Implementation of Relational Operations

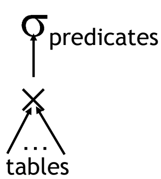
R&G - Chapters 12 and 14

Introduction

- **Today's topic: QUERY PROCESSING**
- **Some database operations are EXPENSIVE**
- **Can greatly improve performance by being "smart"**
  - e.g., can speed up 1,000,000x over naïve approach
- **Main weapons are:**
  1. clever implementation techniques for operators
  2. exploiting relational algebra "equivalences"
  3. using statistics and cost models to choose among these.

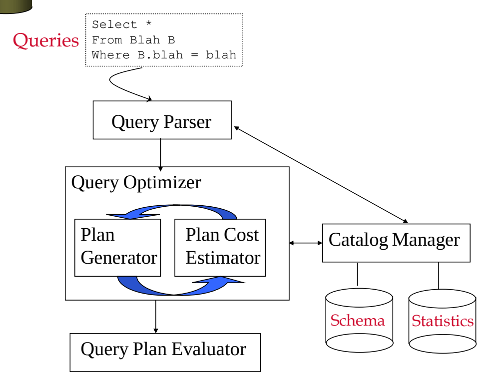
A Really Bad Query Optimizer

- **For each Select-From-Where query block**
  - Create a plan that:
    - Forms the cross product of the FROM clause
    - Applies the WHERE clause



- **Then, as needed:**
  - Apply the GROUP BY clause
  - Apply the HAVING clause
  - Apply any projections and output expressions
  - Apply duplicate elimination and/or ORDER BY

Cost-based Query Sub-System



The Query Optimization Game

- **Goal is to pick a "good" plan**
  - Good = low expected cost, under *cost model*
  - Degrees of freedom:
    - access methods
    - physical operators
    - operator orders
- **Roadmap for this topic:**
  - *First:* implementing individual operators
  - *Then:* optimizing multiple operators

Relational Operations

- **We will consider how to implement:**
  - *Selection* (σ) Select a subset of rows.
  - *Projection* (π) Remove unwanted columns.
  - *Join* ($\bowtie$) Combine two relations.
  - *Set-difference* (-) Tuples in reln. 1, but not in reln. 2.
  - *Union* ($\cup$) Tuples in reln. 1 and in reln. 2.
- **Q: What about Intersection?**

Schema for Examples

Sailors (<u>*sid*: integer</u>, *sname*: string, *rating*: integer, *age*: real)
Reserves (<u>*sid*: integer, *bid*: integer, *day*: dates</u>, *rname*: string)

- **Similar to old schema; *rname* added for variations.**
- **Sailors:**
  - Each tuple is 50 bytes long, 80 tuples per page, 500 pages.
  - $|S|=500$, $p_S=80$.
- **Reserves:**
  - Each tuple is 40 bytes, 100 tuples per page, 1000 pages.
  - $|R|=1000$, $p_R=100$.

Simple Selections

$$\sigma_{R.attr\ op\ value}(R)$$

```
SELECT *
FROM   Reserves R
WHERE  R.rname < 'C%'
```

- **How best to perform? Depends on:**
  - what indexes are available
  - expected size of result
- **Size of result approximated as**
  (size of R) * selectivity
  - selectivity estimated via statistics – we will discuss shortly.

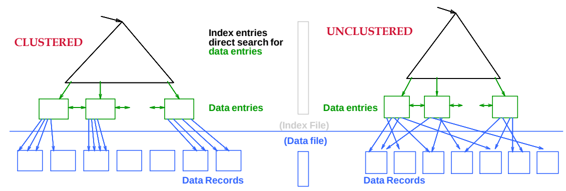
Our options …

- **If no appropriate index exists:**
  Must scan the whole relation
  cost = |R|. For "reserves" = 1000 I/Os.

Our options …

- **With index on selection attribute:**
  1. Use index to find qualifying data entries
  2. Retrieve corresponding data records

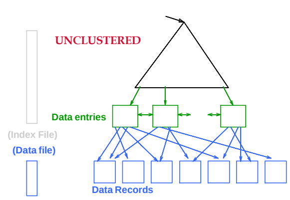
  Total cost = cost of step 1 + cost of step 2
  - For "reserves", if selectivity = 10% (100 pages, 10000 tuples):
    - If *clustered* index, cost is a little over 100 I/Os;
    - If *unclustered*, could be up to 10000 I/Os! *… unless …*



Refinement for unclustered indexes

1. Find qualifying data entries.
2. Sort the rid's of the data records to be retrieved.
3. Fetch rids in order.

Each data page is looked at just once (though # of such pages likely to be higher than with clustering).



General Selection Conditions

✉ *(day<8/9/94 AND rname='Paul') OR bid=5 OR sid=3*

- **First, convert to *<u>conjunctive normal form</u>* (<u>CNF</u>):**
  - *(day<8/9/94* OR *bid=5* OR *sid=3)* AND *(rname='Paul'* OR *bid=5* OR *sid=3)*
- **We only discuss the case with no <u>ORs</u>**
- **Terminology:**
  - A B-tree index *matches* terms that involve only attributes in a *prefix* of the search key. *e.g.*:
  - Index on *<a, b, c>* matches *a=5* AND *b= 3*, but not *b=3*.

2 Approaches to General Selections

Approach I:

1. **Find the *cheapest access path***
2. **retrieve tuples using it**
3. **Apply any remaining terms that don't match the index**

- *Cheapest access path:* An index or file scan that we estimate will require the fewest page I/Os.

Cheapest Access Path - Example

query: ***day < 8/9/94 AND bid=5 AND sid=3***

some options:

B+tree index on day; check bid=5 and sid=3 afterward.
hash index on <bid, sid>; check day<8/9/94 afterward.

- ***How about a B+tree on <rname,day>?***
- ***How about a B+tree on <day, rname>?***
- ***How about a Hash index on <day, rname>?***

2 Approaches to General Selections

Approach II: use 2 or more matching indexes.

1. From each index, get set of rids
2. Compute intersection of rid sets
3. Retrieve records for rids in intersection
4. Apply any remaining terms

EXAMPLE: *day<8/9/94 AND bid=5 AND sid=3*

Suppose we have an index on *day*, and another index on *sid*.

- Get rids of records satisfying *day<8/9/94*.
- Also get rids of records satisfying *sid=3*.
- Find intersection, then retrieve records, then check *bid=5*.

Projection

```
SELECT  DISTINCT
        R.sid, R.bid
FROM    Reserves R
```

- **Issue is removing duplicates.**
- **Use sorting!!**
  1. Scan R, extract only the needed attributes
  2. Sort the resulting set
  3. Remove adjacent duplicates

Cost:

Reserves with size ratio 0.25 = 250 pages.

With 20 buffer pages can sort in 2 passes, so:

1000 +250 + 2 * 2 * 250 + 250 = 2500 I/Os

Projection -- improved

- **Modify the external sort algorithm:**
  - Modify Pass 0 to eliminate unwanted fields.
  - Modify Passes 1+ to eliminate duplicates.

Cost:

Reserves with size ratio 0.25 = 250 pages.

With 20 buffer pages can sort in 2 passes, so:

1. Read 1000 pages
2. Write 250 (in runs of 40 pages each)
3. Read and merge runs

Total cost = 1000 + 250 +250 = 1500.

Other Projection Tricks

If an index search key contains all wanted attrs:

- **Do *index-only* scan**
  - Apply projection techniques to data entries *(much smaller!)*

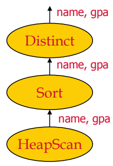
If a B+Tree index search key *prefix* has all wanted attrs:

- **Do *in-order* index-only scan**
  - Compare adjacent tuples on the fly *(no sorting required!)*

Query Execution Framework

```
SELECT DISTINCT name, gpa
  FROM Students
```

One possible query execution plan:



Iterators

- **Relational operators are all subclasses of the class** `iterator`**:**

```
class iterator {
   void init();
   tuple next();
   void close();
   iterator &inputs[];
  // additional state goes here
}
```

- **Note:**
  - Edges in the graph are specified by inputs (max 2, usually)
  - Any iterator can be input to any other!

Example: Sort

```
class Sort extends iterator {
   void init();
   tuple next();
   void close();
   iterator &inputs[1];
   int numberOfRuns;
   DiskBlock runs[];
   RID nextRID[];
}
```

- `init()`:
  - generate the sorted runs on disk *(passes 0 to n-1)*
  - Allocate `runs[]` array and fill in with disk pointers.
  - Initialize numberOfRuns
  - Allocate nextRID array and initialize to first RID of each run
- `next()`:
  - nextRID array tells us where we're "up to" in each run
  - find the next tuple to return based on nextRID array
  - advance the corresponding nextRID entry
  - return tuple (or EOF -- "End of Fun" -- if no tuples remain)
- `close()`:
  - deallocate the runs and nextRID arrays

Postgres Version

- **src/backend/executor/nodeSort.c**
  - ExecInitSort (init)
  - ExecSort (next)
  - ExecEndSort (close)
- **The encapsulation stuff is hardwired into the Postgres C code**
  - Postgres predates even C++!
  - See src/backend/execProcNode.c for the code that "dispatches the methods" explicitly!

Joins

```
SELECT  *
FROM    Reserves R1, Sailors S1
WHERE   R1.sid=S1.sid
```

- **Joins are very common.**
- **R × S is large; so, R × S followed by a selection is inefficient.**
- **Many approaches to reduce join cost.**

- **Join techniques we will cover today:**
  1. Nested-loops join
  2. Index-nested loops join
  3. Sort-merge join

Simple Nested Loops Join

R ⋈ S: foreach tuple r in R do
    foreach tuple s in S do
        if $r_i == s_j$ then add <r, s> to result

Cost = $(p_R * |R|) * |S| + |R|$ = 100*1000*500 + 1000 IOs
- At 10ms/IO, Total time: ???

- **What if smaller relation (S) was "outer"?**
- **What assumptions are being made here?**
- **What is cost if one relation can fit entirely in memory?**

Page-Oriented Nested Loops Join

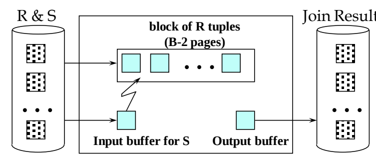
R $\bowtie$ S: foreach page b_R in R do
    foreach page b_S in S do
        foreach tuple r in b_R do
            foreach tuple s in b_S do
                if $r_i == s_j$ then add <r, s> to result

Cost = |R|*|S| + |R| = 1000*500 + 1000

- If smaller relation (S) is outer, cost = 500*1000 + 500
- Much better than naïve per-tuple approach!

Block Nested Loops Join

- **Page-oriented NL doesn't exploit extra buffers :(**
- **Idea to use memory efficiently:**



Cost: Scan outer + (#outer blocks * scan inner)

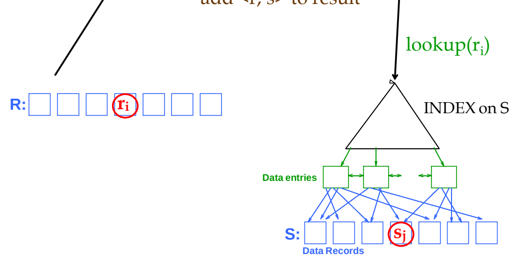
#outer blocks = $\lceil \#\ of\ \ pages\ of\ outer\ /\ blocksize \rceil$

Examples of Block Nested Loops Join

- **Say we have B = 100+2 memory buffers**
- **Join cost = |outer| + (#outer blocks * |inner|)**
  #outer blocks = |outer| / 100
- **With R as outer (|R| = 1000):**
  - Scanning R costs 1000 IO's *(done in 10 blocks)*
  - Per block of R, we scan S; costs 10*500 I/Os
  - Total = 1000 + 10*500.
- **With S as outer (|S| = 500):**
  - Scanning S costs 500 IO's *(done in 5 blocks)*
  - Per block of S, we can R; costs 5*1000 IO's
  - Total = 500 + 5*1000.

Index Nested Loops Join

R $\bowtie$ S: foreach tuple r in R do
    foreach tuple s in S where $r_i == s_j$ do
        add <r, s> to result



Index Nested Loops Join

R $\bowtie$ S: foreach tuple r in R do
    foreach tuple s in S where $r_i == s_j$ do
        add <r, s> to result

Cost = |R| + (|R|*p_R) * cost to find matching S tuples

- If index uses Alt. 1, cost = cost to traverse tree from root to leaf.
- For Alt. 2 or 3:
  1. Cost to lookup RID(s); typically 2-4 IO's for B+Tree.
  2. Cost to retrieve records from RID(s); depends on clustering.
     - Clustered index: 1 I/O per page of matching S tuples.
     - Unclustered: up to 1 I/O per matching S tuple.

Sort-Merge Join

1. Sort R on join attr(s)
2. Sort S on join attr(s)
3. Scan sorted-R and sorted-S in tandem, to find matches

Example:

```
SELECT  *
FROM    Reserves R1, Sailors S1
WHERE   R1.sid=S1.sid
```

sid	sname	rating	age
22	dustin	7	45.0
28	yuppy	9	35.0
31	lubber	8	55.5
44	guppy	5	35.0
58	rusty	10	35.0

sid	bid	day	rname
28	103	12/4/96	guppy
28	103	11/3/96	yuppy
31	101	10/10/96	dustin
31	102	10/12/96	lubber
31	101	10/11/96	lubber
58	103	11/12/96	dustin

Cost of Sort-Merge Join

- **Cost: Sort R + Sort S + (|R|+|S|)**
  - But in worst case, last term could be |R|*|S| *(very unlikely!)*
  - Q: what is worst case?

Suppose B = 35 buffer pages:
- **Both R and S can be sorted in 2 passes**
- **Total join cost = 4*1000 + 4*500 + (1000 + 500) = 7500**

Suppose B = 300 buffer pages:
- **Again, both R and S sorted in 2 passes**
- **Total join cost = 7500**

Block-Nested-Loop cost = 2500 ... 15,000

Other Considerations …

1. **An important refinement:**
   Do the join during the final merging pass of sort !
   - If have enough memory, can do:
     1. Read R and write out sorted runs
     2. Read S and write out sorted runs
     3. Merge R-runs and S-runs, and find R $\bowtie$ S matches

   Cost = 3*|R| + 3*|S|

   Q: how much memory is "enough" *(will answer next time …)*

2. **Sort-merge join an especially good choice if:**
   –one or both inputs are already sorted on join attribute(s)
   –output is required to be sorted on join attributes(s)

   Q: how to take these savings into account? *(stay tuned …)*

Summary

- **A virtue of relational DBMSs:**

  queries are composed of a few basic operators

  - The implementation of these operators can be carefully tuned
- **Many alternative implementation techniques for each operator**
  - No universally superior technique for most operators.
- **Must consider available alternatives**
  - Called "Query optimization" -- we will study this topic soon!