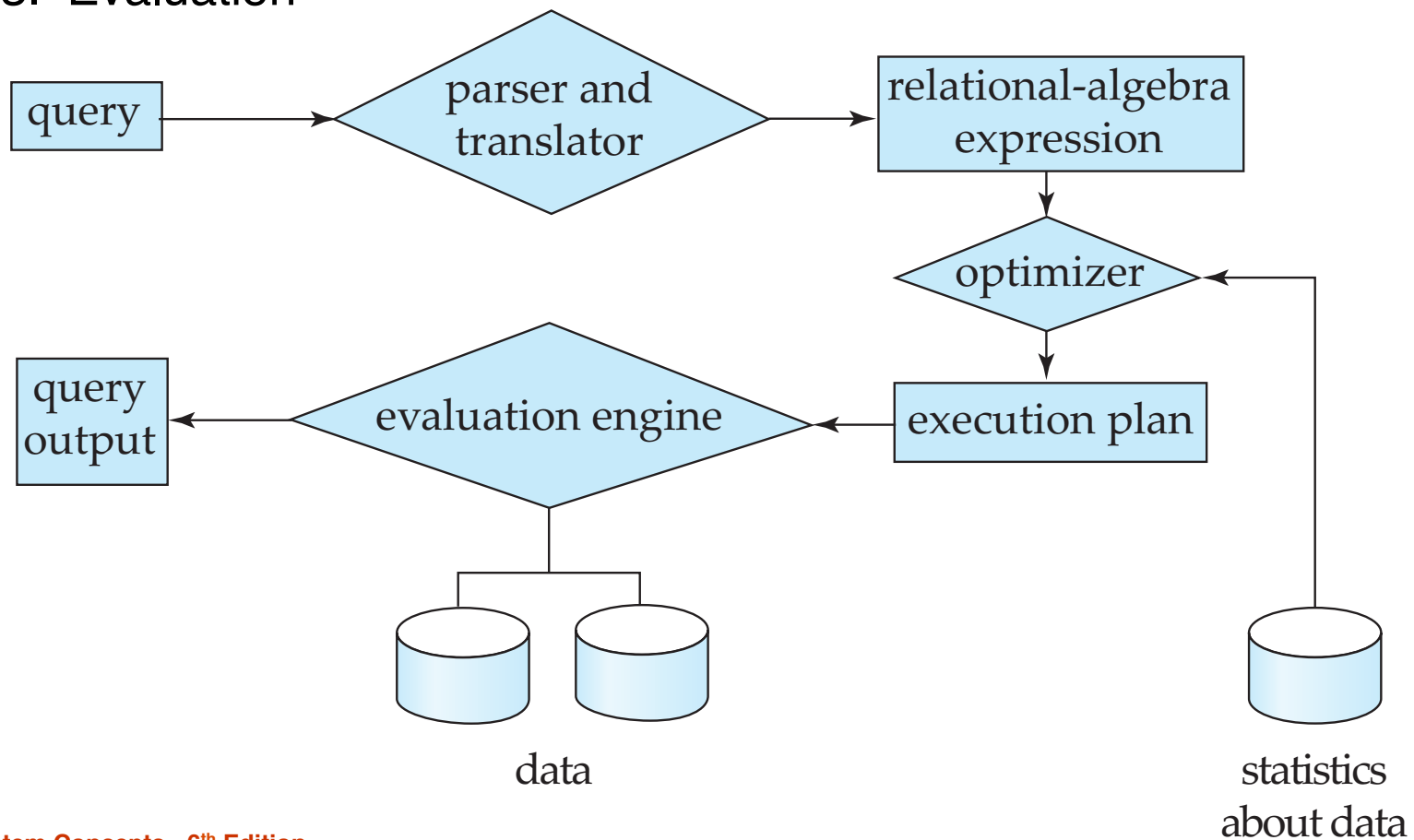# Chapter 12: Query Processing

- Overview

- Measures of Query Cost

- Selection Operation

- Sorting

- Join Operation

- Other Operations

- Evaluation of Expressions

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Basic Steps in Query Processing

1. Parsing and translation
2. Optimization
3. Evaluation

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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

- A relational algebra expression may have many equivalent expressions

  - E.g., $\sigma_{salary<75000}(\prod_{salary}(instructor))$ is equivalent to $\prod_{salary}(\sigma_{salary<75000}(instructor))$

- 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

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

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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

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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Selection Operation

■ **File scan**

■ 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

  ● 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* = $(h_i + 1) * (t_T + t_S)$
- **A3** (**primary index, equality on nonkey**) Retrieve multiple records.
  - Records will be on consecutive blocks
    - ▸ Let b = number of blocks containing matching records
  - *Cost* = $h_i * (t_T + t_S) + t_S + t_T * b$

Selections Using Indices

- **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!

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)
  - 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
- **A6** (**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

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Implementation of 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

■ **Disjunction:** $\sigma_{\theta_1 \vee \theta_2 \vee \ldots \theta_n}(r)$.

■ **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

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 $t_r \cdot t_s$ 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.

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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

$$n_r * b_s + b_r \quad \text{block transfers, plus}$$
$$n_r + b_r \qquad \text{seeks}$$

- 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

- 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.

> **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 $t_r \cdot t_s$ to the result.
>>>> **end**
>>> **end**
>> **end**
> **end**

Block Nested-Loop Join (Cont.)

- Worst case estimate: $b_r * b_s + b_r$ 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 or 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)

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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.
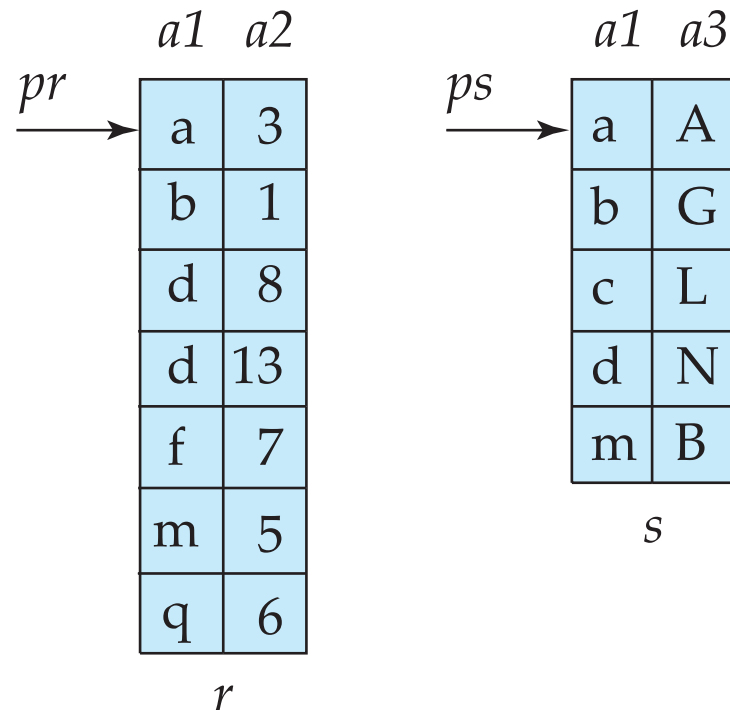
Example of Nested-Loop Join Costs

- Compute *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

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

$pr \longrightarrow$

a1	a2
a	3
b	1
d	8
d	13
f	7
m	5
q	6

r

$ps \longrightarrow$

a1	a3
a	A
b	G
c	L
d	N
m	B

s

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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:

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

  - \+ 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

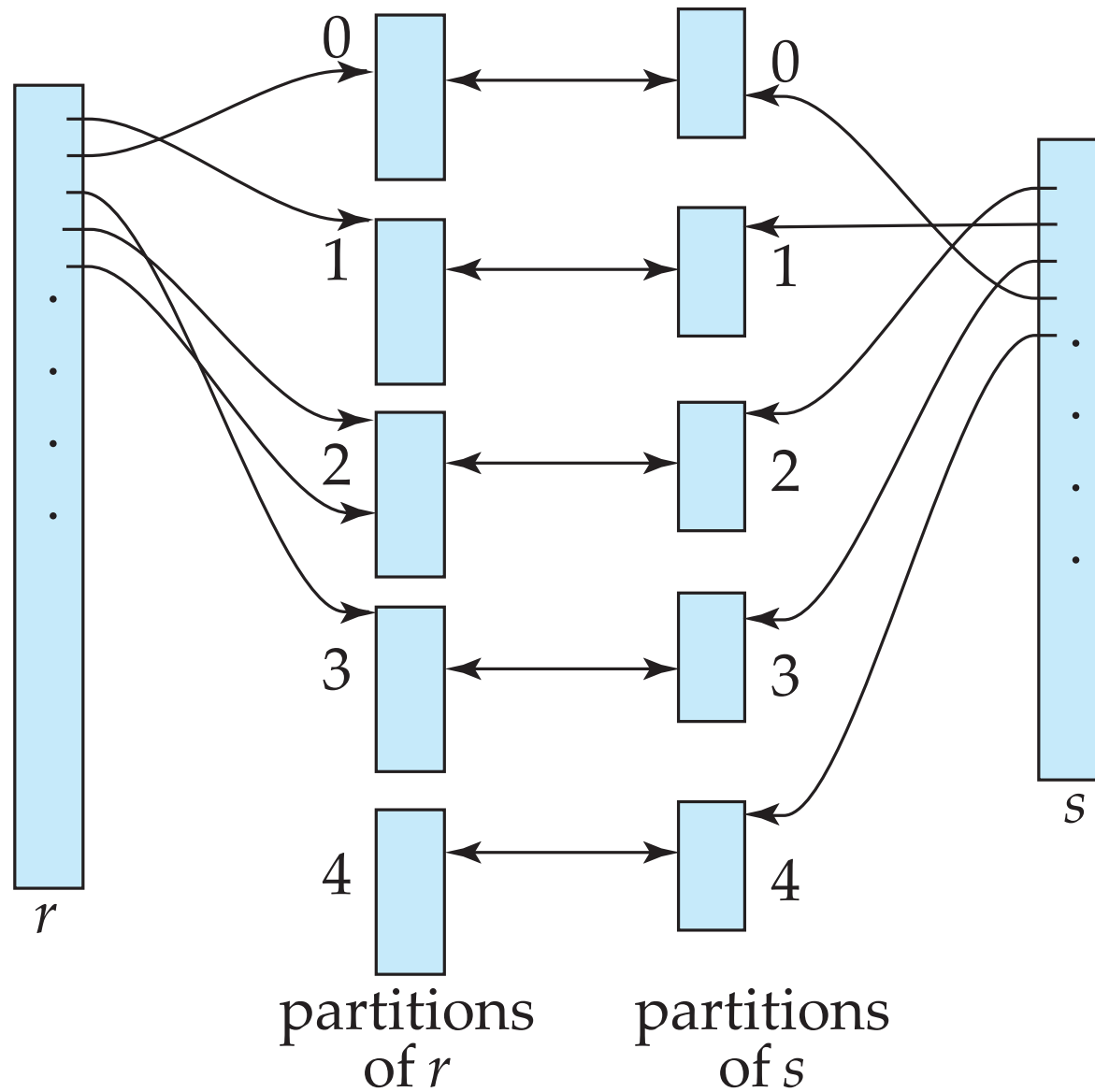   - ▸ Sequential scan more efficient than random lookup

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.

  - $r_0, r_1, ..., r_n$ denote partitions of r tuples

    ‣ Each tuple $t_r \in r$ is put in partition r_i where $i = h(t_r [JoinAttrs])$.

  - $r_{0'}, r_1 ..., r_n$ 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.)

partitions
of r

partitions
of s

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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.

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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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Cost of Hash-Join

- If recursive partitioning is not required: cost of hash join is
$$3(b_r + b_s) + 4 * n_h \text{ block transfers } +$$
$$2(\lceil b_r / b_b \rceil + \lceil b_s / b_b \rceil) \text{ seeks}$$

- If recursive partitioning required:

  - number of passes required for partitioning build relation s is $\lceil \log_{M-1}(b_s) - 1 \rceil$

  - best to choose the smaller relation as the build relation.

  - Total cost estimate is:
  $$2(b_r + b_s)\lceil \log_{M-1}(b_s) - 1 \rceil + b_r + b_s \text{ block transfers } +$$
  $$2(\lceil b_r / b_b \rceil + \lceil b_s / b_b \rceil)\lceil \log_{M-1}(b_s) - 1 \rceil \text{ seeks}$$

- 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 ⋈ *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

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.

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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

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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 $r - \Pi_R(r ⋈ s)$
  - 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.

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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

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 the store its join with *instructor,* and finally compute the projection on *name.*
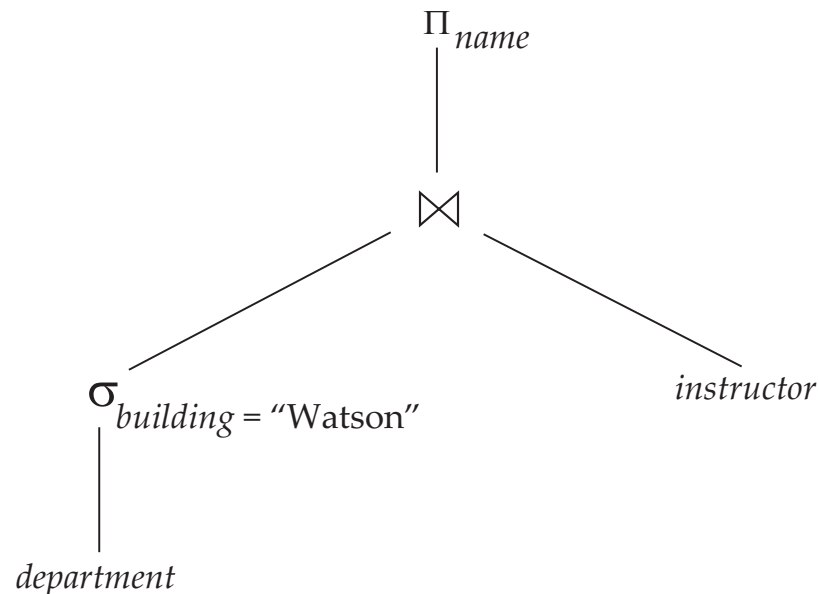
Materialization (Cont.)

■ 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

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

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

  - 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.

- Pipelines can be executed in two ways: **demand driven** and **producer driven**