Query Processing

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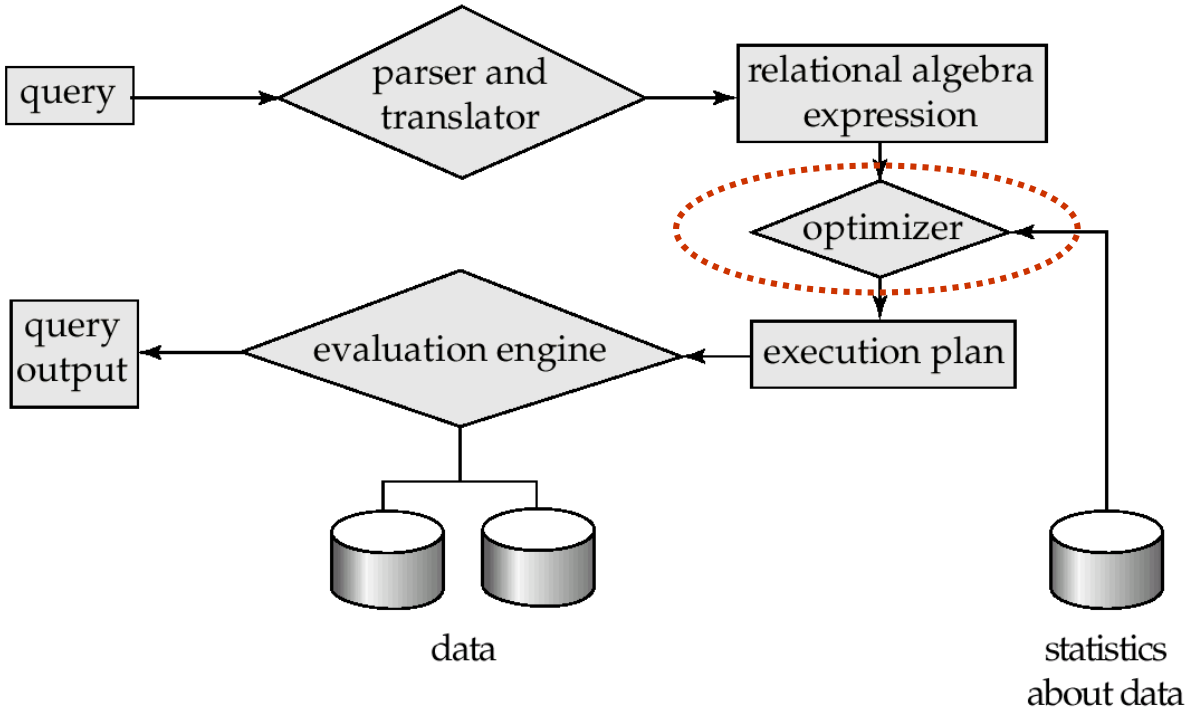
Outline

- 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, which 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

- A relational algebra expression may have many equivalent expressions
- Each relational algebra operation can be evaluated using one of several different algorithms
- Annotated expression specifying detailed evaluation strategy is called an **evaluation-plan**
  - can use an index on *balance* to find accounts with balance < 2500,
  - or can perform complete relation scan and discard accounts with balance ≥ 2500

Basic Steps in Query Processing: Optimization

- Example:

  select *

  from account

  where balance < 2500

- can use an index on *balance* to find accounts with balance < 2500,
- or can perform complete relation scan and discard accounts with balance ≥ 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
- In this lecture 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 next lecture
  - We study how to optimize queries, that is, how to find an evaluation plan with lowest estimated cost

Measures of Query Cost

Measures of Query Cost

- Cost is generally measured as total elapsed time for answering query
  - *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 *number of block transfers* from disk as the cost measure
  - We ignore the difference in cost between sequential and random I/O for simplicity
  - We also ignore CPU costs for simplicity
- Costs depends on the size of the buffer in main memory
  - Having more memory reduces need for disk access
  - We often use worst case estimates, assuming only the minimum amount of memory needed for the operation is available
- Real systems take CPU cost into account, differentiate between sequential and random I/O, and take buffer size into account
- We do not include cost to writing output to disk in our cost formulae

Selection

$\sigma_p(r)$ or

select *

from r

where p

Selection Operation

- **File scan** – search algorithms that locate and retrieve records that fulfill a selection condition.
- *Algorithm **A1** (linear search)*
  - Cost estimate (number of disk blocks scanned) = b_r
  - If selection is on a key attribute, average cost = $(b_r / 2)$
    - stop on finding record
  - 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):
    - $\lceil \log_2(b_r) \rceil$ — cost of locating the first tuple by a binary search on the blocks
    - *Plus* number of blocks containing records that satisfy selection condition
      - Will see how to estimate this cost in next lecture

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* = HT_i + 1 (B^+-tree)
- ***A4*** *(primary index on nonkey, equality)* : Retrieve multiple records
  - Records will be on consecutive blocks
  - *Cost* = HT_i + number of blocks containing retrieved records

Selections Using Indices (Cont.)

- **A5** (*equality on search-key of secondary index*)
  - Retrieve a single record if the search-key is a candidate key
    - *Cost* = $HT_i + 1$
  - Retrieve multiple records if search-key is not a candidate key
    - *Cost* = HT_i + *number of records retrieved*
      - Can be very expensive!
    - Each record may be on a different block
      - One block access for each retrieved record

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

Selections Involving Comparisons (Cont.)

- *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 if many records are to be fetched!

Implementation of Complex Selections

- **Conjunction (合取):** $\sigma_{\theta 1 \wedge \theta 2 \wedge \ldots \theta n}(r)$
- ***A8*** *(conjunctive selection using one index)*
  - Select a condition of θ_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.

Implementation of Complex Selections (Cont.)

- **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.

Implementation of Complex Selections (Cont.)

- **Disjunction (析取):** $\sigma_{\theta 1 \vee \theta 2 \vee \ldots \theta n}(r)$.
- ***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

Implementation of Complex Selections (Cont.)

- **Negation:** $\sigma_{\neg\theta}(r)$
  - Use linear scan on file
  - If very few records satisfy $\neg\theta$, and an index is applicable to $\neg\theta$
    - Find satisfying records using index and fetch from file
  - Example: $\sigma_{\neg(A\neq 0)}(r) = \sigma_{A=0}(r)$

Sorting

Sorting

- Why sorting?
  - For a SQL query with *order by* clause, query answers must be returned in order
  - For join operation with two relations, if the relations are sorted by the join attributes, the join operation can be evaluated very efficiently
  - Sorting for constructing ordered indices

Sorting

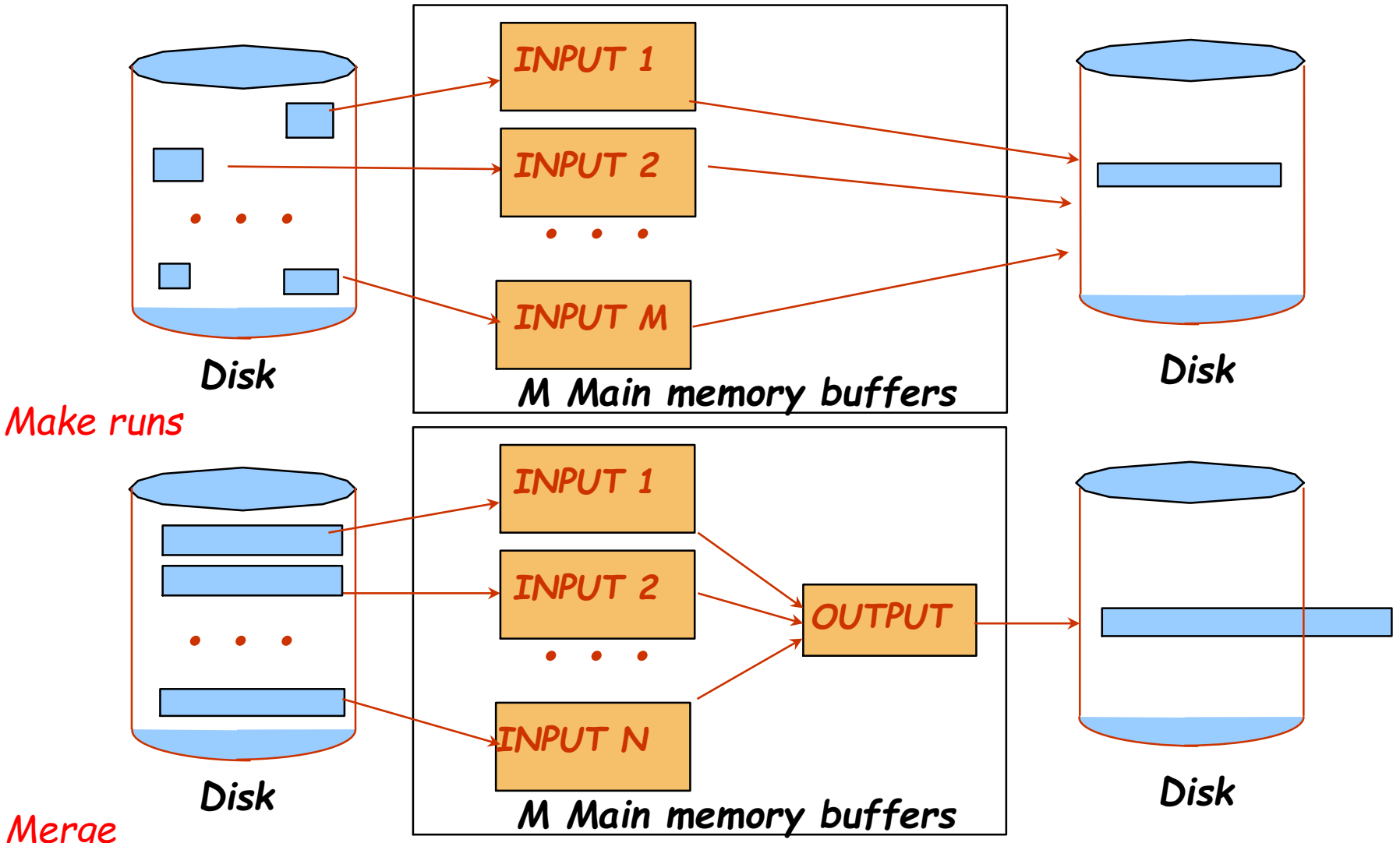
- How to sort relations?
  - For relations that fit in memory, techniques like quick-sort can be used
  - We may build an index on the relation, and then use the index to read the relation in sorted order. May lead to one disk block access for each tuple (for non-primary indices)
  - For relations that 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 (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 of the run into the buffer.
   3. **until** all input buffer pages are empty:

External Sort-Merge



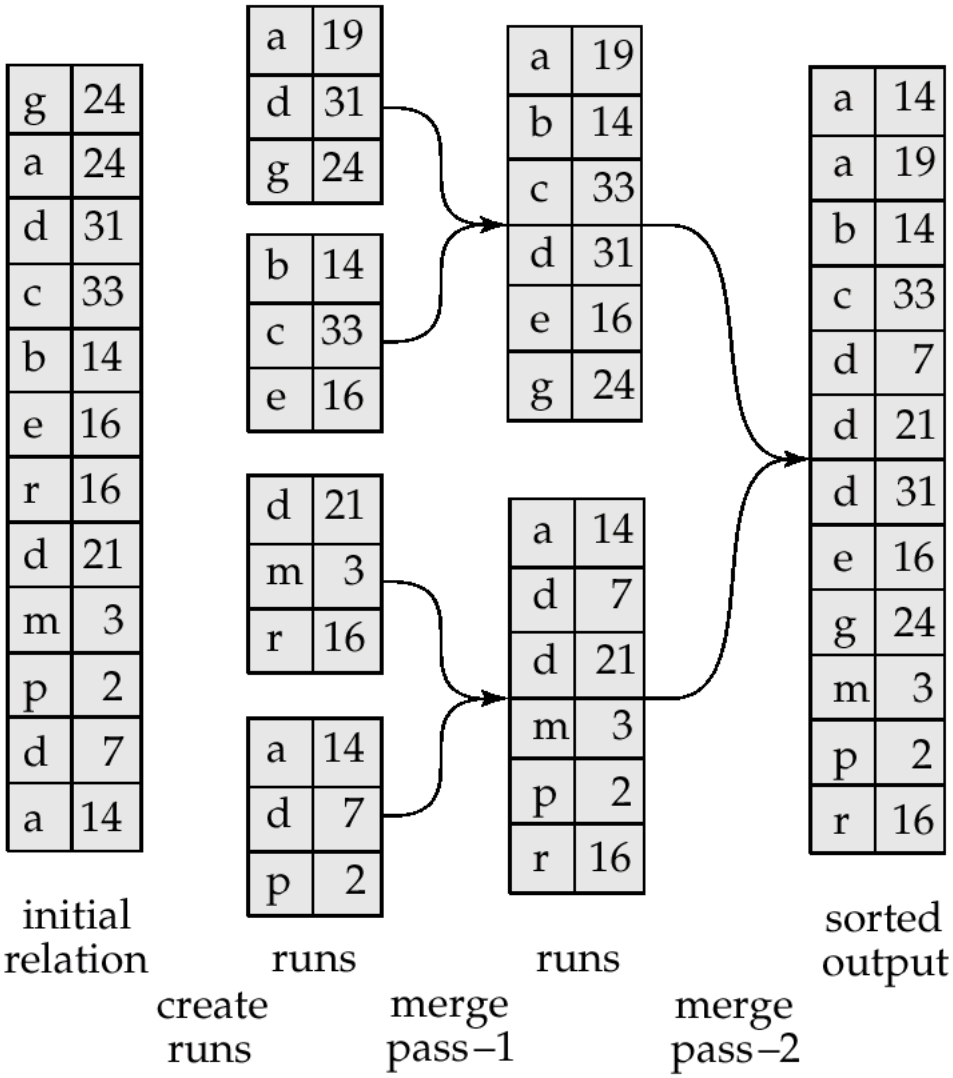
External Sort-Merge (Cont.)

- 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.
    - 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

Sort on the first column!

M=3



External Merge Sort (Cont.)

- Cost analysis:
  - Total number of merge passes required: $\lceil \log_{M-1}(b_r/M) \rceil$.
  - Disk accesses 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 disk accesses for external sorting:

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

Join

- Nested-loop join
- Block nested-loop join
- Indexed nested-loop join
- Merge-join
- Hash-join

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

Tuple 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 θ

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

  end

  end

- r is called the **outer relation** and s the **inner relation**
- 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.

Tuple nested-Loop Join (Cont.)

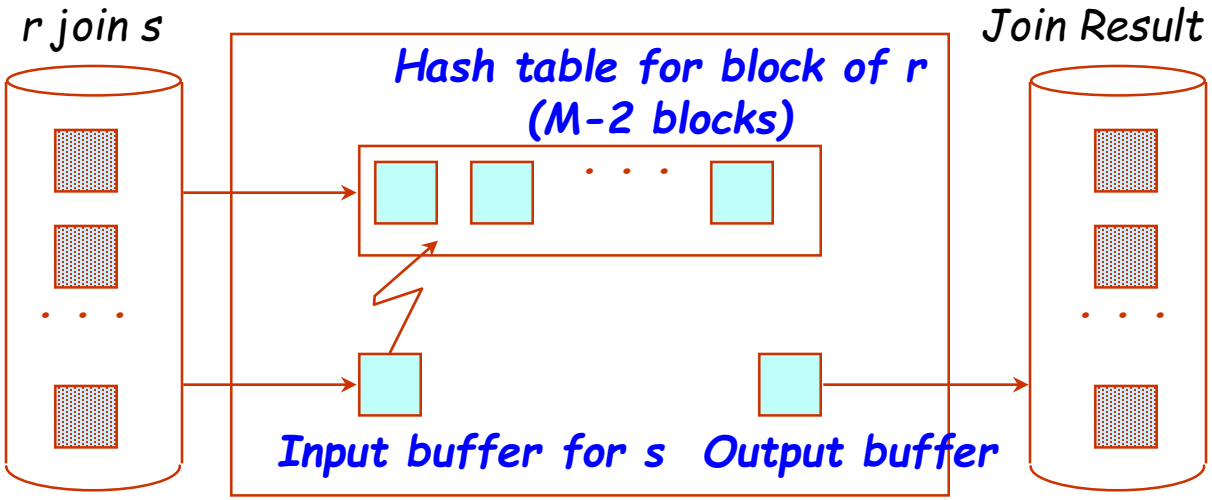
- In the worst case, the estimated cost is $n_r * b_s + b_r$ disk accesses.
- If the best case, reduces cost to $b_r + b_s$.
- Assuming worst case memory availability cost estimate is
  - 5000 * 400 + 100 = 2,000,100 disk accesses with *depositor* as outer relation, and
  - 10000 * 100 + 400 = 1,000,400 disk accesses with *customer* as the outer relation.
- If smaller relation (*depositor*) fits entirely in memory, the cost estimate will be 500 disk accesses.
- 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 • t_s to the result.
            end
        end
    end
end
```

Block Nested-Loop Join (Cont.)



Block Nested-Loop Join (Cont.)

- Worst case estimate: $b_r * b_s + b_r$ block accesses.
- Best case: $b_r + b_s$ block accesses.
- Improvements :
  - 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 = $\lceil b_r / (M-2) \rceil * b_s + b_r$
  - If equi-join attribute forms a **key** of inner relation, stop inner loop on first match
  - Scan inner **relation** forward and backward alternately, to make use of the blocks remaining in buffer.

Indexed Nested-Loop Join

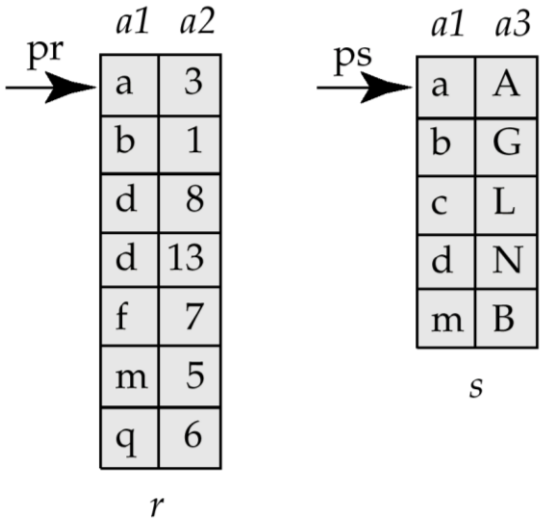
- Index lookups can replace file scans if
  - join is an equi-join or natural join and
  - an index is available on the inner relation's join attribute
- For each tuple t_r in the outer relation r, use the index to look up tuples in s
- Cost of the join: $b_r + n_r * c$
  - Where c is the cost of traversing index and fetching all matching s tuples for one tuple of r
- 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*.
- 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 (400 blocks), the height of the tree is 4 = [log_20 ^10,000]+1, and one more access to find the actual data
- *depositor* has 5000 tuples -> 100 blocks
- Cost of block nested loops join
  - 400***100** + 100 = 40,100 disk accesses
- Cost of indexed nested loops join
  - 100 + 5000 * **5** = 25,100 disk accesses.

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 similar value on join attribute must be matched
   3. Detailed algorithm in book



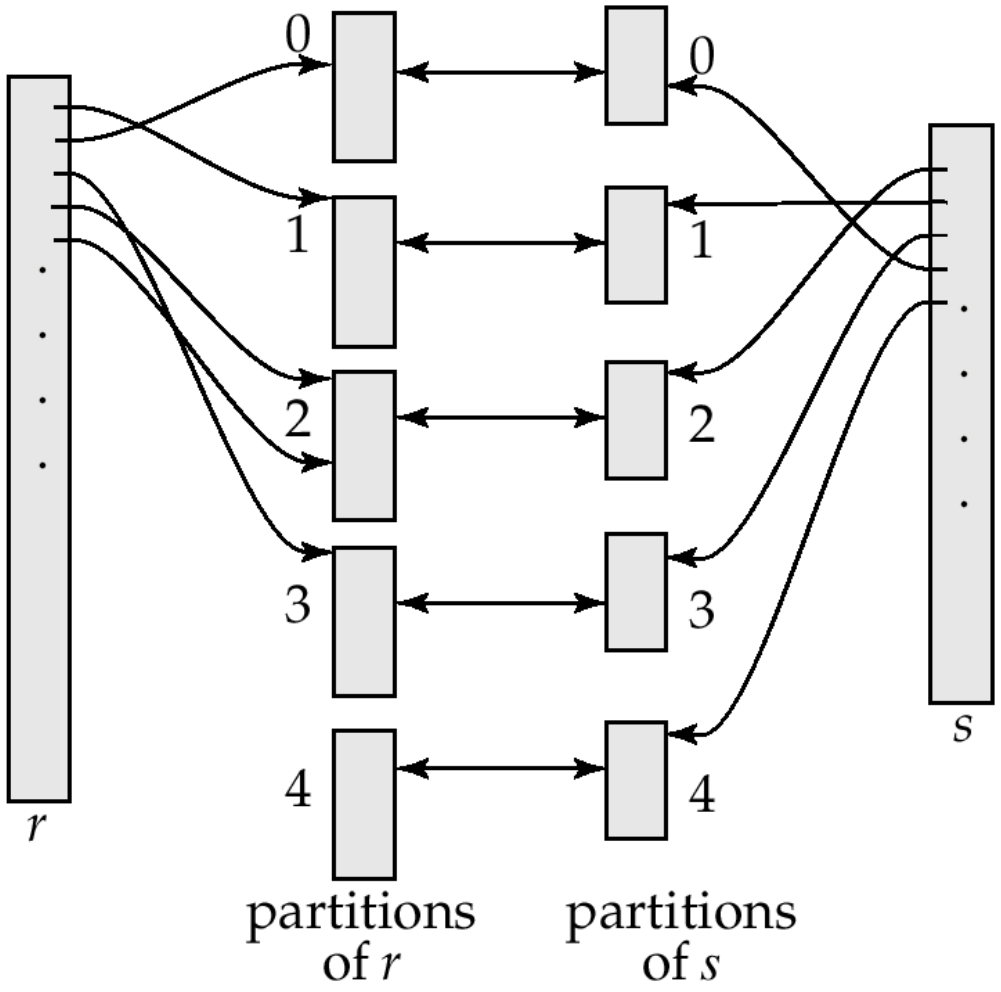
Merge-Join (Cont.)

- 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)
- Thus number of block accesses for merge-join is
  $b_r + b_s$ + the cost of sorting if relations are unsorted.
- **hybrid merge-join (combining indices with merge-join):** If one relation is sorted, and the other has a secondary B^+-tree index on the join attribute
  - Merge the sorted relation with the leaf entries of the B^+-tree, the result file contains tuples from the sorted file and the addresses from the unsorted file
  - Sort the result file on the addresses of the unsorted relation's tuples
  - Scan the unsorted relation in physical address order and merge with previous result, to replace addresses by the actual tuples

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*}.
  - $r_0, r_1, \ldots, r_n$ denote partitions of *r* tuples
  - $s_0, s_1 \ldots, s_n$ denotes partitions of *s* tuples
- *Note:* in the 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 .
  - 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.

Hash-Join Algorithm

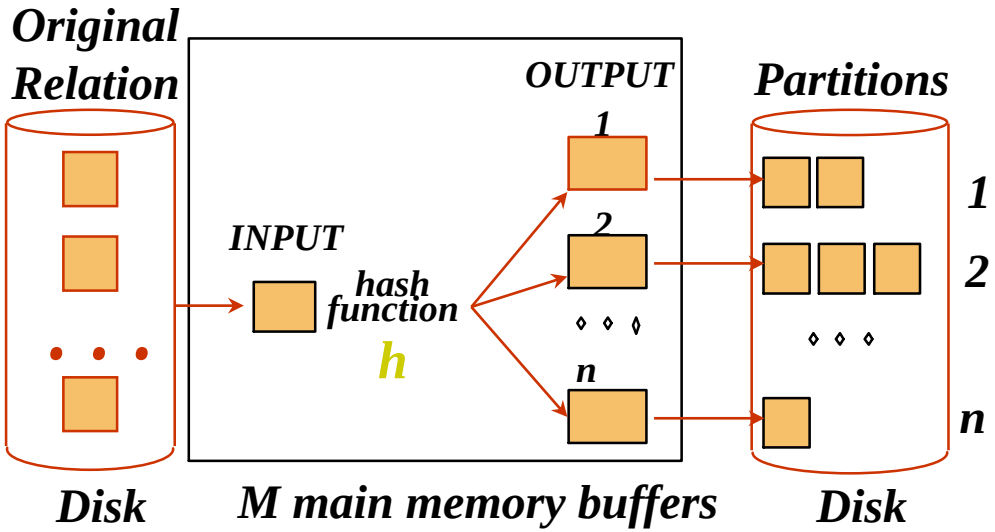
The hash-join of r and s is computed as follows:

1. Partition the relation s using hashing function h. When partitioning a relation, one block of memory is reserved as the output buffer for each partition
2. Partition r similarly
3. For each i:
   (a) Load s_i into memory and build an in-memory hash index on it using the join attribute. This hash index uses a different hash function than the earlier one h.
   (b) Read the tuples in r_i from the disk one by one. For each tuple t_r locate each matching tuple t_s in s_i using the in-memory hash index. Output the concatenation of their attributes

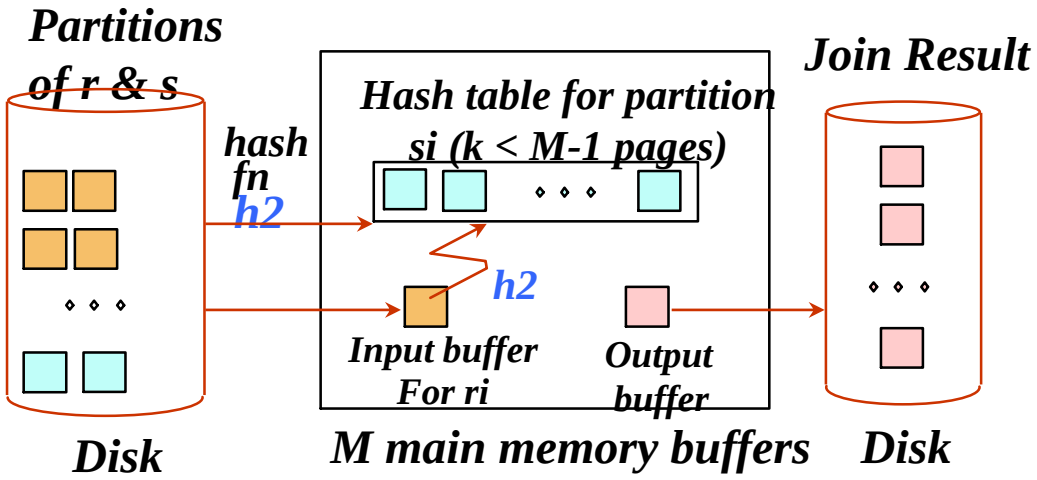
Relation s is called the **build input** and
r is called the **probe input**

Hash-Join Algorithm

- Partition both relations using hash fn h: r tuples in partition i will only match s tuples in partition I



- Read in a partition of r, hash it using h2 (<> h!). Scan matching partition of s, search for matches



Hash-Join algorithm (Cont.)

- The value *n* (# partitions) and the hash function *h* is chosen such that each s_i should fit in memory (say M blocks)
  - Typically n is chosen as $\lceil b_s/M \rceil * f$ where f is a "fudge factor", typically around 1.2
  - The probe relation partitions r_i need not fit in memory
- **Recursive partitioning** required if number of partitions *n* is greater than number of pages *M* of memory.
  - instead of partitioning *n* ways, use *M* – 1 partitions for *s*
  - Further partition the *M* – 1 partitions using a different hash function
  - Use same partitioning method on *r*

Handling of Overflows

- **Hash-table overflow** occurs in partition s_i if s_i does not fit in memory. Reasons could be
  - Many tuples in s with same value for join attributes
  - Bad hash function
- Overflow resolution can be done in build phase
  - Partition s_i is further partitioned using different hash function.
  - Partition r_i must be similarly partitioned.
- Overflow avoidance performs partitioning carefully to avoid overflows during build phase
  - E.g. partition build relation into many partitions, then combine them
- Both approaches fail with large numbers of duplicates
  - Fallback option: use block nested loops join on overflowed partitions

Cost of Hash-Join

- If recursive partitioning is not required: cost of hash join is $2(b_r + b_s) + (b_r + b_s) + 4n$
- If recursive partitioning required, number of passes required for partitioning s is $\lceil log_{M-1}(b_s) - 1 \rceil$.
- the number of passes for partitioning of r is also the same as for s.
- Therefore it is best to choose the smaller relation as the build relation.
- Total cost estimate is:

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

- If the entire build input can be kept in main memory, n can be set to 0 and the algorithm does not partition the relations into temporary files. Cost estimate goes down to $b_r + b_s$.

Example of Cost of Hash-Join

customer $\bowtie$ ***depositor***

- Assume that memory size is 22 blocks
- $b_{depositor}$= 100 and $b_{customer}$ = 400.
- *depositor* is to be used as build input. Partition it into five partitions, each of size 20 blocks. This partitioning can be done in one pass.
- Similarly, partition *customer* into five partitions,each of size 80. This is also done in one pass.
- Therefore total cost: 3(100 + 400) = 1500 block transfers
  - ignores cost of writing partially filled blocks

Hybrid Hash–Join

- Useful when memory size are relatively large, and the build input is bigger than memory.
- **Main feature of hybrid hash join:**

  Keep the first partition of the build relation in memory.
- E.g. With memory size of 25 blocks, *depositor* can be partitioned into five partitions, each of size 20 blocks.
- Division of memory:
  - The first partition occupies 20 blocks of memory
  - 1 block is used for input, and 1 block each for buffering the other 4 partitions.
- *customer* is similarly partitioned into five partitions each of size 80; the first is used right away for probing, instead of being written out and read back.
- Cost of 3(80 + 320) + 20 +80 = 1300 block transfers for hybrid hash join, instead of 1500 with plain hash-join.
- Hybrid hash-join most useful if $M >> \sqrt{b_s}$

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 $r \bowtie_{\theta i} s$:

$$(r \bowtie_{\theta 1} s) \cup (r \bowtie_{\theta 2} s) \cup \ldots \cup (r \bowtie_{\theta n} s)$$

Complex Joins

- Join involving three relations: *loan* ⋈ *depositor* ⋈ *customer*
- **Strategy 1.** Compute *depositor* ⋈ *customer;* use result to compute *loan* ⋈ (*depositor* ⋈ *customer*)
- **Strategy 2.** Computer *loan* ⋈ *depositor* first, and then join the result with *customer.*
- **Strategy 3.** Perform the pair of joins at once. Build and index on *loan* for *loan-number,* and on *customer* for *customer-name.*
  - For each tuple *t* in *depositor,* look up the corresponding tuples in *customer* and the corresponding tuples in *loan.*
  - Each tuple of *depositor* is examined exactly once.
- Strategy 3 combines two operations into one special-purpose operation that is more efficient than implementing two joins of two relations.

Other Operations

Other Operations

- **Duplicate elimination** can be implemented via hashing or sorting.
  - On sorting duplicates will come adjacent to each other, and all but one copy 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** is implemented by performing projection on each tuple followed by duplicate elimination.

Other Operations: Aggregation

- **Aggregation** can be implemented in a manner similar to duplicate elimination.
  - Sorting or hashing can be used to bring tuples in the same group together, and then the aggregate functions can be applied on each group.
  - *Optimization:* combine tuples in the same group during run generation and intermediate merges, by computing partial aggregate values
    - For count, min, max, sum: keep aggregate values on tuples found so far in the group.
    - For avg, keep sum and count, and divide sum by count at the end

Other Operations: Set Operations

- **Set operations** ($\cup$, $\cap$ and —): can either use variant of merge-join after sorting, or variant of hash-join.
- E.g., Set operations using hashing:
  1. Partition both relations using the same hash function, thereby creating $r_1, .., r_n$ and $s_1, s_2.., s_n$
  2. Process each partition *i* as follows. Using a different hashing function, build an in-memory hash index on r_i after it is brought into memory.
  3. ***r* $\cup$ *s*:** Add tuples in s_i to the hash index if they are not already in it. At end of s_i, add the tuples in the hash index to the result.

     ***r* $\cap$ *s*:** output tuples in s_i to the result if they are already there in the hash index.

     ***r* − *s*:** for each tuple in s_i, if it is there in the hash index, delete it from the index. At end of s_i, add remaining tuples in the hash index to the result.

Other Operations: Outer Join

- **Outer join** can be computed either as
  - A join followed by addition of null-padded non-participating tuples.
  - by modifying the join algorithms.
- Modifying merge join to compute $r \mathbin{⟕} s$
  - In $r \mathbin{⟕} s$, non participating tuples are those in $r - \Pi_R(r \bowtie s)$
  - Modify merge-join to compute $r \mathbin{⟕} s$: During merging, for every tuple t_r from r that do not match any tuple in s, output t_r padded with nulls.
  - Right outer-join and full outer-join can be computed similarly.
- Modifying hash join to compute $r \mathbin{⟕} s$
  - If r is probe relation, output non-matching r tuples padded with nulls
  - If r is build relation, when probing keep track of which r tuples matched s tuples. At end of s_i output non-matched r tuples padded with nulls

Evaluation of Expressions

Evaluation of Expressions

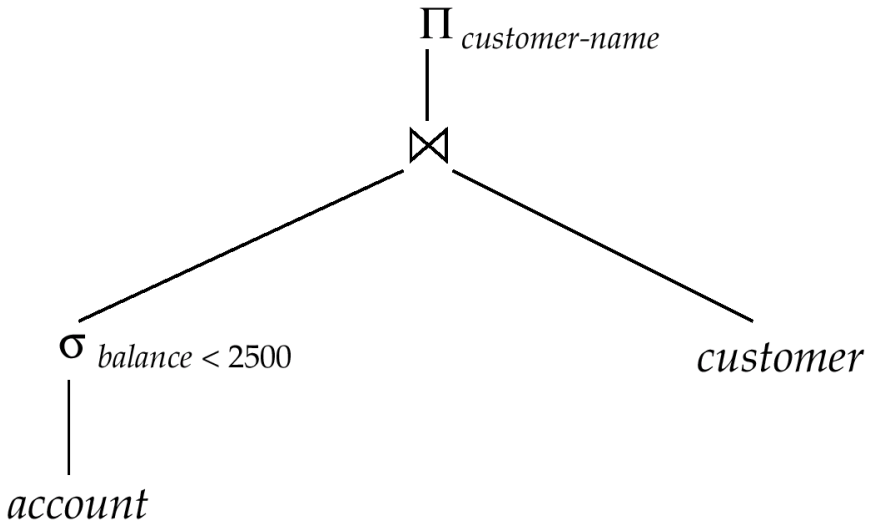
- So far: we have seen algorithms for individual operations
- Alternatives for evaluating an entire expression tree
  - **Materialization**: generate results of an expression whose inputs are relations or are already computed, **materialize** (store) it on disk.
  - **Pipelining**: pass on tuples to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

Materialization

- **Materialized evaluation**: evaluate one operation at a time, starting at the lowest-level.
- E.g., in figure below, compute and store

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

- then compute and store the previous result' 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 formulas 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.
- Pipelining may not always be possible – e.g., sort, hash-join.
- Pipelines can be executed in two ways: **demand driven** and **producer driven**

Pipelining (Cont.)

- In **demand driven** or **lazy** evaluation
  - system repeatedly requests next tuple from top level operation
  - Each operation requests next tuple from children operations as required, in order to output its next tuple
  - Between calls, operation has to maintain "**state**" so it knows what to return next
  - Each operation is implemented as an **iterator** implementing the following operations
    - open()
      - E.g. file scan: initialize file scan, store pointer to beginning of file as state
      - E.g.merge join: sort relations and store pointers to beginning of sorted relations as state
    - next()
      - E.g. for file scan: Output next tuple, and advance and store file pointer
      - E.g. for merge join: continue with merge from earlier state till next output tuple is found. Save pointers as iterator state.
    - close()

Pipelining (Cont.)

- In producer-driven or **eager** pipelining
  - Operators produce tuples eagerly and pass them up to their parents
    - Buffer maintained between operators, child puts tuples in buffer, parent removes tuples from buffer
    - if buffer is full, child waits till there is space in the buffer, and then generates more tuples
  - System schedules operations that have space in output buffer and can process more input tuples

Assignments

- Practice exercises: 13.3, 13.6
- Exercises: 13.11, 13.12