Query Processing: The Basics

Chapter 10

External Sorting

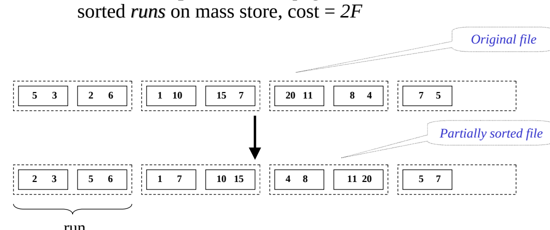
- Sorting is used in implementing many relational operations
- Problem:
  - Relations are typically large, do not fit in main memory
  - So cannot use traditional in-memory sorting algorithms
- Approach used:
  - Combine in-memory sorting with clever techniques aimed at minimizing I/O
  - I/O costs dominate => cost of sorting algorithm is measured in the number of page transfers

External Sorting (cont'd)

- External sorting has two main components:
  - Computation involved in sorting records in buffers in main memory
  - I/O necessary to move records between mass store and main memory

Simple Sort Algorithm

- M = number of main memory page buffers
- F = number of pages in file to be sorted
- Typical algorithm has two phases:
  - **Partial sort phase**: sort M pages at a time; create F/M sorted ***runs*** on mass store, cost = $2F$

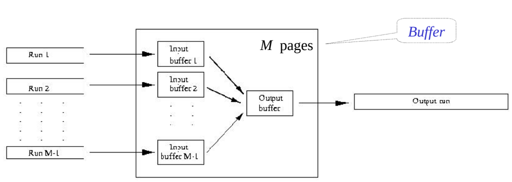


Example: $M = 2, F = 7$

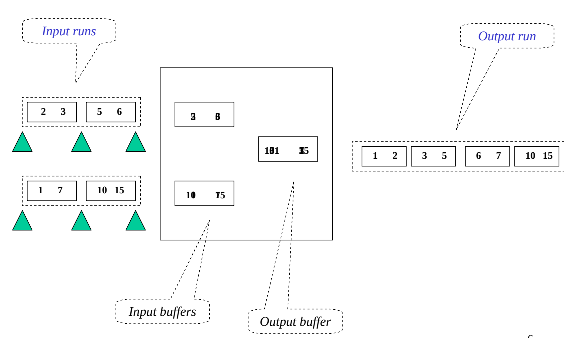
Simple Sort Algorithm

- **Merge Phase***:* merge all runs into a single run using M-1 buffers for input and 1 output buffer
  - Merge step: divide runs into groups of size M-1 and merge each group into a run; cost = $2F$

each step reduces number of runs by a factor of M-1



Merge: An Example



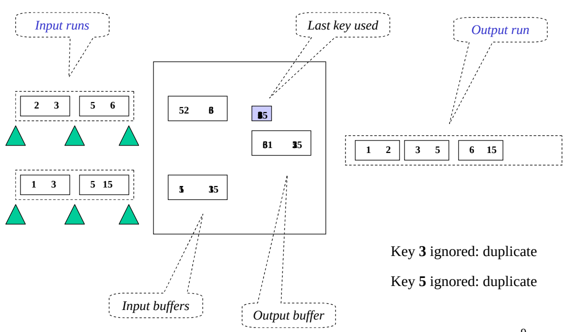
Simple Sort Algorithm

- Cost of merge phase:
  - $(F/M)/(M\text{-}1)^k$ runs after k merge steps
  - $\lceil \text{Log}_{M-1}(F/M) \rceil$ merge steps needed to merge an initial set of F/M sorted runs
  - $cost = \lceil 2F \text{ Log}_{M-1}(F/M) \rceil \approx 2F(\text{Log}_{M-1}F - 1)$
- Total cost = cost of partial sort phase + cost of merge phase $\approx 2F \text{ Log}_{M-1}F$

Duplicate Elimination

- A major step in computing *projection*, *union*, and *difference* relational operators
- Algorithm:
  - Sort
  - At the last stage of the merge step eliminate duplicates on the fly
  - No additional cost (with respect to sorting) in terms of I/O

Duplicate elimination During Merge

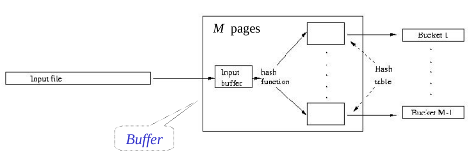


Sort-Based Projection

- Algorithm:
  - Sort rows of relation at cost of $2F \text{ Log}_{M-1}F$
  - Eliminate unwanted columns in partial sort phase (no additional cost)
  - Eliminate duplicates on completion of last merge step (no additional cost)
- Cost: the cost of sorting

Hash-Based Projection

- *Phase* 1:
  - Input rows
  - Project out columns
  - Hash remaining columns using a hash function with range $1 \ldots M\text{-}1$ creating $M\text{-}1$ buckets on disk
  - **Cost** = $2F$
- *Phase* 2:
  - Sort each bucket to eliminate duplicates
  - **Cost** (assuming a bucket fits in $M\text{-}1$ buffer pages) = $2F$
- **Total cost** = $4F$



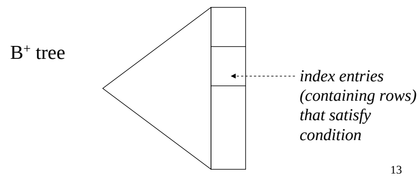
Computing Selection $\sigma_{(attr\ \text{op}\ value)}$

- No index on *attr*:
  - If rows are not sorted on *attr:*
    - Scan all data pages to find rows satisfying selection condition
    - Cost = F
  - If rows are sorted on *attr* and op is =, >, < then:
    - Use *binary search* (at $\log_2 F$) to locate first data page containing row in which ($attr = value$)
    - Scan further to get all rows satisfying (*attr op value*)
    - Cost = $\log_2 F$ + (cost of scan)

Computing Selection $\sigma_{(attr\ \ op\ \ value)}$

- Clustered B+ tree index on *attr* (for "=" or range search):
  - Locate first index entry corresponding to a row in which (*attr* = *value*). Cost = depth of tree
  - Rows satisfying condition packed in sequence in successive data pages; scan those pages.

    Cost: number of pages occupied by qualifying rows



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Computing Selection $\sigma_{(attr\ \ op\ \ value)}$

- Unclustered B+ tree index on *attr* (for "=" or range search):
  - Locate first index entry corresponding to a row in which (*attr* = *value*).

    Cost = depth of tree
  - Index entries with pointers to rows satisfying condition are packed in sequence in successive index pages
    - Scan entries and sort record Ids to identify table data pages with qualifying rows

      Any page that has at least one such row must be fetched once.
    - Cost: number of rows that satisfy selection condition

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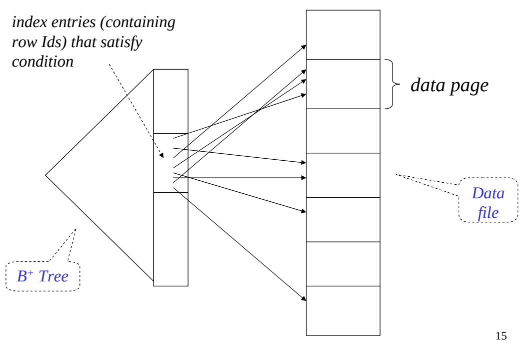
Unclustered B+ Tree Index



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Computing Selection $\sigma_{(attr\ \ =\ \ value)}$

- Hash index on *attr* (for "=" search only):
  - Hash on *value*. Cost ≈ 1.2
    - 1.2 – typical average cost of hashing (> 1 due to possible overflow chains)
    - Finds the (unique) bucket containing all index entries satisfying selection condition
    - Clustered index – all qualifying rows packed in the bucket (a few pages)

      Cost: number of pages occupies by the bucket
    - Unclustered index – sort row Ids in the index entries to identify data pages with qualifying rows

      Each page containing at least one such row must be fetched once

      Cost: min(*number of qualifying rows in bucket, number of pages in file*)

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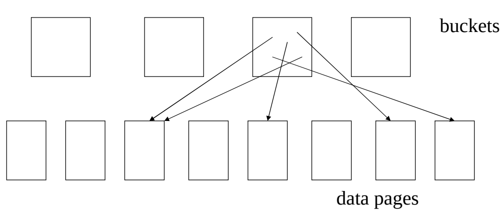
Computing Selection $\sigma_{(attr\ \ =\ \ value)}$

- Unclustered hash index on *attr* (for equality search)



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Access Path

- *Access path* is the notion that denotes *algorithm + data structure* used to locate rows satisfying some condition
- *Examples*:
  - *File scan*: can be used for any condition
  - *Hash*: equality search; *all* search key attributes of hash index are specified in condition
  - *B+ tree*: equality *or* range search; a *prefix* of the search key attributes are specified in condition
    - B+ tree supports a variety of access paths
  - *Binary search*: Relation sorted on a sequence of attributes and some *prefix* of that sequence is specified in condition

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Access Paths Supported by B$^+$ tree

- ***Example***: Given a B$^+$ tree whose search key is the sequence of attributes *a2, a1, a3, a4*
  - Access path for search $\sigma_{a1>5 \wedge a2=3 \wedge a3=\text{'}x\text{'}}(R)$: find first entry having $a2=3 \wedge a1>5 \wedge a3=\text{'}x\text{'}$ and scan leaves from there until entry having $a2>3$ or $a3 \neq \text{'}x\text{'}$. Select satisfying entries
  - Access path for search $\sigma_{a2=3 \wedge a3>\text{'}x\text{'}}(R)$: locate first entry having $a2=3$ and scan leaves until entry having $a2>3$. Select satisfying entries
  - Access path for search $\sigma_{a1>5 \wedge a3=\text{'}x\text{'}}(R)$: Scan of R

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Choosing an Access Path

- *Selectivity* of an access path = number of pages retrieved using that path
- If several access paths support a query, DBMS chooses the one with *lowest* selectivity
- Size of domain of attribute is an indicator of the selectivity of search conditions that involve that attribute
- Example: $\sigma_{CrsCode=\text{'CS305'} \wedge Grade=\text{'B'}}$ (Transcript)
  - a B$^+$ tree with search key *CrsCode* has lower selectivity than a B$^+$ tree with search key *Grade*

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Computing Joins

- The cost of joining two relations makes the choice of a join algorithm crucial
- Simple *block-nested loops* join algorithm for computing $\mathbf{r} \bowtie_{A=B} \mathbf{s}$

foreach page p_r in r **do**
  foreach page p_s in **s** **do**
    output $p_r \bowtie_{A=B} p_s$

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Block-Nested Loops Join

- If β_r and β_s are the number of pages in r and s, the cost of algorithm is

Number of scans of relation **s**

$\beta_r + \beta_r * \beta_s +$ *cost of outputting final result*

- If **r** and **s** have 10^3 pages each, cost is $10^3 + 10^3 * 10^3$
- *Choose smaller relation for the outer loop*:
  - If $\beta_r < \beta_s$ then $\beta_r + \beta_r * \beta_s < \beta_s + \beta_r * \beta_s$

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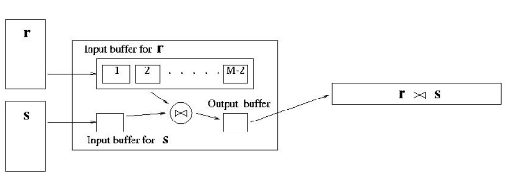
Block-Nested Loops Join

- Cost can be reduced to

Number of scans of relation **s**

$\beta_r + (\beta_r/(M-2)) * \beta_s +$ *cost of outputting final result*

by using M buffer pages instead of 1.



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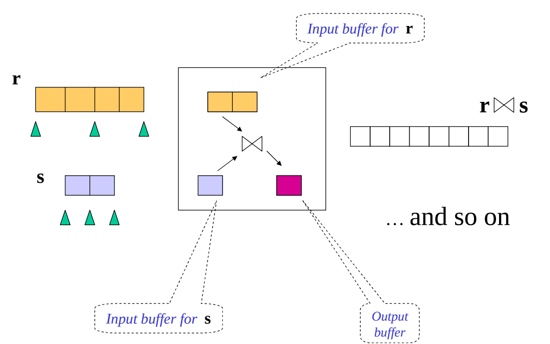
Block-Nested Loop Illustrated



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Index-Nested Loop Join $\mathbf{r} \bowtie_{A=B} \mathbf{s}$

- Use an index on **s** with search key B (instead of scanning **s**) to find rows of **s** that match $t_{\mathbf{r}}$
  - Cost = $\beta_r + \tau_r * \omega$ + *cost of outputting final result*

Number of rows in **r**

avg cost of retrieving *all* rows in **s** that match t_r

  - Effective if number of rows of **s** that match tuples in **r** is small (i.e., ω is small) and index is <u>clustered</u>

foreach tuple t_r in **r** **do {**
    use index to find all tuples t_s in **s** satisfying $t_{\mathbf{r}}.A = t_s.B$;
    output (t_r, t_s)
}

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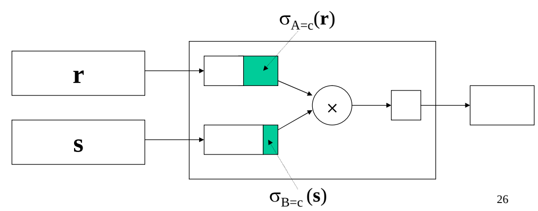
Sort-Merge Join $\mathbf{r} \bowtie_{A=B} \mathbf{s}$

sort **r** on A;
sort **s** on B;
while !*eof*(**r**) and !*eof*(**s**) **do** {
    Scan **r** and **s** concurrently until $t_{\mathbf{r}}.A = t_s.B = c$;
    Output $\sigma_{A=c}(\mathbf{r}) \times \sigma_{B=c}(\mathbf{s})$
}



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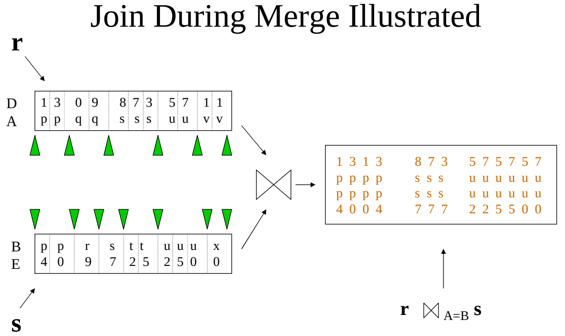
Join During Merge Illustrated



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Cost of Sort-Merge Join

- Cost of *sorting* assuming *M* buffers:

$$2\,\beta_{\mathbf{r}} \log_{M-1} \beta_{\mathbf{r}} + 2\,\beta_{\mathbf{s}} \log_{M-1} \beta_{\mathbf{s}}$$

- Cost of *merging:*
  - Scanning $\sigma_{A=c}(\mathbf{r})$ and $\sigma_{B=c}(\mathbf{s})$ can be combined with the last step of sorting of **r** and **s** --- costs nothing
  - Cost of $\sigma_{A=c}(\mathbf{r}) \times \sigma_{B=c}(\mathbf{s})$ depends on whether $\sigma_{A=c}(\mathbf{r})$ can fit in the buffer
    - If yes, this step costs 0
    - In no, each $\sigma_{A=c}(\mathbf{r}) \times \sigma_{B=c}(\mathbf{s})$ is computed using *block-nested* join, so the cost is the cost of the join. (Think why indexed methods or sort-merge are inapplicable to Cartesian product.)
- Cost of outputting the *final result* depends on the size of the result

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Hash-Join $\mathbf{r} \bowtie_{A=B} \mathbf{s}$

- *Step* 1: Hash **r** on A and **s** on B into the same set of buckets
- *Step* 2: Since matching tuples must be in same bucket, read each bucket in turn and output the result of the join
- *Cost*: $3(\beta_{\mathbf{r}} + \beta_{\mathbf{s}})$ + *cost of output of final result*
  - assuming each bucket fits in memory

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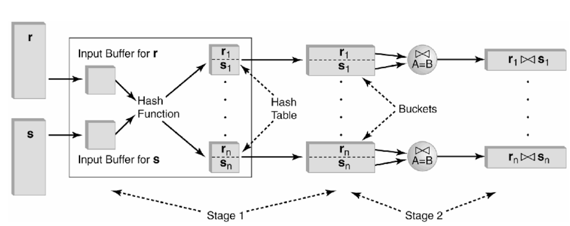
Hash Join



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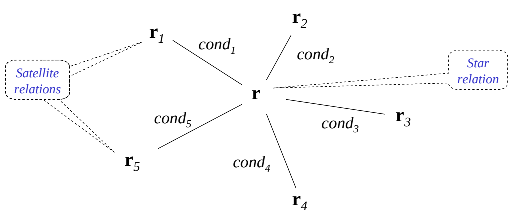
Star Joins

- $\mathbf{r} \bowtie_{cond_1} \mathbf{r}_1 \bowtie_{cond_2} \cdots \bowtie_{cond_n} \mathbf{r}_n$
  - Each $cond_i$ involves only the attributes of $\mathbf{r}_i$ and $\mathbf{r}$



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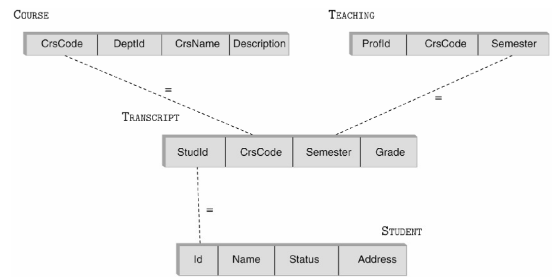
Star Join



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Computing Star Joins

- Use *join index* (Chapter 11)
  - Scan $\mathbf{r}$ and the join index $\{<r, r_1, \ldots, r_n>\}$ (which is a set of tuples of rids) in one scan
  - Retrieve matching tuples in $\mathbf{r}_1, \ldots, \mathbf{r}_n$
  - Output result

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Computing Star Joins

- Use *bitmap indices* (Chapter 11)
  - Use one bitmapped join index, J_i, per each partial join $\mathbf{r} \bowtie_{cond_i} \mathbf{r}_i$
  - *Recall*: J_i is a set of $<v, bitmap>$, where v is an rid of a tuple in $\mathbf{r}_i$ and *bitmap* has 1 in k-th position iff k-th tuple of $\mathbf{r}$ joins with the tuple pointed to by v

1. Scan J_i and logically OR all bitmaps. We get all rids in $\mathbf{r}$ that join with $\mathbf{r}_i$
2. Now logically AND the resulting bitmaps for $J_1, \ldots, J_n$.
3. Result: a subset of $\mathbf{r}$, which contains all tuples that can possibly be in the star join
   - *Rationale*: only a few such tuples survive, so can use indexed loops

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Choosing Indices

- DBMSs may allow user to specify
  - Type (hash, B^+ tree) and search key of index
  - Whether or not it should be clustered
- Using information about the frequency and type of queries and size of tables, designer can use cost estimates to choose appropriate indices
- Several commercial systems have tools that suggest indices
  - Simplifies job, but index suggestions must be *verified*

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Choosing Indices – Example

- If a frequently executed query that involves selection or a join and has a large result set, use a clustered B^+ tree index

  Example: Retrieve all rows of Transcript for *StudId*
- If a frequently executed query is an equality search and has a small result set, an unclustered hash index is best
  - Since only one clustered index on a table is possible, choosing unclustered allows a different index to be clustered

  Example: Retrieve all rows of Transcript for (*StudId*, *CrsCode*)

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