ECS 165B: Database System Implementation
Lecture 15

UC Davis
April 30, 2010

Acknowledgements: portions based on slides by Raghu Ramakrishnan and Johannes Gehrke, as well as slides by Zack Ives.

Class Agenda

- Last time:
  - Quiz #1
  - Query optimization
- Today:
  - Query optimization, continued
- Reading
  - Chapter 15 of Ramakrishnan and Gehrke (or Chapter 14 of Silberschatz et al)

Announcements

Reminder: DavisDB Part 2 due Sunday @11:59pm

DavisDB Part 3: out Sunday night, due Sunday 5/8 @11:59pm

Statistics for Quiz #1:

avg	15.9/19
median	16/19
std	2.5
min	10/19
max	20/19

Reminder: Implementation Hints for DavisDB Part 2

- Handling duplicates: what if many records have the same key value? Can circumvent by **including (internally) the record id as part of the key**
  - i.e., "key" becomes a pair <key, recordID>
  - No duplicates, by construction!
- Handling deletions: **you are permitted to just use tombstones**
  - When an entry is deleted, replace by a special marker indicating an empty slot (which may be reused later)
  - Internal nodes are never deleted or merged!

Relational Query Optimization, Continued

Query Optimization

- Given a SQL query:
  - Build a *logical query plan*: tree of algebraic operations
  - Transform into "better" logical plan
  - Convert into a *physical query plan*, using implementations of operators we've seen in the previous lectures
- Goal: find the physical query plan that has minimum cost
  - In practice: avoid the plans with the highest costs
  - Sources of cost: Interactions with other concurrent tasks; sizes of intermediate results; choices of algorithms, access methods; I/O and CPU; properties of data such as skew, order, placement; …

Optimization Strategies

- Many possible strategies, all boil down to a **search** over the space of possible plans
  - Super-exponential complexity in the # of operators
  - Hence, exhaustive search generally not feasible
- What can you do?
  - Heuristics only: INGRES, Oracle until the mid-90s
  - Randomized, simulated annealing, … : many efforts in the mid-90s
  - **Heuristics plus cost-based join enumeration: System R**
  - Stratifed search (heuristics plus cost-based enumeration of joins and a few other operators): Starbust
  - Unified search (full cost-based search): EXODUS, Volcano, Cascades

Highlights of System R Optimizer

- Historically, the most influential optimizer design
- Cost estimation: approximate art at best
  - Statistics, maintained in system catalogs, used to estimate cost of operations and result sizes
  - Considers combination of CPU and I/O costs
- Plan space: too large, must be pruned using heuristics
  - Only the space of *left-deep plans* is considered
  - *Pipelined execution model*: output of each operator is pipelined into the next operator, without storing it in a temporary relation
  - Cartesian products avoided
- Dynamic programming approach

Query Blocks: Units of Optimization in System R

```
select S.name
from Sailors S
where S.age in (select max(S2.age)
                from Sailors S2
                group by S2.rating)
```

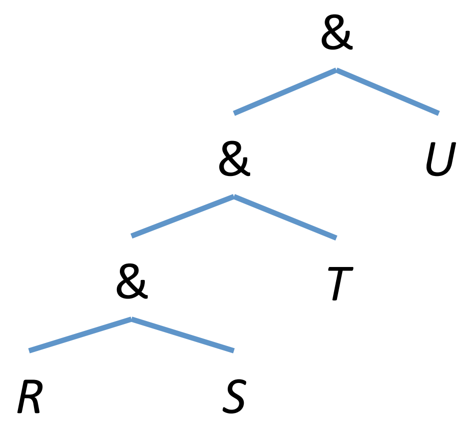
outer block

nested block

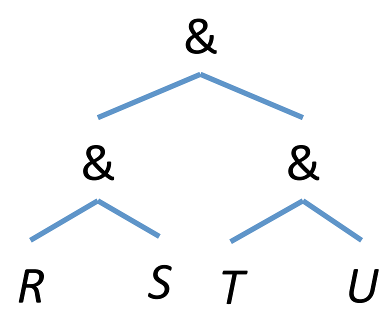
- SQL query parsed into a collection of *query blocks*, to be optimized one block at a time
- Nested blocks treated as calls to a subroutine, made once per outer tuple
- For each block, the plans considered are
  - All available access methods, for each relation in `from` clause
  - All *left-deep join trees*: i.e., all ways to join the relations one-at-a-time, with the inner relation in the from clause, considering all join order permuations and join methods

Left-Deep Join Trees

- Left-deep join tree:



- "Bushy" join tree:



Relational Algebra Equivalences

- Allow us to choose different join orders; to "push" selections and projections ahead of joins; etc

1. $\sigma_{F_1}(\sigma_{F_2}(E)) \equiv \sigma_{F_1 \wedge F_2}(E)$
2. $\sigma_F(E_1\ [\cup, \cap, -]\ E_2) \equiv \sigma_F(E_1)\ [\cup, \cap, -]\ \sigma_F(E_2)$
3. $\sigma_F(E_1 \times E_2) \equiv \sigma_{F0}(\sigma_{F1}(E_1) \times \sigma_{F2}(E_2))$;

   $F \equiv F0 \wedge F1 \wedge F2$, Fi contains only attributes of E_i, $i = 1, 2$.
4. $\sigma_{A=B}(E_1 \times E_2) \equiv E_1 \underset{A=B}{\bowtie} E_2$
5. $\pi_{\mathbf{A}}(E_1\ [\cup, \cap, -]\ E_2) \equiv \pi_{\mathbf{A}}(E_1)\ [\cup, \cap, -]\ \pi_{\mathbf{A}}(E_2)$

Relational Algebra Equivalences (2)

6. $\pi_{\mathbf{A}}(\mathtt{E}_1 \times \mathtt{E}_2) \equiv \pi_{\mathbf{A1}}(\mathtt{E}_1) \times \pi_{\mathbf{A2}}(\mathtt{E}_2)$,
   with $\mathbf{Ai} = \mathbf{A} \cap \{$ attributes in $\mathtt{E}_\mathtt{i}\}$, $\mathtt{i} = 1, 2$.

7. $\mathtt{E}_1 \; [\cup, \cap] \; \mathtt{E}_2 \equiv \mathtt{E}_2 \; [\cup, \cap] \; \mathtt{E}_1$
   $(\mathtt{E}_1 \cup \mathtt{E}_2) \cup \mathtt{E}_3 \equiv \mathtt{E}_1 \cup (\mathtt{E}_2 \cup \mathtt{E}_3)$ (the analogous holds for $\cap$)

8. $\mathtt{E}_1 \times \mathtt{E}_2 \equiv \pi_{\mathbf{A1},\mathbf{A2}}(\mathtt{E}_2 \times \mathtt{E}_1)$
   $(\mathtt{E}_1 \times \mathtt{E}_2) \times \mathtt{E}_3 \equiv \mathtt{E}_1 \times (\mathtt{E}_2 \times \mathtt{E}_3)$
   $(\mathtt{E}_1 \times \mathtt{E}_2) \times \mathtt{E}_3 \equiv (\mathtt{E}_1 \times \mathtt{E}_3) \times \mathtt{E}_2$

9. $\mathtt{E}_1 \bowtie \mathtt{E}_2 \equiv \mathtt{E}_2 \bowtie \mathtt{E}_1$ $(\mathtt{E}_1 \bowtie \mathtt{E}_2) \bowtie \mathtt{E}_3 \equiv \mathtt{E}_1 \bowtie (\mathtt{E}_2 \bowtie \mathtt{E}_3)$

(Theoretical aside: is this set of equivalences **complete**?)

Enumeration of Alternative Plans

- There are two main cases:
  - Single-relation plans
  - Multiple-relation plans
- Single-relation plans: queries consist of a combination of selections, projections, and aggregates (no joins)
  - Each available *access path* (file or index scan) is considered, and the one with the least estimated cost is chosen
  - The different operations are carried out together in a pipeline (e.g., if an index is used for a selection, projection is done for each retrieved tuple, and the resulting tuples are pipelined into the aggregate computation)

Cost Estimation

- Must estimate cost of each plan considered
- To do this, must estimate cost of each operation in plan tree
  - Depends on input cardinalities, statistical properties, etc
- Must also estimate *size of result* for each operation in tree!
  - Use information about the input relations
  - For selections and joins, assume independence of predicates
- Dirty little secret of DBMS world: estimation works well for simple plans, but poorly for complex plans

Cost Estimation for Single-Relation Plans

- Clustered index *I* matching one or more selections:
  - cost ≈ (# pages in *I*) × product of RF's* of matching selects
- Non-clustered index *I* matching one or more selections:
  - cost ≈ (# pages in *I* + # tuples in *R*) × product of RF's of matching selects
- Sequential scan of file:
  - cost ≈ # of pages in *R*
- Extra cost for duplicate elimination if user says `select distinct`

* RF is "reduction factor" : what % of the data passes the selection condition

Queries Over Multiple Relations

- Fundamental heuristic in System R: *only left-deep join trees are considered*
- As the # of joins increases, the # of alternative plans grows very rapidly; we need to restrict the search space
- Left-deep join trees allow us to generate all *fully pipelined* plans
  - i.e., intermediate results not written to temporary files (not "materialized")
  - not all left-deep physical plans are fully pipelined
- Bushy join trees: can't have fully pipelined plans
  - Inner table must always be materialized for each tuple of the outer table
  - So, a plan in which the inner table is the result of a join forces us to materialize the result of that join

Enumeration of Left-Deep Plans

- Left-deep plans differ only in the order of relations, the access method for each relation, and the join method for each join
- Enumeration via dynamic programming strategy: *n* passes, where *n* = # relations joined
  - Pass 1: find best 1-relation plan for each relation
  - Pass 2: find best way to join result of each 1-relation plan (as outer) to another relation
  - Pass *n*: find best way to join result of each (*n*-1)-relation plan (as outer) to the *n*th relation
- For each subset of relations, retain only:
  - Cheapest plan overall, plus
  - Cheapest plan for each "interesting order" of the tuples

Enumeration of Plans (2)

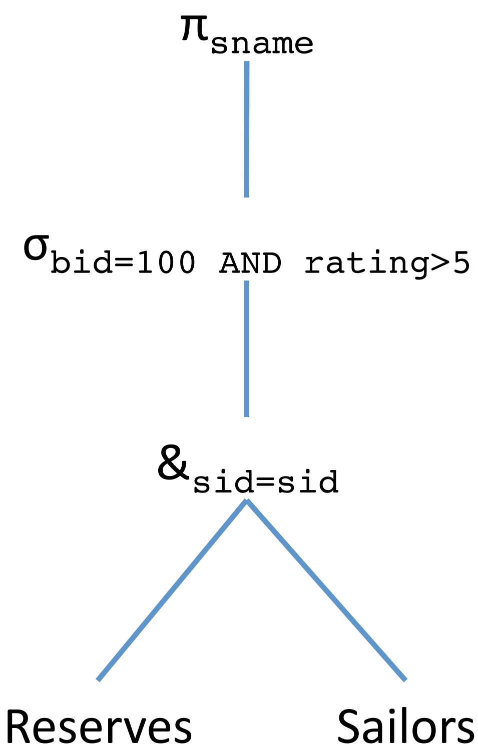
- `order by`, `group by`, aggregates, etc. handled as a final step, using either an "interestingly ordered" plan or an additional sorting operator

- An (*n*-1)-way plan is not combined with an additional relation unless there is a join condition between them, unless all predicates in `where` have been used up
  - i.e., avoid Cartesian products if possible

- In spite of pruning plan space, this approach is still exponential in the # of tables

Enumeration of Plans: Example

```
SELECT S.sname
FROM   Reserves R, Sailors S
WHERE  R.sid = S.sid AND
       R.bid = 100 AND
       S.rating > 5
```



- Assume: B+ tree index on `Sailors.rating`; hash index on `Sailors.sid`; B+ tree index on `Reserves.bid` (all unclustered)

Enumeration of Plans Example: Pass 1

- Consider access path methods for single relations
  - **`Sailors`**: three access methods (B+ tree, hash index, sequential scan), taking into account selection $\sigma_{\texttt{rating>5}}$.
    - B+ tree? Yes, matches σ; also returns tuples sorted by rating
    - Hash index? Sequential scan? More costly than B+ tree

    => B+ tree preferred, with tuples sorted by rating
  - **`Reserves`**: two access methods (B+ tree, sequential scan), taking into account selection $\sigma_{\texttt{bid=100}}$.
    - B+ tree? yes, matches σ
    - Sequential scan? Slower than B+ tree

    => B+ tree preferred

Enumeration of Plans Example: Pass 2

- Consider all two-relation plans, using access method from Pass 1 for outer relation in join

  `Reserves` outer, `Sailors` inner:

  - Need only `Sailors` tuples that satisfy $\sigma_{\texttt{rating>5}}$ and $\sigma_{\texttt{sid=value}}$ where `value` is some value from an outer tuple
  - Access method for `Sailors`:
    - B+ tree? Yes, matches $\sigma_{\texttt{rating>5}}$
    - Hash index? Yes, matches $\sigma_{\texttt{sid=value}}$; = more selective than >

      => Hash index preferred
  - Alternative join methods: all are considered, e.g.,
    - Sort-merge join: inputs must be sorted by `sid`; no single-relation access method returns them sorted this way, so requires extra sort
    - Index nested loops: can use, since have hash index on `Sailors.sid`
    - etc

  => Index nested loops join preferred

Enumeration of Plans Example: Pass 2 (cont)

`Sailors` outer, `Reserves` inner:

- Need only `Reserves` tuples that satisfy $\sigma_{bid=100}$ and $\sigma_{sid=value}$ where `value` is some value from an outer tuple
- Choose access method for `Reserves`
  - ...
- Choose preferred join algorithm
  - ...
- Retain cheapest plan overall: e.g.,

Index nested loops join with `Reserves` outer, `Sailors` inner preferred

- Pass 2 is the last pass, so we output this as the plan

Enumeration of Plans Example (2): Pass 3

```
SELECT S.sid, B.bid
FROM   Reserves R, Sailors S, Boats B
WHERE  R.sid = S.sid AND B.bid = R.bid
    AND B.color = "red"
```

- For each plan retained in Pass 2, taken as the outer relation, consider how to join the remaining relation as the inner one
  - {`Reserves`, `Sailors`} outer, `Boats` inner
  - {`Reserves`, `Boats`} outer, `Sailors` inner: not considered!
    - no join condition for {`Reserves`, `Boats`}
  - {`Sailors`, `Boats`} outer, `Reserves` inner: also not considered!
    - no join condition for {`Sailors`, `Boats`}

Cost Estimation for Multi-Relation Plans

```
SELECT attribute-list
FROM relation-list
WHERE term1 AND ... AND termk
```

- Key issue: estimating cardinalities of intermediate results
- Maximum # tuples in result is the product of the cardinalities of relations in the from clause
- *Reduction factor* (RF) associated with each *term* reflects the impact of the term in reducing result size. Result cardinality ≈ max # tuples × product of all RF's
- Multirelation plans are built up by joining one new relation at a time
  - Cost of join method plus estimation of join cardinality gives us both cost estimate and result size estimate
- Errors at each step are compounded!

Nested Queries

```
SELECT S.sname
FROM Sailors S
WHERE EXISTS (SELECT *
              FROM Reserves R
              WHERE R.bid = 103
               AND R.sid = S.sid)
```

- Nested block is optimized independently, with the outer tuple considered as providing a selection condition
- Outer block is optimized with the cost of "calling" nested block computation taken into consideration
- Implicit order of these blocks means that some good strategies are not considered. *The non-nested version of the query is typically optimized better.*

Nested block to optimize:

```
SELECT *
FROM Reserves R
WHERE R.bid = 103
    AND R.sid = outer value
```

Equivalent non-nested query:

```
SELECT S.sname
FROM Sailors S, Reserves R
WHERE S.sid = R.sid
    AND R.bid = 103
```

Summary

- Query optimization: crucial task in relational DBMS
  - Declarative query language requires powerful optimizer
- Even an end-user (DBA) must understand optimization in order to understand the performance impact of a given database design (schema, indices, etc) on a workload (expected queries and updates)
- Two parts to optimizing a query:
  - Explore the space of alternative plans
    - Must prune search space; System R considers left-deep plans only
  - Must estimate cost of each plan that is considered
    - Must estimate size of result and cost for each plan node
    - Key issues: statistics, indices, operator implementations

Summary (continued)

- Single-relation queries:
  - All access paths considered, cheapest is chosen
  - Issues: selections that match index, whether index key has all needed fields and/or provides tuples in a desired order
- Multiple-relation queries: greedy, inductive approach
  - Base case: All single-relation plans are first enumerated
    - Selections/projections considered as early as possible
  - Inductive case: for each *n*-relation plan, all ways of joining another relation (as inner) are considered, to produce an *n*+1 relation plan
  - At each level, for each subset of relations, only best plan (for each "interesting order" of tuples) is retained