Database Technology
Query Processing

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Today

• We’re still opening the mysterious RDBMS black box
  – We can query a database
  – e.g., queries across multiple tables

• Today
  – How are those queries executed?
  – Which parts are evaluated first?
  – How are sorts carried out?
  – ...
Outline

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

• Suppose you are a RDBMS
  – and you are asked to execute
    SELECT name, building, salary
    FROM instructor, building
    WHERE instructor.dept_name = department.dept_name
    AND salary > 75000
    ORDER BY name

• How do you want to proceed?
  – Start with instructor or building relation?
  – Sort instructor by name table first, or filter by salary first?
  – ...
Basic Steps in Query Processing

1) Parsing and translation
2) Optimization
3) Evaluation
Basic Steps in Query Processing

• 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

• A relational algebra expression may have many equivalent expressions
  − e.g., $\sigma_{\text{salary}<75000} (\Pi_{\text{salary}}(\text{instructor}))$ is equivalent to $\Pi_{\text{salary}} (\sigma_{\text{salary}<75000} (\text{instructor}))$

• 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 $\geq$ 75000
Query Optimization

• **Query Optimization:** Among 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.

• Today’s lecture:
  – 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

• Next week’s lecture
  – How to optimize queries,
  – i.e., how to find an evaluation plan with lowest estimated cost
Measuring Query Cost

• We want to execute the query as “cheap” as possible
• But what is “cheap”?  
  – Execution time 
  – Memory consumption 
  – Electrical power consumption 
  – ...
• Most approaches seek to minimize the execution time
Measuring 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
Recap: Data Access from Hard Disks

• Typically, not all the database can be kept in memory
• Databases are stored on hard disks
• Minimal unit of transfer: block
  - optimizing cost means minimizing block transfer
Measuring Query Cost

• 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 disk seek (i.e., finding a block on the disk)
  – Cost for $b$ block transfers plus $S$ seeks
    $$b \cdot t_T + S \cdot t_S$$

• We ignore CPU costs for simplicity
  – Real systems do take CPU cost into account
  – We do not include cost of writing output to disk
Measuring Query Cost

- Several algorithms can reduce disk IO by using extra buffer space
  - Amount of real memory available to buffer depends on other concurrent queries and OS processes, known only during execution
  - We often use worst case estimates, assuming only the minimum amount of memory needed for the operation is available
- Required data may be buffer resident already, avoiding disk I/O
  - But hard to take into account for cost estimation
Selection Operation

- **File scan**
- Algorithm **A1** *(linear search)*.
  - Seek first block
  - Scan this and each consecutive file block and test all records to see whether they satisfy the selection condition
  - \( \text{cost} = b_r \times t_T + t_S \)
  - \( b_r \) denotes number of blocks containing records from relation \( r \)

Assumption: File is stored in consecutive blocks
Selection Operation

• If selection is on a key attribute, can stop on finding the single record (if it exists)
  – \( cost = (b_r/2) \ast t_T + t_S \)

• 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 in order
  – except when there is an index available
  – and binary search requires more seeks than index search
Selections Using Indices

- Assuming a B+ tree of height $h_i$
- **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** = $(h_i + 1) \times (t_T + t_S)$
Selections Using Indices

- Assuming a B+ tree of height $h_i$
- **A3 (primary index, equality on nonkey)** Retrieve multiple records.
  - Records will be on consecutive blocks
  - Let $b =$ number of blocks containing matching records
  - Cost $= h_i * (t_T + t_S) + t_S + t_T * b$
Selection Using Secondary Index

- **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 an index

• **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
  – $Cost = h_i \times (t_T + t_S) + t_S + t_T \times b$
    • identical to A3 (index on nonkey)
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 an index

• **A6 (secondary index, comparison).** (Relation not sorted on A)
  – 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, retrieving records that are pointed to
    • requires an I/O for each record
    • may be more expensive than linear file scan
  – Cost = $(h_i + n) * (t_T + t_S)$
    • identical to A4 (index on nonkey)
Implementation of Complex Selections

• **Conjunction:** $\sigma_{\theta_1 \land \theta_2 \land \ldots \land \theta_n}(r)$
  - e.g., all students enrolled in the MMDS, in semester 4 or higher with GPA<2.0

• **A7 (conjunctive selection using one index).**
  - Select a combination of $\theta_i$ and algorithms A2 through A6 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
  - Use one of the algorithms A2-A4 with the least cost
  - Test other conditions on tuple after fetching it into memory buffer
Implementation of Complex Selections

• **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
    • all record pointers of students with program “MMDS”,
    • all record pointers of students with semester \( \geq 4 \)
    • all record pointers of students with GPA<2.0
  - Then fetch records from file
    • minimizes block transfers as far as possible
  - If some conditions do not have appropriate indices
    • apply remaining tests in memory
Implementation of Complex Selections

- **Disjunction:** $\forall_{\theta_1} \lor \forall_{\theta_2} \lor \ldots \lor \forall_{\theta_n}(r)$.

- **A10** (disjunctive selection by union of identifiers)
  - Use corresponding index for each condition
  - Collect pointers for each condition
  - Use union of all the obtained sets of record pointers
  - Then fetch records from file

- Applicable only if all conditions have available indices
  - Otherwise use linear scan
Implementation of Complex Selections

- **Negation:** $\sigma_{\neg \theta}(r)$
  - Use linear scan on file
- Special case:
  - if very few records satisfy $\neg \theta$, and an index is applicable to $\theta$
  - find satisfying records using index and fetch from file
Sorting

• Recap initial example:
  
  SELECT name, building, salary  
  FROM instructor, building  
  WHERE instructor.dept_name = department.dept_name  
  AND salary > 75000  
  ORDER BY name

• Assuming we have indices on dept_name and salary  
  – how do we sort the results efficiently?

• Variant 1: build an index on the sorting relation  
  – and read from that index  
  – hard to combine with other conditions

• Variant 2: sort in memory (e.g., QuickSort)

• Variant 3: use external sort merge
External Sort-Merge

• Two steps:
  1) Created partially sorted data chunks
  2) Merge the partially sorted chunks

• First step:
  • Let M be the memory capacity
  • 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 \( N \)
External Sort-Merge

- Second step: merge the runs

- **Merge the runs (N-way merge).** We assume (for now) that $N < M$.
  - 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

    ```plaintext
    repeat
    Select the first record (in sort order) among all buffer pages
    Write the record to the output buffer.
    If the output buffer is full write it to disk.
    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.
    until all input buffer pages are empty
    ```

- If $N \geq M$, several merge passes are required
  - In each pass, contiguous groups of $M - 1$ runs are merged
External Sort-Merge

Initial relation:
- g 24
- a 19
- d 31
- c 33
- b 14
- e 16
- r 16
- d 21
- m 3
- p 2
- d 7
- a 14

Create runs:
- a 19
- d 31
- g 24
- b 14
- c 33
- e 16

Merge pass-1:
- a 19
- b 14
- c 33
- d 31
- e 16
- g 24

Sorted output:
- a 14
- d 7
- m 3
- p 2
- r 16
External Sort-Merge

Initial relation:
- g: 24
- a: 19
- d: 31
- c: 33
- b: 14
- e: 16
- r: 16
- d: 21
- m: 3
- p: 2
- d: 7
- a: 14

Runs:
- a: 19
d: 31
b: 14
c: 33
e: 16
g: 24

Merge pass 1:
- a: 19
- b: 14
c: 33
d: 31
e: 16
g: 24

Merge pass 2:
- a: 14
d: 7
e: 16
g: 24
m: 3
p: 2
r: 16

Sorted output:
- a: 14
d: 7
e: 16
g: 24
m: 3
p: 2
r: 16
External Sort-Merge

• At each merge step, only three blocks need to be kept in memory
  – the two (sorted) blocks which are currently merged
  – the current output block
  – after half way through sorting two blocks
    • the current output block is written to disk
    • a second output block is started

• Speed up:
  – the more blocks fit in memory at a same time,
    the larger the chunks can be
  – Ultimately, less passes are required
Join Operations

• Recap: Initial example:
  SELECT name, building, salary
  FROM instructor, building
  WHERE instructor.dept_name = department.dept_name
  AND salary > 75000
  ORDER BY name

• Several different algorithms to implement joins, e.g.
  – 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 instructor: 5,000  department: 10,000
  – Number of blocks of instructor: 100  department: 400
Nested Loop Join

- To compute the theta join \( r \Join_{\theta} s \)
  
  **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

- 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

- In the worst case, if there is enough memory only to hold one block of each relation, the estimated cost is
  \[ n_r \times b_s + b_r \] block transfers, plus
  \[ n_r + b_r \] seeks

- Assuming worst case memory availability cost estimate is
  - with instructor as outer relation:
    \[ 5000 \times 400 + 100 = 2,000,100 \] block transfers,
    \[ 5000 + 100 = 5,100 \] seeks
  - with department as the outer relation
    \[ 10000 \times 100 + 400 = 1,000,400 \] block transfers and 10,400 seeks
Nested Loop Join

• Best case: the smaller relation fits entirely in memory
  – use that as the inner relation
  – reduces cost to $b_r + b_s$ block transfers and two seeks

• If smaller relation (*instructor*) fits entirely in memory, the cost estimate will be 500 block transfers
  – 100 blocks reading the *instructor* relation into memory
  – 400 blocks of the *department* relation
Block Nested Loop Join

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

• Algorithm uses four nested loops

```plaintext
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

- Worst case: only one block of each relation fits in memory
  - estimate: $b_r \times b_s + b_r$ block transfers + $2 \times b_r$ 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:
  - 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
  – 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 \( s \) 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 \( s \)

• If indices are available on join attributes of both \( r \) and \( s \)
  – use the relation with fewer tuples as the outer relation
Cost of Nested Loop with and without Index

• Compute instructor \( \bowtie \) department, with department as the outer relation
  – Let department have a primary B\(^+\)-tree index on the attribute dept_name, which contains 20 entries in each index node
  – Since department has 10,000 tuples, the height of the tree is 4
  – i.e.: five block transfers to find the actual data

• instructor has 5000 tuples

• Cost of block nested loops join
  – \( 400 \times 100 + 100 = 40,100 \) block transfers + \( 2 \times 100 = 200 \) seeks
  – assuming worst case memory
    (may be significantly less with more memory)

• Cost of indexed nested loops join
  – \( 100 + 5000 \times 5 = 25,100 \) block transfers and seeks
Merge Join

- Sort both relations on their join attribute (if not already sorted on the join attributes):
  - move two pointers $pr$ and $ps$
  - if $pr=ps \rightarrow$ add join result to result set
  - else
    - if $pr<ps$
      - advance $pr$
    - else
      - advance $ps$

- Main difference is handling of duplicate values in join attribute:
  - every pair with same value on join attribute must be matched

- Detailed algorithm in book
Merge Join

- Example from http://sqlity.net/en/1480/a-join-a-day-the-sort-merge-join/
Merge Join

• 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
  – plus the cost of sorting if relations are unsorted

$b_b$: no- of buffer blocks allocated to each relation
Merge Join

- Actual comparisons carried out by a merge join
  - roughly linear instead of quadratic

http://www.dcs.ed.ac.uk/home/tz/phd/thesis/node20.htm
Hash Join

• Applicable for equi-joins and natural joins
  – idea: partition joined relations using hashes
  – only compute joins based on the hash partitions

• 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 $i = h(t_r[JoinAttrs])$
  – $s_0, s_1, ..., s_n$ denotes partitions of $s$ tuples
    • Each tuple $t_s \in s$ is put in partition $s_i$ where $i = h(t_s[JoinAttrs])$
Hash Join
Hash Join

Computing Hash Join:
1. Partition the relation \( s \) using hashing function \( h \)
2. Partition \( r \) similarly
3. For each \( i \) (\( 1 \leq i \leq \text{number of partitions} \)):
   (a) Load \( s_i \) into memory and build an in-memory hash index on it using the join attribute (using a different hash function)
   (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

Relation \( s \) is called the \textbf{build input} and \( r \) is called the \textbf{probe input}
Hash Join

• Complexity
  – Building the hash: reading each block in each relation, and writing the partition back to disk: \(2(b_r + b_s)\)
  – Computing the join: reading each partition

• Partitions can also be underfull blocks
  – i.e., there might be \(n_h\) extra partitions for each relation
  – each of those needs to be written and read

• Thus, the total number of block transfers is
  – \(3(b_r + b_s) + 4n_h\)

• Number of seeks
  – need to seek original and partitioned blocks, respecting underfull blocks
  – i.e. \(2\left(\left\lceil \frac{b_r}{b_b} \right\rceil + \left\lceil \frac{b_s}{b_b} \right\rceil\right)\)

for simplicity, overflow partitions are not considered here
Joins with Complex Conditions

• Join with a conjunctive condition:
  \[ r \Join_{\theta_1 \land \theta_2 \land \ldots \land \theta_n} s \]
  – Either use nested loops/block nested loops, or
  – Compute the result of one of the simpler joins \( r \Join_{\theta_i} s \)
  – 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
  \[ r \Join_{\theta_1 \lor \theta_2 \lor \ldots \lor \theta_n} s \]
  – Either use nested loops/block nested loops, or
  – Compute as the union of the records in individual joins \( r \Join_{\theta_i} s \):\[ (r \Join_{\theta_1} s) \cup (r \Join_{\theta_2} s) \cup \ldots \cup (r \Join_{\theta_n} s) \]
Duplicate Elimination & Projection

- In relational algebra, there are no duplicates by definition
  - i.e., each projection yields a unique result
- In SQL queries, they can be explicitly discarded
  - SELECT DISTINCT ...
- Duplicates can be eliminated either via sorting or hashing
  - After sorting, duplicates are adjacent, and can be easily removed passing over the data
    - with sort merge, duplicate elimination can be done early
  - With hashing, they are sorted into the same bucket, and can be detected locally
- Projection
  - perform projection on each tuple
  - then run duplicate removal
Aggregation

- **Aggregation** can be implemented similarly to duplicate elimination
- Sorting or hashing
  - bring tuples in the same group together
  - then apply aggregate functions on each group
- Optimization:
  - combine tuples in the same group during run generation and intermediate merges
  - compute partial aggregate values
    - count, min, max, sum: keep aggregate values on tuples found so far in the group
    - avg: keep sum and count, and divide sum by count at the end
Outer Joins

• **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 $r \bowtie s$
  – In $r \bowtie s$, non participating tuples are those in $r - \Pi_R(r \bowtie s)$
  – 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 $r \bowtie s$
  – If $r$ is probe relation, output non-matching $r$ tuples padded with nulls
  – If $r$ is build relation, keep track of which $r$ tuples matched $s$ tuples
    • at the end of $s$, output non-matched $r$ tuples padded with nulls
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

  \[ \sigma_{\text{building} = "Watson"}(\text{department}) \]

  then compute the store its join with instructor, and finally compute the projection on name.
Cost of Materialization

• 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, do not store result of $\sigma_{building="Watson"}(department)$
  - instead, pass tuples directly to the join
  - 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

- **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 names: **pull** and **push** models of pipelining
Summary

• How are queries executed?
  – Each query is a sequence of operations
  – Sequence: materialization vs. pipelining

• Implementation of different operations
  – Selection
  – Joins
  – Sorting
  – Projection
  – …

• Estimation of query cost
  – block seeks and block transfers
  – gives way to query optimization (next lecture)
Questions?