CSE462/562: Database Systems (Fall 24)

Lecture 13: Access Methods and indexing

10/17/2024

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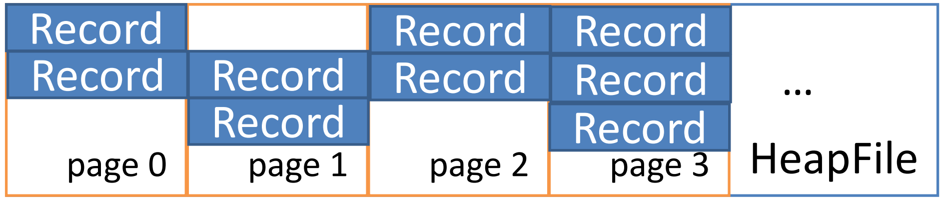
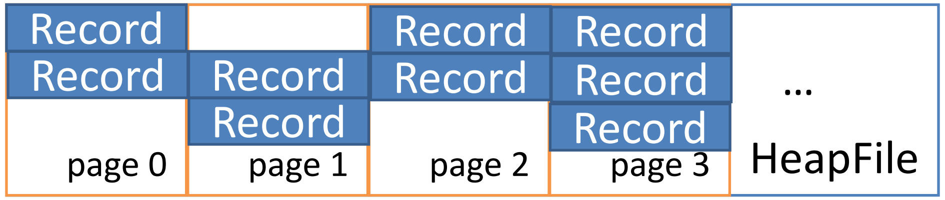
Revisit of the big picture of file organization

- Fields → Records → Pages → Heap Files (→ Files on File System) → Storage Device



- What do we support?

Heap file



What do we support?

- Insert a record -- O(1) time & I/O, insert into any free page
- Update/delete of a record with known record ID -- O(1) time & I/O, pin page & update
- Enumerating all data records -- linear time & I/O, scan through all pages & enumerate records on each page

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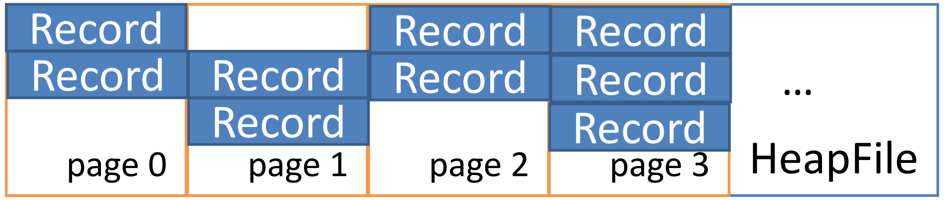

- What do we support?
  - Insert a record
  - Update/delete of a record with known record ID
  - Enumerating all data records

  - How do I find the student with name “Alice”?
    - Enumerating all records to locate Alice -- linear time & I/O for one record!
  - Can we do better?
    - Binary search? Search trees? Hash table? Partitioning?
    - Do we always need to store records as a whole?

- Needs alternative file organization
  - These are called access methods (a name that comes from mainframe OS)
    - data structures and algorithms for sequentially or randomly retrieving data by keys

Access methods

- Heap file: unordered, good for enumerating all records
- Sorted file: best for random retrieval by *search key* and/or in search key order
  - A *search key* is a set of attributes (can be a single attribute) that the underlying file is sorted w.r.t.
    - Has nothing to do with (primary/candidate) keys.
    - Implication: there may be *duplicate* keys in a sorted file
  - Must be based on files that support random access of data pages with consecutive page numbers
    - e.g., for a sorted file with M pages, page numbers are 0, 1, 2, …, M-1.
    - Need support for random access of page i efficiently without linear traversal

- Compare the costs of record insertion/deletion/search in sorted file vs heap file?

Cost Model for Analysis

- We assume fixed-length records and ignore CPU costs for simplicity:
  - N: the number of records
  - **B:** Number of records per page
  - T: Number of matching record in a search
  - Cost model: # of I/Os (also ignoring pre-fetching and/or random vs sequential access), and thus even I/O cost is loosely approximated.
  - Average-case analysis (unless o/w specified); based on several simplistic assumptions.
    - Good enough for knowing the overall trends.
    - Reality is a lot messier than this.
- Additional assumptions
  - Single record to insert and delete; unless o/w specified
  - Equality selection - exactly one match; unless o/w specified
  - Heap Files:
    - Insert always appends to end of file.
  - Sorted Files:
    - Two alternatives:
      - No need to compact the file after deletions.
      - Files compacted after deletions.
    - Selections on search key (the attribute(s) used for sorting).

Cost of operations

N: Number of records
N/B: The number of data pages
B: Number of records per page
T: Number of matching records

# of I/Os	Heap File	Sorted File
Scan all records	N/B	N/B
Equality Search: if we know there's only 1 matching record	0.5N/B, Best Case: 1, Worst Case: N/B	$\log_2$ (N/B) Best case: 1.
Range Search	N/B	$\log_2$ (N/B) + #match pages = $\log_2$ (N/B) + T/B
Insert: compact for sorted file	2	$\log_2$ (N/B) + N/B (read + write for 0.5N/B pages on average)
Delete: no compact for sorted file	0.5N/B + 1	$\log_2$ (N/B) + 1

Cost of operations

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N/B: The number of data pages
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Access methods

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    - Has nothing to do with (primary/candidate) keys!
- Columnar store: store individual column/column sets in separate files
  - Also called vertical partitioning
  - Good for queries with projection -- saves I/O, SIMD friendly

Columnar Storage

- Good compression, fast scan, but more expensive to update in general

Column segment: compressed and has min/max stats

row group 1

sid	name	major	adm_year
100	Alice	CS	2021
101	Bob	CE	2020

row group 2

sid	name	major	adm_year
102	Charlie	CS	2021
103	David	CS	2020

Example: `SELECT COUNT(*) from student WHERE major = 'CS';`

Assumptions: adm_year stored as 32-bit integers, no compression, no page/group/column header

B = # of records/page on average, B'=# of 32-bit values/page

Row store (heap file): $\frac{N}{B} = N/\left\lfloor\frac{PAGE\ SIZE}{RECORD\ LENGTH}\right\rfloor$ I/O

Columnar store (uncompressed): $\frac{N}{B'} = N/\left\lfloor\frac{PAGE\ SIZE}{4}\right\rfloor$ I/O

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- Indexes
  - Data structures for efficient search with a search key
  - Similar to sorted files, but *can be* a secondary storage format

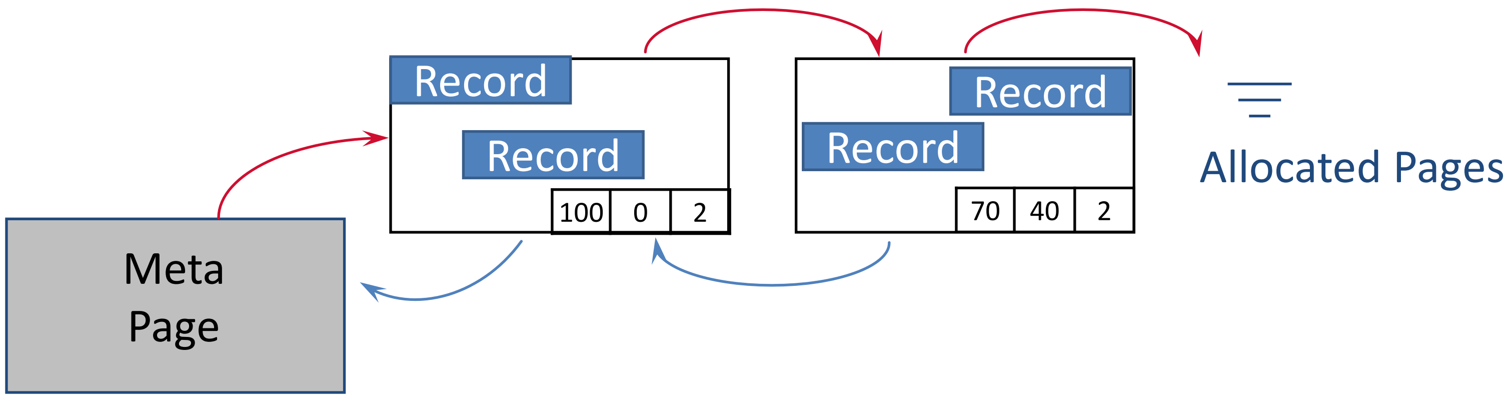
Index

- Sometimes, we want to retrieve records by specifying the values in one or more fields
  - Find all students in CSE
  - Find all students admitted in year 2021

- Not very efficient to handle with heap file/sorted file
  - Heap file: always need to linear scan
  - Sorted file: only (somewhat) efficient for the sorted column
    - i.e., can't use binary search on a file sorted on *major* for specific *adm_year*

student

sid	name	major	adm_year
100	Alice	CS	2021
101	Bob	CE	2020
102	Charlie	CS	2021
103	David	CS	2020



Index

- An index: a data structure that speeds up search on a few fields on a relation
  - Maps index key k to data entry k^*
    - Any subset of the columns of a relation can be the index key k
      - Index key is not (candidate/primary) key; doesn't have to be unique
    - Data entry k^*
      - e.g., the data record itself
      - Store the key k with the data entry k^*?
        - Sometimes we do, sometimes we don't
  - Essentially an associative container, but more with more functionalities
    - std::map/std::unordered_map in C++
    - java.util.TreeMap/java.util.HashMap in Java
    - dictionary in Python

student

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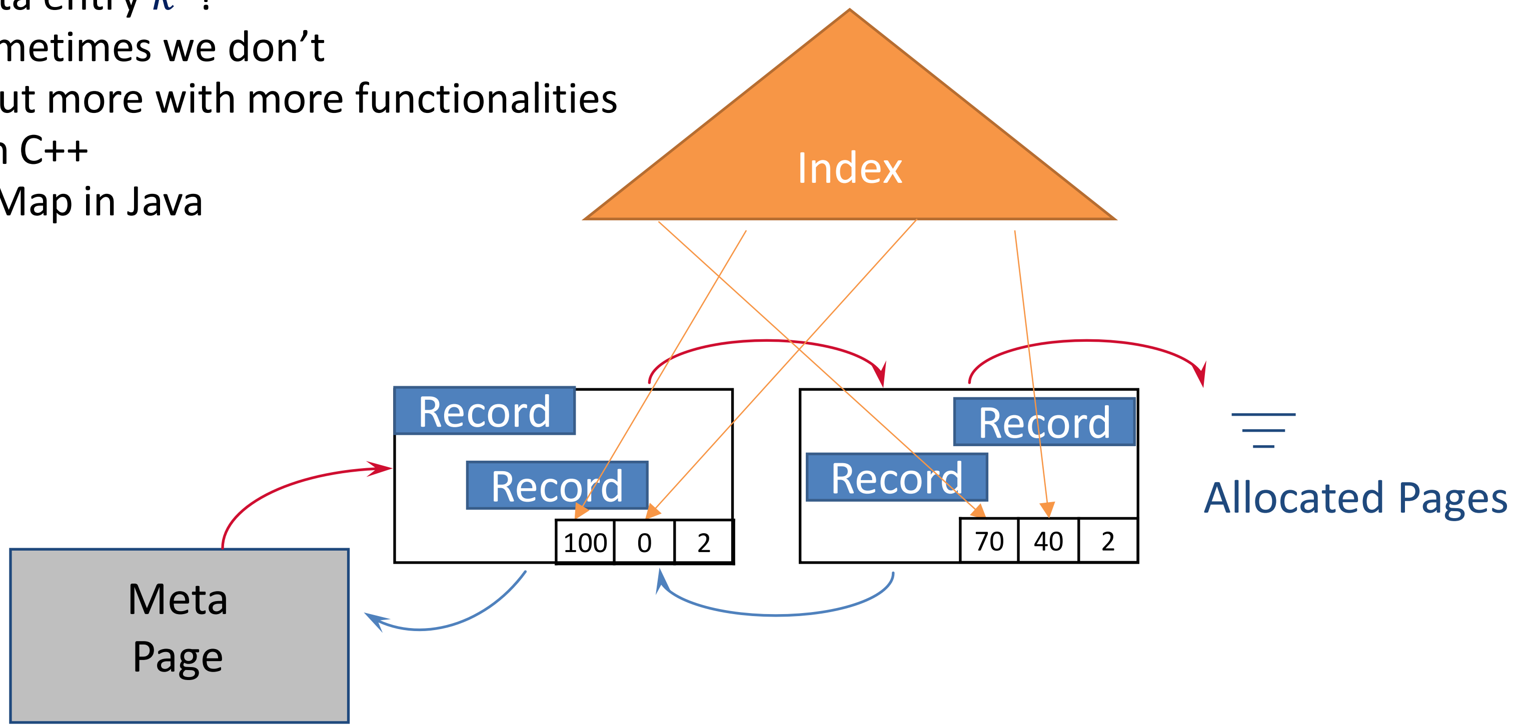


Index classification

- Representation of data entries in index
  - i.e., what kind of info is the index actually storing?
  - 3 alternatives
- What selections does it support
- Indexing techniques: tree/hash/other
- Primary vs. Secondary Indexes
  - Unique indexes
- Clustered vs. Unclustered Indexes
- Single Key vs. Composite Indexes

Alternatives for the data entry $\boldsymbol{k}^*$ in index

- Three alternatives:
  - Alternative 1: the record itself (with its key k)
  - Alternative 2: <k, record ID of a matching record>
  - Alternative 3: <k, list of record IDs of matching records>
- Choice of the alternative is orthogonal to the indexing technique
  - Example of indexing techniques: B+-Tree, hash index, R-Tree, KD-Tree, and etc…
- A heap/sorted file can have multiple indexes
  - e.g., a B-tree index on adm_year and a hash index on major for the heap file of student relation
  - each usually stored as a separate file
  - usually at most *one* alternative-1 index per file (why?)

More on the alternatives of the data entries in index

- Alternative 1: actual data record (with its key k^*)
  - If this is used, it is another file organization for data records (aka index file)
  - At most *one* alt-1 index
  - Good: avoids record id/pointer lookups
  - Bad: less efficient to maintain for insertion/deletion/update
- Alternative 2 & 3
  <k, record id of a matching record> or <k, list of record ids of matching records>
  - Good: Can have multiple alt-2/alt-3 indexes
  - Good: more efficient to maintain than alternative 1
  - Bad: additional record id/pointer lookup (usually random I/O)
    - How to work around it? Include non-key columns.
  - Alt-3 is more compact than alt-2, but the variation in data entry size can be much larger
    - Harder to deal with when they need to be split/merged
  - Alt-3: key skew could lead to extremely long record id lists
    - Workaround: split them into shorter alt-3 data entries that fit into individual data pages

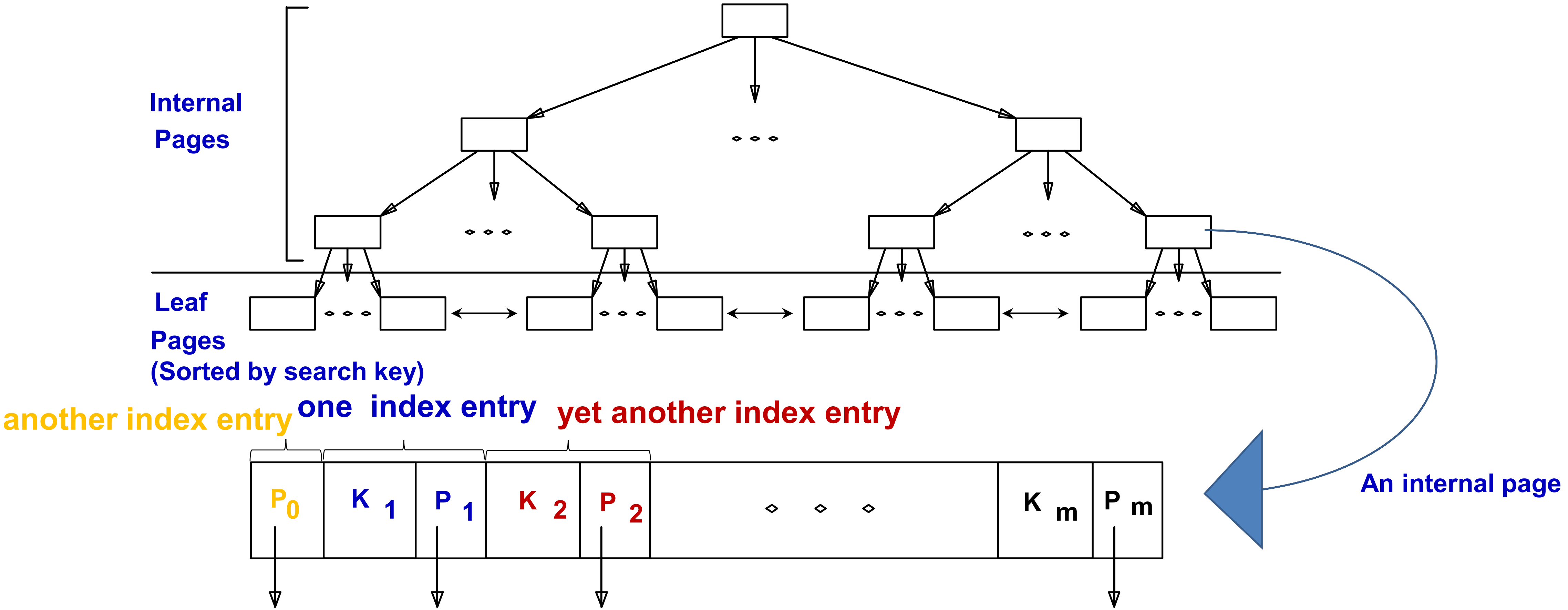
Index operations

- Inserts a data entry the index
- Deletes a data entry from the index
- Updates the value of a data entry
  - Can you change the index key of a data entry?
- Search and scan
  - Point lookup: find the data entry (entries) of a *search key*
  - Range scan: enumerate all the data entries in a range of *search keys*
    - e.g., adm_year $\in [2020, 2021]$, adm_year > 2020, adm_year ≤ 2015
    - sometimes the search key is a subset of the index key
  - Full index scan: enumerate all data entries in an index
    - Might be useful for ordering/efficiency
  - Other search operations:
    - String prefix matching
    - 2-D, 3-D, or higher dimensional range search
    - …

Index Types

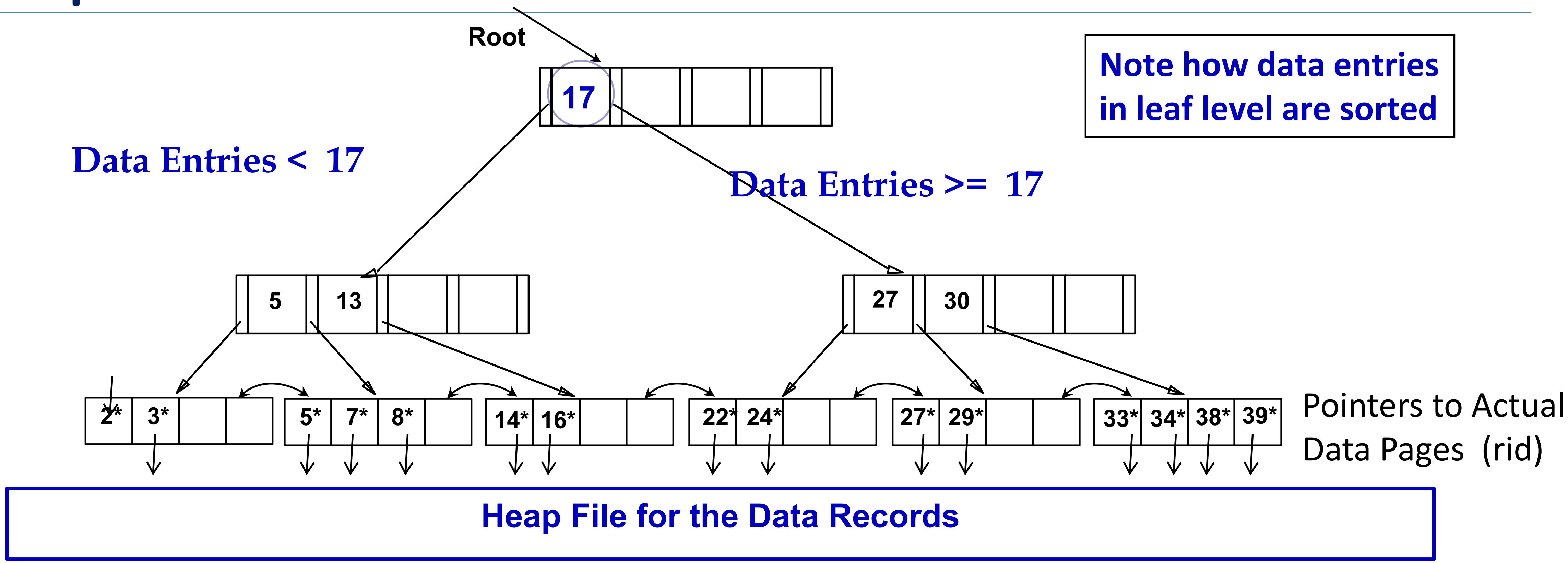
- Tree and hash indexes are the two most common categories of indexes
  - More details in the next 3-4 lectures
  - Example: B-Tree and static hash index

Tree-based indexes



- Leaf pages contain data entries, and are chained (prev & next page ids)
- Internal pages have index entries; only used to direct searches
- Good for equality and range selection
  - Results are ordered by index key

Example: B-Tree index



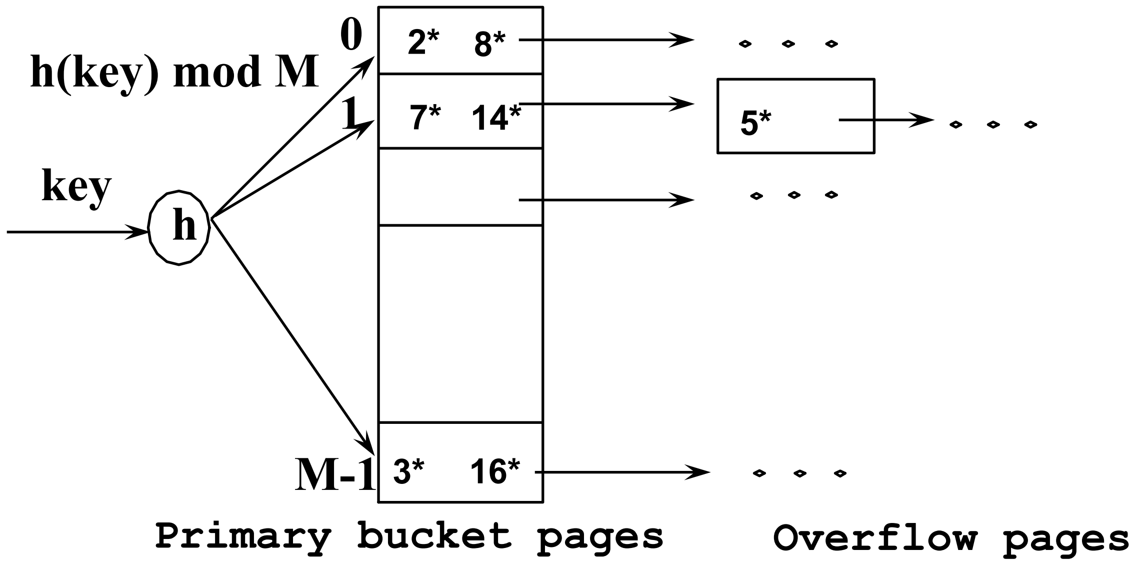
- Technically, this is the B+-Tree index, not the original B-Tree
  - Difference: B+-Tree only stores keys rather than data entries in internal nodes
  - But most DBMS uses B+-Tree, but use the term B-Tree…

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 *index key* fields of *r*.
  - *No need for "index entries" in this scheme.*

Example: static hashing index

- Fixed number of primary pages = # of buckets (denoted as M)
    - allocated sequentially; never de-allocated
    - allocate overflow pages if needed
- **h**(*k*) % M = the bucket id for a data entry with *index key k.*



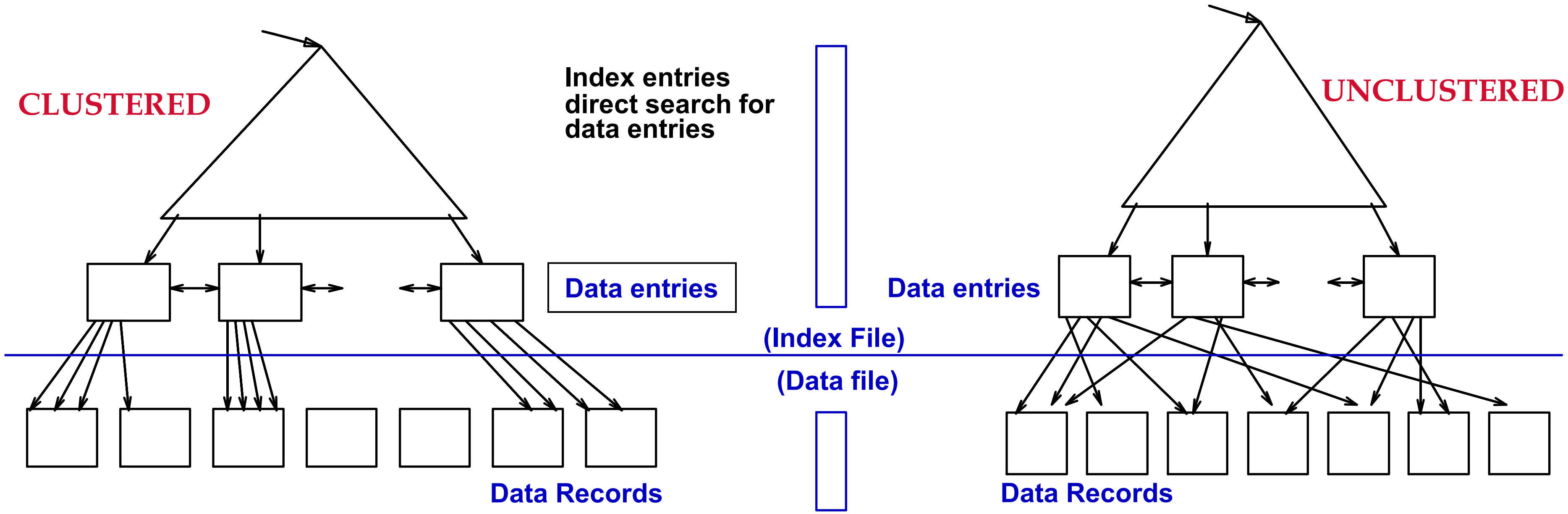
Clustered vs unclustered index

- Clustered index
  - An index over a file such that the order of the data records is the same as, or "close to" that of the index data entries
    - A file can only be clustered on one index key
    - Sorted file can be used for clustering, but may be expensive to maintain
      - Can we use heap file? Yes, but with some tricks.

  - Using Alternative 1 in a B+-tree implies clustered, *but not vice-versa*.
    - aka clustered file

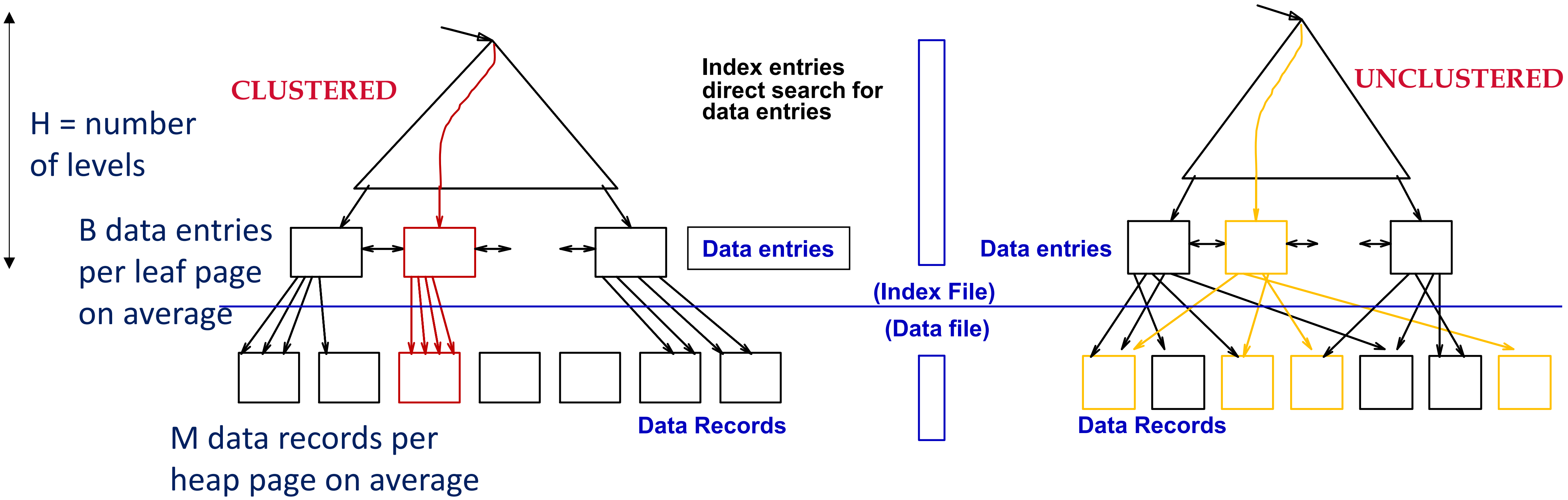
Clustered vs unclustered index

- Assume alternative 2 for data entries, and 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 updates/inserts.
    - The percentage of free space in the initial sort/append is called *fill factor*
  - Overflow pages may be needed for inserts/updates.
    - Thus, the order of data records is "close to", if not not identical to, the sort order.



Access cost of clustered vs unclustered index

- Cost of accessing data records through index varies *greatly* based on whether index is clustered!
  - e.g. range scan with n matching data records in a B-Tree
    - assuming we ignore the buffer pool's effect
    - clustered: $H + \left\lceil \frac{n}{M} \right\rceil$ I/Os
    - unclustered: $H + \left\lceil \frac{n}{B} \right\rceil - 1 + n$ I/Os



Tradeoffs between clustered and unclustered indexes

- What are the tradeoffs?
- Clustered Pros
  - Efficient for range searches for records: sequential access in a sorted file
  - May be able to do some types of compression
  - Locality benefits
- Clustered Cons
  - Expensive to maintain (on the fly or sloppy with reorganization)
- Unclustered
  - Pros: easy and efficient to maintain, allow multiple indexes
  - Cons: expensive for range scans for records: 1 random IO for each matching record.

Primary, secondary and unique index

- Primary index: index key contains the primary key
  - e.g., for student table, an index over (sid) is its primary index
  - at most one per relation
- Unique index: index key contains a candidate key
  - Primary index is a unique index, but not vice versa
  - Can be clustered or unclustered.
- Secondary index (not well-defined but often used)
  - It may have different meanings
    - an index that is not indexed over the primary key
    - unclustered
    - or both