CompSci 516
Database Systems

Lecture 9
Index Selection
and
External Sorting

Instructor: Sudeepa Roy

Announcements

- Project proposal and HW1 due today (Thurs, 09/27) 11:55 pm
  - project proposal: sakai
  - HW1: gradescope
- If gradescope does not work, submit a zip file on sakai (a backup folder has been created)
    - timeout has been increased to 60 mins from 20 mins
  - Submit by (well before) the deadline (strict)
    - note that it may take > 20 mins for autograder to run!
  - Late marks may lose all or some points
- Remember to write only one query per question!

Today

- Index selection
- External sort

Reading Material

- Index: as in Lecture 7/8
- External sorting:
- [RG]
  - External sorting: Chapter 13
- [GUW]
  - Chapter 15.4.1

Acknowledgement:
The following slides have been created adapting the instructor material of the [RG] book provided by the authors Dr. Ramakrishnan and Dr. Gehrke.

Selection of Indexes

Different File Organizations

We need to understand the importance of appropriate file organization and index

Search key = <age, sal>

Consider following options:

- Heap files
  - random order; insert at end-of-file
- Sorted files
  - sorted on *<age, sal>*
- Clustered B+ tree file
  - 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>*

Possible Operations

- Scan
  - Fetch all records from disk to buffer pool
- Equality search
  - Find all employees with age = 23 and sal = 50
  - Fetch page from disk, then locate qualifying record in page
- Range selection
  - Find all employees with age > 35
- Insert a record
  - identify the page, fetch that page from disk, inset record, write back to disk (possibly other pages as well)
- Delete a record
  - similar to insert

Understanding the Workload

- A workload is a mix of queries and updates

- 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 each update in the workload:
  - Which attributes are involved in selection/join conditions? How selective are these conditions likely to be?
  - The type of update (INSERT/DELETE/UPDATE), and the attributes that are affected

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?

More on Choice of Indexes

- One approach:
  - Consider the most important queries
  - Consider the best plan using the current indexes
  - 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
  - We will learn query execution and optimization later - For now, we discuss simple 1-table queries.

- Before creating an index, must also consider the impact on updates in the workload

Trade-offs for Indexes

- 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

- 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

- Multi-attribute search keys should be considered when a WHERE clause contains several conditions
  - Order of attributes is important for range queries

- Note: clustered index should be used judiciously
  - expensive updates, although cheaper than sorted files

Examples of Clustered Indexes

What is a good indexing strategy?

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

Which attribute(s)?
Clustered/Unclustered?
B+ tree/Hash?

- B+ tree index on E.age can be used to get qualifying tuples
- How selective is the condition?
  - everyone > 40, index not of much help, scan is as good
  - Suppose 10% > 40. Then?
- Depends on if the index is clustered
  - otherwise can be more expensive than a linear scan
  - if clustered, 10% I/O (+ index pages)

Examples of Clustered Indexes

Group-By query

What is a good indexing strategy?

- Use E.age as search key?
  - Bad If many tuples have *E.age* > 10 or if not clustered….
  - …using *E.age* index and sorting the retrieved tuples by E.dno may be costly

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

- Clustered *E.dno* index may be better
  - First group by, then count tuples with age > 10
  - good when age > 10 is not too selective

Which attribute(s)?
Clustered/Unclustered?
B+ tree/Hash?

- Note: the first option is good when the WHERE condition is highly selective (few tuples have age > 10), the second is good when not highly selective

Examples of Clustered Indexes

What is a good indexing strategy?

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

Which attribute(s)?
Clustered/Unclustered?
B+ tree/Hash?

```
SELECT  E.dno
FROM  Emp E
WHERE  E.eid=50
```

Equality queries and duplicates

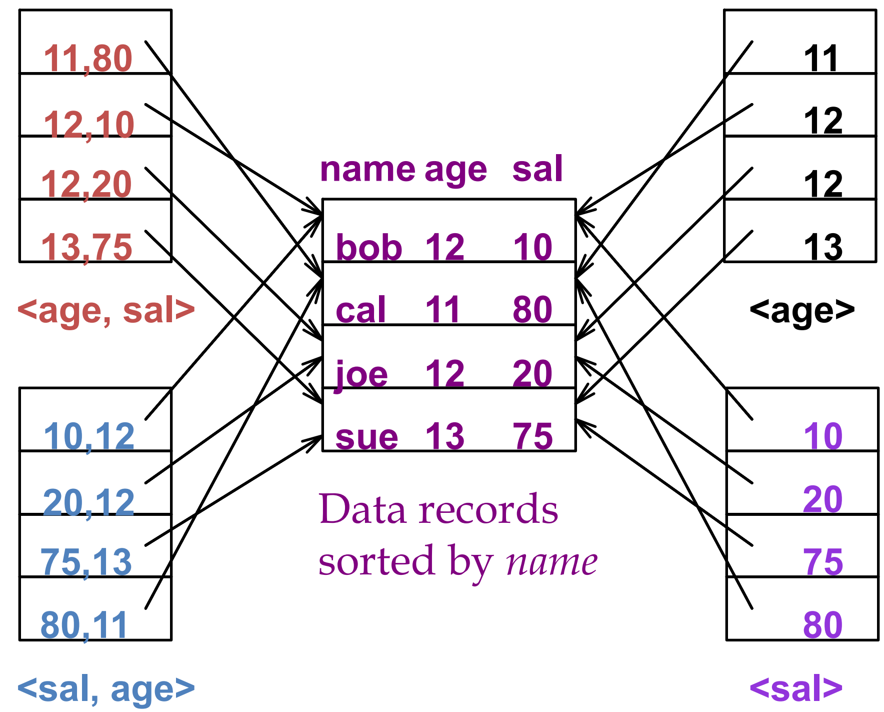
- Clustering on *E.hobby* helps
  - hobby not a candidate key, several tuples possible
- Does clustering help now?
  - (eid = key)
  - Not much
  - at most one tuple satisfies the condition

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=20 and sal =75
- Range query: Some field value is not a constant. E.g.:
  - sal > 10 – which combination(s) would help?

  - <age, sal> does not help
  - B+tree on <sal> or <sal, age> helps
  - has to be a prefix

Examples of composite key indexes using lexicographic order.



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* or an index on sal
  - first find age = 30, among them search sal = 4000
- 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
  - more index entries are retrieved for the latter
- Composite indexes are larger, updated more often

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 index is available

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

<E.dno>

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

<E.dno,E.sal>

Tree index!

<E. age,E.sal>

Tree index!

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

- For index-only strategies, clustering is not important

External Sorting

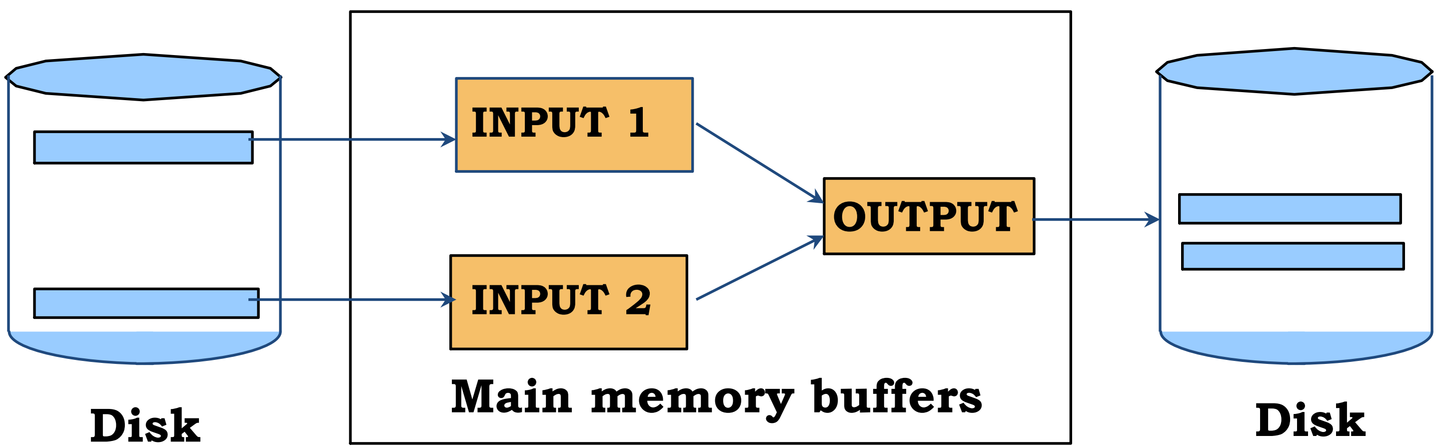
Why Sort?

- A classic problem in computer science
- Data requested in sorted order
  - e.g., find students in increasing gpa order
- Sorting is first step in bulk loading B+ tree index
- Sorting useful for eliminating duplicate copies in a collection of records
- Sort-merge join algorithm involves sorting
- Problem: sort 1Gb of data with 1Mb of RAM
  - need to minimize the cost of disk access

quick review of mergesort on whiteboard

2-Way Sort: Requires 3 Buffers

- Suppose N = 2^k pages in the file
- Pass 0: Read a page, sort it, write it.
  - repeat for all 2^k pages
  - only one buffer page is used
- Pass 1:
  - Read two pages, sort (merge) them using one output page, write them to disk
  - repeat 2^{k-1} times
  - three buffer pages used
- Pass 2, 3, 4, ….. continue



Two-Way External Merge Sort

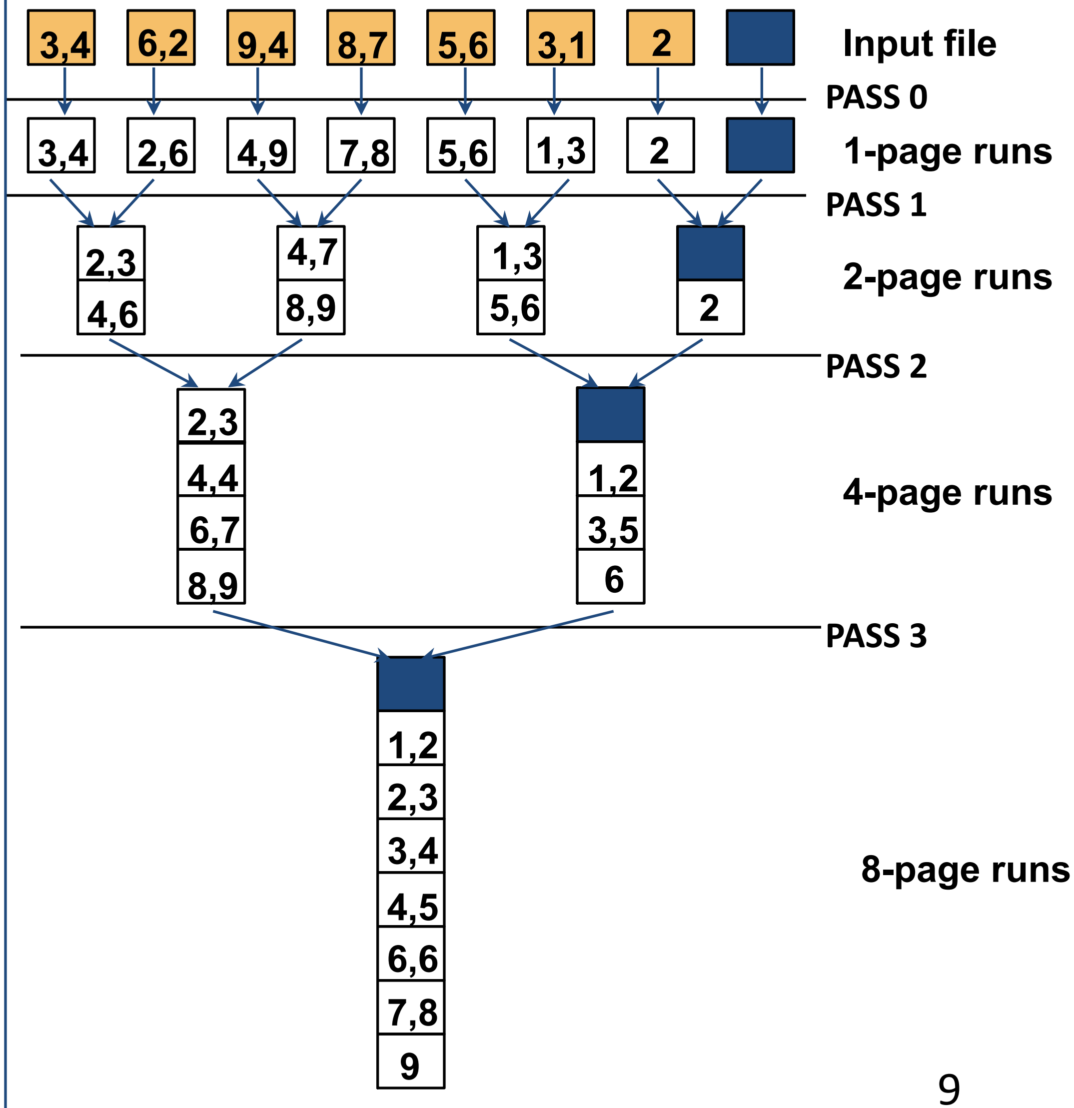
- Each sorted sub-file is called a run
  - each run can contain multiple pages
- Each pass we read + write each page in file.
- N pages in the file,
- => the number of passes

$$= \lceil \log_2 N \rceil + 1$$

- So toal cost is:

$$2N\left(\lceil \log_2 N \rceil + 1\right)$$

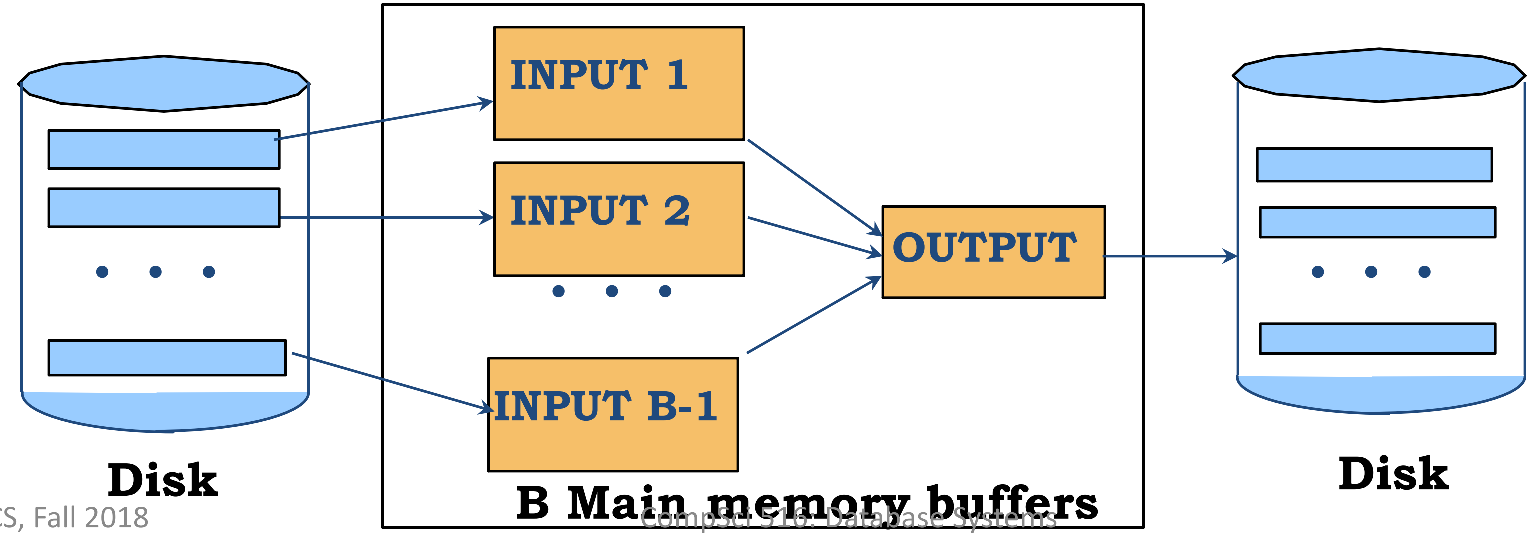
- Not too practical, but useful to learn basic concepts for external sorting



General External Merge Sort

- Suppose we have more than 3 buffer pages.
- How can we utilize them?

- To sort a file with N pages using B buffer pages:
  - Pass 0: use B buffer pages:
    - Produce ⌈N/B⌉ sorted runs of B pages each.
  - Pass 1, 2, …, etc.: merge B-1 runs to one output page
    - keep writing to disk once the output page is full



Cost of External Merge Sort

- Number of passes: $1 + \lceil \log_{B-1} \lceil N/B \rceil \rceil$
- Cost = 2N * (# of passes) – why 2 times?
- E.g., with 5 buffer pages, to sort 108 page file:
- Pass 0: sorting 5 pages at a time
  - $\lceil 108/5 \rceil$ = 22 sorted runs of 5 pages each (last run is only 3 pages)
- Pass 1: 4-way merge
  - $\lceil 22/4 \rceil$ = 6 sorted runs of 20 pages each (last run is only 8 pages)
- Pass 2: 4-way merge
  - (but 2-way for the last two runs)
  - $\lceil 6/4 \rceil$ = 2 sorted runs, 80 pages and 28 pages
- Pass 3: 2-way merge (only 2 runs remaining)
  - Sorted file of 108 pages

Number of Passes of External Sort

High B is good, although CPU cost increases

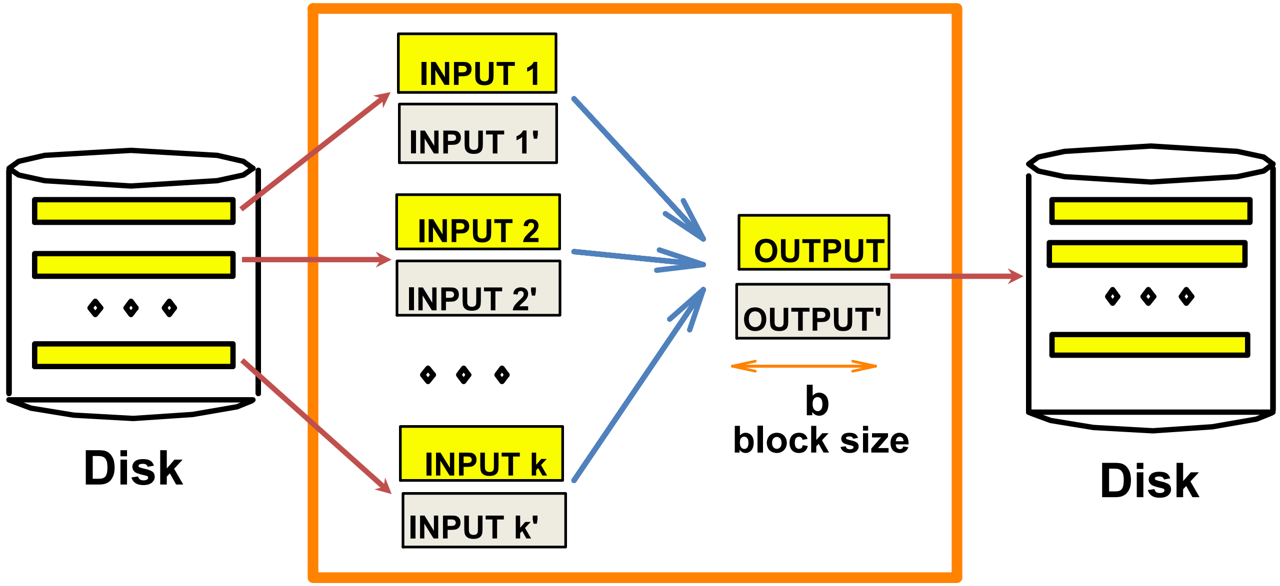
N	B=3	B=5	B=9	B=17	B=129	B=257
100	7	4	3	2	1	1
1,000	10	5	4	3	2	2
10,000	13	7	5	4	2	2
100,000	17	9	6	5	3	3
1,000,000	20	10	7	5	3	3
10,000,000	23	12	8	6	4	3
100,000,000	26	14	9	7	4	4
1,000,000,000	30	15	10	8	5	4

I/O for External Merge Sort

- If 10 buffer pages
  - either merge 9 runs at a time with one output buffer
  - or 8 runs with two output buffers
- If #page I/O is the metric
  - goal is minimize the #passes
  - each page is read and written in each pass
- If we decide to read a block of b pages sequentially
  - Suggests we should make each buffer (input/output) be a block of pages
  - But this will reduce fan-out during merge passes
    - i.e. not as many runs can be merged again any more
  - In practice, most files still sorted in 2-3 passes

Double Buffering

- To reduce CPU wait time for I/O request to complete, can prefetch into `shadow block'.



B main memory buffers, k-way merge

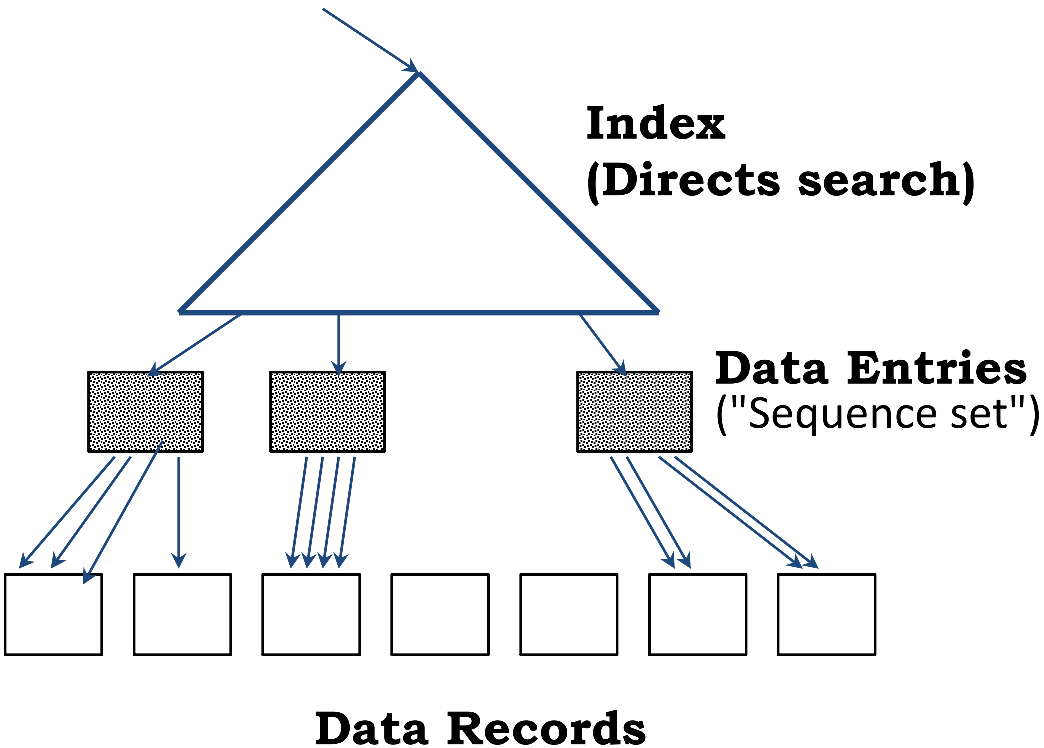
Using B+ Trees for Sorting

- Scenario: Table to be sorted has B+ tree index on sorting column(s)
- Idea: Can retrieve data entries (then records) in order by traversing leaf pages.
- Is this a good idea?
- Cases to consider:
  - B+ tree is clustered: Good idea!
  - B+ tree is not clustered: Could be a very bad idea!

Clustered B+ Tree Used for Sorting

- Cost: root to the left-most leaf, then retrieve all leaf pages (Alternative 1)

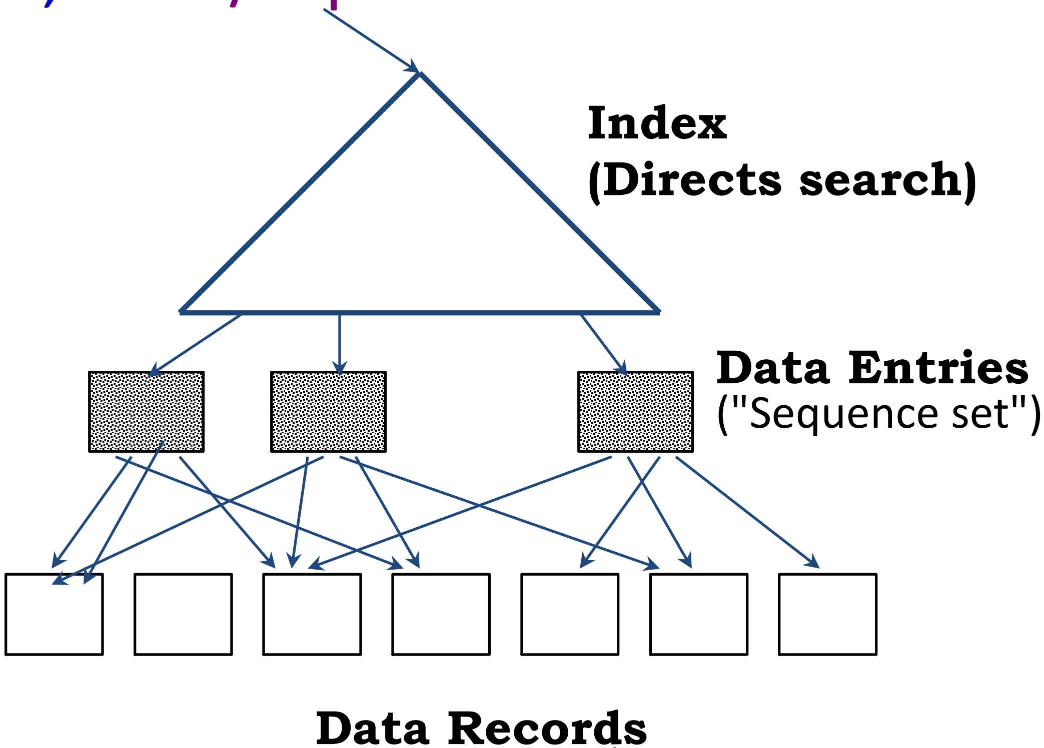
- If Alternative 2 is used? Additional cost of retrieving data records: each page fetched just once



☛ *Always better than external sorting!*

Unclustered B+ Tree Used for Sorting

- Alternative (2) for data entries; each data entry contains *rid* of a data record
- In general, one I/O per data record!



Summary

- External sorting is important; DBMS may dedicate part of buffer pool for sorting!
- External merge sort minimizes disk I/O cost:
  - Pass 0: Produces sorted runs of size B (# buffer pages)
  - Later passes: merge runs
  - # of runs merged at a time depends on B, and block size.
  - Larger block size means less I/O cost per page.
  - Larger block size means smaller # runs merged.
  - In practice, # of passes is rarely more than 2 or 3