# CptS 451- Introduction to Database Systems

## Storage and Indexing

(DMS Ch-9.5-9.7 and Ch-8)

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WASHINGTON STATE UNIVERSITY
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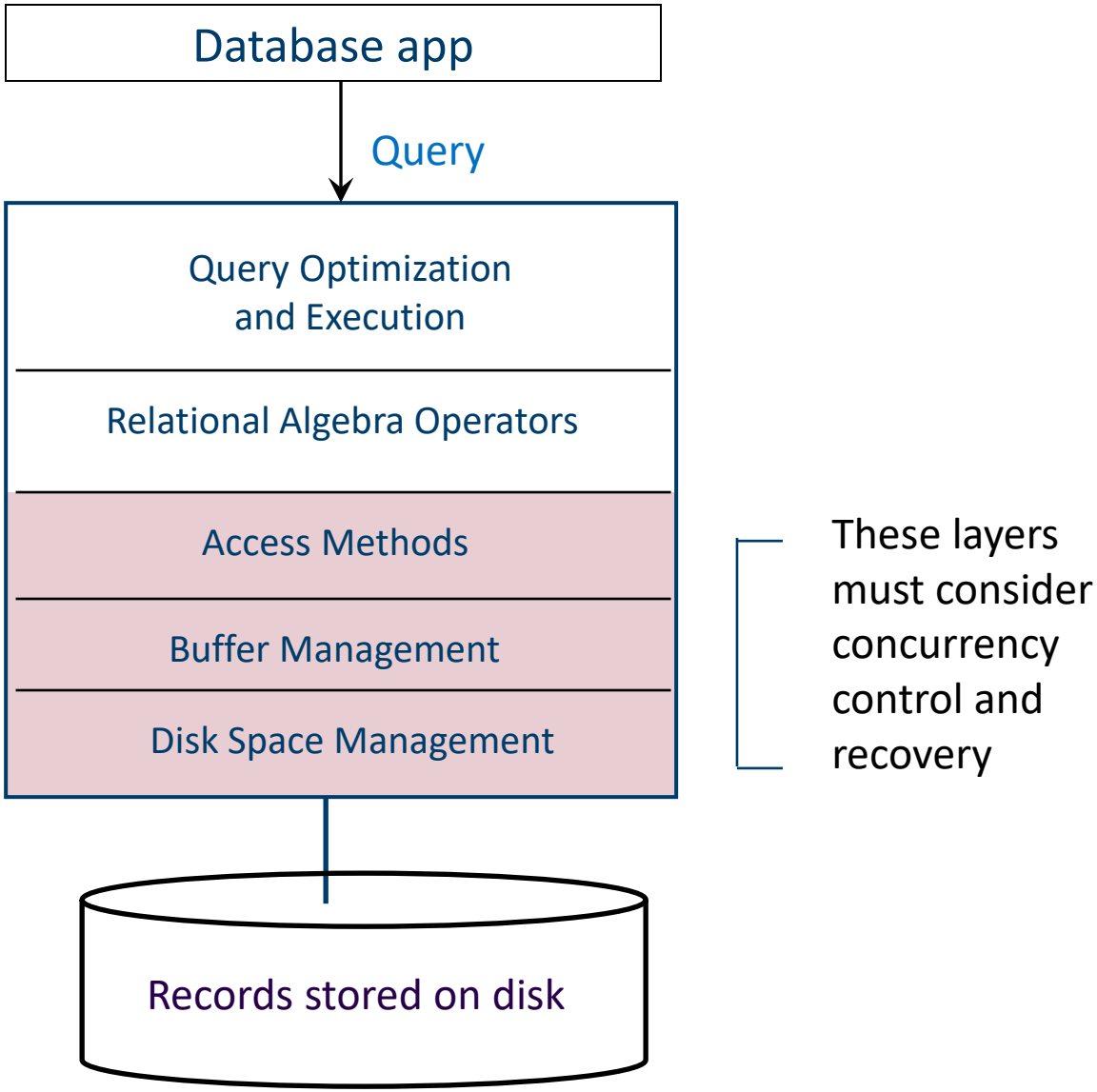
# Storage and Indexing (topics)


- DBMS Architecture Overview
- File Management
- Storage and Indexing

Later:

- Database tuning and choosing indexes

# DBMS Architecture Overview



# Query Optimization and Execution


Query

```
SELECT S. sname
FROM Sailors S, Reserves R
WHERE R.bid=100  AND S.rating>5
      AND S.sid = R.sid;
```

**Step1**

Query Parser

**Step2 and Step3**

Query Optimizer

Plan Generator

Plan Cost Estimator

Catalog Manager

Schema

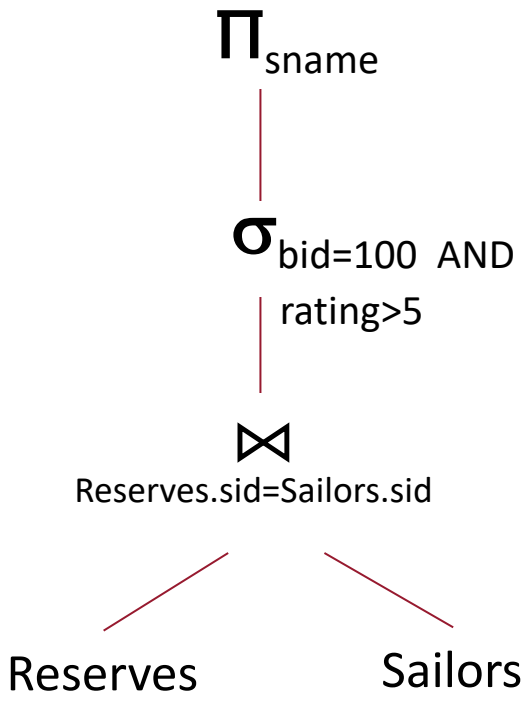
Statistics

**Step4**

Query Plan Evaluator

# Steps in Query Evaluation


- **Step 1: Query parsing**
  - Parse and analyze SQL query
  - Perform various checks using catalog (correctness, authorization, integrity constraints)
  - Translate SQL to a special internal "language" (relational algebra)

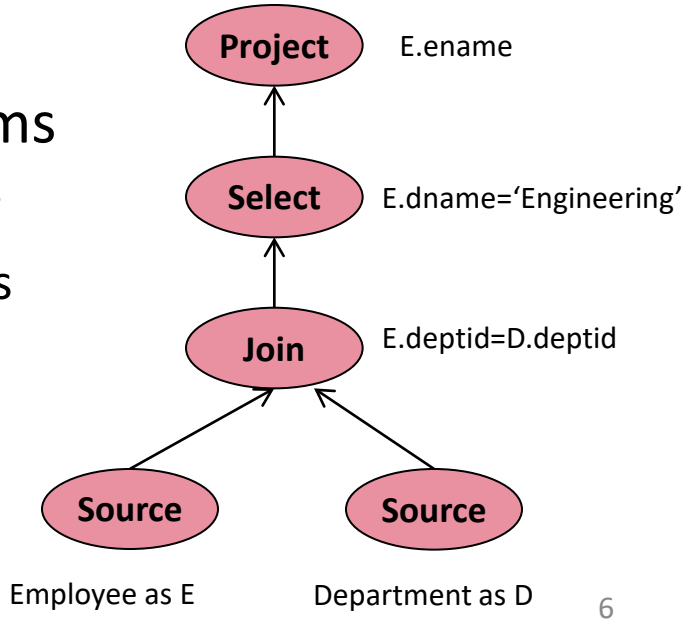



**Step 2: Query rewrite**

- View rewriting, subquery flattening, etc.

# Steps in Query Evaluation (cont.)


- **Step 3: Query optimization**
  - Perform cost-based optimization
  - Goal is to pick a "good" query plan considering
    - Available access paths (indexes)
    - Physical table structures
    - Data statistics (if known)
    - Cost model (for relational operations)
- Think of query plans as dataflow diagrams
  - Each node implements a relational operator
  - Edges represent a flow of tuples (columns as specified)



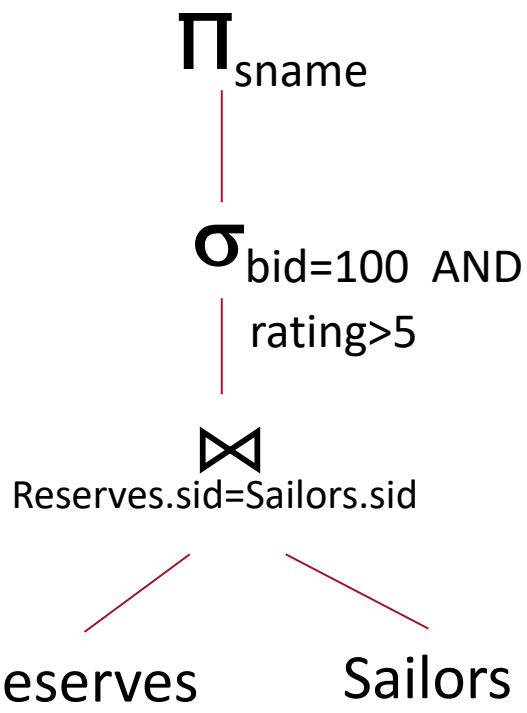

**Step 4: Query Execution**

# Query Plans

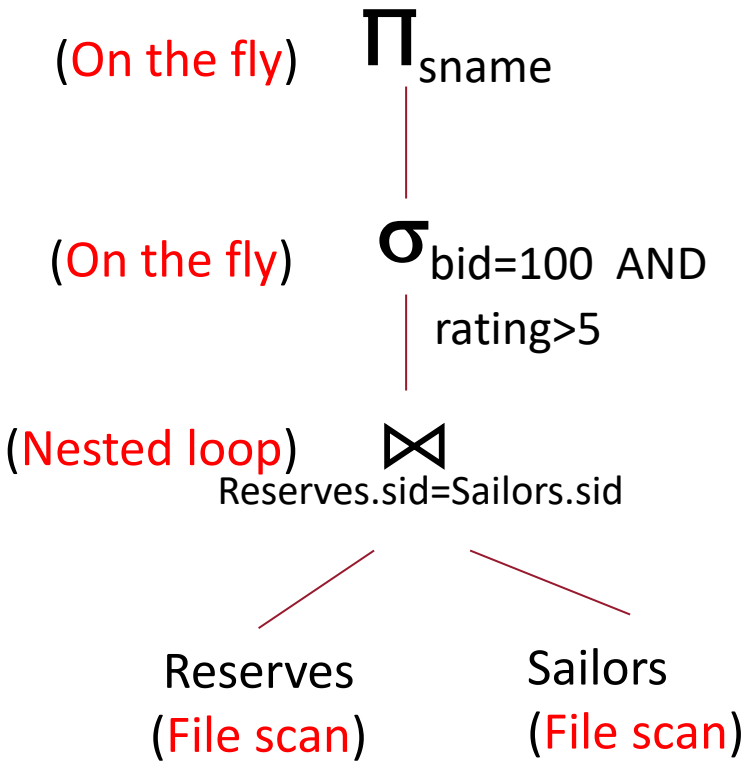
Sailors(***sid***, ***sname***, ***rating***, ***age***)
Reserves (***sid***, ***bid***, ***day***, ***rname***)

```
SELECT S. sname
FROM Sailors S, Reserves R
WHERE R.bid=100  AND S.rating>5
    AND S.sid = R.sid;
```

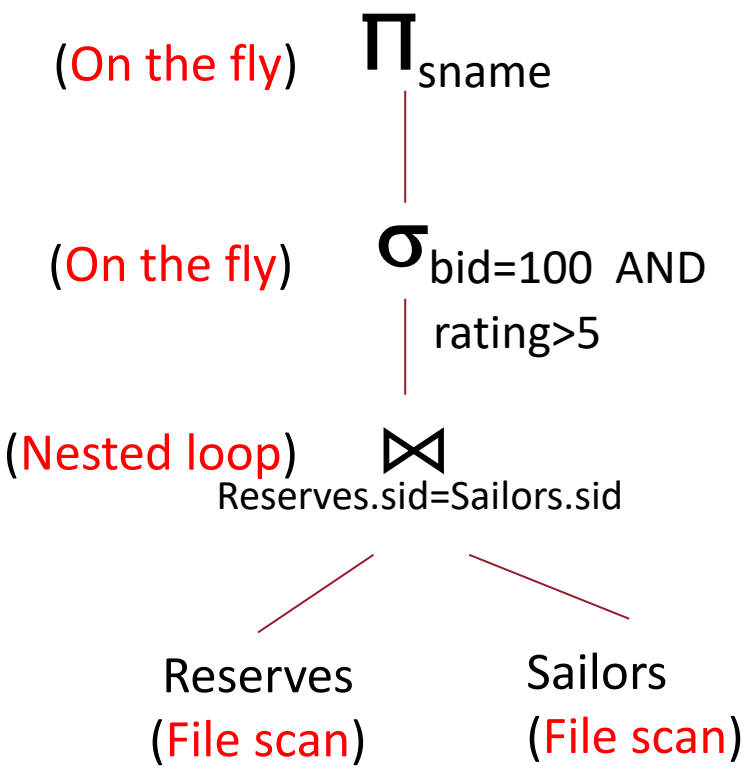
## Logical Query Plan




## Physical Query Plan



# Physical Query Plan




Pipelined execution (On-the-fly): The result of one operator is pipelined to another operator without creating a temporary table to hold intermediate result, called on-the-fly.

Materialized : Otherwise, intermediate results must be materialized

- Logical query plan with extra annotations

**1. Access path selection for each relation**

- Use a file scan or use an index with a predicate
- We will learn these alternatives in the new few lectures

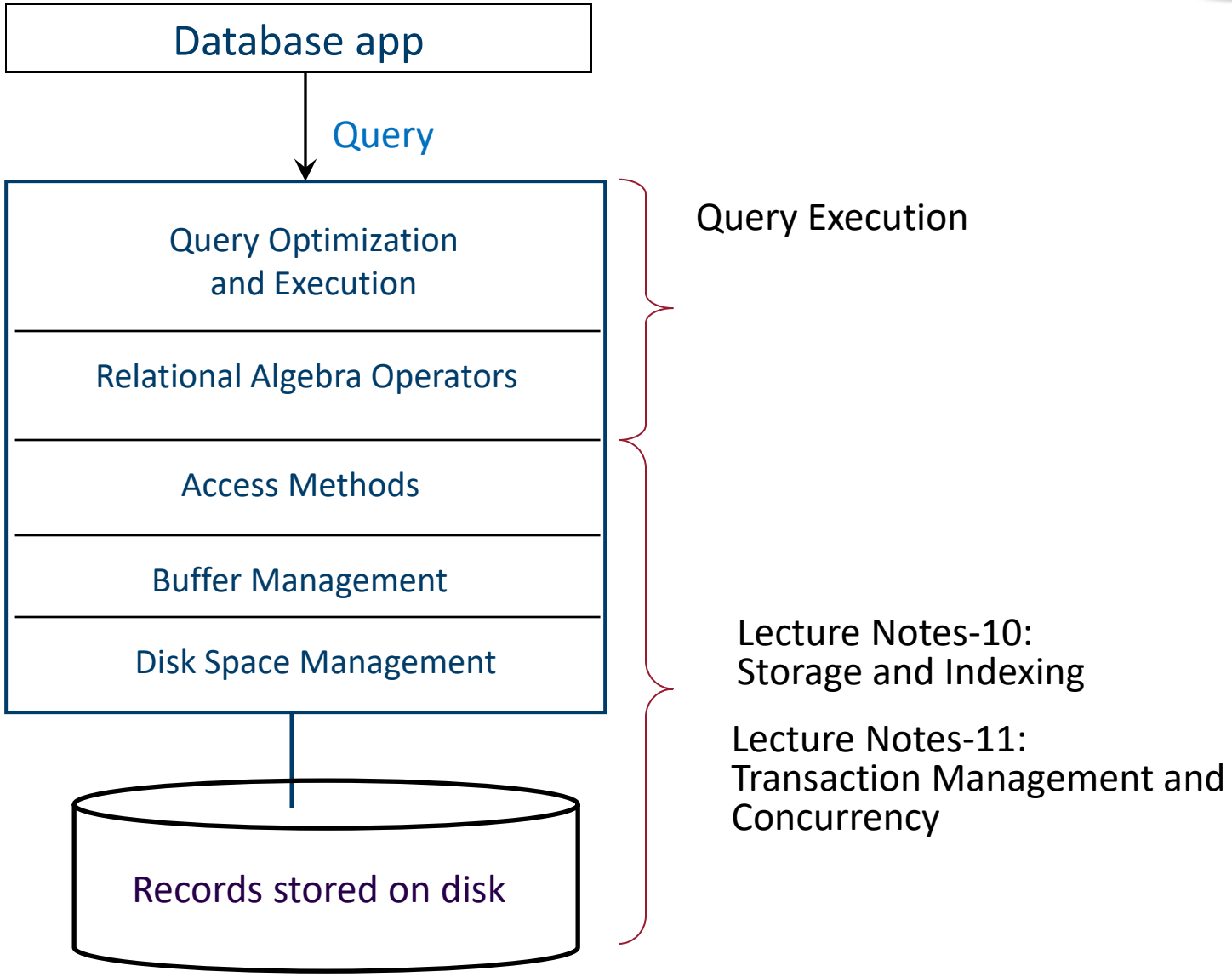
**2. Implementation choice for each operator**

- We will review the operator algorithms later

**3. Scheduling decisions for operators**

- Iterator interface with,
  - pipelined execution, or
  - intermediate result materialization

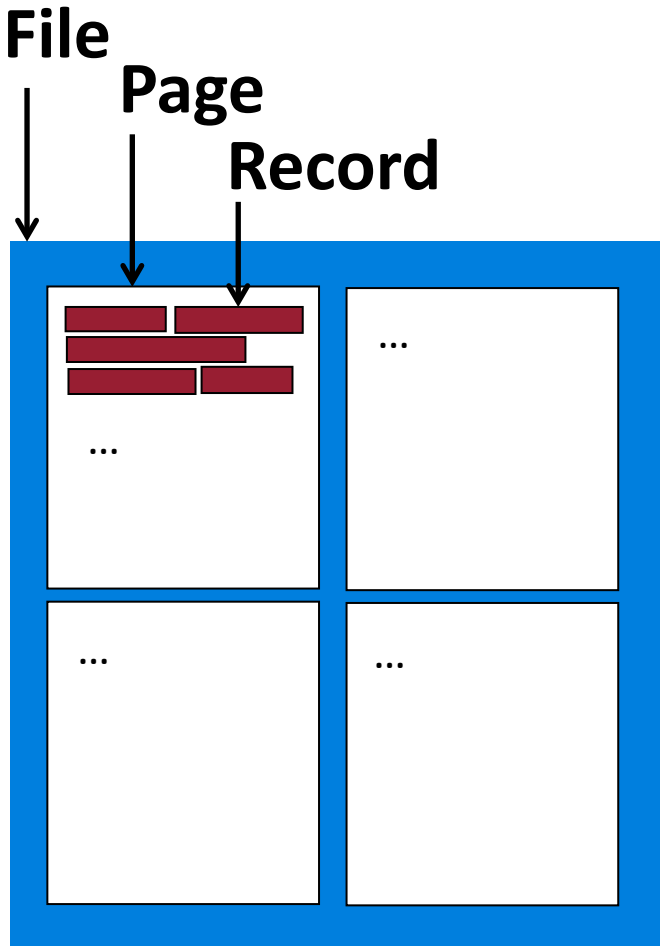
# Where are we?


Database app
Query
Query Optimization and Execution
Relational Algebra Operators
Access Methods
Buffer Management
Disk Space Management
Records stored on disk
Query Execution
Lecture Notes-10: Storage and Indexing
Lecture Notes-11: Transaction Management and Concurrency


# File and Disk Management

# Data Storage

- How is data of a relation stored on disk?




**FILE:** A collection of pages, each containing a number of records. The File API must support:

- **insert**/**delete**/**modify** record (specified by *record id*)
- **fetch** a particular record (specified by *record id*)
- **scan** all records (possibly with some conditions on the records to be retrieved)

**PAGE:** Fixed number of bytes

**RECORD:** Variable or fixed size (depends on schema)

**Typically**:

file page size = disk block size = buffer frame size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# Records

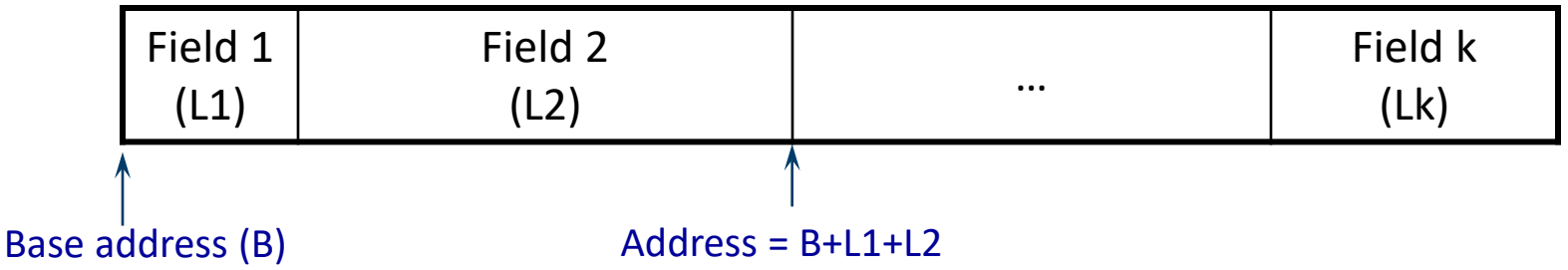

- Records represent tuples of a relation
- Records are stored in pages
- When a record need to be accessed or updated, the entire page (disk block) that the record is stored need to be moved into main memory.

- Record id = RID
  - Typically RID = (pageID, slot#)

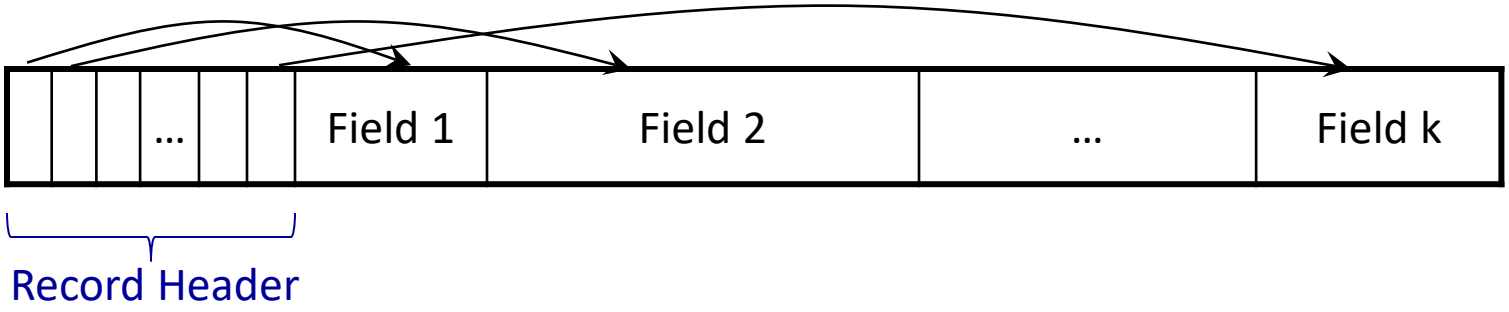
- Records:
  - Fixed length
  - Variable length

# Record Formats

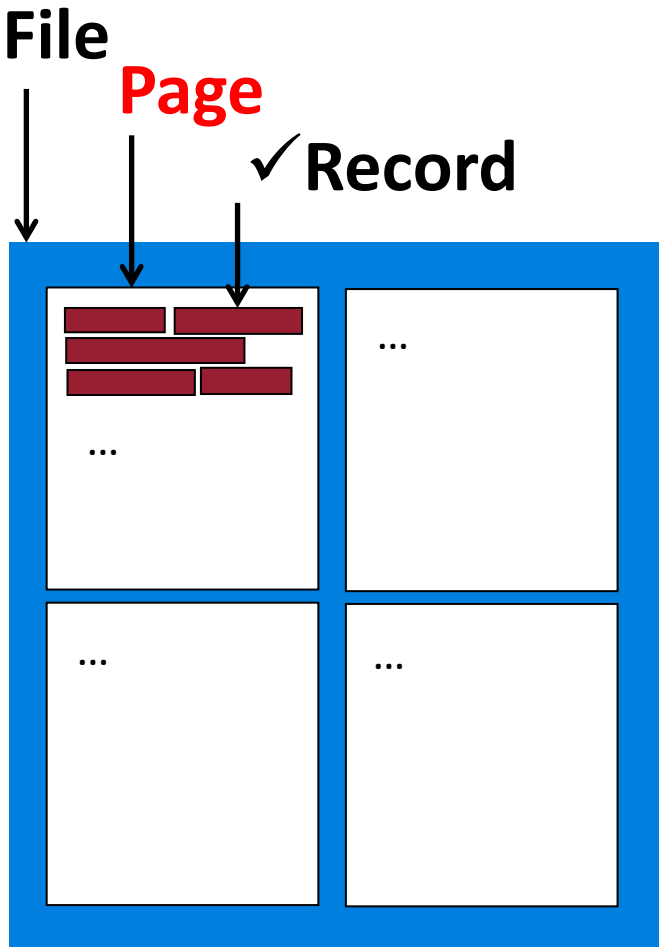
- Fixed-length records → Each field has the same length in all the records)




- Variable length records
  - Remarks: NULLS require no space at all; there is some directory overhead

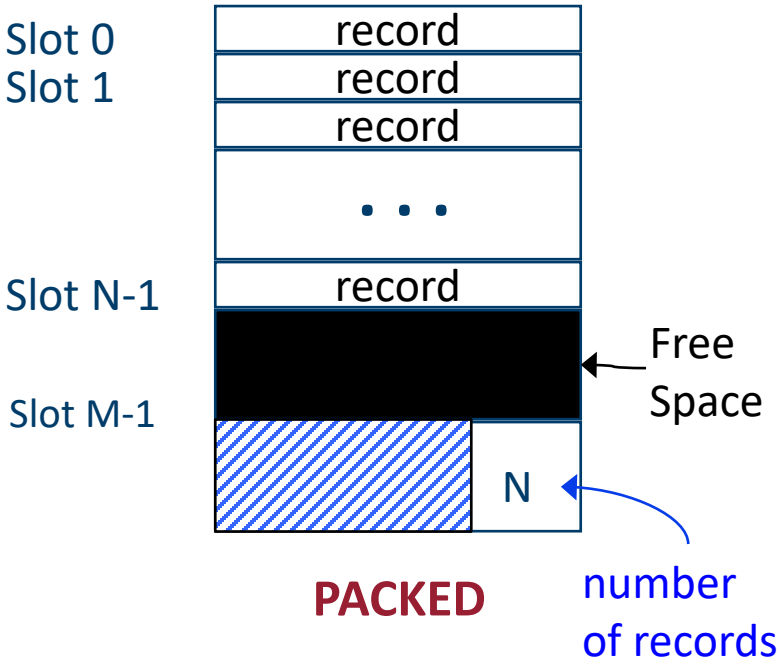


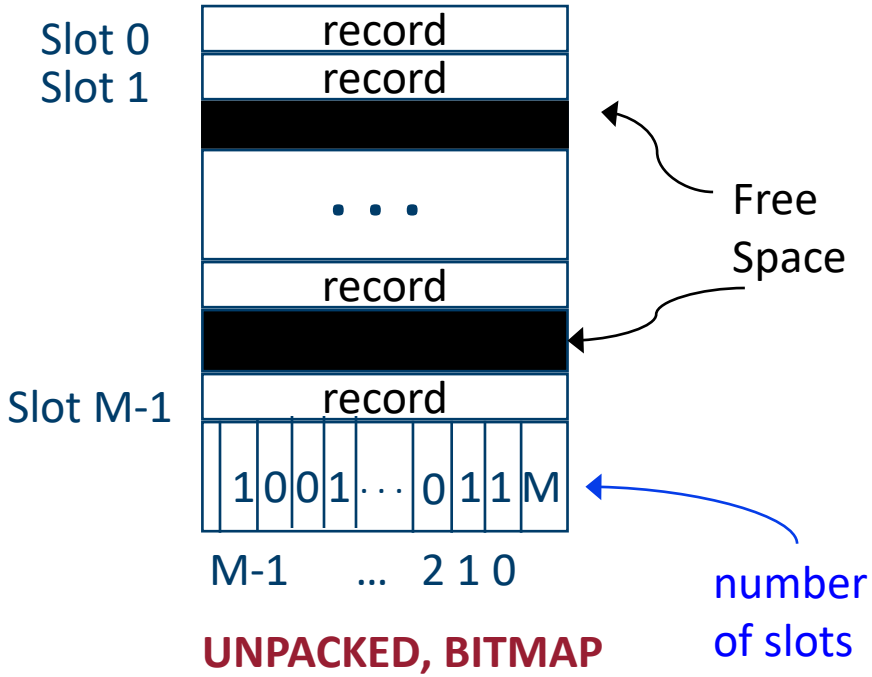
# Data Storage




- **Next**: Page Formats

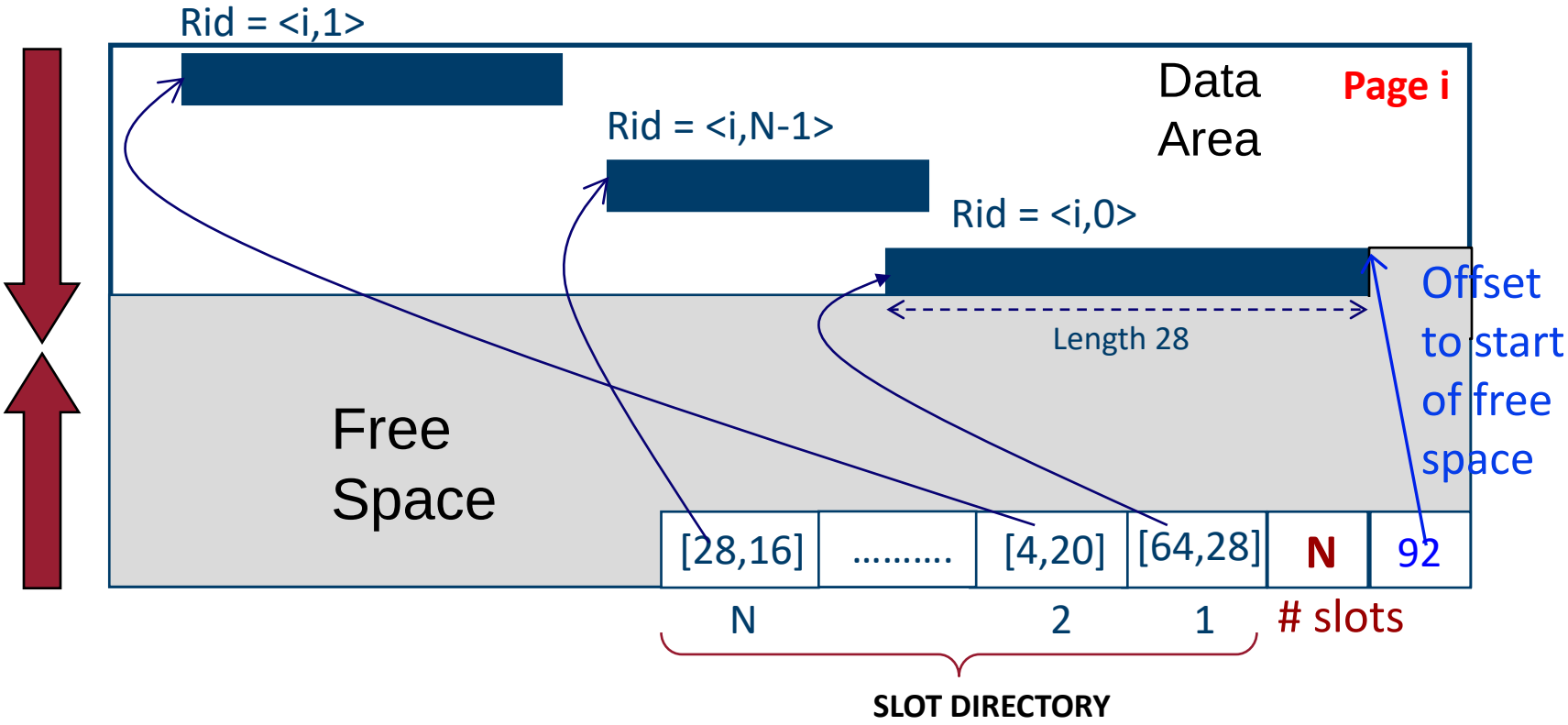
# Page Formats: Fixed Length Records




- A page is a collection of slots, each containing a record.
- In first alternative (left), free space management requires record movement.
  - *Changes RIDs - may not be acceptable.*

# Page Formats: Variable Length Records - "Slotted Page"

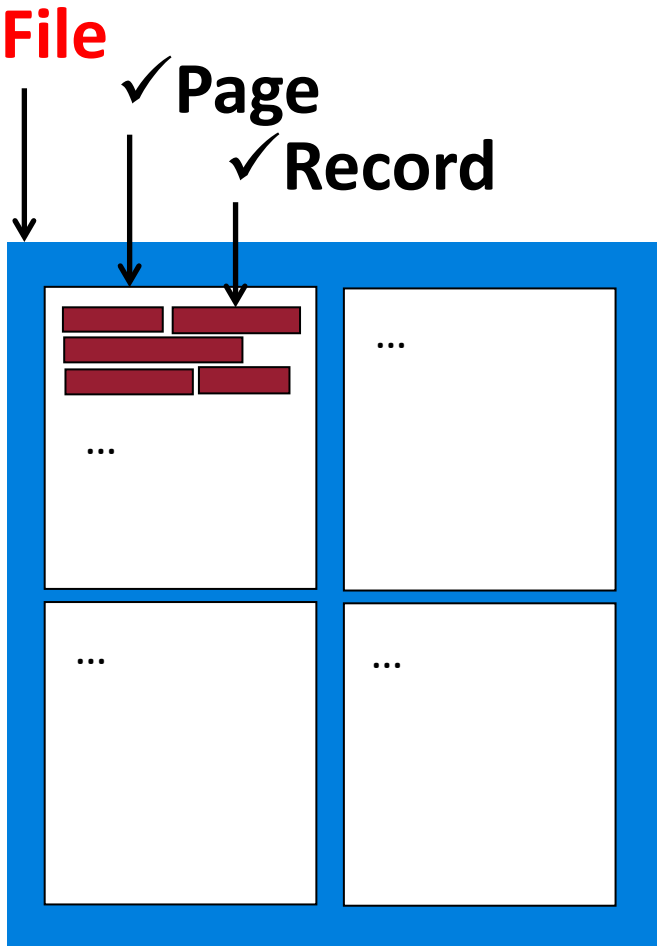



- Slot contains: [*offset* (from start of page), *length*]
  - both in bytes
- *Record id = <page id, slot #>*
- Page is full when data space and slot array meet.

# So far we've organized:

- Fields into Records
  (fixed and variable length)
- Records into Pages
  (fixed and variable length)

Now we need to organize
Records and Pages into Files



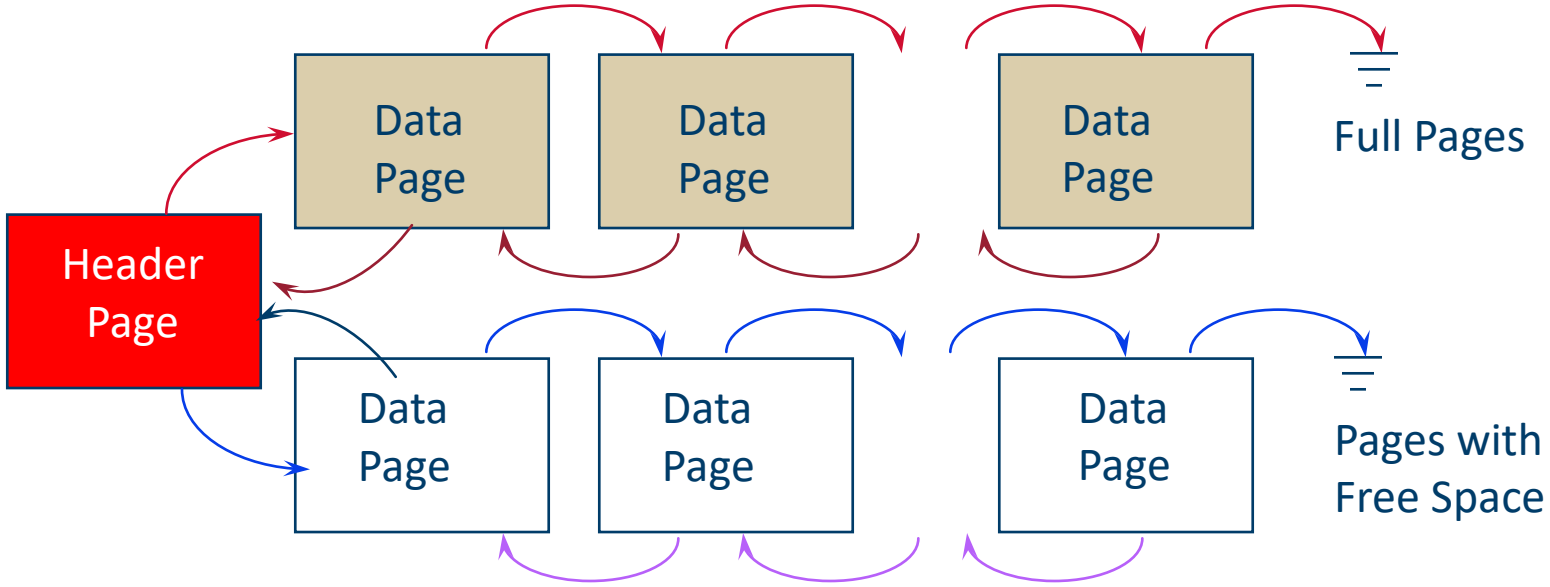
# Alternative File Organizations


- Many alternatives exist, each good for some situations, and not so good in others:
  - **Heap files:** Unordered. Fine for file scan retrieving all records. Easy to maintain.
  - **Sorted Files:** Best for retrieval in *search key* order, or if only a `range' of records is needed. Expensive to maintain.
  - **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.

# Unordered (Heap) Files

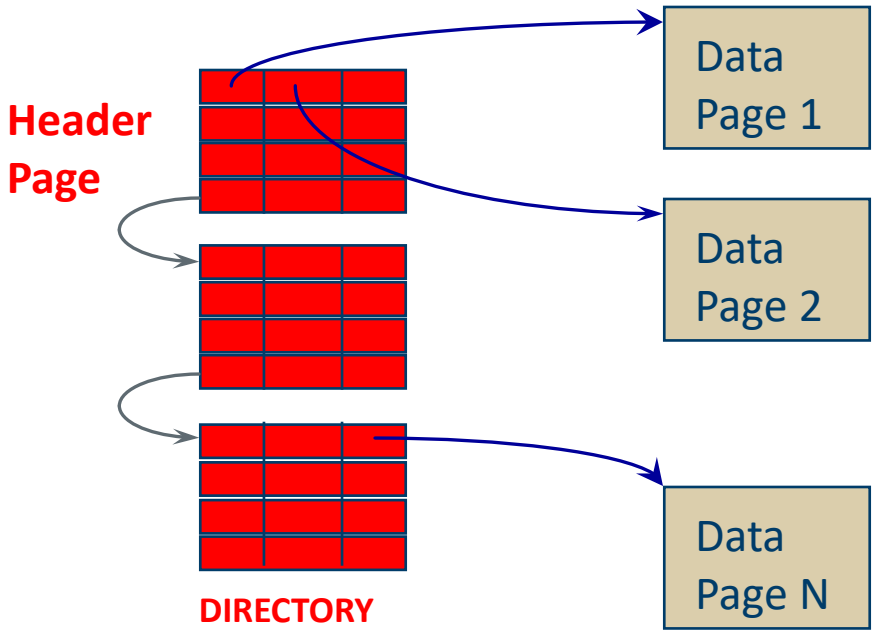

- Simplest file structure contains records in no particular order.
- As file grows and shrinks, pages are allocated and de-allocated.
- To support record level operations, we must:
  - keep track of the *pages* in a file
  - keep track of *free space* on pages
  - keep track of the *records* on a page
- Can organize pages as a list, as a directory, etc…

# Heap File Implemented as a List




- The Heap file name and header page id must be stored persistently. (*<heap_file_name, header_page_addr>*)
  - The catalog is a good place for this.
- Each page contains 2 `pointers' plus data.
- Q: drawback?

# Heap File Using a Page Directory




- Directory is a collection of pages; linked list implementation is just one alternative.
- Directory may contain **free-space count for each page.**
  - Faster inserts for variable-length records
- **Q: How to find a particular record in a Heap file???**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# Cost Model for Analysis


- Average-case analysis; based on several simplistic assumptions.
- We ignore CPU costs, for simplicity:

  **D:** The average time to read or write a disk page (initially we will ignore D)

  **B:** The number of pages (data blocks)

  **R:** Number of records per block

- Initially, we simply count number of disk block I/O's
  - ignores gains of pre-fetching and sequential access; thus, even I/O cost is only loosely approximated.

 ***Good enough to show some overall trends!***

# Operations to Compare


- **Scan**: Fetch all records from disk
- **Equality search**: Fetch the pages that contain qualifying records from disk.
- **Range selection**: Fetch the pages that contain the records that satisfy a range selection.
- **Insert a record**: Identify the page where record should be inserted, fetch that page, modify it, write back to disk.
- **Delete a record**

# Some Assumptions in the Analysis


- Single record insert and delete.
- Equality selection on key - exactly one match (what if more or less???).
- For Heap Files we'll assume:
  - Insert always appends to end of file.
  - Delete just leaves free space in the page.
  - Empty pages are not de-allocated.
  - If using directory implementation assume directory is in-memory.

# Average Case I/O Counts for Operations (B = # of pages in file)


| | Scan all records | Equality Search (avg) (1 match) | Range Search | Insert | Delete |
|---|---|---|---|---|---|
| Heap File | | | | | |
| Sorted File | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

# Searching in a Heap File


- File is not sorted on any attribute
- Consider relation:

```
Student(sid: int, name: varchar(20), age: int, …)
```

| | | | |
|---|---|---|---|
| 1111 | Jack | 18 | … |
| 2222 | Mary | 21 | … |
| 1122 | Joe | 19 | … |
| 2221 | John | 20 | … |
| 3333 | Mike | 21 | … |
| 1113 | Tom | 21 | … |
| 3331 | Jill | 18 | … |
| 2223 | Joy | 19 | … |
| 1110 | Sue | 22 | … |
| 4440 | Sam | 18 | … |

1 record

1 page

….

| | | | |
|---|---|---|---|
| 5550 | Tom | 19 | … |
| 4444 | Tim | 22 | … |
| 5555 | Kate | 20 | … |
| 6660 | Kelly | 17 | … |
| 7771 | Cole | 22 | … |
| 8881 | Carl | 18 | … |
| | | | |
| | | | |
| | | | |
| | | | |

- 10,000 students
- 10 student records per page
- Total number of pages: 1000 pages

- Find student whose **sid** is 5555
  - Must read on average 500 pages
- Find all students who are between 17 and 20 years old
  - Must read all 1000 pages

# Average Case I/O Counts for Operations (B = # disk blocks in file)


| | Scan all records | Equality Search (avg) (1 match) | Range Search | Insert | Delete |
|---|---|---|---|---|---|
| Heap File | B | 0.5B | B | 2 | 0.5B+1 |
| Sorted File | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

# Sorted Files


- Heap files are lazy on update - you end up paying on searches.

- Sorted files eagerly maintain the file on update.
  - The opposite choice in the trade-off

- Assumptions for sorted file analysis:
  - No gaps allowed, pages fully packed always. Files compacted after deletions.
  - Searches are on sort key field(s).

# Average Case I/O Counts for Operations (B = # disk blocks in file)


| | Scan all records | Equality Search (1 match) | Range Search | Insert | Delete |
|---|---|---|---|---|---|
| **Heap File** | B | 0.5B | B | 2 | 0.5B+1 |
| **Sorted File** | | | | | |
| **Indexes** | | | | | |
| | | | | | |
| | | | | | |

# Searching in a Sorted File


- File is sorted on an attribute, usually on the primary key (ex: sid)

```
Student(sid: int, name: varchar(20), age: int, …)
```

| 1110 | Sue | 22 | … |
|---|---|---|---|
| 1111 | Jack | 18 | … |
| 1113 | Tom | 21 | … |
| 1122 | Joe | 19 | … |
| 2221 | John | 20 | … |
| 2222 | Mary | 21 | … |
| 2223 | Joy | 19 | … |
| 3331 | Jill | 18 | … |
| 3333 | Mike | 21 | … |
| 4440 | Sam | 18 | … |

….

| 5000 | Tim | 22 | … |
|---|---|---|---|
| 5550 | Tom | 19 | … |
| 5555 | Kate | 20 | … |
| 6660 | Kelly | 17 | … |
| 7771 | Cole | 22 | … |
| 8881 | Carl | 18 | … |
| | | | |
| | | | |
| | | | |
| | | | |

- Total number of blocks: 1,000 blocks
- Find student whose **sid** is 5555
  - Could do binary search, read $\log_2(1{,}000) \approx 10$ blocks
- Find all students with sid>5000
- Find all students older than 20
- Note: Sorted files are inefficient for inserts/deletes

# Average Case I/O Counts for Operations (B = # disk blocks in file)


| | Scan all records | Equality Search (1 match) | Range Search | Insert | Delete |
|---|---|---|---|---|---|
| **Heap File** | B | 0.5B | B | 2 | 0.5B+1 |
| **Sorted File** | B | $\log_2 B$ (if on sort key) 0.5B (otherwise) | $\log_2 B$ + (selectivity * B) | $\log_2 B$ + B | $\log_2 B$ + B |
| **Indexes** | | | | | |
| | | | | | |
| | | | | | |

# Average Case I/O Counts for Operations (B = # disk blocks in file, D=avg time to read/write a disk page )


| | Scan all records | Equality Search (1 match) | Range Search | Insert | Delete |
|---|---|---|---|---|---|
| **Heap File** | BD | 0.5BD | BD | 2D | 0.5D(B+1) |
| **Sorted File** | BD | $(\log_2 B)D$ (if on sort key) 0.5BD (otherwise) | $D(\log_2 B + (\text{selectivity} * B))$ | $D(\log_2 B + B)$ | $D(\log_2 B + B)$ |
| **Indexes** | | | | | |
| | | | | | |
| | | | | | |

# File Structure Summary


- File Access layer manages access to records in pages.
  - Record and page formats depend on fixed vs. variable-length.
  - Free space management is an important issue.
- Many alternative file organizations exist, each appropriate in some situation.
  - We looked at Heap and Sorted so far.
  - If selection queries are frequent, sorting the file or building an *index* is important.
- Our cost calculations are imprecise, but can expose fundamental systems tradeoffs.
- **Next up: Indexes**.

# Alternative File Organizations (revisited)


- Many alternatives exist, each good for some situations, and not so good in others:
  - **Heap files:** Unordered. Fine for file scan retrieving all records. Easy to maintain.
  - **Sorted Files:** Best for retrieval in *search key* order, or if only a `range' of records is needed. Expensive to maintain.
  - **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.

# Indexing: Motivation


## How to answer queries on relation Emp?

SELECT * FROM Student WHERE ssn = “111-11-1111”;

SELECT * FROM  Student WHERE age > 30 AND age < 40;

1. Scan file, reading blocks one by one
2. For each tuple in block check condition

- Inefficient if very few tuples satisfy condition!
- The relation may be huge…


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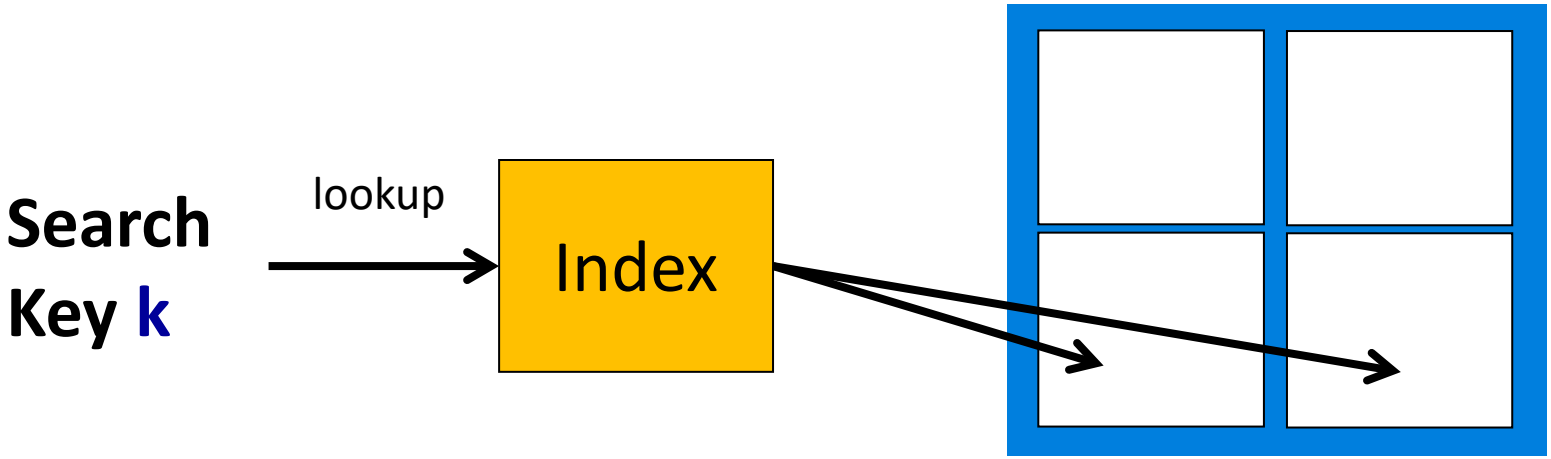
# Indexes


- 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 the ***key*** of the relation.
    (However the indexes are often built on the relation *keys* – why?)

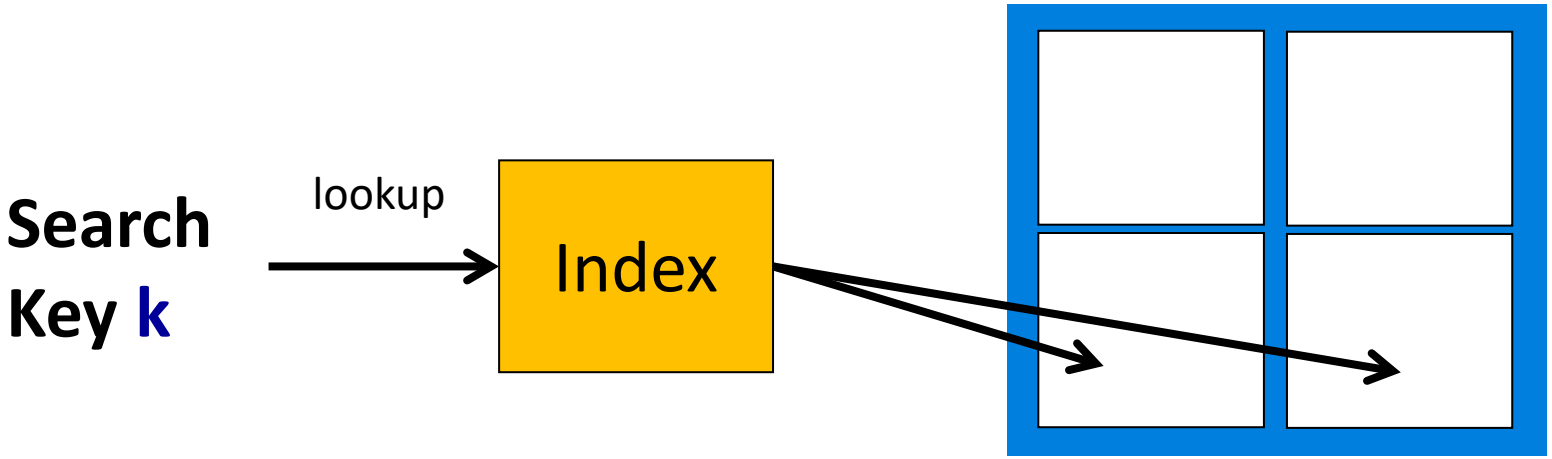


# Indexes

- An index contains a collection of *data entries* (**k***) –usually– of the form:

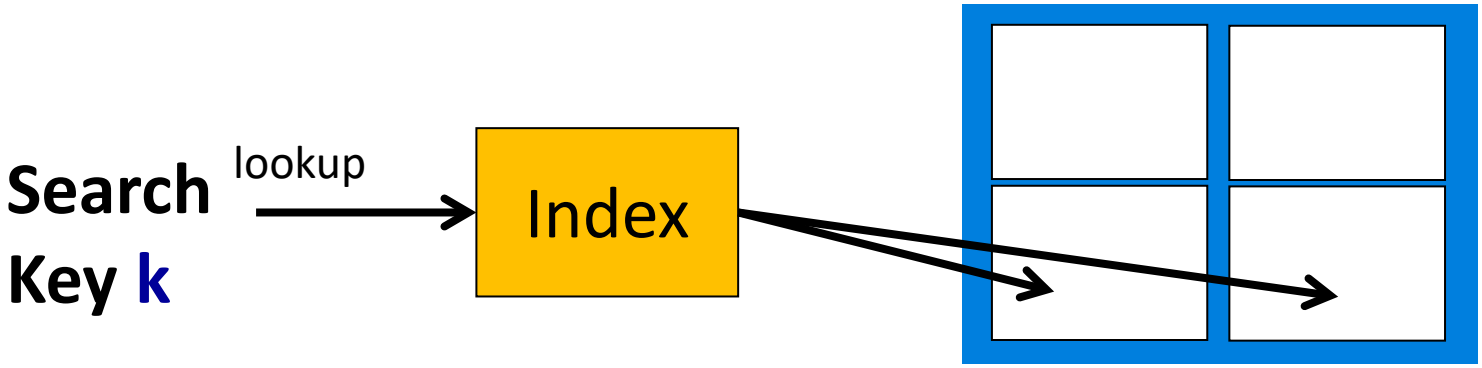
| *search key* | **pointer to rid(s)** |
|---|---|

- It supports efficient retrieval of all data entries **k*** with a given key value **k**.
- Given data entry **k*** in the index, we can find the actual record (with key **k**) in at most one disk I/O.



# Alternatives for Data Entry k* in Index


- In a data entry k* we can store:
  - Data record with key value **k,** or *(alternative 1)*
  - <**k**, *rid* of data record with search key value **k**>, or *(alternative 2)*
  - <**k**, list of rids of data records with search key **k**> *(alternative 3)*
- Choice of alternative for data entries is orthogonal to the indexing technique used to locate data entries with a given key value **k**.

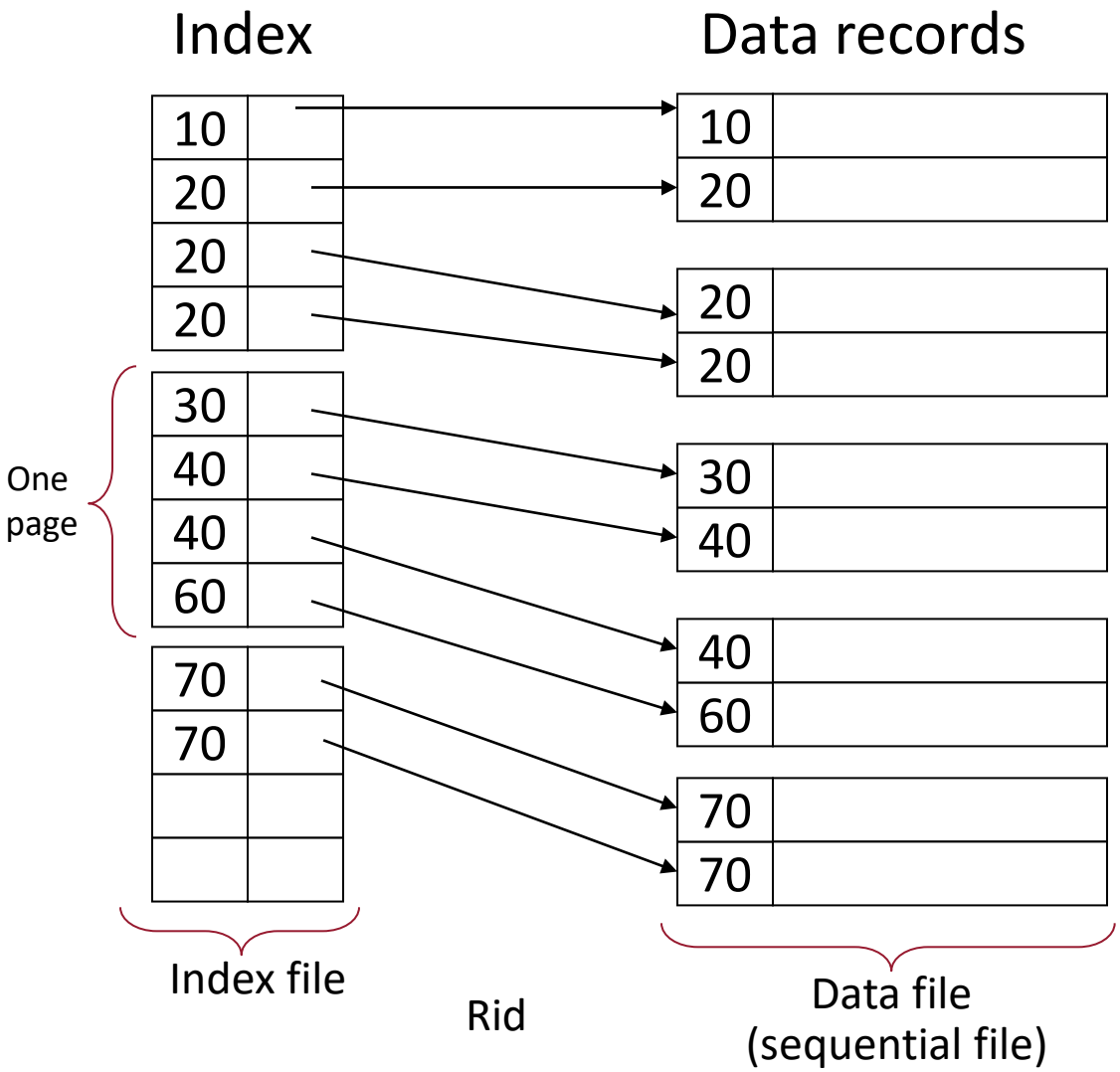


# Alternative2- Example


- Each entry in index is a pair of :

(Search Key, **Rid** Pointer)

- Every record in the data file has an entry in the index
- Index file is **much** smaller than the data file, since we only store the key Rid, not the record content

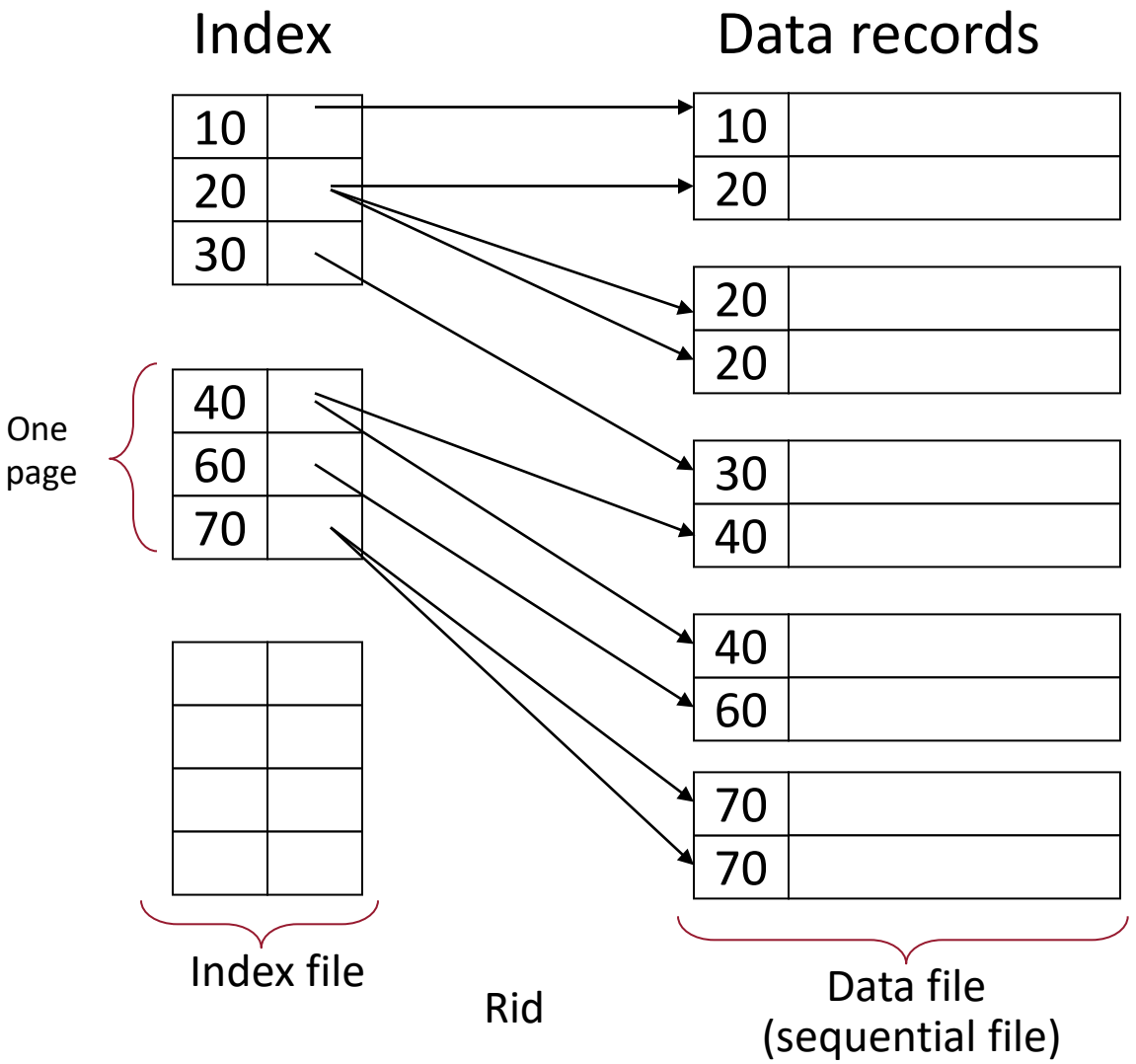


# Alternative3- Example


- Each entry in index is a pair of :

(Search Key, List of **Rid** Pointers)

- Every search key value has an entry in the index
- Index file is **much** smaller than the data file, since we only store the key Rid, not the record content



# Alternatives for Data Entries (Contd.)


- **Alternative 1:**
  - If this is used, index structure is a file organization for data records.
  - At most one index on a given collection of data records can use Alternative 1. (Otherwise, data records are duplicated)
- **Alternatives 2 and 3:**
  - Data entries typically much smaller than data records. So, better than Alternative 1 with large data records, especially if search keys are small.
  - Alternative 3 more compact than Alternative 2, but leads to variable sized data entries even if search keys are of fixed length.

# Index Classification

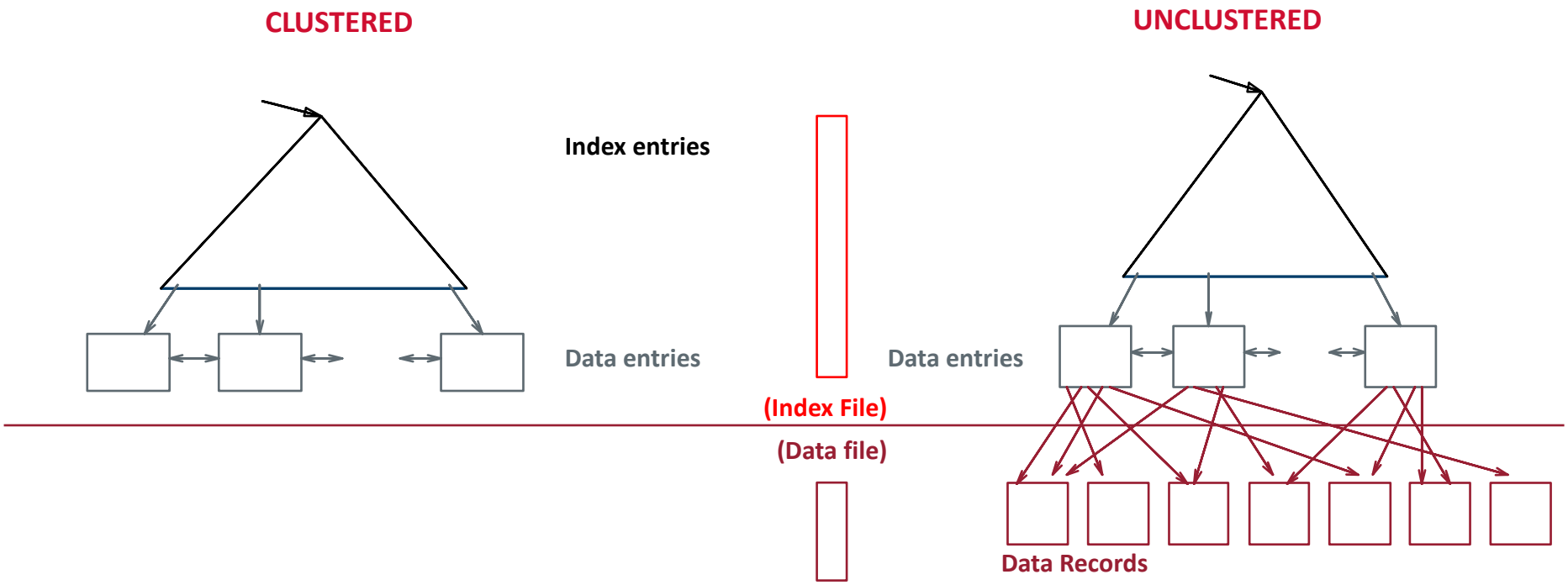

## 1. Primary vs. secondary:

- If search key is the primary key, then called primary index. The index is guaranteed not to have duplicate search key values
- Otherwise called secondary key. May have duplicates.
- ***Unique*** index: A secondary index with no duplicate search keys. (i.e., search key contains a candidate key).

## 2. Clustered vs. unclustered:

- If order of data records is the same as, or `close to', order of data entries, then called clustered index.
  - A file can be clustered on at most one search key.
  - Alternative 1 implies clustered; in practice, clustered also implies Alternative 1 (since sorted files are rare).
  - Cost of retrieving data records through index varies *greatly* based on whether index is clustered or not!
  - How about cost of inserting data records?

# Clustered vs. Unclustered Index

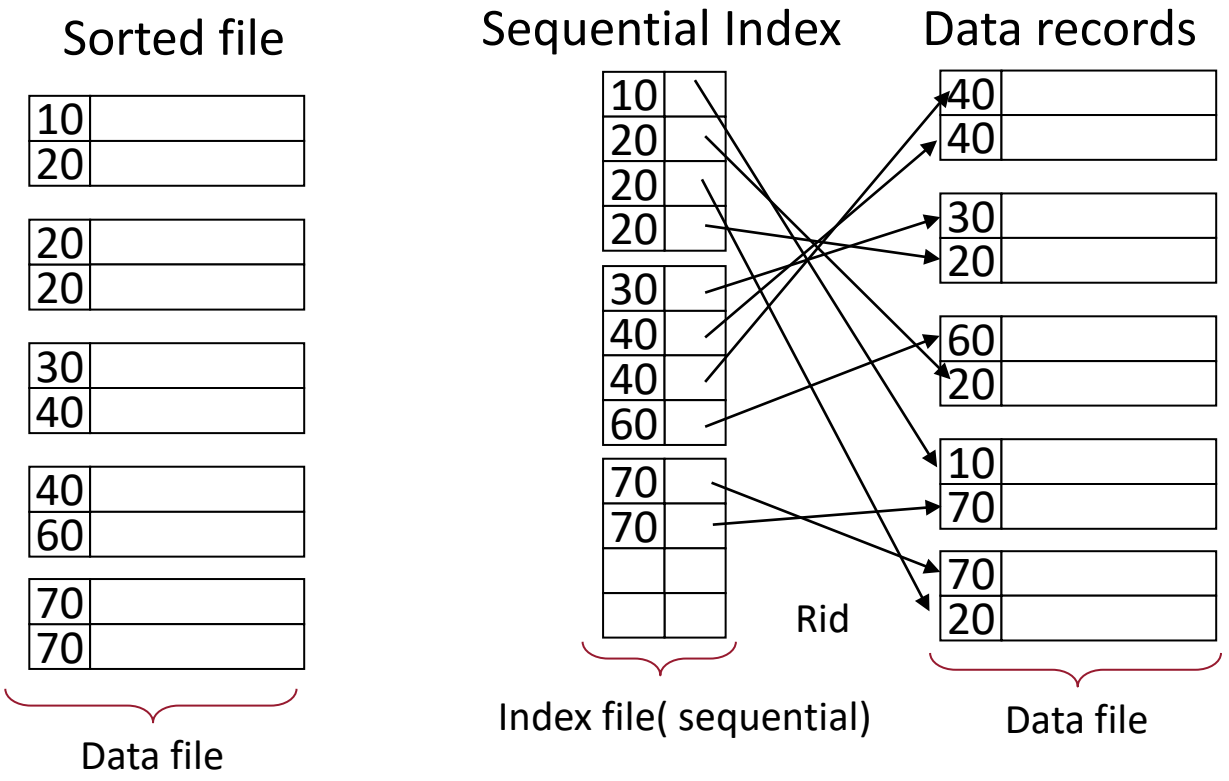



- Clustered = records close in index are close in data
- Generally, in a clustered B+ Tree index data entries are data records

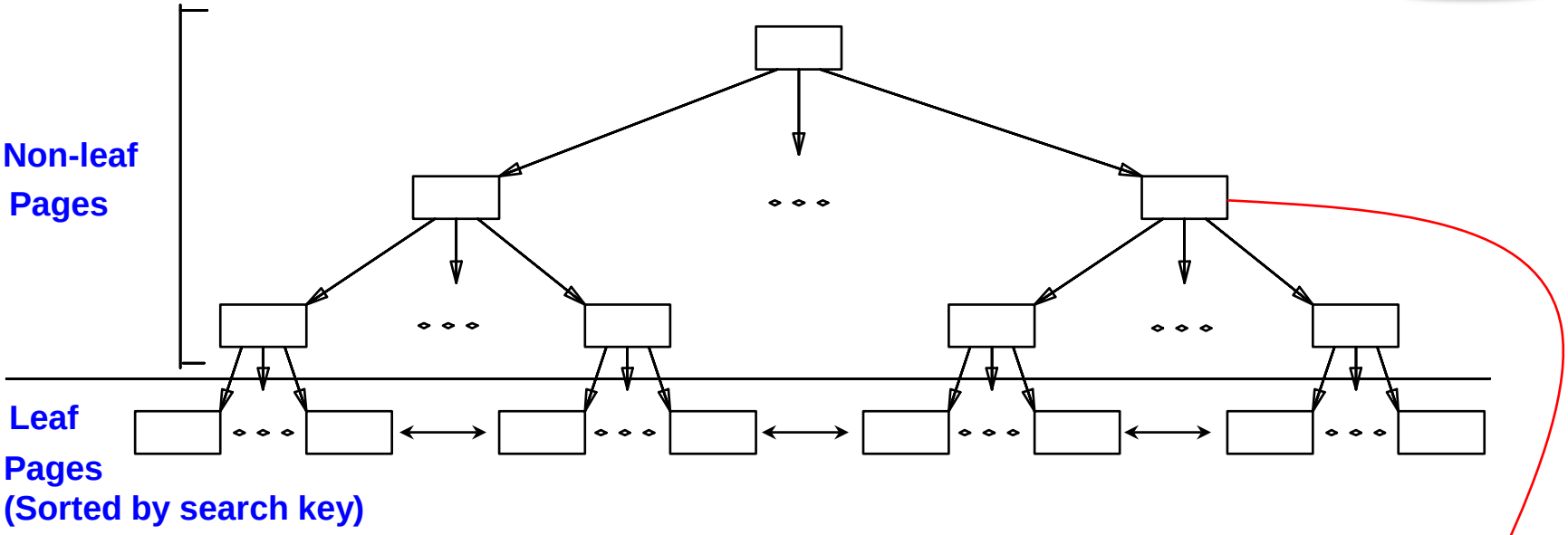
# Large Indexes (sequential)

- Disadvantage of indexed-sequential files
  - Performance degrades as file grows,
  - Maintenance is costly

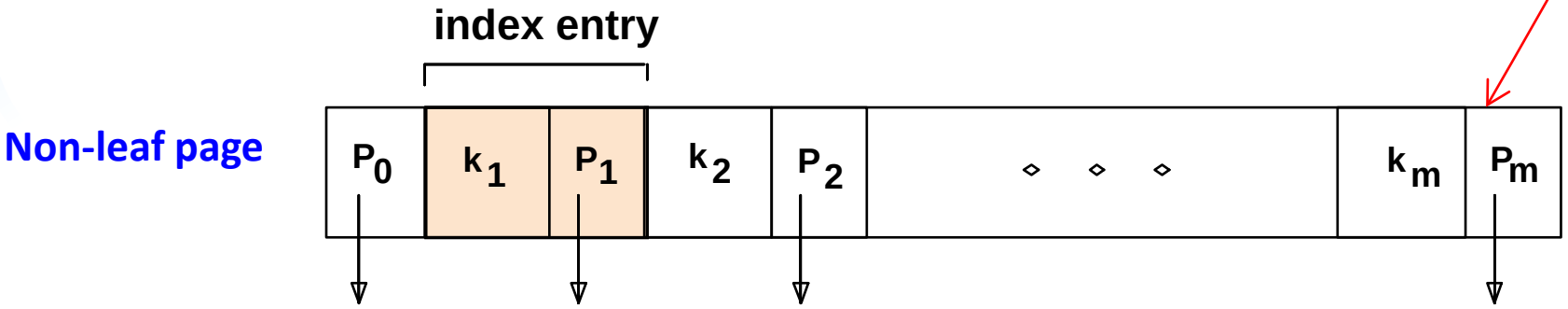
- In DBMS indexes are stored in disk-blocks
- Indexes designed to reside on disk are very different from those designed to be in-memory, due to the access characteristics of disks!
- Would like to index the data entries:
  - Hash-based index
  - Tree-based index



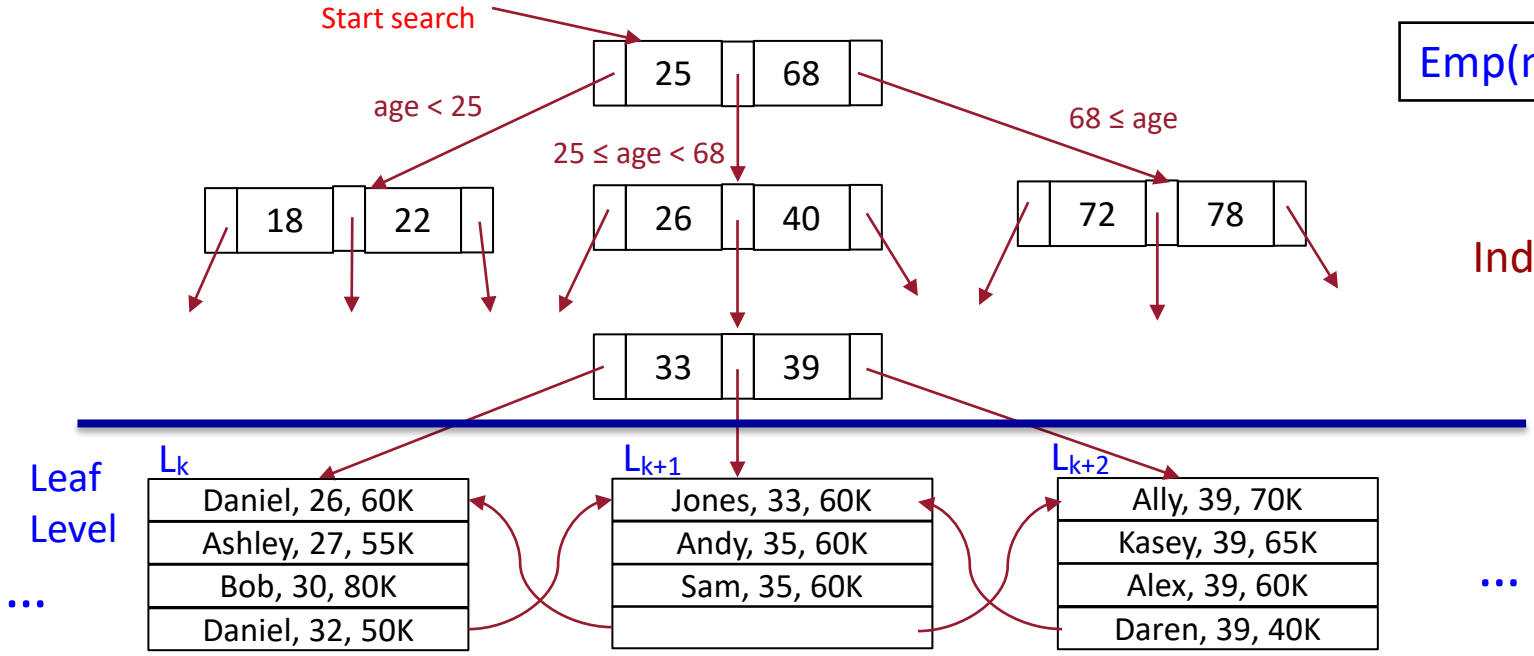
# B+ Tree Indexes




- Leaf pages contain *data entries*, and are chained (prev & next)
- Non-leaf pages contain node pointers separated by search key values.



# Example Clustered B+ Tree



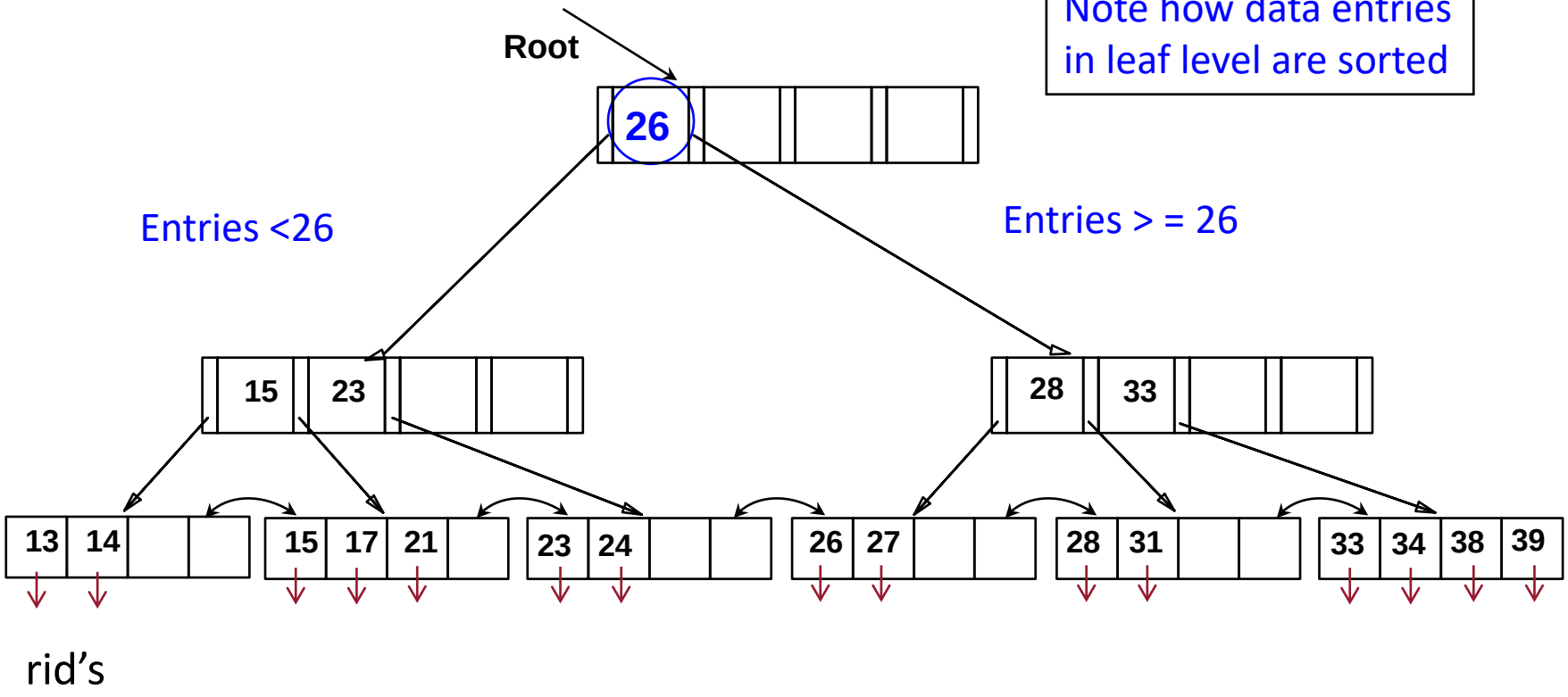

Emp(name, age, sal)

Index search key?

Note how data entries in leaf level are sorted

- Find 35, 39? All > 27 and < 39
- Insert/delete: Find data entry in leaf, then change it. Need to adjust parent sometimes.
  - And change sometimes bubbles up the tree

# Example Unclustered B+ Tree

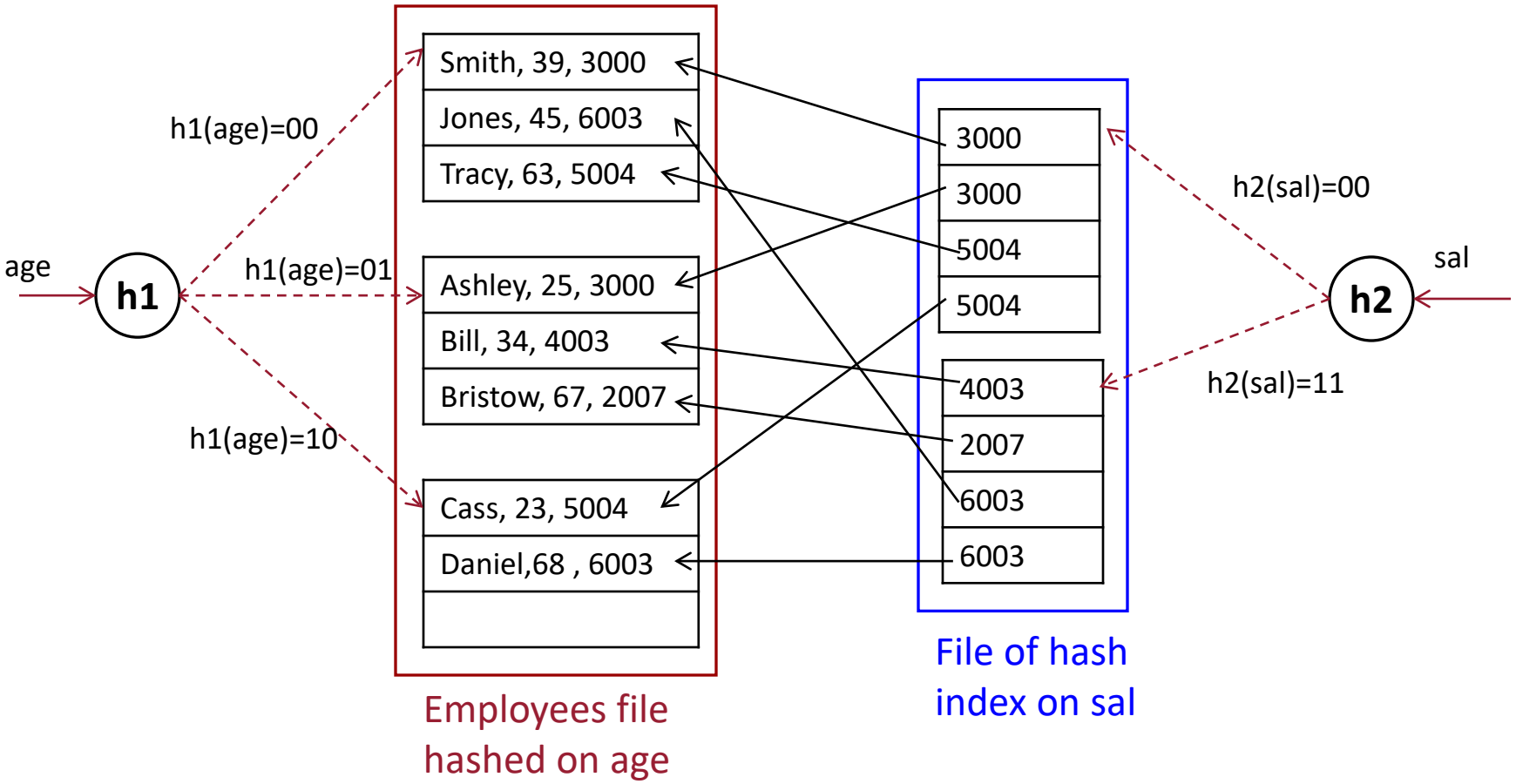



Note how data entries in leaf level are sorted

# 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*.

# Hash-Based Indexes




Clustered hash-index on *age*, with unclustered hash-index on *sal*

# Cost Model for Our Analysis


We ignore CPU costs, for simplicity:

- **B :** The number of data pages
- **D :** (Average) time to read or write disk page
- Average-case analysis; based on several simplistic assumptions.

 *Good enough to show the overall trends!*

# Comparing File Organizations


1. Heap files (random order; insert at eof)
2. Sorted files, sorted on *<age, sal>*
3. Clustered B+ tree file, Alternative (1), search key *<age>*
4. Heap file with unclustered B+ tree index on search key *<age>*
5. Heap file with unclustered hash index on search key *<age>*

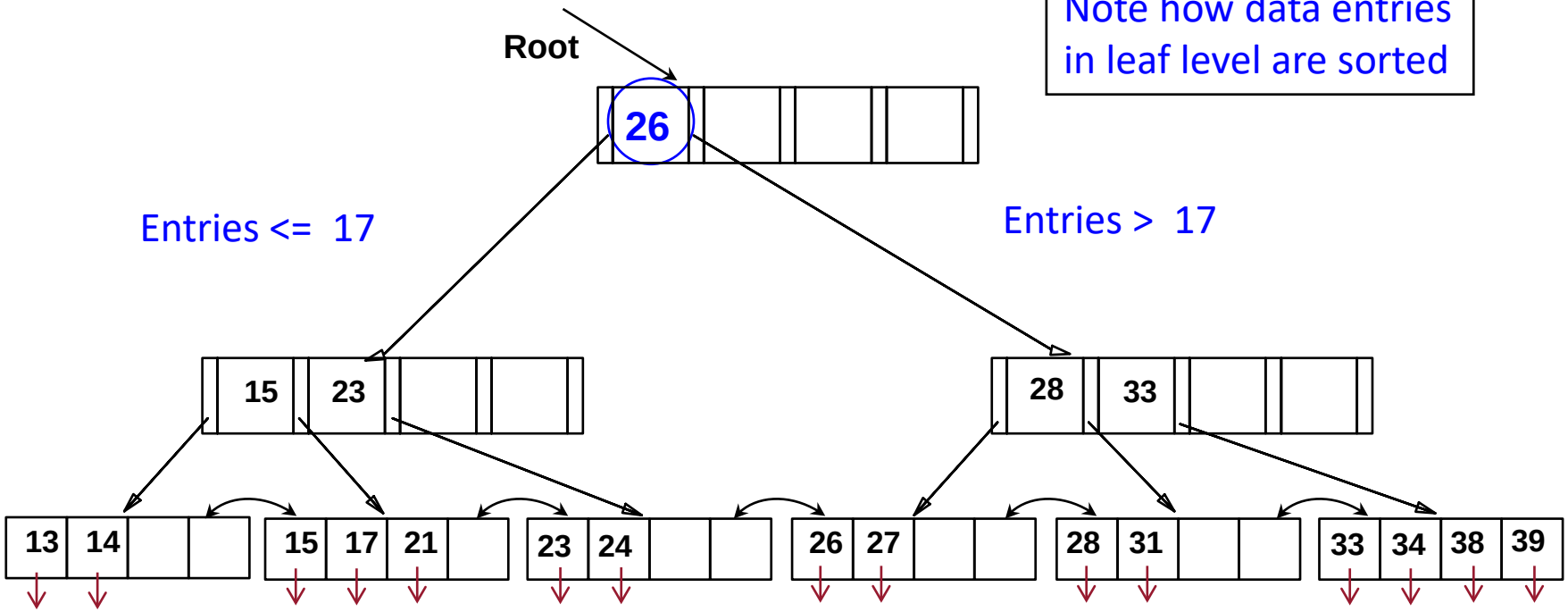
# Operations to Compare


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

# Assumptions in Our Analysis

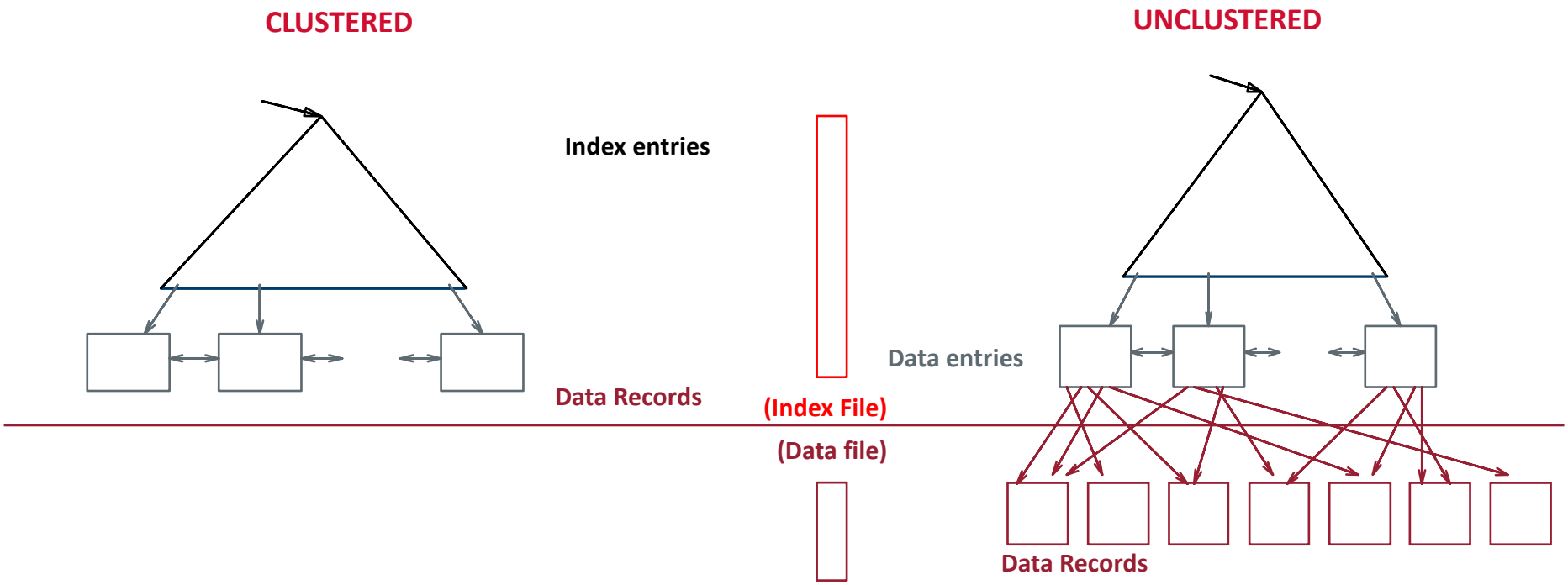

- Heap Files:
  - Equality selection on key; exactly one match.
- Sorted Files:
  - Files compacted after deletions.
- Indexes:
  - Alternative (2),(3): index data entry size = 10% size of record
  - Clustered B+ Tree file: 67% occupancy (this is typical).
    - Implies file size = 1.5 data size
  - Unclustered B+ Tree: 67% occupancy of index pages
    - Implies index size = 1.5*0.1*data size (since index data entry size is 10% size of record )
  - B+ Tree: fan-out is F
  - B+ Tree: Assume we can directly access the first leaf page
  - Hash: No overflow buckets.
    - 80% page occupancy => File size = 1.25 data size
- 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.

# Example Unclustered B+ Tree




Note how data entries in leaf level are sorted

# Clustered vs. Unclustered Index




Clustered = records close in index are close in data

# Cost of Operations


| | (a) Scan | (b) Equality | (c) Range | (d) Insert | (e) Delete |
|---|---|---|---|---|---|
| (1) Heap | BD | 0.5BD | BD | 2D | Search +D |
| (2) Sorted | BD | $D\log_2 B$ | $D(\log_2 B +$ # pgs with match recs) | Search + BD | Search + BD |
| (3) Clustered B+ tree file | | | | | |
| 4) Unclustered B+ tree index | | | | | |
| 4) Unclustered Hash index | | | | | |

 *Several assumptions underlie these (rough) estimates!*

# Cost of Operations


| | (a) Scan | (b) Equality Search | (c) Range | (d) Insert | (e) Delete |
|---|---|---|---|---|---|
| (1) Heap | BD | 0.5BD | BD | 2D | Search +D |
| (2) Sorted | BD | $D\log_2 B$ | $D(\log_2 B +$ # matching pages$)$ | Search+ BD | Search + BD |
| (3) Clustered B+ tree file | 1.5BD (sorted) | $D\log_F 1.5B$ | $D(\log_F 1.5B$ + # matching pages$)$ | Search +D | Search +D |
| 4) Unclustered B+ Tree index | | | | | |
| 4) Unclustered Hash index | | | | | |

** Don't use index.* ***Includes cost of sorting*

****Search time also includes the time to fetch data block*

*Several assumptions underlie these (rough) estimates!*

# Cost of Operations


| | (a) Scan | (b) Equality Search | (c) Range | (d) Insert | (e) Delete |
|---|---|---|---|---|---|
| (1) Heap | BD | 0.5BD | BD | 2D | Search +D |
| (2) Sorted | BD | $D\log_2 B$ | $D(\log_2 B$ + # matching pages) | Search+ BD | Search + BD |
| (3) Clustered B+ tree file | 1.5BD (sorted) | $D\log_F 1.5B$ | $D(\log_F 1.5B$ + # matching pages) | Search +D | Search +D |
| 4) Unclustered B+ Tree index | BD* (unsorted) 4BD** (sorted) | $D(\log_F 0.15B+1)$ | $D(\log_F 0.15B$ + # matching records) | Search*** +2D | Search*** +2D |
| 4) Unclustered Hash index | BD* (unsorted) 4BD** (sorted) | 2D | BD* | Search*** +2D | Search*** +2D |

* *Don't use index.* ***Includes cost of sorting*

****Search time also includes the time to fetch data block*

 *Several assumptions underlie these (rough) estimates!*

# Indexes in SQL (review)

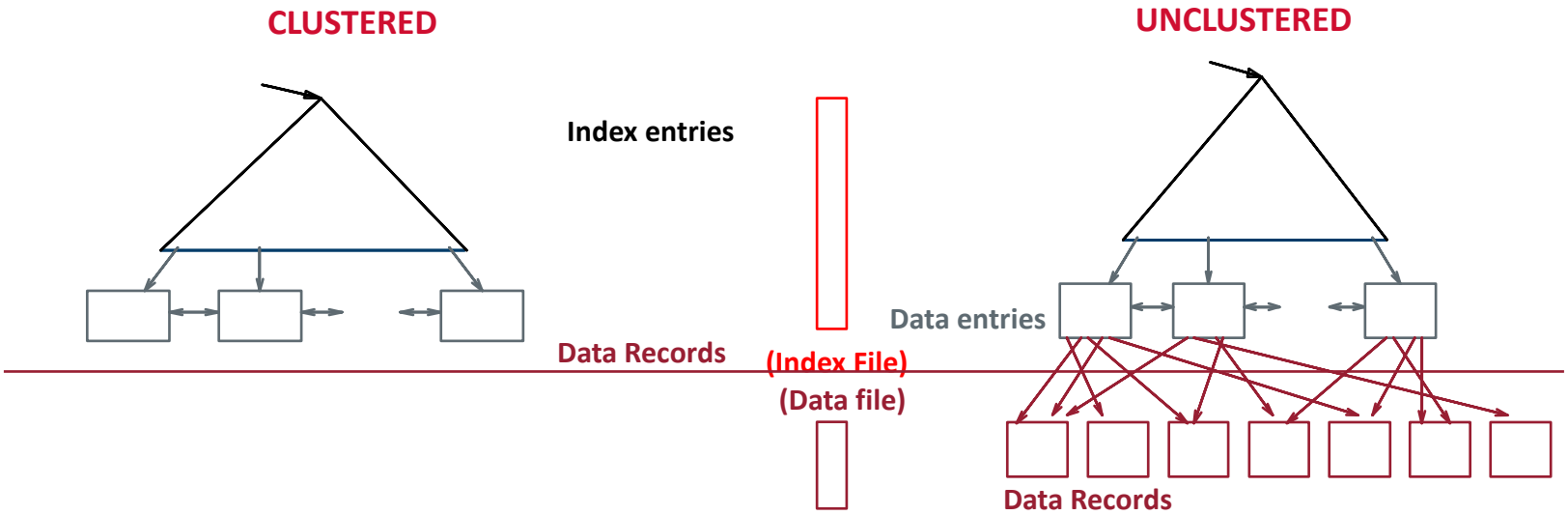

- **Create an index**
  - Syntax:
    CREATE INDEX <index_name> ON <table_name>(<col1, col2,…>);
  - Example:
    CREATE INDEX sal_index ON emp(sal);
- **Drop an index**
  - Syntax:
    DROP INDEX <index-name>;
  - Example:
    DROP INDEX sal_index;
- **Unique index**
  - Syntax: CREATE UNIQUE INDEX <index_name> ON <table_name>(<cols>);
  - Semantics: <cols> are constrained to be unique (i.e., a key)
  - Example: CREATE UNIQUE INDEX name_index ON emp(ename);
    → All employees must have different names

- **Most database systems will automatically create an index for any primary key and/or unique attributes**

# Indexes in SQL


- **Microsoft SQL Server**
- Create a CLUSTERED vs. NONCLUSTERED index
  - Syntax:

    CREATE CLUSTERED INDEX <index_name> ON <table_name>(<col1, col2,…>);
    CREATE NONCLUSTERED INDEX <index_name> ON <table_name>(<col1, col2,…>);

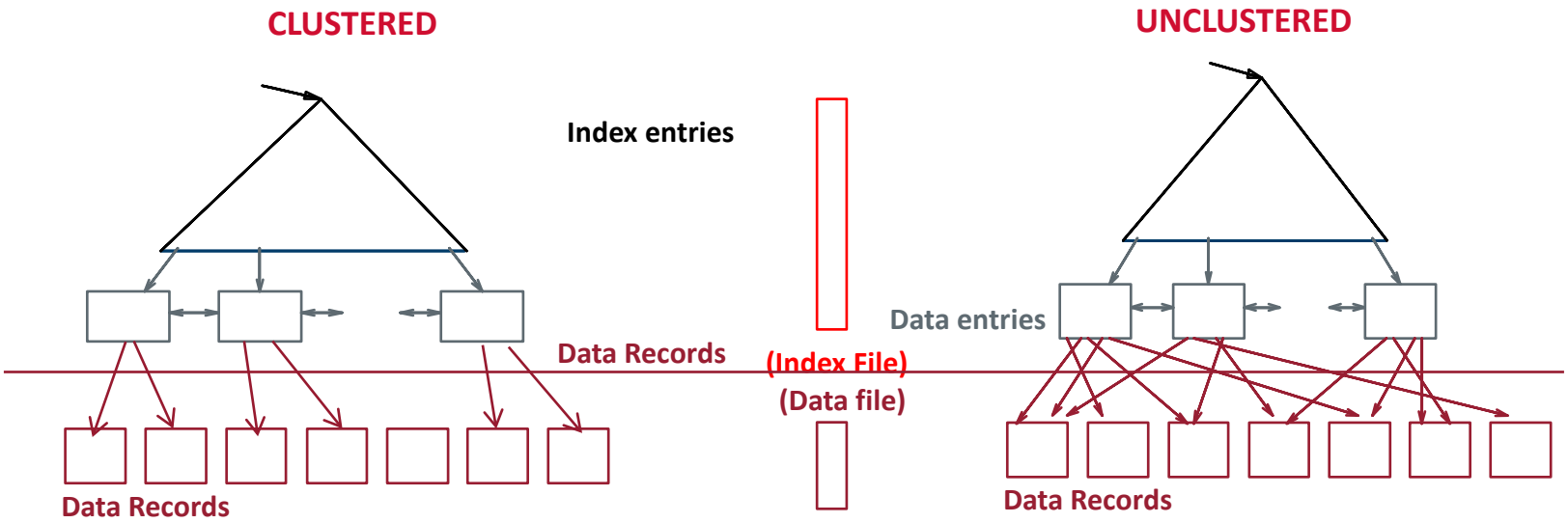


# Indexes in SQL


- **PostgreSQL**
- CLUSTER an existing index
  - Syntax:

    CREATE INDEX <index_name> ON <table_name>(<col1, col2,…>);

    CLUSTER <table_name> USING <index_name> ;



# Indexes in SQL


- **PostgreSQL**
- Create hash vs B-tree indexes
  - Syntax:

    CREATE INDEX <index_name> ON <table_name> USING hash (<col1, col2,…>);

    CREATE INDEX <index_name> ON <table_name> USING btree (<col1, col2,…>);

    – B-tree is default.

# Understanding the Workload


- For each query in the workload:
  - Which relations does it access?
  - Which attributes are retrieved?
  - Which attributes are involved in selection/join conditions? How selective are these conditions likely to be?
- For updates in the workload:
  - The type of update (INSERT/DELETE/UPDATE), and the attributes that are affected.
  - Frequency of the updates.

# 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/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.
  - Obviously, this implies that we must understand how a DBMS evaluates queries and creates query evaluation plans!
  - For now, we discuss simple queries.

- 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


1. 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.
2. 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.
     - For index-only strategies, clustering is not important!
3. Try to choose indexes that benefit as many queries as possible. 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?
  - Should the index be clustered?

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

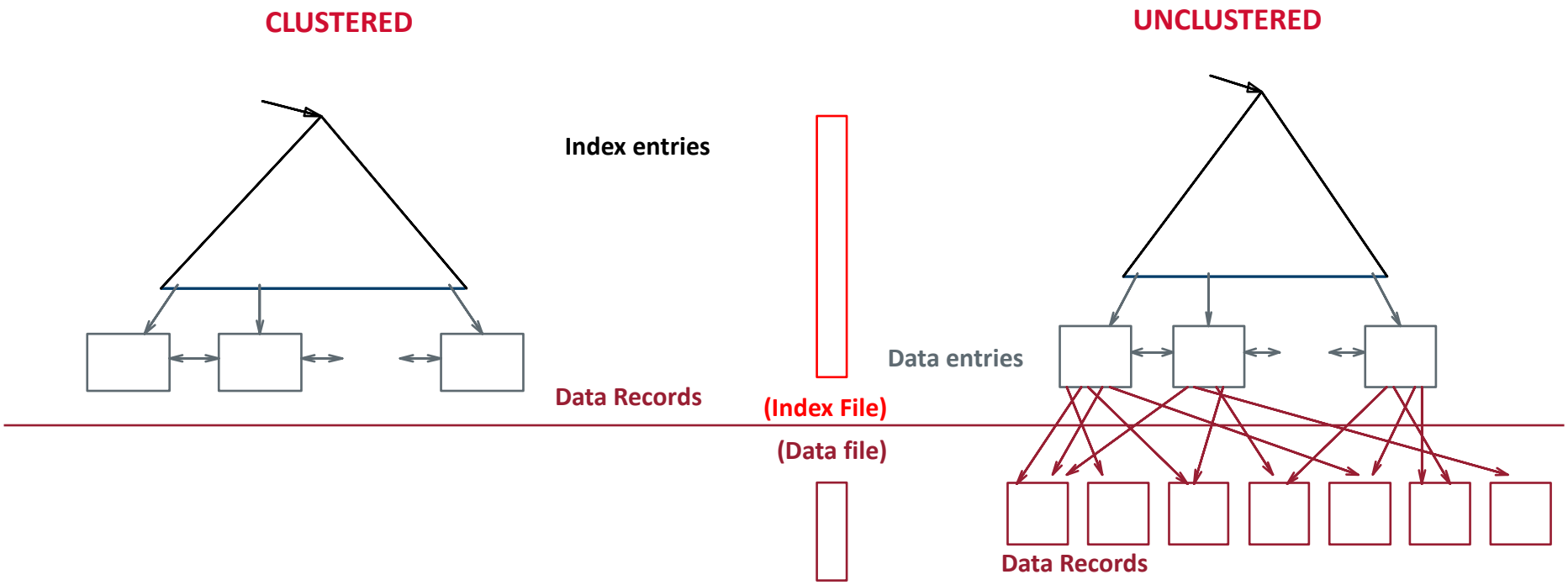
- Consider the GROUP BY query.
  - If many tuples have *E.age* > 10, using *E.age* index and sorting the retrieved tuples may be costly.
    - Clustered *E.dno* index may be better!
    - How about <*E.dno, E.age*>

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

- Equality queries and duplicates:
  - A hash index on *E.hobby* helps!
  - Should the index be clustered?

```
SELECT  *
FROM  Emp as E
WHERE  E.hobby='Stamps'
```

# Clustered vs. Unclustered Index




Clustered = records close in index are close in data

# Composite Search Keys


- To retrieve Emp records with *age*=22 AND *sal*=20K,
  - An index on <*age,sal*> would be better than an index on <*age*> or an index on <*sal*>.
- If condition is: 20<*age*<30 AND 30K<*sal*<80K:
  - Clustered tree index on <*age,sal*> or <*sal,age*> is best.
- If condition is: *age*=23 AND 30K<*sal*<50K:
  - Clustered <*age,sal*> index much better than <*sal,age*> index!
- Composite indexes are larger, updated more often.

```
SELECT *
FROM Emp as E
WHERE E.age =22
AND  E.sal = 20K
```

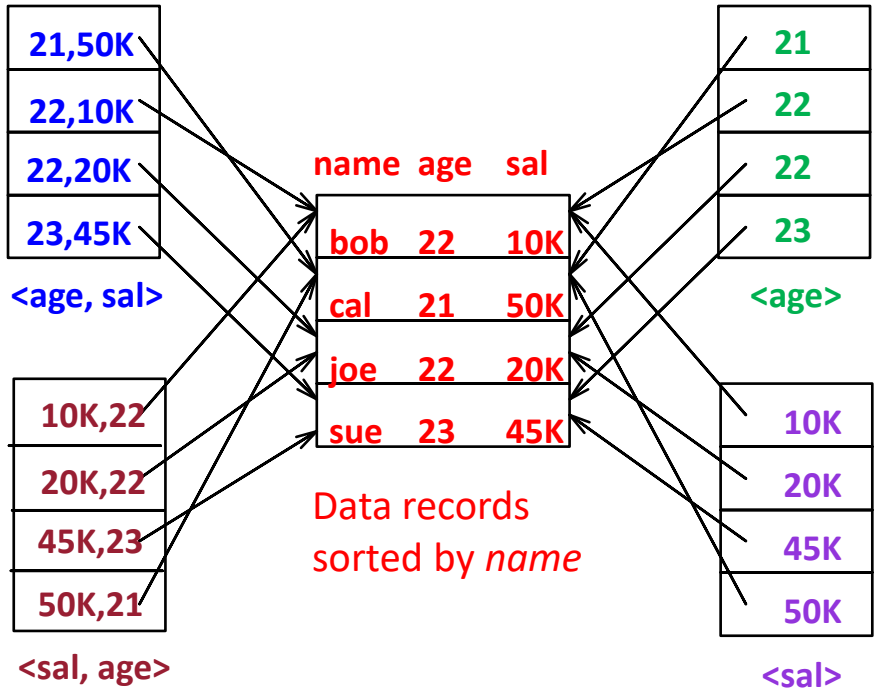
```
SELECT *
FROM Emp as E
WHERE E.age>20 AND E.age<30
AND E.sal>30K AND E.sal<80K
```

```
SELECT *
FROM Emp as E
WHERE E.age=23 AND
E.sal>30K AND E.sal<50K
```

# Indexes with Composite Search Keys


- ***Composite Search Keys***: Search on a combination of fields.
  - Equality query: Every field value is equal to a constant value. E.g. wrt <sal,age> index:
    - age=22 and sal =10K
  - Range query: Some field value is not a constant. E.g.:
    - age=22 and sal > 10K

Examples of composite key indexes using lexicographic order.




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

Data entries sorted by *<sal>*

# Index-Only Plans


- A number of queries can be answered without retrieving any tuples from one or more of the relations involved if a suitable (unclustered) index is available.

*<E.dno>*

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

*<E.dno,E.sal>*

*Tree index!*

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

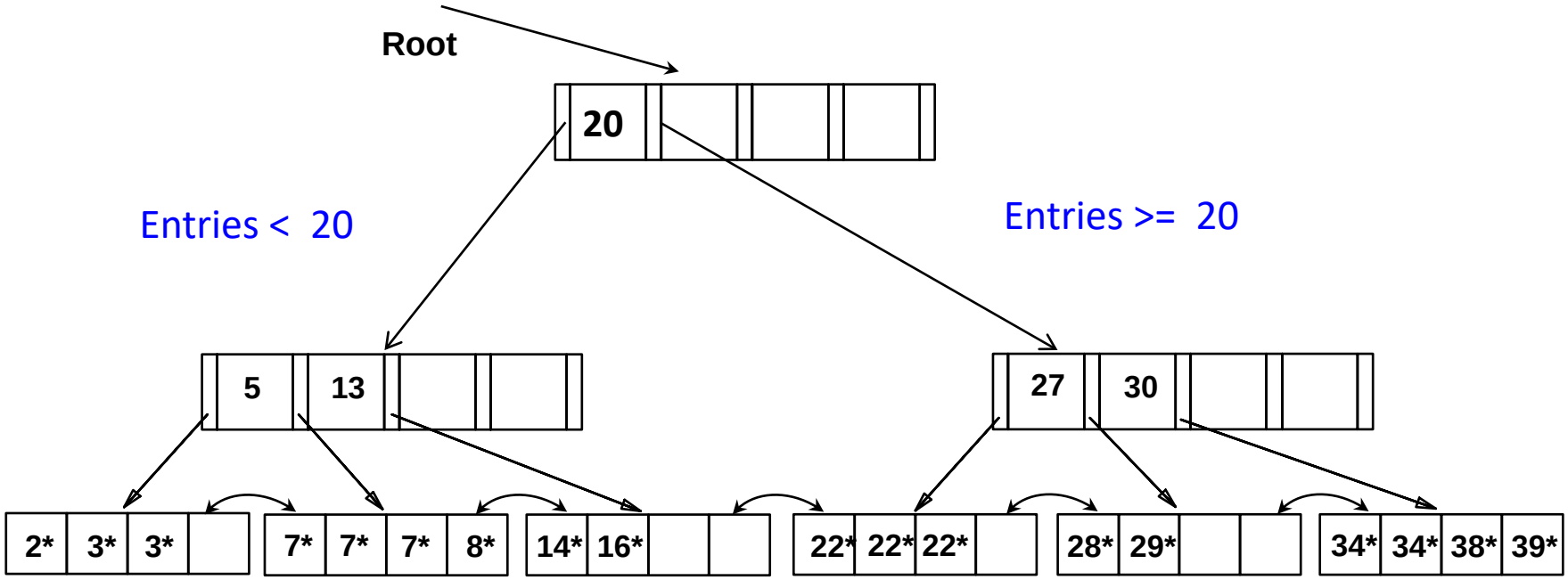
Which one is better?

*<E. age,E.sal>*
or
*<E.sal, E.age>*

*Tree index!*

```
SELECT AVG(E.sal)
FROM  Emp as E
WHERE  E.age=25 AND
  E.sal > 30K AND E.sal < 50K
```

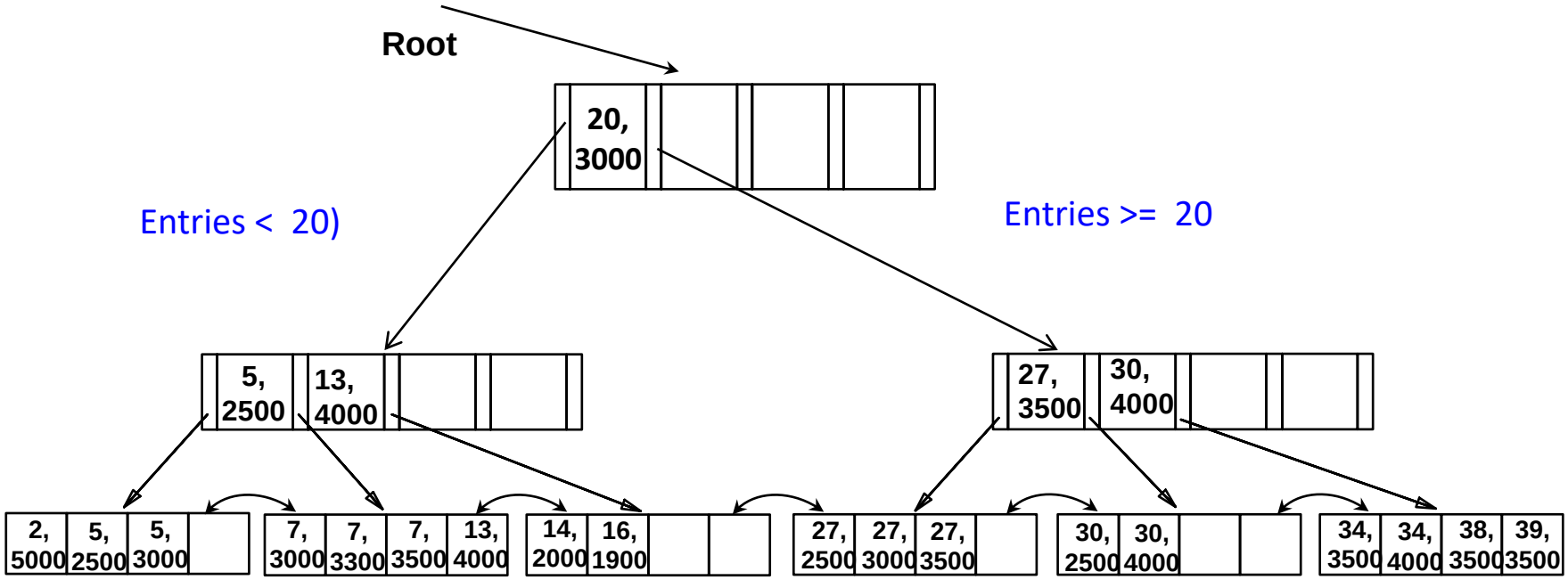
# Index-Only Plans - Examples




Index on *<E.dno>*

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

# Index-Only Plans - Examples




Index on <*E.dno,E.sal*>

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

# Index-Only Plans (Contd.)

- Index-only plans are possible if we have a index on <dno,sal> or <sal,dno>.
  - Which is better?
  - What if we consider the second query?

```
SELECT  E.dno,  COUNT (*)
FROM  Emp as E
WHERE  E.sal=3000
GROUP BY E.dno
```

```
SELECT  E.dno,  COUNT (*)
FROM  Emp as E
WHERE  E.sal>3000
GROUP BY E.dno
```

# Indexes for Joins

- Indexes can be helpful to speed up joins.

*<E.dno>*

```
SELECT  E.dno, E.name, E.age, E.sal
FROM  Dept as D, Emp as E
WHERE  D.dno=E.dno AND
          D.mgr = 'Alice'
```

*<D.dno>* → helpful if not many employees have sal=100K

```
SELECT  D.dno, D.dname
FROM  Dept as D, Emp as E
WHERE  D.dno=E.dno  AND
          E.sal = 100K
```

# Index-Only Plans (Contd.)

- Index-only plans can also be found for queries involving more than one table.

*<E.dno>*

```
SELECT  D.mgr
FROM  Dept as D, Emp as E
WHERE  D.dno=E.dno
```

*<E.dno,E.eid>*

```
SELECT  D.mgr, E.eid
FROM  Dept as D, Emp as E
WHERE  D.dno=E.dno
```

*<E.sal, E.dno>*
*<D.dno, D.dname>*

```
SELECT  D.dno, D.dname
FROM  Dept as D, Emp as E
WHERE  D.dno=E.dno  AND
            E.sal = 100K
```

# Query Plans - EXPLAIN


- Most databases have an EXPLAIN-type command
  - Performs query planning and optimization phases, then outputs details about the execution plan
  - Reports, among other things, what indexes are used
  - PostgreSQL EXPLAIN command:
    - `EXPLAIN SELECT * FROM Emp WHERE eid = '11-11-1111';`
    - This query uses the index on "eid" to look up the record
    - PostgreSQL knows that the result will be one row, or no rows

# YelpDB Examples


```
EXPLAIN
SELECT  B.name, B.address, B.numcheckins, B.reviewcount
FROM    Business as B, Category as C
WHERE   B.business_id = C.business_id AND
        C.name = 'Burgers'
```

```
EXPLAIN
SELECT *
FROM Business as B, Review as R, User as U, Friends as F
WHERE B.business_id = R. business_id AND R.user_id = F.friend_id AND
      F.friend_id = U.user_id  AND
      F.user_id = 'BfcNxKpnF9z5wJLXY7elRg'
```

# Indexes cannot solve everything…


- **Watch out for inequalities!**
  - SELECT * FROM R WHERE R.A != 10;
    - B+Tree and Hash Index won't help
    - Scanning the table is likely to be best
- **Watch out for wildcards!**
  - SELECT * FROM R. WHERE R.B LIKE 'Hello%';
    - B+Tree can help by finding prefixes
    - Hash Index unable to help
  - SELECT * FROM R. WHERE R.B LIKE '%Hello%';
    - Even B+Tree cannot help…

# 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, primary vs. secondary. Differences have important consequences for utility/performance.

# Summary (Contd.)


- Understanding the nature of the *workload* for the application, and the performance goals, is essential to developing a good design.
  - What are the important queries and updates? What attributes/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.