IF3140 – Sistem Basis Data
Query Processing

SEMESTER I TAHUN AJARAN 2024/2025

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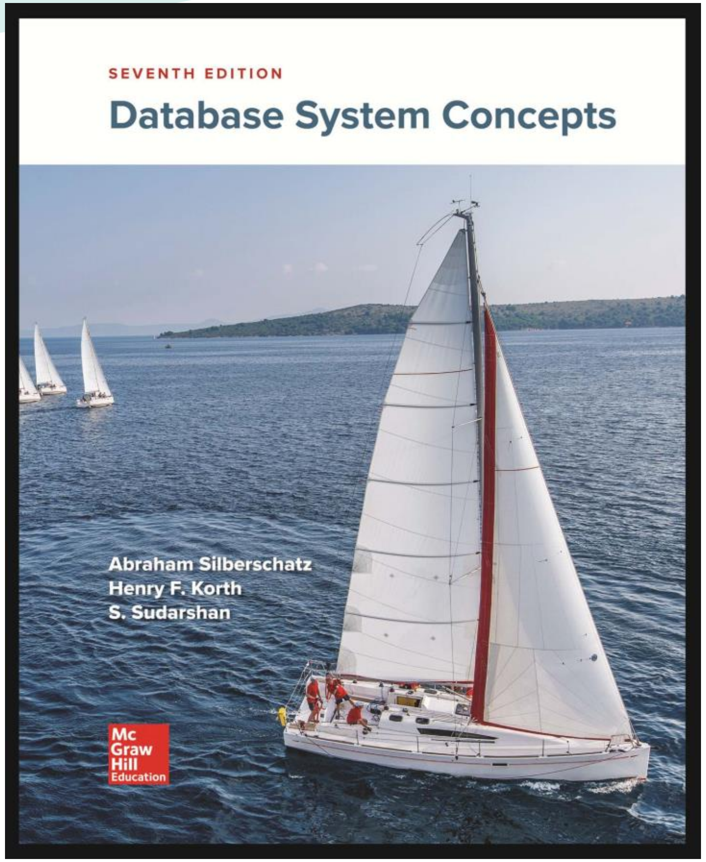
References



- Abraham Silberschatz, Henry F. Korth, S. Sudarshan : "**Database System Concepts**", 7th Edition
  - Chapter 15: Query Processing

Objectives

- Students are able to explain:
  - 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

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Content

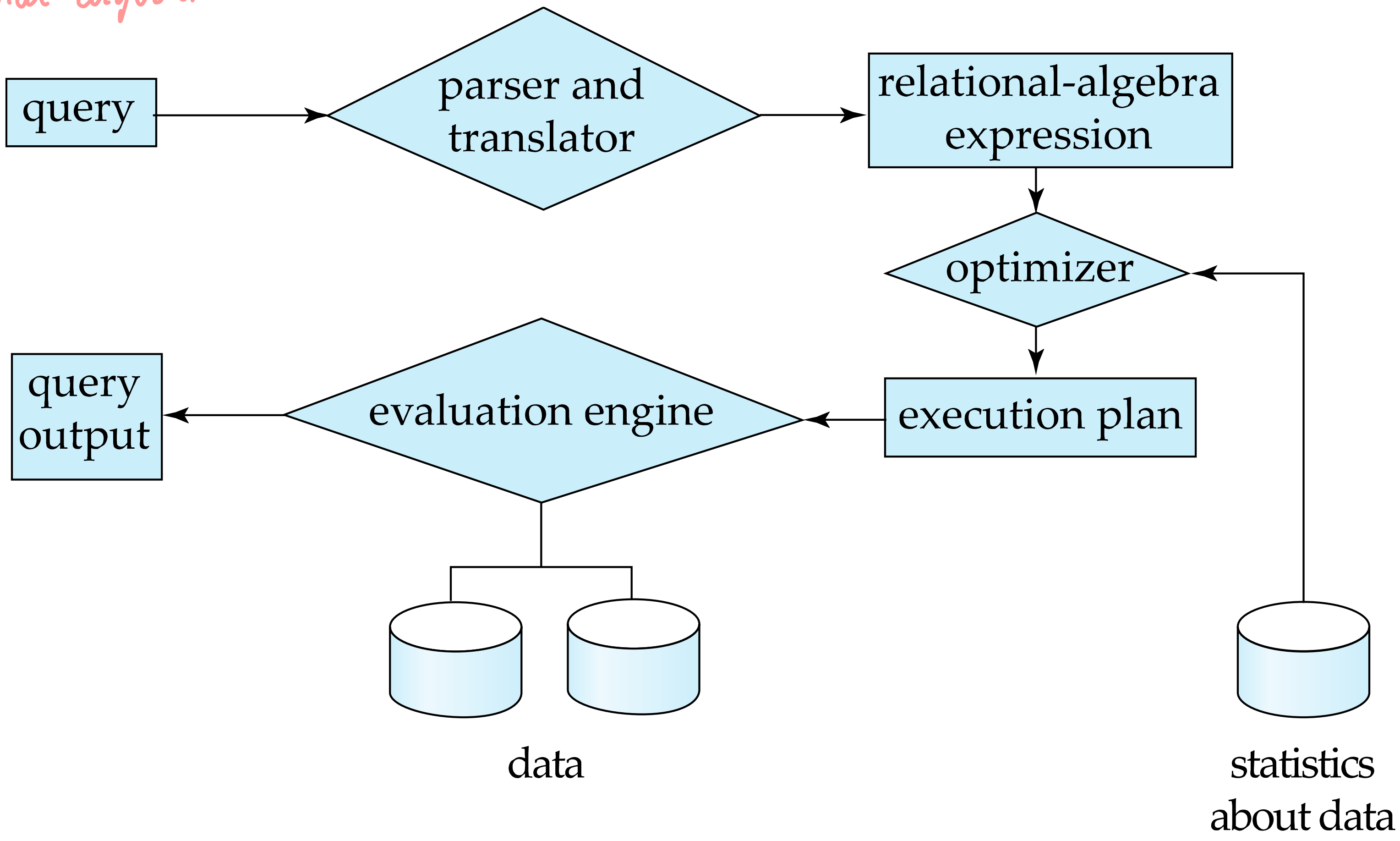
- Overview
- Measures of Query Cost
- Selection Operation
- Sorting
- Join Operation
- Other Operations
- Evaluation of Expressions

Basic Steps in Query Processing

relational query is derived from relational algebra

1. Parsing and translation
2. Optimization
3. Evaluation

buat setiap relational query bisa ada beberapa relational algebra yang setara



Basic Steps in Query Processing (Cont.)

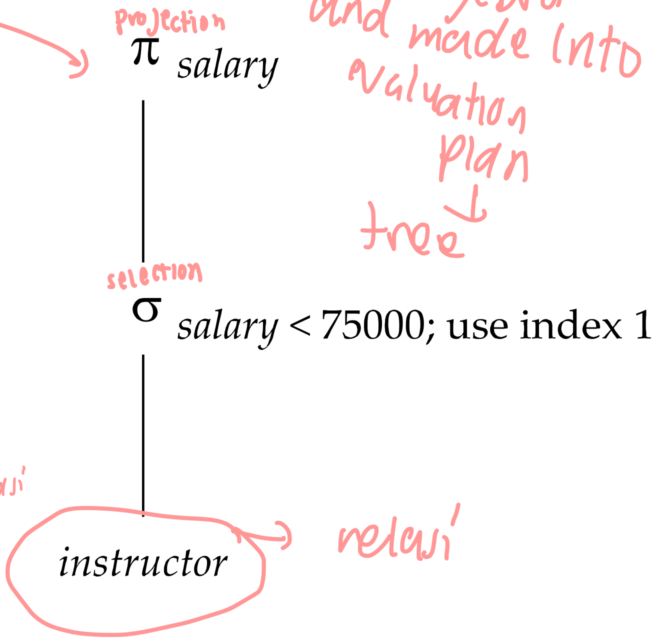
- Parsing and translation
  - Translate the query into its internal form. This is then translated into relational algebra.
    kl0 ada yang salah ga diproses yang lainnya
  - Parser checks syntax, verifies relations
- Optimization
  - *Next slides…*
- Evaluation
  - The query-execution engine takes a 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
  - E.g., $\sigma_{salary<75000}(\Pi_{salary}(instructor))$ is equivalent to $\Pi_{salary}(\sigma_{salary<75000}(instructor))$
- 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 salary to find instructors with salary < 75000,
  - or can perform complete relation scan and discard instructors with salary ≥ 75000

materialisasi ⇒ selalu bisa dilakukan
pipeline ⇒ ada restrictions

from a single query will be translated to equivalent relational algebra and made into evaluation plan tree



A query evaluation plan

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 the next chapter:
  - We study how to optimize queries, that is, how to find an evaluation plan with lowest estimated cost

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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

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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
  - t_S – time for one seek
  - 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

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Measures of Query Cost (Cont.)

- 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

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Algorithms for Individual Operations

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Selection Operation

Π_{salary}

$\sigma_{salary < 75000}$

instructor

SELECT salary
FROM instructor
WHERE salary < 75000

File scan

check satu-satu

- 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 → untuk dapat record pertama
        - br 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 ↳ krn unique
    - Linear search can be applied regardless of
        - selection condition or
        - ordering of records in the file, or
        - availability of indices
- Note: binary search generally does not make sense since data is not stored consecutively
    - except when there is an index available,
    - and binary search requires more seeks than index search

Selections Using Indices

Index scan

- search algorithms that use an index
- selection condition must be on search-key of index.

- **A2 (primary index, equality on key)**. Retrieve a single record that satisfies the corresponding equality condition
  - Cost = $(h_i + 1) * (t_T + t_S)$

h tinggi b+ tree

- **A3 (primary index, equality on nonkey)**. Retrieve multiple records.
  - Records will be on consecutive blocks
    - Let b = number of blocks containing matching records
  - Cost = $h_i * (t_T + t_S) + t_S + t_T * b$

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Selections Using Indices (Cont.)

- **A4 (secondary index, equality on nonkey)**
  - 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!

n = jumlah matching 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 by using indices in the following ways:
  - **A5 (primary index, comparison)**. Relation is sorted on A   cost = hi * (tt +ts) + ts + tt * b
    - For $\sigma_{A \geq V}$(r) use index to find first tuple ≥ 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
  - **A6 (secondary index, comparison).**   cost = (hi + n) * (tt + ts)
    - For $\sigma_{A \geq V}$(r) use index to find first index entry ≥ 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

Algorithms for Complex Selections

Conjunction: $\sigma_{\theta 1 \wedge \theta 2 \wedge \ldots \theta n}(r)$

- **A7 (conjunctive selection using one index)**
  - Select a combination 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.
- **A8 (conjunctive selection using composite index)**
  - Use appropriate composite (multiple-key) index if available.
- **A9 (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 (Cont.)

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

- **A10 (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 θ
  - Find satisfying records using index and fetch from file

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Sorting

- 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 relations that fit in memory, techniques like *quick-sort* can be used. For relations that do not fit in memory, **external sort-merge** is a good choice.

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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:

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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.

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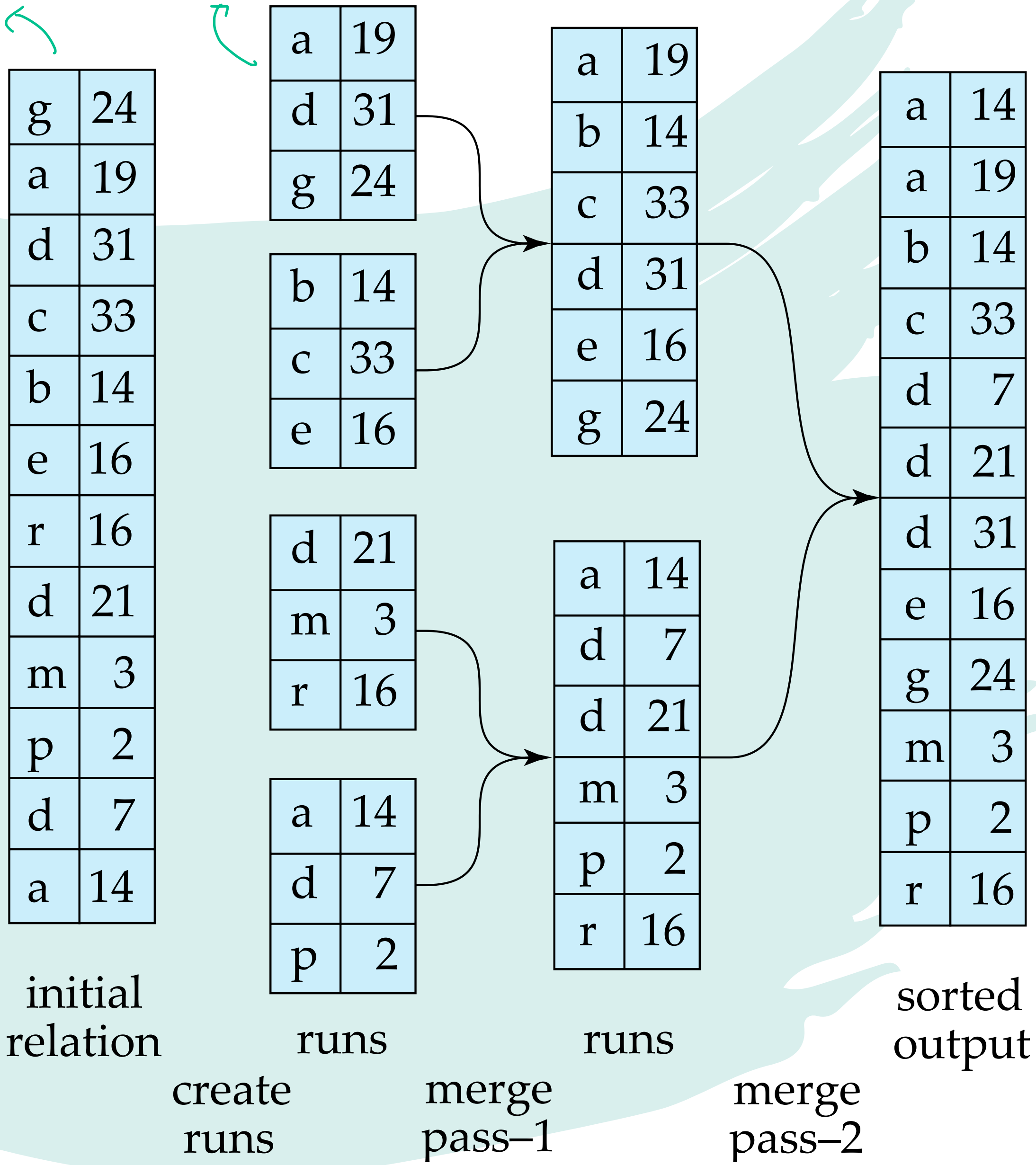
Example: External Sorting Using Sort-Merge

mau sort bedasarkan kolom

4 krn ukuran page

datanya bolak-balik memory - disk



External Merge Sort (Cont.)

merge sort kompleksitas nlogn

- Cost analysis:
  - 1 block per run leads to too many seeks during merge
    - Instead use b_b buffer blocks per run → read/write b_b blocks at a time
    - Can merge $\lfloor M/b_b \rfloor - 1$ runs in one pass
  - Total number of merge passes required: $\lceil \log_{\lfloor M/bb \rfloor - 1}(b_r/M) \rceil$.

    buffer block
  - Block transfers for initial run creation as well as in each pass is $2b_r$
    - for final pass, we do not 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:

      $b_r \left(2 \lceil \log_{\lfloor M/bb \rfloor - 1} (b_r / M) \rceil + 1 \right)$
  - Seeks: next slide

bb = buffer blocks per run

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
    - 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:
      $2\lceil b_r / M \rceil + \lceil b_r / b_b \rceil (2 \lceil \log_{\lfloor M/bb \rfloor - 1}(b_r / M) \rceil - 1)$

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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 ***student*** = 5,000 ***takes*** = 10,000
  - Number of blocks of ***student*** = 100 ***takes*** = 400

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 $t_r \bullet t_s$ 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.)

↳ urutan relasi matters

- In the worst case, if there is enough memory only to hold one block of each relation, the estimated cost is
  $n_r * b_s + b_r$ 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 ***student*** as outer relation:
    - 5000 ∗ 400 + 100 = 2,000,100 block transfers,
    - 5000 + 100 = 5100 seeks
  - with ***takes*** as the outer relation:
    - 10000 ∗ 100 + 400 = 1,000,400 block transfers and 10,400 seeks

Number of records of
student = 5,000 ***takes*** = 10,000
Number of blocks of
student = 100 ***takes*** = 400

- If smaller relation (student) 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.

instead of tuple, pakai block

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 Bs **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

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Block Nested-Loop Join (Cont.)

studen ⋈ takes
klo pak blok
100 * 400 + 100
= 40100 block transfer

- Worst case estimate: $\boxed{b_r * b_s + b_r}$ block transfers + 2 * b_r seeks
  - Each block in the inner relation s is read once for each block in the outer relation
- 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 = $\lceil b_r / (M-2) \rceil * b_s + b_r$ block transfers + $2 \lceil b_r / (M-2) \rceil$ seeks
  - If equi-join attribute forms a key on inner relation, stop inner loop on first match
  - Scan inner loop forward and backward alternately, to make use of the blocks remaining in buffer (with LRU replacement)
  - 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 → join condition =
  - 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 tr.
- 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 ***student*** ⋈ ***takes***, with student as the outer relation.
- Let ***takes*** have a primary B^+-tree index on the attribute ***ID***, which contains 20 entries in each index node.
- Since takes has 10,000 tuples, the height of the tree is 4, and one more access is needed to find the actual data
- ***student*** 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

Number of records of
student = 5,000 ***takes*** = 10,000
Number of blocks of
student = 100 ***takes*** = 400

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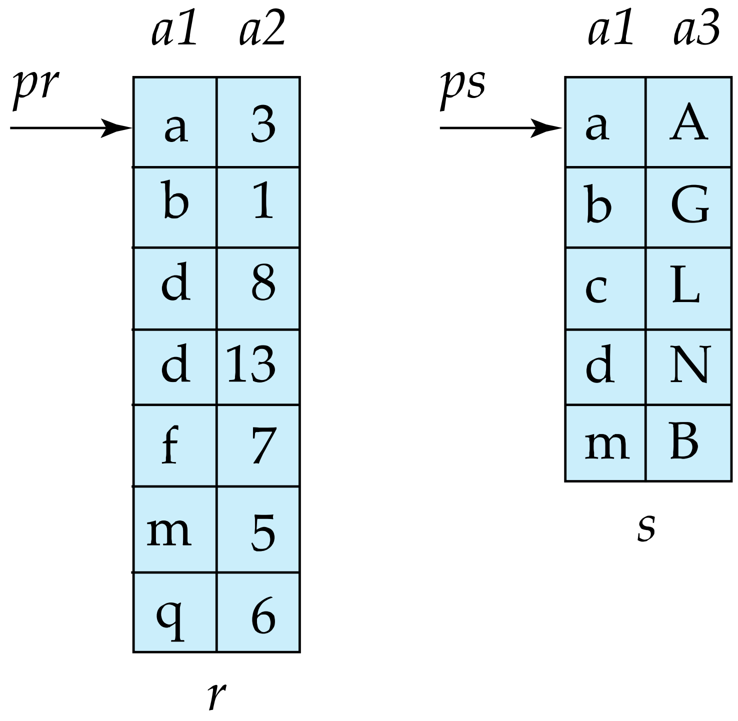
Merge-Join

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
- Thus 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
- **hybrid 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
  - Sort the result 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
    - Sequential scan more efficient than random lookup

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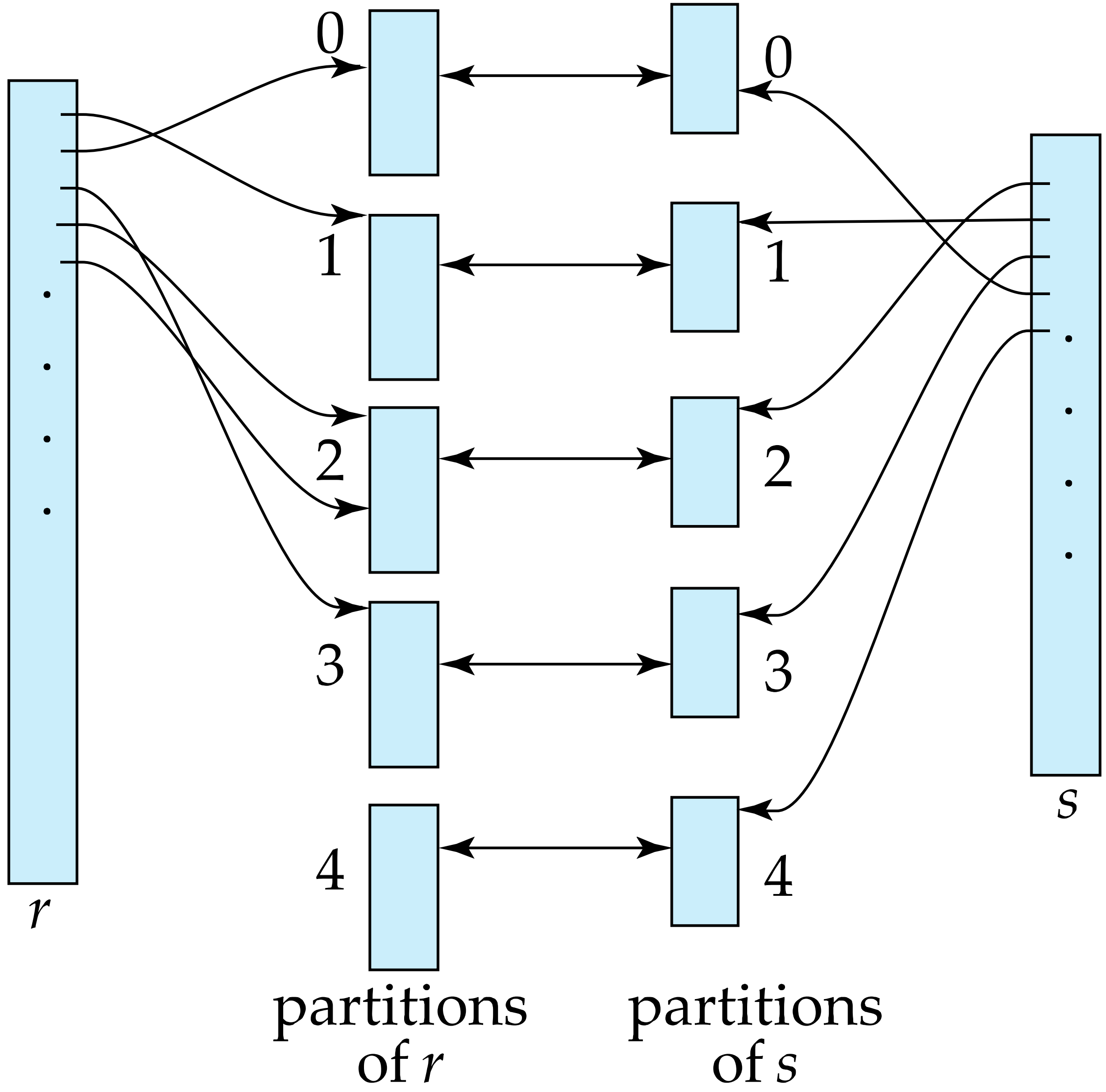
Hash-Join

- 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.

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 (Cont.)

- The value *n* and the hash function *h* is chosen such that each s_i should fit in memory.
  - 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 s_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*
  - Rarely required: e.g., with block size of 4 KB, recursive partitioning not needed for relations of < 1GB with memory size of 2MB, or relations of < 36 GB with memory of 12 MB

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Handling of Overflows

- Partitioning is said to be **skewed** if some partitions have significantly more tuples than some others
- **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

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Cost of Hash-Join

- If recursive partitioning is not required: cost of hash join is
  $3(b_r + b_s) + 4 * n_h$ block transfers +
  $2(\lceil b_r / b_b \rceil + \lceil b_s / b_b \rceil)$ seeks
- If recursive partitioning required:
  - number of passes required for partitioning build relation s to less than M blocks per partition is $\lceil \log_{\lfloor M/bb \rfloor - 1}(b_s/M) \rceil$
  - best to choose the smaller relation as the build relation.
  - Total cost estimate is:
    $2(b_r + b_s) \lceil \log_{\lfloor M/bb \rfloor - 1}(b_s/M) \rceil + b_r + b_s$ block transfers +
    $2(\lceil b_r / b_b \rceil + \lceil b_s / b_b \rceil) \lceil \log_{\lfloor M/bb \rfloor - 1}(b_s/M) \rceil$ seeks
- If the entire build input can be kept in main memory no partitioning is required
  - Cost estimate goes down to $b_r + b_s$

Example of Cost of Hash-Join

instructor* $\bowtie$ *teaches

- Assume that memory size is 20 blocks
- $b_{instructor} = 100$ and $b_{teaches} = 400$.
- ***instructor*** 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 ***teaches*** into five partitions, each of size 80. This is also done in one pass.
- Therefore total cost, ignoring cost of writing partially filled blocks:

  3(100 + 400) = 1500 block transfers +
  $2(\lceil 100/3 \rceil + \lceil 400/3 \rceil) = 336$ seeks

Hybrid Hash–Join

- Useful when memory sized 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, instructor 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.
- teaches is similarly partitioned into five partitions each of size 80
  - the first is used right away for probing, instead of being written out
- 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:

$$r \bowtie_{\theta 1 \land \theta 2 \land \ldots \land \theta n} s$$

  - 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:

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

- Join with a disjunctive condition:

$$r \bowtie_{\theta 1 \lor \theta 2 \lor \ldots \lor \theta n} s$$

  - 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.

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. Repeat.
  - **Pipelining**: pass on tuples to parent operations even as an operation is being executed
- We study above alternatives in more detail

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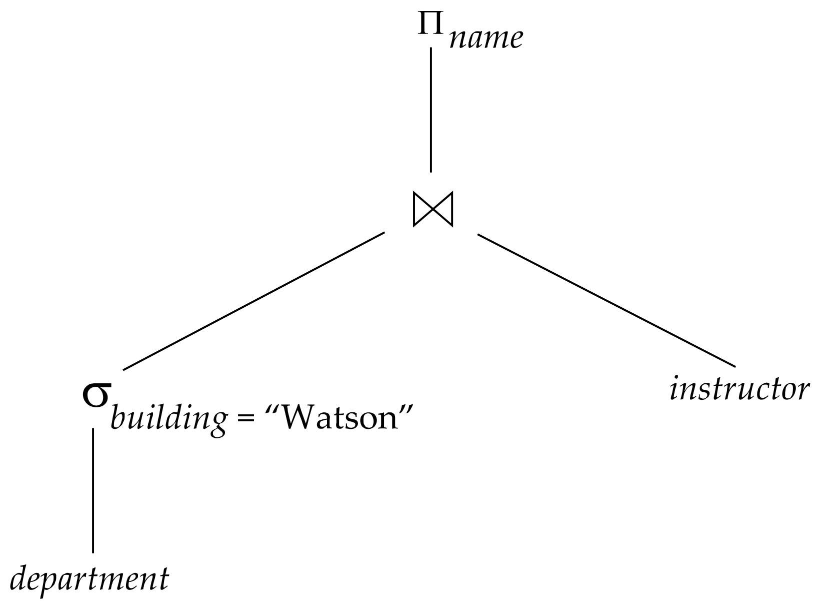
Materialization

- **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

$$\sigma_{building="Watson"}(department)$$

then compute and store its join with instructor, and finally compute the projection on 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

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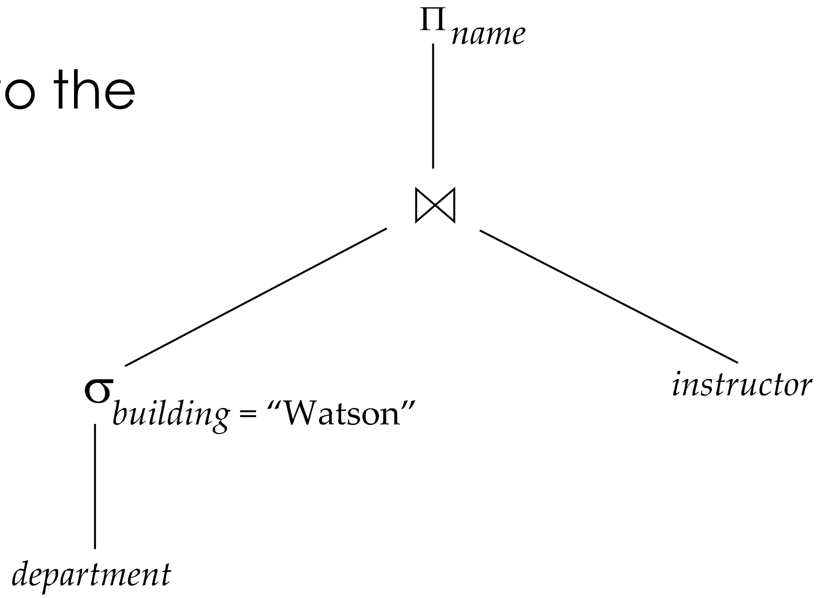
Pipelining

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

$$\sigma_{building="Watson"}(department)$$

  - instead, pass tuples directly to the join. Similarly, do not 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.
- 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
  - In between calls, operation has to maintain **state** so it knows what to return next
- 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
- Alternative name: **pull** and **push** models of pipelining

Pipelining (Cont.)

- Implementation of demand-driven pipelining
  - Each operation is implemented as an **iterator** implementing the following operations
    - **open()**
      - E.g. file scan: initialize file scan
        - state: pointer to beginning of file
      - E.g.merge join: sort relations;
        - state: pointers to beginning of sorted relations
    - **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()**

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Evaluation Algorithms for Pipelining

- Some algorithms are not able to output results even as they get input tuples
  - E.g. merge join, or hash join
  - intermediate results written to disk and then read back
- Algorithm variants to generate (at least some) results on the fly, as input tuples are read in
  - E.g. hybrid hash join generates output tuples even as probe relation tuples in the in-memory partition (partition 0) are read in
  - **Double-pipelined join technique**: Hybrid hash join, modified to buffer partition 0 tuples of both relations in-memory, reading them as they become available, and output results of any matches between partition 0 tuples
    - When a new r_0 tuple is found, match it with existing s_0 tuples, output matches, and save it in r_0
    - Symmetrically for s_0 tuples

End

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.
      - When combining partial aggregate for count, add up the aggregates
    - 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
  2. Process each partition *i* as follows.
     1. Using a different hashing function, build an in-memory hash index on r_i.
     2. Process s_i as follows

        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.

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Other Operations: Set Operations

- E.g., Set operations using hashing:
  1. as before partition *r* and *s*,
  2. as before, process each partition *i* as follows
     - build a hash index on r_i
     - Process si as follows
       - r ∩ 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 $r ⟕ s$
  - In $r ⟕ s$, non participating tuples are those in $r - \Pi_R(r \bowtie s)$
  - Modify merge-join to compute $r ⟕ s$:
    - 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.

Other Operations: Outer Join (Cont.)

- Modifying hash join to compute r ⟕ 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.

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Selection Operation (Cont.)

- **Old-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
      - Will see how to estimate this cost in Chapter 13