# Database Development and Design (CPT201)

## Lecture 4c:
## Query Evaluation - Join

Dr. Wei Wang
Department of Computing

# Learning Outcomes

- Algorithms for evaluating join operators
- Algorithms for evaluating other expressions

# Natural-Join Operation

**Notation: r ⋈ s**

- Let $r$ and $s$ be relations on schemas $R$ and $S$ respectively. Then, r ⋈ s is a relation on schema $R \cup S$ obtained as follows:
  - Consider each pair of tuples $t_r$ from $r$ and $t_s$ from $s$.
  - If $t_r$ and $t_s$ have the same value on each of the attributes in $R \cap S$, add a tuple $t$ to the result, where
    - $t$ has the same value as $t_r$ on $r$
    - $t$ has the same value as $t_s$ on $s$
- Example:

  $R = (A, B, C, D)$

  $S = (E, B, D)$

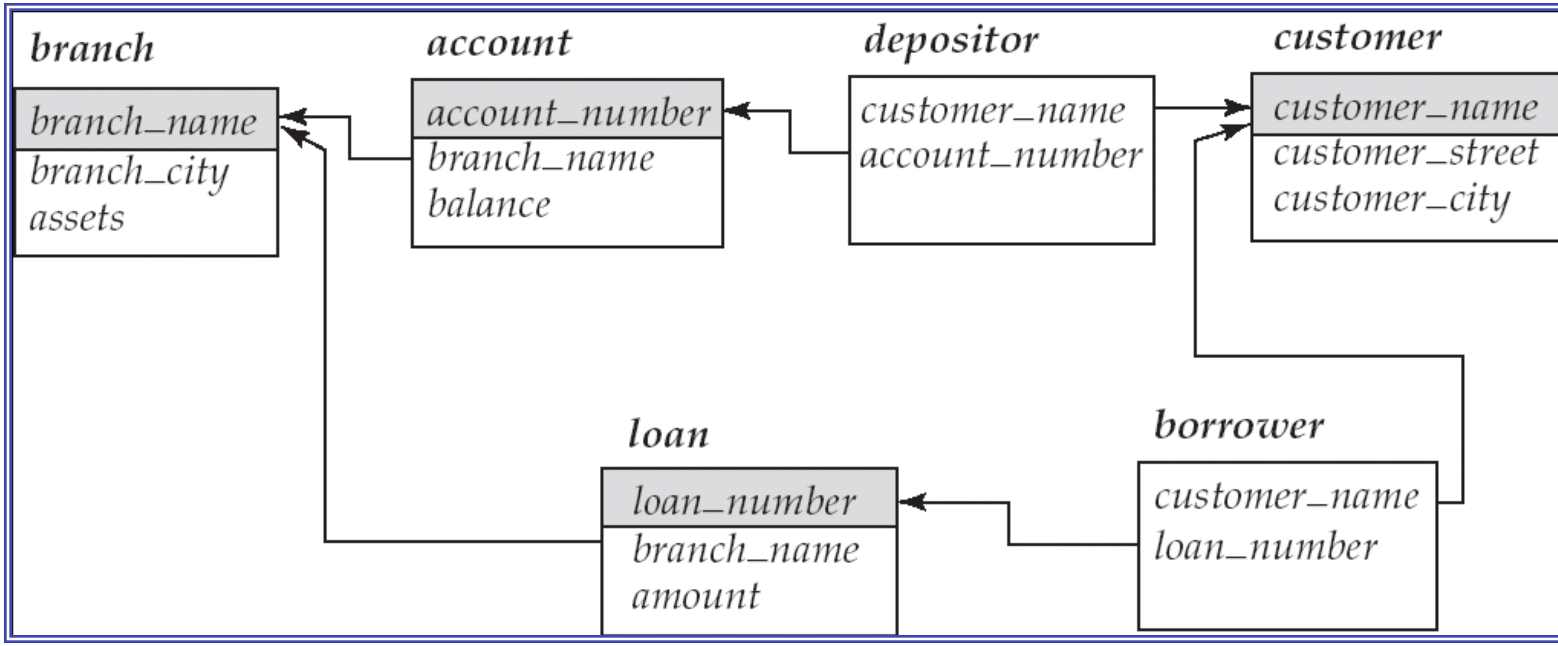
  - Result schema = $(A, B, C, D, E)$
  - $r \bowtie s$ is defined as:

    $$\Pi_{r.A,\ r.B,\ r.C,\ r.D,\ s.E}(\sigma_{r.B = s.B \wedge r.D = s.D}(r \times s))$$

# Join Operation

- Several different algorithms to implement joins exist (not counting with the ones involving parallelism)
  - Nested-loop join
  - Block nested-loop join
  - Indexed nested-loop join
  - Merge-join
  - Hash-join
- As for selection, the choice is based on cost estimate.

# Banking Example




- Examples in next slides use the following information:
  - Number of records of *customer*: 10,000
  - Number of blocks of *customer*: 400
  - Number of records of *depositor*: 5,000
  - Number of blocks of *depositor: 100*

# Nested-Loop Join

- The simplest join algorithms, that can be used independently of everything (like the linear search for selection)
- 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 $t_r \cdot t_s$ to the result.
  **end**
  **end**
- $r$ is called the **outer relation** and $s$ the **inner relation** of the join.
- Quite expensive in general, since it requires to examine every pair of tuples in the two relations.

# Nested-Loop Join cont'd

- In the worst case, if there is enough memory only to hold one block of each relation, $n_r$ is the number of tuples in relation $r$, 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
- But in general, it is much better to have the smaller relation as the outer relation
- The choice of the inner and outer relation strongly depends on the estimate of the size of each relation.

# Nested-Loop Join Cost in Example

- Assuming worst case memory availability cost estimate is
  - with *depositor* as outer relation:
    - 5,000 * 400 + 100 = 2,000,100 block transfers,
    - 5,000 + 100 = 5,100 seeks
  - with *customer* as the outer relation
    - 10,000 * 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 and 2 seeks
- Instead of iterating over records, one could iterate over blocks. This way, instead of $n_r * b_s + b_r$ we would have $b_r * b_s + b_r$ block transfers
- This is the basis of the block nested-loops algorithm.

# 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 Br of r do begin
   for each block Bs of s do begin
      for each tuple tr in Br do begin
         for each tuple ts in Bs do begin
            Check if (tr,ts) satisfy the join condition
            if they do, add tr • ts to the result.
         end
      end
   end
end
```

# Block Nested-Loop Join Cost

- Worst case estimate: $b_r * b_s + b_r$ block transfers and $2 * b_r$ 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 (when smaller relation fits into memory): $b_r + b_s$ block transfers plus 2 seeks.
- Some improvements to nested loop and block nested loop algorithms can be made:
  - Scan inner loop forward and backward alternately, to make use of the blocks remaining in buffer, reduce the number of disk access
  - Use index on inner relation (if available) to quickly get the tuples which match the tuple of the outer relation.

# 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
    - In some cases, it pays to construct an index just to compute a join.
- For each tuple $t_r$ in the outer relation *r*, use the index on *s* 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: $b_r + n_r * c$ *block transfers and seeks*
  - Where *c* is the cost of traversing index and fetching all matching *s* tuples for one tuple in *r*
  - *c* can be estimated as cost of a single selection on *s* using the join condition (usually quite low, when compared to the join)
- If indices are available on join attributes of both *r* and *s*, use the relation with fewer tuples as the outer relation.

# Example of Indexed Nested-Loop Join Costs

- Compute *depositor* $\bowtie$ *customer*, with *depositor* as the outer relation.
- Let *customer* have a primary $B^+$-tree index on the join attribute *customer-name*, with n=20.
- 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 5,000 tuples
- Nested loop join: 2,000,100 block transfers and 5,100 seeks
- Cost of block nested loops join
  - 400*100 + 100 = 40,100 block transfers + 2 * 100 = 200 seeks
- Cost of indexed nested loops join
  - 100 + 5,000 * (4+1) = 25,100 block transfers and seeks.
  - The number of block transfers is less than that for block nested loops join
  - But number of seeks is much larger
  - In this case using the index doesn't pay (this is specially so because the relations are small)

# Merge-Join

1. Sort both relations on their join attribute (if not already sorted on the join attributes). Join step is similar to the merge stage of the sort-merge algorithm.
2. Merge-join algorithm
   1. Initialise two pointers point to r and s
   2. While not done
      1. the pointers to r and s move through the relation.
      2. A group of tuples of inner relation s with the same value on the join attributes is read into $S_s$ .
      3. Do join on tuple pointed by $p_r$ and tuples in $S_s$;
   3. End while

# Merge-Join cont'd

Read pseudocode in the textbook!

*pr* →

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

*r*

*ps* →

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

*s*

# Merge-Join cont'd

- Can be used only for equi-joins and natural joins
- Each block needs to be read only once (assuming that all tuples for any given value of the join attributes fit in memory)
- Thus the cost of merge join is (where $b_b$ is the number of blocks in allocated in memory for each relation):

  $b_r + b_s$ block transfers +

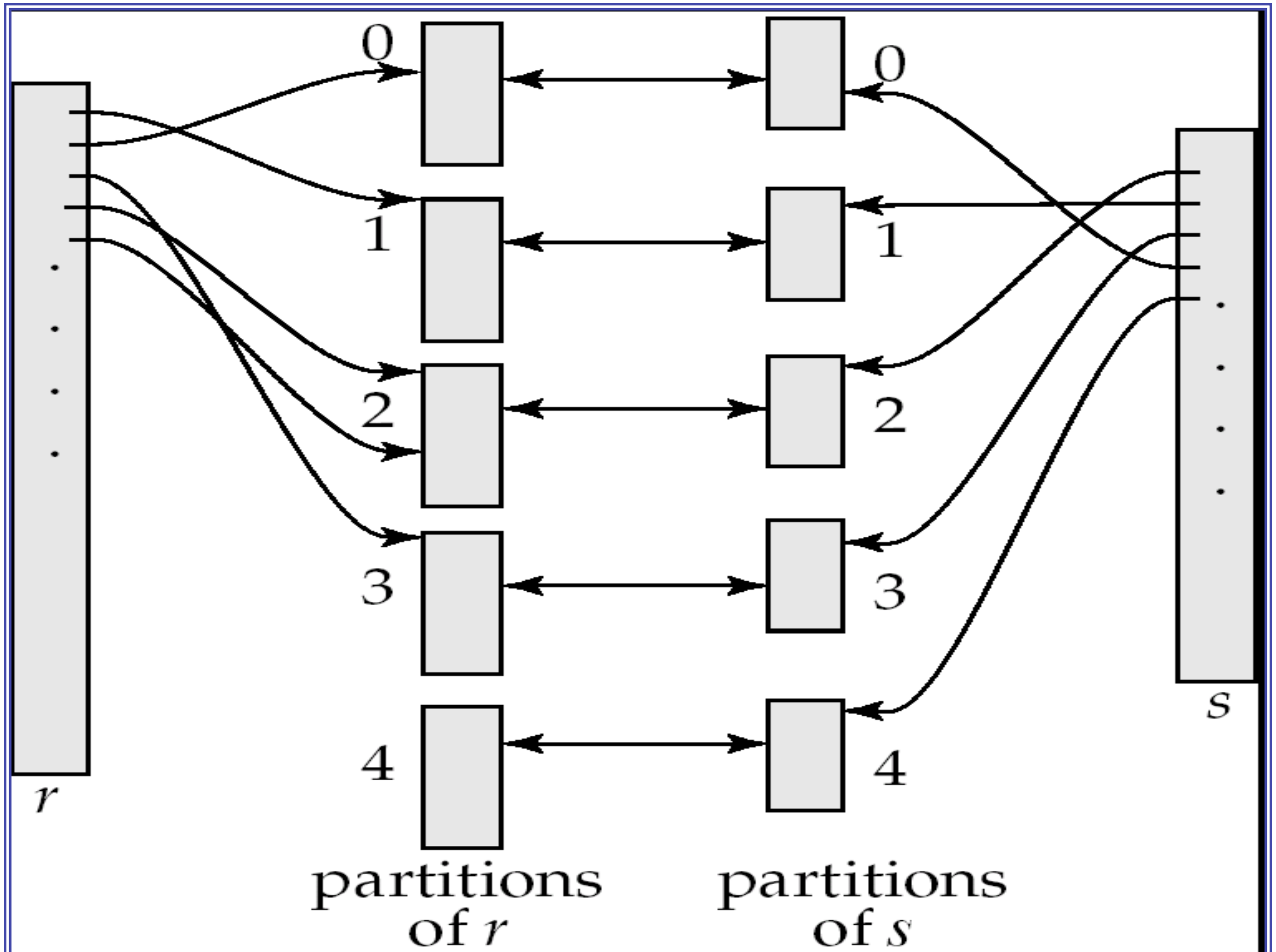
  $\lceil b_r / b_b \rceil + \lceil b_s / b_b \rceil$ seeks

  - Plus the cost of sorting if relations are unsorted.
  - Since seeks are much more expensive than data transfer, it makes sense to allocate multiple buffer blocks to each relation, provided extra memory is available.

# Hash-Join

- Also only 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 $i = h(t_s[JoinAttrs])$.
- General idea:
  - Partition the relations according to this
  - Then perform the join on each partition $r_i$ and $s_i$
    - There is no need to compute the join between different partitions 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 cont'd



# Hash-Join Algorithm

1. Partition the relation *s* using hashing function *h*. When partitioning a relation, some blocks of memory ($b_b$) are 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 *h* for partitioning.
   (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'd

- The number of partitions *n* for 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, to avoid overflows
  - The probe relation partitions $r_i$ need not fit in memory

# Cost of Hash-Join

- The cost of hash join is
  $3(b_r + b_s) + 4 * n_h$ block transfers, and
  $2(\lceil b_r / b_b \rceil + \lceil b_s / b_b \rceil) + 2 * n_h$ seeks
  - each of the $n_h$ partitions could have a partially filled block that has to be written and read back
  - The build and probe phases require only one seek for each of the $n_h$ partitions of each relation, since each partition can be read sequentially.
- If the entire build input can be kept in main memory (then no partitioning is required), Cost estimate goes down to $b_r + b_s$ *and 2 seeks*.

# Cost of Hash-Join in Example

- For the running example, assume that memory size is 20 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.
- Assuming 3 blocks are allocated for the input buffer and each output buffer
- Therefore total cost, ignoring cost of writing partially filled blocks:

  3(100 + 400) = 1, 500 block transfers +
  $2(\lceil 100/3 \rceil + \lceil 400/3 \rceil) + 2*5 =$ 344 seeks
- We had up to here:
  - 40,100 block transfers plus 200 seeks (for block nested loop)
  - 25,100 block transfers and seeks (for index nested loop).

# Other Operations: Duplicate Elimination

- **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.
  - *Optimisation:* 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.

# Other Operations: Aggregation

- ***Aggregation*** can be implemented similarly 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.
  - *Optimisation:* 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** (∪, ∩ and -): can either use variant of merge-join after sorting, or variant of hash-join.
- 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
        - $r \cup s$:
          1. Add tuples in $s_i$ to the hash index if they are not in it.
          2. At the end, add the tuples in the hash index to the result.
        - $r \cap s$:
          1. output tuples in $s_i$ to the result if they are already in the hash index
        - $r - s$:
          1. for each tuple in $s_i$, if it is in the hash index, delete it from the index.
          2. At the end, add remaining tuples in the hash index to the result.

# End of Lecture

- Summary
  - Join
    - Nested-Loop Join
    - Block-Nested-Loop Join
    - Indexed-Nested-Loop Join
    - Sorted-Merge-Join
    - Hash Join
  - Other Operations
- Reading
  - 6th edition, Chapters 12.5 and 12.6
  - 7th edition, Chapters 15.5 and 15.6