Database Management Systems

Module 56: Query Processing and Optimization/1: Processing

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Week Recap

- Learnt the importance of backup an analysed different backup strategies
- Failures may be due to variety of sources – each needs a strategy for handling
- A proper mix and management of volatile, non-volatile and stable storage can guarantee recovery from failures and ensure Atomicity, Consistency and Durability
- Log-based recovery is efficient and effective
- Learnt how Hot backup of transaction log helps in recovering consistent database.
- Studied the recovery algorithms for concurrent transactions
- Recovery based on operation logging supplements log-based recovery
- Planning for Backup
- Understood RAID - array of redundant disks in parallel to enhance speed and reliability

Module Objectives

- To understand the overall flow for Query Processing
- To define the Measures of Query Cost
- To understand the algorithms for processing Selection Operations, Sorting, Join Operations, and a few Other Operations

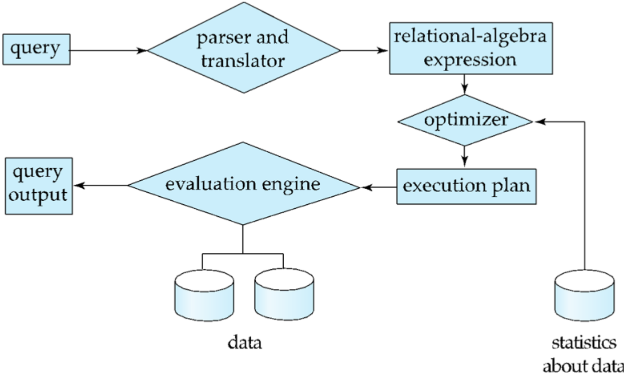
Module Outline

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

Overview of Query Processing

Basic Steps in Query Processing

a) Parsing and translation
b) Optimization
c) Evaluation



Basic Steps in Query Processing (2)

- 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 (3): Optimization

- Consider the query

  select salary
  from instructor
  where salary $<$ 75000;

  which can be translated into either of the following relational-algebra expressions:
  - $\sigma_{salary<75000}(\Pi_{salary}(instructor))$
  - $\Pi_{salary}(\sigma_{salary<75000}(instructor))$
- 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**.
  - For example, 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

Basic Steps in Query Processing (4): Optimization

- **Query Optimization**: Amongst all equivalent evaluation plans choose the one with lowest cost
  - Cost is estimated using statistical information from the database catalog
    - For example, number of tuples in each relation, size of tuples, etc.
- In this module 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 module
  - We study how to optimize queries, that is, how to find an evaluation plan with lowest estimated cost

Measures of Query Cost

Measures of Query Cost

- Cost is generally measured as total elapsed time for answering query
  - 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

Measures of Query Cost (2)

- 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 (3)

- 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

Selection Operation: File / Index Scan

A#	Algorithm	Cost	Reason
A1	Linear Search	$t_S + b_r \times t_T$	One initial seek plus b_r block transfers
A1	Linear Search, Eq. on Key	Average case $t_S + (b_r/2) \times t_T$	Since at most one record satisfies condition, scan can be terminated as soon as the required record is found. b_r blocks transfers in worst case
A2	Prm. Index, Eq. on Key	$(h_i+1) \times (t_T+t_S)$	Index lookup traverses the height of the tree plus one I/O to fetch the record; each of these I/O operations requires a seek and a block transfer
A3	Prm. Index, Eq. on Nonkey	$h_i \times (t_T + t_S) +$ $b \times t_T$	One seek for each level of the tree, one seek for the first block. Here all of b are read. These blocks are leaf blocks assumed to be stored sequentially (for a primary index) and don't require additional seeks
A4	Snd. Index, Eq. on Key	$(h_i+1) \times (t_T+t_S)$	This case is similar to primary index
A4	Snd. Index, Eq. on Nonkey	$(h_i+n) \times (t_T+t_S)$	Here, cost of index traversal is the same as for $A3$, but each record may be on a different block, requiring a seek per record. Cost is potentially very high if n is large
A5	Prm. Index, Comparison	$h_i \times (t_T + t_S) +$ $b \times t_T$	Identical to the case of $A3$, equality on nonkey
A6	Snd. Index, Comparison	$(h_i+n) \times (t_T+t_S)$	Identical to the case of $A4$, equality on nonkey

t_T is time to transfer one block. t_S is time for one seek
b_r denotes the number of blocks in the file
b denotes the number of blocks containing records with the specified search key
h_i denotes the height of the index. n is the number of records fetched

Complex Selections: Conjunction

- **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 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
- **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

Complex Selections: Disjunction

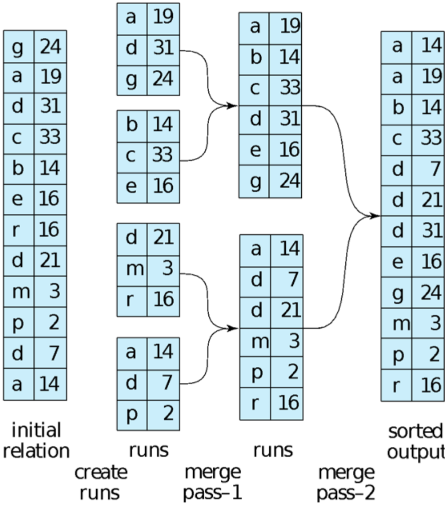
- **Disjunction**: $\sigma_{\theta 1} \vee_{\theta 2} \vee_{\ldots \theta n}$ (r).
- **A10** (**disjunctive selection by union of identifiers**)
  - Applicable if *all* conditions have available indices
    - ▷ Otherwise use linear scan
  - Use corresponding index for each condition, and take union of 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

Sorting

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

External Sort-Merge: Example



External Sort-Merge: Algorithm

a) **Create sorted runs**. Let `M` denote the number of blocks in the main-memory buffer available for sorting. First, a number of sorted runs are created; each run is sorted, but contains only some of the records of the relation.

```
i = 0;
repeat
    read M blocks of the relation, or the rest of the relation, whichever is smaller;
    sort the in-memory part of the relation;
    write the sorted data to run file Ri;
    i = i + 1;
until the end of the relation
```

b) **Merge the runs (N-way merge)**: Now, the runs are merged. For the total number of runs, `N` < `M`, so that we can allocate one block to each run and have space left to hold one block of output. The merge stage operates as follows:

```
read one block of each of the N files Ri into a buffer block in memory;
repeat
    choose the first tuple (in sort order) among all buffer blocks;
    write the tuple to the output, and delete it from the buffer block;
    if the buffer block of any run Ri is empty and not end-of-file(Ri)
    then read the next block of Ri into the buffer block;
until all input buffer blocks are empty
```

c) 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
  - For M=11 and 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

Join Operation

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*: $n_{students} = 5{,}000$
  - Number of records of *takes*: $n_{takes} = 10{,}000$
  - Number of blocks of *student*: $b_{students} = 100$
  - Number of blocks of *takes*: $b_{takes} = 400$

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 (2)

- 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, where n_r (n_s) denotes the number of tuples in r (s) and b_r (b_s) denotes the number of blocks containing tuples of in r (s)
- 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
- Example of join of *students* and *takes*: $n_{students} = 5{,}000$, $n_{takes} = 10{,}000$, $b_{students} = 100$, $b_{takes} = 400$
- 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 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 $t_r \bullet t_s$ to the result.
              end
          end
      end
  end

Block Nested-Loop Join (2)

- 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

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: $b_r \times (t_T + t_S) + n_r * c$
  - 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* $\bowtie$ *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

Other Operations

Other Operations

- **Duplicate Elimination**
- **Projection**
- **Aggregation**
- Set Operations
- Outer Join

Other Operations: Duplicate Elimination & Projection

- **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

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

Module Summary

- Understood the overall flow for Query Processing and defined the Measures of Query Cost
- Studied the algorithms for processing Selection Operations, Sorting, Join Operations and a few Other Operations

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