# Advanced Database Systems

Lecture 3

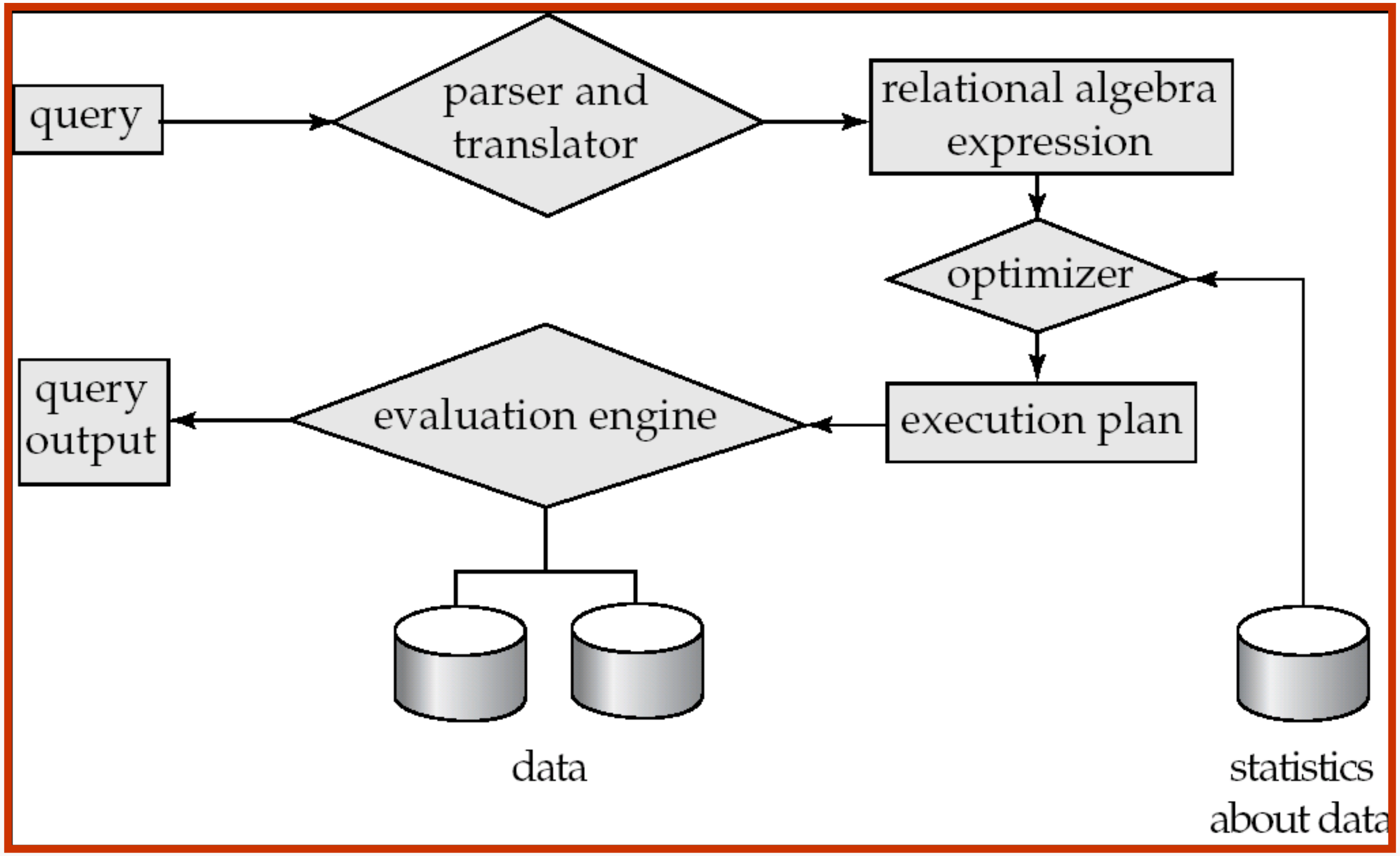
Query Processing

# Chapter 13:  Query Processing

- Overview
- Measures of Query Cost
- Selection Operation
- Sorting
- Join Operation
- Other Operations
- Evaluation of Expressions

# Basic Steps in Query Processing

1. Parsing and translation
2. Optimization
3. Evaluation



# Basic Steps in Query Processing (Cont.)

- Parsing and translation
  - translate the query into its internal form. This is then translated into relational algebra.
  - Parser checks syntax, verifies relations
- Evaluation
  - The query-execution engine takes a query-evaluation plan, executes that plan, and returns the answers to the query.

# Basic Steps in Query Processing : Optimization

**select** *balance*

**from** *account*

**where** *balance<2500*

- A relational algebra expression may have many equivalent expressions
  - E.g., $\sigma_{balance<2500}(\Pi_{balance}(account))$ is equivalent to
    $\Pi_{balance}(\sigma_{balance<2500}(account))$
- Each relational algebra operation can be evaluated using one of several different algorithms
  - Correspondingly, a relational-algebra expression can be evaluated in many ways.
- Annotated expression specifying detailed evaluation strategy is called an **evaluation-plan**.
  - E.g., can use an index on *balance* to find accounts with balance < 2500,
  - or can perform complete relation scan and discard accounts with balance $\geq$ 2500

# Basic Steps: Optimization (Cont.)

- **Query Optimization**: Amongst all equivalent evaluation plans choose the one with lowest cost.
  - Cost is estimated using statistical information from the database catalog
    - e.g. number of tuples in each relation, size of tuples, etc.
- In this chapter we study
  - How to measure query costs
  - Algorithms for evaluating relational algebra operations
  - How to combine algorithms for individual operations in order to evaluate a complete expression
- In Chapter 14
  - We study how to optimize queries, that is, how to find an evaluation plan with lowest estimated cost

# Measures of Query Cost

- Cost is generally measured as total elapsed time for answering query
  - Many factors contribute to time cost
    - *disk accesses, CPU*, or even network *communication*
- Typically disk access is the predominant cost, and is also relatively easy to estimate. Measured by taking into account
  - Number of seeks * average-seek-cost
  - Number of blocks read * average-block-read-cost
  - Number of blocks written * average-block-write-cost
    - Cost to write a block is greater than cost to read a block
      - data is read back after being written to ensure that the write was successful

# Measures of Query Cost (Cont.)

- For simplicity we just use the *number of block transfers from disk and the number of seeks* as the cost measures
  - $t_T$ – time to transfer one block (around 0.1 ms)
  - $t_S$ – time for one seek (around 4 ms)
  - Cost for b block transfers plus S seeks

    $b * t_T + S * t_S$
- We ignore CPU costs for simplicity
  - Real systems do take CPU cost into account
- We do not include cost to writing output to disk in our cost formulae
- Several algorithms can reduce disk IO by using extra buffer space
  - Amount of real memory available to buffer depends on other concurrent queries and OS processes, known only during execution
    - We often use worst case estimates, assuming only the minimum amount of memory needed for the operation is available
- Required data may be buffer resident already, avoiding disk I/O
  - But hard to take into account for cost estimation

# Selection Operation

- **File scan** – search algorithms that locate and retrieve records that fulfill a selection condition.
- Algorithm **A1** (*linear search*). Scan each file block and test all records to see whether they satisfy the selection condition.
  - Cost estimate = $b_r$ block transfers + 1 seek
    - $b_r$ denotes number of blocks containing records from relation $r$
  - If selection is on a key attribute, can stop on finding record
    - cost = ($b_r$/2) block transfers + 1 seek (on average)
  - Linear search can be applied regardless of
    - selection condition or
    - ordering of records in the file, or
    - availability of indices

# Selection Operation (Cont.)

- **A2** *(binary search).* Applicable if selection is an equality comparison on the attribute on which file is ordered.
  - Assume that the blocks of a relation are stored contiguously
  - Cost estimate (number of disk blocks to be scanned):
    - cost of locating the first tuple by a binary search on the blocks
      - $\lceil \log_2(b_r) \rceil * (t_T + t_S)$
    - If there are multiple records satisfying selection
      - *Add transfer cost of the* number of blocks containing records that satisfy selection condition

# Selections Using Indices

- **Index scan** – search algorithms that use an index
  - selection condition must be on search-key of index.
- **A3** (*primary index on candidate key, equality*). Retrieve a single record that satisfies the corresponding equality condition
  - *Cost* = $(h_i + 1) * (t_T + t_S)$
- **A4** (*primary index on nonkey, equality)* Retrieve multiple records.
  - Records will be on consecutive blocks
    - Let b = number of blocks containing matching records
  - *Cost* = $h_i * (t_T + t_S) + t_S + t_T * b$
- **A5** (*equality on search-key of secondary index).*
  - Retrieve a single record if the search-key is a candidate key
    - *Cost* = $(h_i + 1) * (t_T + t_S)$
  - Retrieve multiple records if search-key is not a candidate key
    - each of *n* matching records may be on a different block
    - Cost = $(h_i + n) * (t_T + t_S)$
      - Can be very expensive! (even more than linear search)

# Selections Involving Comparisons

- Can implement selections of the form $\sigma_{A \leq V}(r)$ or $\sigma_{A \geq V}(r)$ by using
  - a linear file scan or binary search,
  - or by using indices in the following ways:
- **A6** (*primary index, comparison).* (Relation is sorted on A)
  - For $\sigma_{A \geq V}(r)$ use index to find first tuple $\geq v$ and scan relation sequentially from there
  - For $\sigma_{A \leq V}(r)$ just scan relation sequentially till first tuple $> v$; do not use index
- **A7** (*secondary index, comparison*).
  - For $\sigma_{A \geq V}(r)$ use index to find first index entry $\geq v$ and scan index sequentially from there, to find pointers to records.
  - For $\sigma_{A \leq V}(r)$ just scan leaf pages of index finding pointers to records, till first entry $> v$
  - In either case, retrieve records that are pointed to
    - requires an I/O for each record
    - Linear file scan may be cheaper

# Implementation of Complex Selections

- **Conjunction:** $\sigma_{\theta 1} \wedge _{\theta 2} \wedge \ldots _{\theta n}(r)$
- **A8** (*conjunctive selection using one index).*
  - Select a combination of $\theta_i$ and algorithms A1 through A7 that results in the least cost for $\sigma_{\theta i}\,(r)$.
  - Test other conditions on tuple after fetching it into memory buffer.
- **A9** (*conjunctive selection using multiple-key index*).
  - Use appropriate composite (multiple-key) index if available.
- **A10** (*conjunctive selection by intersection of identifiers).*
  - Requires indices with record pointers.
  - Use corresponding index for each condition, and take intersection of all the obtained sets of record pointers.
  - Then fetch records from file
  - If some conditions do not have appropriate indices, apply test in memory.

# Algorithms for Complex Selections

- **Disjunction:** $\sigma_{\theta_1 \vee \theta_2 \vee \ldots \theta_n}(r)$.
- **A11** (*disjunctive selection by union of identifiers*).
  - Applicable if *all* conditions have available indices.
    - Otherwise use linear scan.
  - Use corresponding index for each condition, and take union of all the obtained sets of record pointers.
  - Then fetch records from file
- **Negation:** $\sigma_{\neg\theta}(r)$
  - Use linear scan on file
  - If very few records satisfy $\neg\theta$, and an index is applicable to $\theta$
    - Find satisfying records using index and fetch from file

# Sorting

- Sorting is important because
  - Queries can specify that output be sorted
  - Several of relational operations (e.g. :- joins) can be implemented efficiently if the relations are first sorted
- We may build an index on the relation, and then use the index to read the relation in sorted order.  May lead to one disk block access for each tuple (not a good choice).
- For relations that fit in memory, techniques like quicksort can be used. For relations that don't fit in memory, **external sort-merge** is a good choice.

# External Sort-Merge

Let $M$ denote memory size (in pages).

1. **Create sorted runs**. Let $i$ be 0 initially.

   Repeatedly do the following till the end of the relation:

   (a) Read $M$ blocks of relation into memory

   (b) Sort the in-memory blocks

   (c) Write sorted data to run $R_i$; increment $i$.

   Let the final value of $i$ be $N$

2. *Merge the runs (next slide)…..*

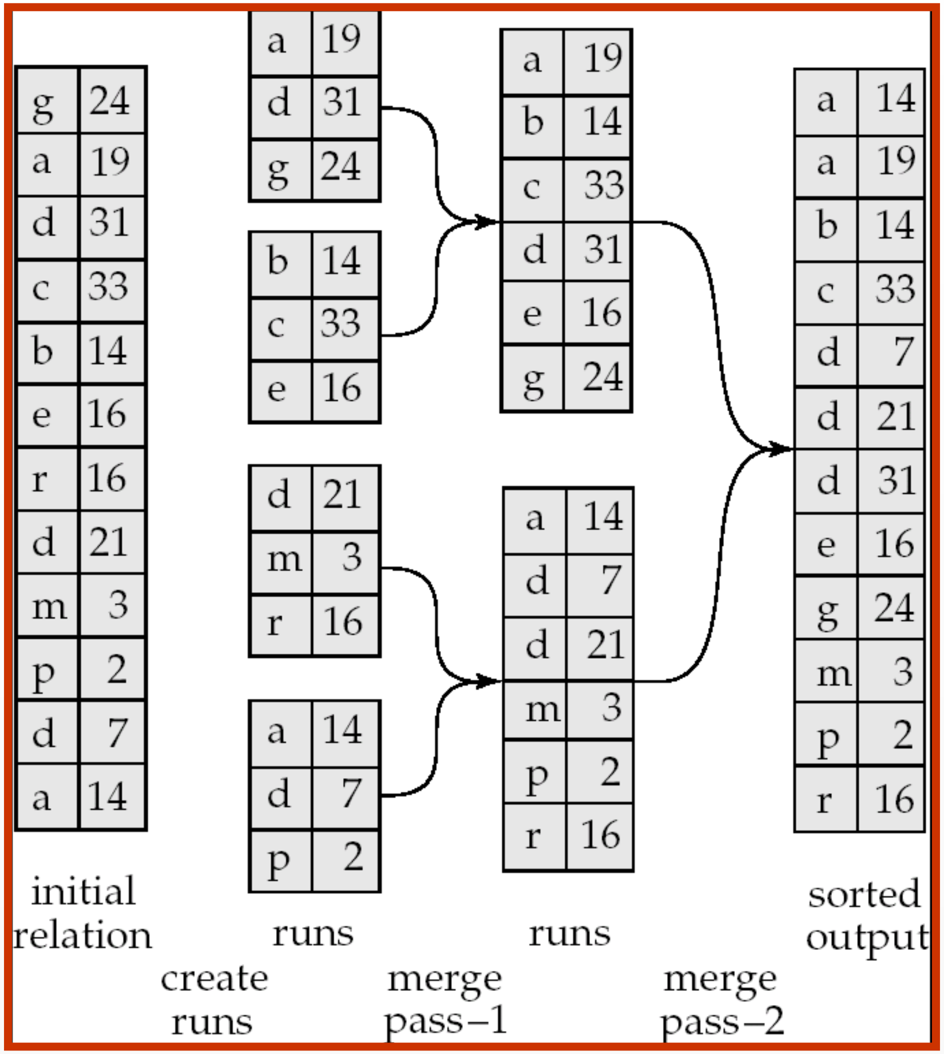
# External Sort-Merge (Cont.)

2. **Merge the runs (N-way merge).** We assume (for now) that $N < M$.
   1. Use $N$ blocks of memory to buffer input runs, and 1 block to buffer output. Read the first block of each run into its buffer page
   2. **repeat**
      1. Select the first record (in sort order) among all buffer pages
      2. Write the record to the output buffer. If the output buffer is full write it to disk.
      3. Delete the record from its input buffer page.
         **If** the buffer page becomes empty **then**
         read the next block (if any) of the run into the buffer.
   3. **until** all input buffer pages are empty:

# External Sort-Merge (Cont.)

- If $N \geq M$, several merge *passes* are required.
  - In each pass, contiguous groups of $M$ - 1 runs are merged.
  - A pass reduces the number of runs by a factor of $M$ -1, and creates runs longer by the same factor.
    - E.g. If M=11, and there are 90 runs, one pass reduces the number of runs to 9, each 10 times the size of the initial runs
  - Repeated passes are performed till all runs have been merged into one.

# Example: External Sorting Using Sort-Merge



# External Merge Sort (Cont.)

- Cost analysis:
  - Total number of merge passes required: $\lceil \log_{M-1}(b_r/M) \rceil$.
  - Block transfers for initial run creation as well as in each pass is $2b_r$
    - for final pass, we don't count write cost
      - we ignore final write cost for all operations since the output of an operation may be sent to the parent operation without being written to disk
    - Thus total number of block transfers for external sorting:

$$b_r ( 2 \lceil \log_{M-1}(b_r / M) \rceil + 1)$$

  - Seeks: next slide

# External Merge Sort (Cont.)

- Cost of seeks
  - During run generation: one seek to read each run and one seek to write each run
    - $2 \lceil b_r / M \rceil$
  - During the merge phase
    - Buffer size: $b_b$ (read/write $b_b$ blocks at a time)
    - Need $2 \lceil b_r / b_b \rceil$ seeks for each merge pass
      - except the final one which does not require a write
    - Total number of seeks:
      $2 \lceil b_r / M \rceil + \lceil b_r / b_b \rceil \, (2 \lceil \log_{M-1}(b_r / M) \rceil - 1)$

# Join Operation

- Several different algorithms to implement joins
  - Nested-loop join
  - Block nested-loop join
  - Indexed nested-loop join
  - Merge-join
  - Hash-join
- Choice based on cost estimate
- Examples use the following information
  - Number of records of *customer*: 10,000 *depositor*: 5000
  - Number of blocks of *customer*: 400 *depositor*: 100
- $n_r$ represents the number of records of relation r while $b_r$ represents the number of blocks of relation r

# Nested-Loop Join

- To compute the theta join $r \bowtie_\theta s$

  **for each** tuple $t_r$ **in** *r* **do begin**

      **for each tuple** $t_s$ **in** *s* **do begin**

          test pair $(t_r, t_s)$ to see if they satisfy the join condition $\theta$

          if they do, add $t_r \bullet t_s$ to the result.

      **end**

  **end**
- *r* is called the **outer relation** and *s* the **inner relation** of the join.
- Requires no indices and can be used with any kind of join condition.
- Expensive since it examines every pair of tuples in the two relations.

# Nested-Loop Join (Cont.)

- In the worst case, if there is enough memory only to hold one block of each relation, the estimated cost is

  $$n_r \ast b_s + b_r$$

  block transfers, plus

  $$n_r + b_r$$

  seeks
- If the smaller relation fits entirely in memory, use that as the inner relation.
  - Reduces cost to $b_r + b_s$ block transfers and 2 seeks
- Assuming worst case memory availability cost estimate is
  - with *depositor* as outer relation:
    - $5000 \ast 400 + 100 = 2{,}000{,}100$ block transfers,
    - $5000 + 100 = 5100$ seeks
  - with *customer* as the outer relation
    - $10000 \ast 100 + 400 = 1{,}000{,}400$ block transfers and 10,400 seeks
- If smaller relation (*depositor)* fits entirely in memory, the cost estimate will be 500 block transfers.
- Block nested-loops algorithm (next slide) is preferable.

# Block Nested-Loop Join

- Variant of nested-loop join in which every block of inner relation is paired with every block of outer relation.

**for each** block $B_r$ **of** $r$ **do begin**
    **for each** block $B_s$ **of** ***s*** **do begin**
        **for each** tuple $t_r$ **in** $B_r$ **do begin**
            **for each** tuple $t_s$ **in** $B_s$ **do begin**
                Check if $(t_r, t_s)$ satisfy the join condition
                if they do, add $t_r \bullet t_s$ to the result.
            **end**
        **end**
    **end**
**end**

# Block Nested-Loop Join (Cont.)

- Worst case estimate: $b_r \ast b_s + b_r$ block transfers + 2 * $b_r$ seeks
  - Each block in the inner relation *s* is read once for each *block* in the outer relation (instead of once for each tuple in the outer relation
- Best case: $b_r + b_s$ block transfers + 2 seeks.
- Improvements to nested loop and block nested loop algorithms:
  - In block nested-loop, use *M* — 2 disk blocks as blocking unit for outer relations, where *M* = memory size in blocks; use remaining two blocks to buffer inner relation and output
    - Cost = $\lceil b_r / (M\text{-}2) \rceil \ast b_s + b_r$ block transfers + $2 \lceil b_r / (M\text{-}2) \rceil$ seeks
  - If equi-join attribute forms a key of inner relation, stop inner loop on first match
  - Scan inner loop forward and backward alternately, to make use of the blocks remaining in buffer
  - Use index on inner relation if available (next slide)

# Indexed Nested-Loop Join

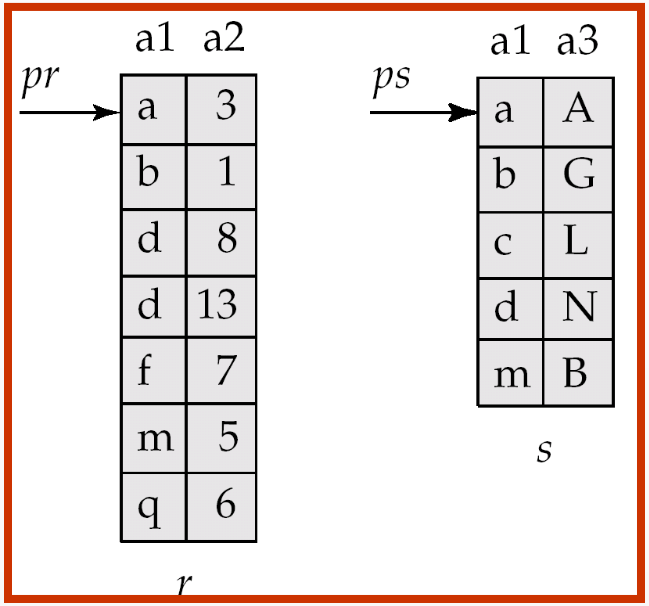
- Index lookups can replace file scans if
  - join is an equi-join or natural join and
  - an index is available on the inner relation's join attribute
    - Can construct an index just to compute a join.
- For each tuple $t_r$ in the outer relation *r,* use the index to look up tuples in *s* that satisfy the join condition with tuple $t_r$.
- Worst case: buffer has space for only one page of *r*, and, for each tuple in *r*, we perform an index lookup on *s.*
- Cost of the join: $b_r\,(t_T + t_S) + n_r * c$
  - Where *c* is the cost of traversing index and fetching all matching *s* tuples for one tuple or *r*
  - *c* can be estimated as cost of a single selection on *s* using the join condition.
- If indices are available on join attributes of both *r* and *s,* use the relation with fewer tuples as the outer relation.

# Example of Nested-Loop Join Costs

- Compute *depositor* ⋈ *customer,* with *depositor* as the outer relation.
- Let *customer* have a primary B+-tree index on the join attribute *customer-name,* which contains 20 entries in each index node.
- Since *customer* has 10,000 tuples, the height of the tree is 4, and one more access is needed to find the actual data
- *depositor* has 5000 tuples
- Cost of block nested loops join
  - 400*100 + 100 = 40,100 block transfers + 2 * 100 = 200 seeks
    - assuming worst case memory
    - may be significantly less with more memory
- Cost of indexed nested loops join
  - 100 + 5000 * 5 = 25,100 block transfers and seeks.
  - CPU cost likely to be less than that for block nested loops join

# Merge-Join

1. Sort both relations on their join attribute (if not already sorted on the join attributes).
2. Merge the sorted relations to join them
   1. Join step is similar to the merge stage of the sort-merge algorithm.
   2. Main difference is handling of duplicate values in join attribute — every pair with same value on join attribute must be matched
   3. Detailed algorithm in book



# Merge-Join (Cont.)

- Can be used only for equi-joins and natural joins
- Each block needs to be read only once (assuming all tuples for any given value of the join attributes fit in memory
- The cost of merge join is:

  $b_r + b_s$ block transfers $+ \lceil b_r / b_b \rceil + \lceil b_s / b_b \rceil$ seeks

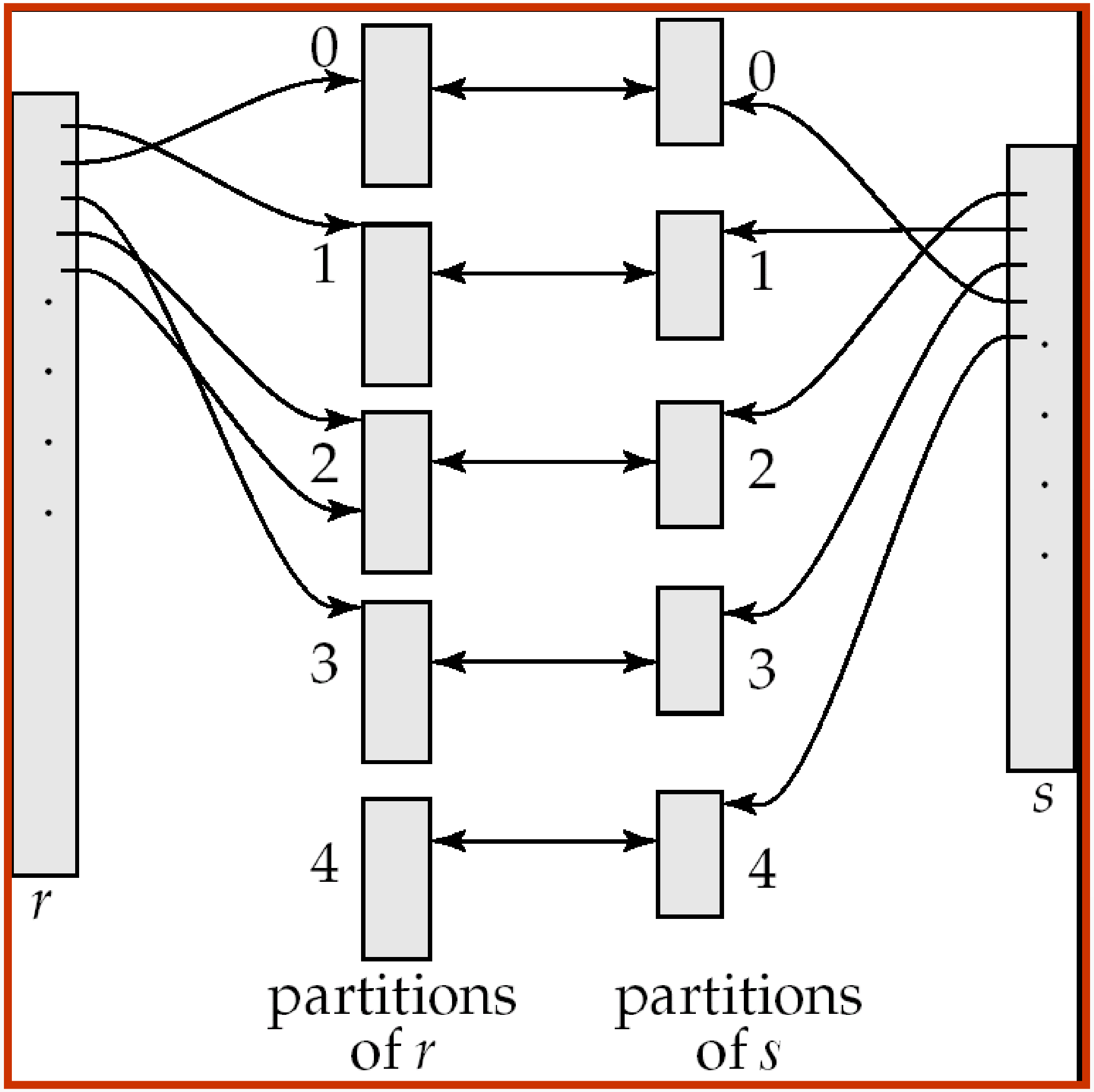
  - + the cost of sorting if relations are unsorted.

# Hash-Join

- Applicable for equi-joins and natural joins.
- A hash function $h$ is used to partition tuples of both relations
- $h$ maps *JoinAttrs* values to {0, 1, ..., $n$}, where *JoinAttrs* denotes the common attributes of $r$ and $s$ used in the natural join.
  - $r_0, r_1, \ldots, r_n$ denote partitions of $r$ tuples
    - Each tuple $t_r \in r$ is put in partition $r_i$ where $i = h(t_r[JoinAttrs])$.
  - $s_0, s_1, \ldots, s_n$ denotes partitions of $s$ tuples
    - Each tuple $t_s \in s$ is put in partition $s_i$, where $i = h(t_s[JoinAttrs])$.

- *Note:* In book, $r_i$ is denoted as $H_{ri}$, $s_i$ is denoted as $H_{si}$ and $n$ is denoted as $n_h$.

# Hash-Join (Cont.)



# Hash-Join (Cont.)

- *r* tuples in $r_i$ need only to be compared with *s* tuples in $s_i$ Need not be compared with *s* tuples in any other partition, since:
  - an *r* tuple and an *s* tuple that satisfy the join condition will have the same value for the join attributes.
  - If that value is hashed to some value *i*, the *r* tuple has to be in $r_i$ and the *s* tuple in $s_i$.

# Complex Joins

- Join with a conjunctive condition:

$$r \bowtie_{\theta_1 \wedge \theta_2 \wedge \ldots \wedge \theta_n} s$$

  - Either use nested loops/block nested loops, or
  - Compute the result of one of the simpler joins $r \bowtie_{\theta_i} s$
    - final result comprises those tuples in the intermediate result that satisfy the remaining conditions

$$\theta_1 \wedge \ldots \wedge \theta_{i-1} \wedge \theta_{i+1} \wedge \ldots \wedge \theta_n$$

- Join with a disjunctive condition

$$r \bowtie_{\theta_1 \vee \theta_2 \vee \ldots \vee \theta_n} s$$

  - Either use nested loops/block nested loops, or
  - Compute as the union of the records in individual joins $r \bowtie_{\theta_i} s$:

$$(r \bowtie_{\theta_1} s) \cup (r \bowtie_{\theta_2} s) \cup \ldots \cup (r \bowtie_{\theta_n} s)$$

# Other Operations

- **Duplicate elimination** can be implemented via hashing or sorting.
  - On sorting duplicates will come adjacent to each other, and all but one set of duplicates can be deleted.
  - *Optimization:* duplicates can be deleted during run generation as well as at intermediate merge steps in external sort-merge.
  - Hashing is similar – duplicates will come into the same bucket.
- **Projection:**
  - perform projection on each tuple
  - followed by duplicate elimination.
- There are evaluation plans for other operations such as aggregation, set operations and outer join.

# Evaluation of Expressions

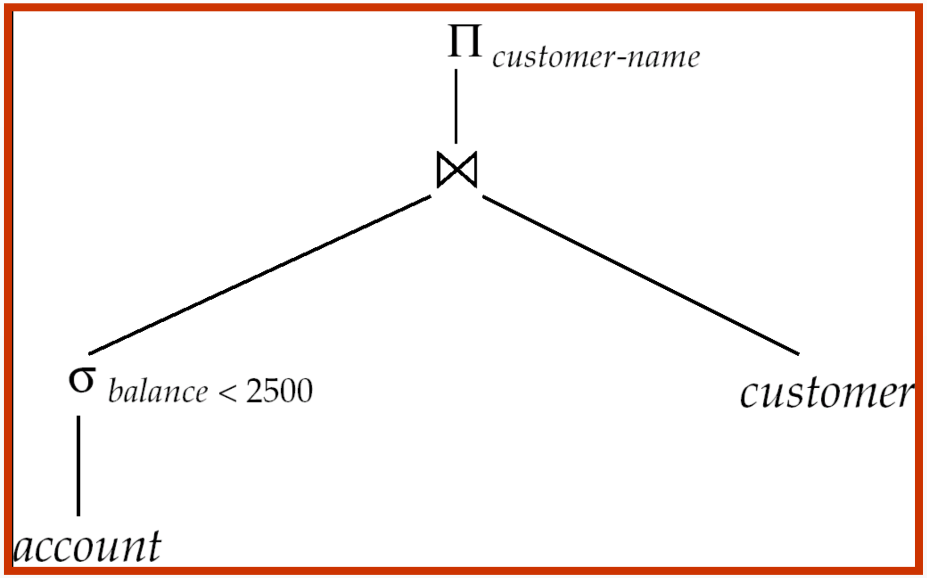
- So far: we have seen algorithms for individual operations
- Alternatives for evaluating an entire expression tree
  - **Materialization**: generate results of an expression whose inputs are relations or are already computed, **materialize** (store) it on disk. Repeat.
  - **Pipelining**: pass on tuples to parent operations even as an operation is being executed

# Materialization

- **Materialized evaluation:** evaluate one operation at a time, starting at the lowest-level. Use intermediate results materialized into temporary relations to evaluate next-level operations.
- E.g., in figure below, compute and store

$$\sigma_{balance<2500}(account)$$

then compute and store its join with *customer,* and finally compute the projections on *customer-name.*



# Materialization (Cont.)

- Materialized evaluation is always applicable
- Cost of writing results to disk and reading them back can be quite high
  - Our cost formulae for operations ignore cost of writing results to disk, so
    - Overall cost = Sum of costs of individual operations + cost of writing intermediate results to disk
- Double buffering: use two output buffers for each operation, when one is full write it to disk while the other is getting filled
  - Allows overlap of disk writes with computation and reduces execution time

# Pipelining

- **Pipelined evaluation** **:** evaluate several operations simultaneously, passing the results of one operation on to the next.
- E.g., in previous expression tree, don't store result of

$$\sigma_{balance<2500}(account)$$

  - instead, pass tuples directly to the join. Similarly, don't store result of join, pass tuples directly to projection.
- Much cheaper than materialization: no need to store a temporary relation to disk.
- Pipelining may not always be possible – e.g., sort, hash-join.
- For pipelining to be effective, use evaluation algorithms that generate output tuples even as tuples are received for inputs to the operation.

Let relations r1(A,B,C) and r2(C,D,E) have the following properties: r1 has 20,000 tuples, r2 has 45,000 tuples, 25 tuples of r1 fit on one block, and 30 tuples of r2 fit on one block. Estimate the number of block transfers and the seeks required, using each of the following join strategies for r1,r2.

1. Nested-loop join
2. Block nested-loop join
3. Merge join
4. Hash join

## Exercise :

## Draw the expression trees and select the best options

$$\Pi_{proj\_name,budget}((\sigma_{emp\_city = \text{“Moratuwa”}}(Employee)) \bowtie Assignment \bowtie Project)$$

$$\Pi_{proj\_name,budget}(\sigma_{emp\_city = \text{“Moratuwa”}}(Employee \bowtie Assignment \bowtie Project))$$

If the following information is given can we write a better evaluation plan?

Employee(emp_no, emp_name, emp_city, …….)

Assignment(emp_no,proj_no,hours,……….)

Project(proj_name, budget, proj_no,……..)