Query Optimization

Introduction to Databases
CompSci 316 Fall 2017
Announcements (Tue., Nov. 28)

• Homework #4 due next Tuesday
• Project demos—sign-up instructions to be emailed
  • Early in-class demos on 12/7
• Final exam Sat. Dec. 16 2-5pm
  • Open-book, open-notes
  • Comprehensive, but with strong emphasis on the second half of the course
  • Sample final already posted
Query optimization

• One logical plan → “best” physical plan

• Questions
  • How to enumerate possible plans
  • How to estimate costs
  • How to pick the “best” one

• Often the goal is not getting the optimum plan, but instead avoiding the horrible ones

Any of these will do

1 second  1 minute  1 hour
Plan enumeration in relational algebra

• Apply relational algebra equivalences

Join reordering: $\times$ and $\bowtie$ are associative and commutative (except column ordering, but that is unimportant)
More relational algebra equivalences

- Convert $\sigma_p \times$ to/from $\bowtie_p$: $\sigma_p (R \times S) = R \bowtie_p S$
- Merge/split $\sigma$’s: $\sigma_{p_1} (\sigma_{p_2} R) = \sigma_{p_1 \land p_2} R$
- Merge/split $\pi$’s: $\pi_{L_1} (\pi_{L_2} R) = \pi_{L_1} R$, where $L_1 \subseteq L_2$
- Push down/pull up $\sigma$:
  $\sigma_{p \land p_r \land p_s} (R \bowtie_{p'} S) = (\sigma_{p_r} R) \bowtie_{p \land p'} (\sigma_{p_s} S)$, where
  - $p_r$ is a predicate involving only $R$ columns
  - $p_s$ is a predicate involving only $S$ columns
  - $p$ and $p'$ are predicates involving both $R$ and $S$ columns
- Push down $\pi$: $\pi_{L} (\sigma_{p} R) = \pi_{L} \left( \sigma_{p} (\pi_{L'} R) \right)$, where
  - $L'$ is the set of columns referenced by $p$ that are not in $L$
- Many more (seemingly trivial) equivalences...
  - Can be systematically used to transform a plan to new ones
Relational query rewrite example

\[
\pi_{\text{Group.name}} \\
\sigma_{\text{User.name} = \text{“Bart”} \land \text{User.uid} = \text{Member.uid} \land \text{Member.gid} = \text{Group.gid}} \\
\times \\
\text{Group} \\
\times \\
\text{User} \\
\times \\
\text{Member} \\
\pi_{\text{Group.name}} \\
\sigma_{\text{Member.gid} = \text{Group.gid}} \\
\times \\
\text{Group} \\
\times \\
\text{User} \\
\sigma_{\text{User.uid} = \text{Member.uid}} \\
\times \\
\text{Member} \\
\sigma_{\text{name} = \text{“Bart”}} \\
\text{User}
Heuristics-based query optimization

• Start with a logical plan
• **Push selections/projections down as much as possible**
  • Why? Reduce the size of intermediate results
  • Why not? May be expensive; maybe joins filter better
• **Join smaller relations first, and avoid cross product**
  • Why? Reduce the size of intermediate results
  • Why not? Size depends on join selectivity too
• Convert the transformed logical plan to a physical plan (by choosing appropriate physical operators)
SQL query rewrite

• More complicated—subqueries and views divide a query into nested “blocks”
  • Processing each block separately forces particular join methods and join order
  • Even if the plan is optimal for each block, it may not be optimal for the entire query

• Unnest query: convert subqueries/views to joins
  ➕ We can just deal with select-project-join queries
    • Where the clean rules of relational algebra apply
SQL query rewrite example

• SELECT name
  FROM User
  WHERE uid = ANY (SELECT uid FROM Member);

• SELECT name
  FROM User, Member
  WHERE User.uid = Member.uid;
  • Wrong—consider two Bart’s, each joining two groups

• SELECT name
  FROM (SELECT DISTINCT User.uid, name
         FROM User, Member
         WHERE User.uid = Member.uid);
  • Right—assuming User.uid is a key
Dealing with correlated subqueries

• SELECT gid FROM Group
  WHERE name LIKE 'Springfield%'
  AND min_size > (SELECT COUNT(*) FROM Member
                 WHERE Member.gid = Group.gid);

• SELECT gid
  FROM Group, (SELECT gid, COUNT(*) AS cnt
              FROM Member GROUP BY gid) t
  WHERE t.gid = Group.gid AND min_size > t.cnt
  AND name LIKE 'Springfield%';

  • New subquery is inefficient (it computes the size for every group)

  • Suppose a group is empty?
“Magic” decorrelation

- SELECT gid FROM Group
  WHERE name LIKE 'Springfield'
  AND min_size > (SELECT COUNT(*) FROM Member
                  WHERE Member.gid = Group.gid);

- WITH Supp_Group AS (SELECT * FROM Group WHERE name LIKE 'Springfield%'),
  Magic AS (SELECT DISTINCT gid FROM Supp_Group),
  DS AS ((SELECT Group.gid, COUNT(*) AS cnt
          FROM Magic, Member WHERE Magic.gid = Member.gid
          GROUP BY Member.gid) UNION
          (SELECT gid, 0 AS cnt
           FROM Magic WHERE gid NOT IN (SELECT gid FROM Member)))

SELECT Supp_Group.gid FROM Supp_Group, DS
WHERE Supp_Group.gid = DS.gid
AND min_size > DS.cnt;

1. Process the outer query without the subquery
2. Collect bindings
3. Evaluate the subquery with bindings
4. Finally, refine the outer query
Heuristics- vs. cost-based optimization

• **Heuristics-based optimization**
  • Apply heuristics to rewrite plans into cheaper ones

• **Cost-based optimization**
  • **Rewrite** logical plan to combine “blocks” as much as possible
  • **Optimize** query block by block
    • Enumerate logical plans (already covered)
    • Estimate the cost of plans
    • Pick a plan with acceptable cost
  • **Focus**: select-project-join blocks
Cost estimation

Physical plan example:

Input to \text{SORT}(gid):

- \text{SCAN} (User)
- \text{SORT} (uid)
- \text{MERGE-JOIN} (uid)
- \text{FILTER} (\text{name} = \text{“Bart”})
- \text{SCAN} (Member)
- \text{SORT} (uid)
- \text{MERGE-JOIN} (gid)
- \text{SCAN} (Group)
- \text{SORT} (gid)
- \text{PROJECT} (\text{Group.title})

\text{SORT}(gid):

- \text{SCAN} (User)
- \text{FILTER} (\text{name} = \text{“Bart”})
- \text{SCAN} (Member)
- \text{SORT} (uid)
- \text{MERGE-JOIN} (uid)
- \text{SCAN} (Group)
- \text{SORT} (gid)
- \text{PROJECT} (\text{Group.title})

- We have: cost estimation for each operator
  - Example: \text{SORT}(gid) takes $O(B(\text{input}) \times \log M B(\text{input}))$
    - But what is $B(\text{input})$?
- We need: \text{size of intermediate results}
Cardinality estimation

http://www.learningresources.com/product/estimation+station.do
Selections with equality predicates

• $Q: \sigma_{A=v} R$

• Suppose the following information is available
  • Size of $R$: $|R|$
  • Number of distinct $A$ values in $R$: $|\pi_A R|$

• Assumptions
  • Values of $A$ are uniformly distributed in $R$
  • Values of $v$ in $Q$ are uniformly distributed over all $R. A$ values

• $|Q| \approx \frac{|R|}{|\pi_A R|}$
  • Selectivity factor of $(A = v)$ is $\frac{1}{|\pi_A R|}$
Conjunctive predicates

• $Q: \sigma_{A=u} \land B=v R$

• Additional assumptions
  • $(A = u)$ and $(B = v)$ are independent
    • Counterexample: major and advisor
  • No “over”-selection
    • Counterexample: $A$ is the key

• $|Q| \approx \frac{|R|}{|\pi_A R| \cdot |\pi_B R|}$
  • Reduce total size by all selectivity factors
Negated and disjunctive predicates

- $Q: \sigma_{A \neq v} R$
  - $|Q| \approx |R| \cdot \left(1 - \frac{1}{|\pi_{AR}|}\right)$
  - Selectivity factor of $\neg p$ is $(1 - \text{selectivity factor of } p)$

- $Q: \sigma_{A = u \lor B = v} R$
  - $|Q| \approx |R| \cdot \left(\frac{1}{|\pi_{AR}|} + \frac{1}{|\pi_{BR}|}\right)$?
    - No! Tuples satisfying $(A = u) \text{ and } (B = v)$ are counted twice
  - $|Q| \approx |R| \cdot \left(\frac{1}{|\pi_{AR}|} + \frac{1}{|\pi_{BR}|} - \frac{1}{|\pi_{AR}| |\pi_{BR}|}\right)$
    - Inclusion-exclusion principle
Range predicates

- \( Q: \sigma_{A \geq v} R \)
- Not enough information!
  - Just pick, say, \( |Q| \approx |R| \cdot \frac{1}{3} \)
- With more information
  - Largest R.A value: \( \text{high}(R.A) \)
  - Smallest R.A value: \( \text{low}(R.A) \)
  - \( |Q| \approx |R| \cdot \frac{\text{high}(R.A) - v}{\text{high}(R.A) - \text{low}(R.A)} \)
- In practice: sometimes the second highest and lowest are used instead
  - The highest and the lowest are often used by inexperienced database designer to represent invalid values!
Two-way equi-join

• \( Q: R(A, B) \bowtie S(A, C) \)

• Assumption: \textit{containment of value sets}
  • Every tuple in the “smaller” relation (one with fewer distinct values for the join attribute) joins with some tuple in the other relation
  • That is, if \(|\pi_A R| \leq |\pi_A S|\) then \(\pi_A R \subseteq \pi_A S\)
  • Certainly not true in general
  • But holds in the common case of foreign key joins

• \(|Q| \approx \frac{|R| \cdot |S|}{\max(|\pi_A R|,|\pi_A S|)}\)
  • Selectivity factor of \( R.A = S.A \) is \(\frac{1}{\max(|\pi_A R|,|\pi_A S|)}\)
Multiway equi-join

• $Q: R(A, B) \bowtie S(B, C) \bowtie T(C, D)$

• What is the number of distinct $C$ values in the join of $R$ and $S$?

• Assumption: preservation of value sets
  • A non-join attribute does not lose values from its set of possible values
  • That is, if $A$ is in $R$ but not $S$, then $\pi_A(R \bowtie S) = \pi_A R$
  • Certainly not true in general
  • But holds in the common case of foreign key joins (for value sets from the referencing table)
Multiway equi-join (cont’d)

• \( Q: R(A, B) \bowtie S(B, C) \bowtie T(C, D) \)

• Start with the product of relation sizes
  • \( |R| \cdot |S| \cdot |T| \)

• Reduce the total size by the selectivity factor of each join predicate
  • \( R.B = S.B: \frac{1}{\max(|\pi_{BR}|,|\pi_{BS}|)} \)
  • \( S.C = T.C: \frac{1}{\max(|\pi_{CS}|,|\pi_{CT}|)} \)
  • \( |Q| \approx \frac{|R| \cdot |S| \cdot |T|}{\max(|\pi_{BR}|,|\pi_{BS}|) \cdot \max(|\pi_{CS}|,|\pi_{CT}|)} \)
Cost estimation: summary

• Using similar ideas, we can estimate the size of projection, duplicate elimination, union, difference, aggregation (with grouping)

• Lots of assumptions and very rough estimation
  • Accurate estimate is not needed
  • Maybe okay if we overestimate or underestimate consistently
  • May lead to very nasty optimizer “hints”
    
    SELECT * FROM User WHERE pop > 0.9;
    SELECT * FROM User WHERE pop > 0.9 AND pop > 0.9;

• Not covered: better estimation using histograms
Search strategy

http://1.bp.blogspot.com/-Motdu8reRKs/TgyAi4ki5QI/AAAAAAAAAKE/mi8ejfZ8S7U/s1600/cornMaze.jpg
Search space

• Huge!
• “Bushy” plan example:

- Just considering different join orders, there are \(\frac{(2n-2)!}{(n-1)!}\) bushy plans for \(R_1 \bowtie \cdots \bowtie R_n\)
  - 30240 for \(n = 6\)

- And there are more if we consider:
  - Multiway joins
  - Different join methods
  - Placement of selection and projection operators
Left-deep plans

• Heuristic: consider only “left-deep” plans, in which only the left child can be a join
  • Tend to be better than plans of other shapes, because many join algorithms scan inner (right) relation multiple times—you will not want it to be a complex subtree

• How many left-deep plans are there for $R_1 \bowtie \cdots \bowtie R_n$?
  • Significantly fewer, but still lots—$n!$ (720 for $n = 6$)
A greedy algorithm

- \( S_1, \ldots, S_n \)
  - Say selections have been pushed down; i.e., \( S_i = \sigma_p(R_i) \)
- Start with the pair \( S_i, S_j \) with the smallest estimated size for \( S_i \bowtie S_j \)
- Repeat until no relation is left:
  Pick \( S_k \) from the remaining relations such that the join of \( S_k \) and the current result yields an intermediate result of the smallest size

Pick most efficient join method
Minimize expected size
Current subplan

..., \( S_k \), \( S_l \), \( S_m \), ...
Remaining relations to be joined
A dynamic programming approach

• Generate optimal plans **bottom-up**
  • Pass 1: Find the best single-table plans (for each table)
  • Pass 2: Find the best two-table plans (for each pair of tables) by combining best single-table plans
  • ...
  • Pass $k$: Find the best $k$-table plans (for each combination of $k$ tables) by combining two smaller best plans found in previous passes
  • ...

• Rationale: Any subplan of an optimal plan must also be optimal (otherwise, just replace the subplan to get a better overall plan)

☞ Well, not quite...
The need for “interesting order”

- Example: $R(A, B) \bowtie S(A, C) \bowtie T(A, D)$
- Best plan for $R \bowtie S$: hash join (beats sort-merge join)
- Best overall plan: sort-merge join $R$ and $S$, and then sort-merge join with $T$
  - Subplan of the optimal plan is not optimal!
- Why?
  - The result of the sort-merge join of $R$ and $S$ is sorted on $A$
  - This is an interesting order that can be exploited by later processing (e.g., join, dup elimination, GROUP BY, ORDER BY, etc.!)
Dealing with interesting orders

When picking the best plan

• Comparing their costs is not enough
  • Plans are not totally ordered by cost anymore

• Comparing interesting orders is also needed
  • Plans are now partially ordered
  • Plan $X$ is better than plan $Y$ if
    • Cost of $X$ is lower than $Y$, and
    • Interesting orders produced by $X$ “subsume” those produced by $Y$

• Need to keep a set of optimal plans for joining every combination of $k$ tables
  • At most one for each interesting order
Summary

- Relational algebra equivalence
- SQL rewrite tricks
- Heuristics-based optimization
- Cost-based optimization
  - Need statistics to estimate sizes of intermediate results
  - Greedy approach
  - Dynamic programming approach