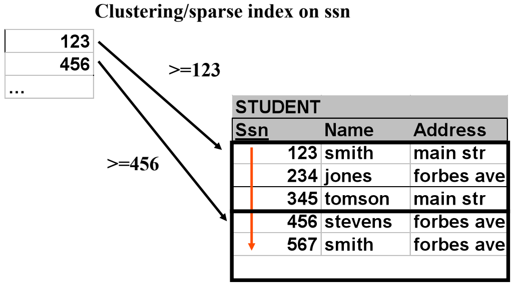
## Indexing - clustered index example

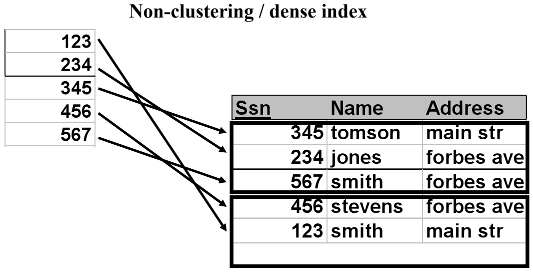
Clustering/sparse index on ssn




| STUDENT | | |
|---|---|---|
| Ssn | Name | Address |
| 123 | smith | main str |
| 234 | jones | forbes ave |
| 345 | tomson | main str |
| 456 | stevens | forbes ave |
| 567 | smith | forbes ave |

## Indexing - non-clustered

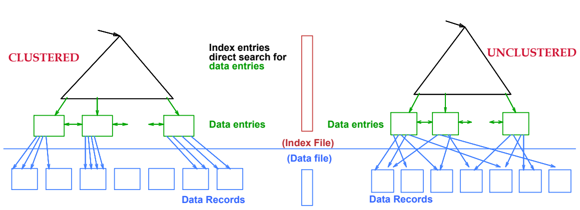
Non-clustering / dense index




| Ssn | Name | Address |
|---|---|---|
| 345 | tomson | main str |
| 234 | jones | forbes ave |
| 567 | smith | forbes ave |
| 456 | stevens | forbes ave |
| 123 | smith | main str |

## Index Classification - clustered

- *Clustered* vs. *unclustered*: If order of data records is the same as, or \`close to', order of index data entries, then called *clustered index*.



## Index Classification - clustered

- A file can have a clustered index on at most one search key.
- Cost of retrieving data records through index varies *greatly* based on whether index is clustered!
- Note: Alternative 1 implies clustered, *but not vice-versa*.

**But, for simplicity, you may think of them as equivalent..**

## Clustered vs. Unclustered Index

- Cost of retrieving records found in range scan:
  - Clustered: cost =
  - Unclustered: cost ≈
- What are the tradeoffs????

## Clustered vs. Unclustered Index

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  - Unclustered: cost ≈ # of matching index data entries
- What are the tradeoffs????

## Clustered vs. Unclustered Index

- Cost of retrieving records found in range scan:
  - Clustered: cost = # pages in file w/matching records
  - Unclustered: cost ≈ # of matching index data entries
- What are the tradeoffs????
  - Clustered Pros:
    - Efficient for range searches
    - May be able to do some types of compression
  - Clustered Cons:
    - Expensive to maintain (on the fly or sloppy with reorganization)

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## Primary vs. Secondary Index

- *Primary*: index key includes the file's primary key
- *Secondary*: any other index
  - Sometimes confused with Alt. 1 vs. Alt. 2/3
  - Primary index never contains duplicates
  - Secondary index may contain duplicates
    - If index key contains a candidate key, no duplicates => unique index

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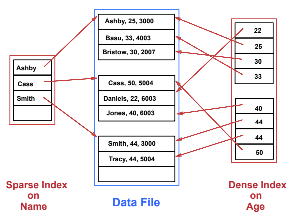
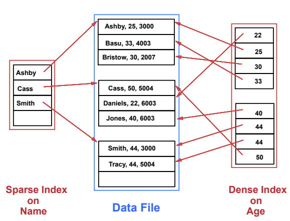
## Dense vs. Sparse Index

- *Dense:* at least one data entry per key value
- *Sparse:* an entry per data page in file
  - **Every sparse index is clustered**!
  - Sparse indexes are smaller; however, some useful optimizations are based on dense indexes.




## Dense vs. Sparse Index

- Sparse <-> Clustering <-> Alt#1 (full record)



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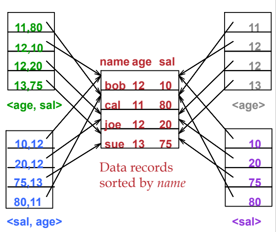
## Composite Search Keys

- Search on *combination* of fields.
  - Equality query: Every field is equal to a constant value. E.g. wrt <sal,age> index:
    - age=12 and sal =75
  - Range query: Some field value is not a constant. E.g.:
    - age =12; or age=12 and sal > 20
- Data entries in index sorted by search key for range queries.
  - "Lexicographic" order.

Examples of composite key indexes using lexicographic order.

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## Tree vs. Hash-based index

- Hash-based index
  - Good for equality selections.
    - File = a collection of *buckets.* Bucket = *primary* page plus 0 or more *overflow* pages.
    - *Hash function* **h**: **h**(*r.search_key*) = bucket in which record *r* belongs.
- Tree-based index
  - Good for range selections.
    - Hierarchical structure (Tree) directs searches
    - Leaves contain data entries sorted by search key value
    - B+ tree: all root->leaf paths have equal length *(height)*

## Overview

- Review
- Index classification
  - Representation
  - …
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## Cost estimation

- Heap file
- Sorted
- Clustered
- Unclustured tree index
- Unclustered hash index

Methods Operations(?)

## Cost estimation

- Heap file
- Sorted
- Clustered
- Unclustured tree index
- Unclustered hash index

Methods

- scan
- equality search
- range search
- insertion
- deletion

Operations

- Consider only I/O cost;
- suppose file spans *B* pages

## Cost estimation

| | scan | eq | range | ins | del |
|---|---|---|---|---|---|
| Heap | | | | | |
| sorted | | | | | |
| Clust. | | | | | |
| u-tree | | | | | |
| u-hash | | | | | |

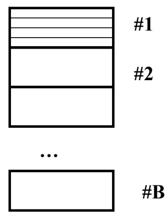
Assume that:
- Clustered index spans 1.5*B* pages (due to empty space)
- Data entry= 1/10 of data record

## Cost estimation

| | scan | eq | range | ins | del |
|---|---|---|---|---|---|
| Heap | B | | | | |
| sorted | B | | | | |
| Clust. | 1.5B | | | | |
| u-tree | ~B | | | | |
| u-hash | ~B | | | | |

## Cost estimation

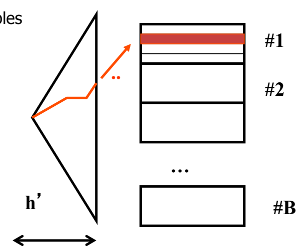
- heap: seq. scan
- sorted: binary search
- index search




## Cost estimation

index – cost? In general

- levels of index +
- blocks w/ qual. tuples




for primary key – cost:

h for clustering index

h'+1 for non-clustering

## Cost estimation

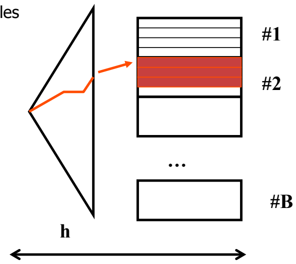
| | scan | eq | range | ins | del |
|---|---|---|---|---|---|
| Heap | B | B/2 | | | |
| sorted | B | $\log_2 B$ | | | |
| Clust. | 1.5B | h | | | |
| u-tree | ~B | 1+h' | | | |
| u-hash | ~B | ~2 | | | |

h= height of btree ~ $\log_F (1.5B)$
h' = height of unclustered index btree ~ $\log_F (1.5B)$

## Cost estimation

index – cost?
- levels of index +
- blocks w/ qual. tuples

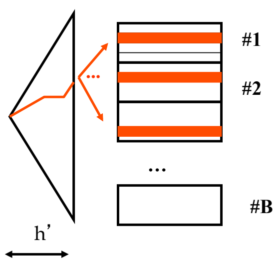
sec. key – clustering index
h + #qual-pages




## Cost estimation

index – cost?
- levels of index +
- blocks w/ qual. tuples

sec. key – non-clust. index
h' + #qual-records
(actually, a bit less...)




## Cost estimation

| | scan | eq | range | ins | del |
|---|---|---|---|---|---|
| Heap | B | B/2 | B | | |
| sorted | B | $\log_2 B$ | <- +m | | |
| Clust. | 1.5B | h | <- +m | | |
| u-tree | ~B | 1+h' | <- +m' | | |
| u-hash | ~B | ~2 | B | | |

m: # of qualifying pages
m' : # of qualifying **records**

## Cost estimation

| | scan | eq | range | ins | del |
|---|---|---|---|---|---|
| Heap | B | B/2 | B | 2 | Search+1 |
| sorted | B | $log_2B$ | <- +m | Search+B | Search+B |
| Clust. | 1.5B | h | <- +m | Search+1 | Search+1 |
| u-tree | ~B | 1+h' | <- +m' | Search+2 | Search+2 |
| u-hash | ~B | ~2 | B | Search+2 | Search+2 |

## Cost estimation - big-O notation:

| | scan | eq | range | ins | del |
|---|---|---|---|---|---|
| Heap | B | B | B | 2 | B |
| sorted | B | $log_2B$ | $log_2B$ | B | B |
| Clust. | B | $log_FB$ | $log_FB$ | $log_FB$ | $log_FB$ |
| u-tree | B | $log_FB$ | $log_FB$ | $log_FB$ | $log_FB$ |
| u-hash | B | 1 | B | 1 | 1 |

## Index specification in SQL:1999

```
CREATE INDEX IndAgeRating ON Students
    WITH STRUCTURE=BTREE,
    KEY = (age, gpa)
```

## Summary

- To speed up selection queries: **index**.
- Terminology:
  - Clustered / non-clustered index
    - Clustered = sparse = alt#1
  - primary / secondary index
- Typically, B-tree index
- hashing is only good for equality search
- At most one clustered index per table
  - many non-clustered ones are possible
  - composite indexes are possible