Relational Query Optimization

15-415, Spring 2003, Lecture 15
R & G Chapter 15

> It is safer to accept any chance that offers itself, and extemporize a procedure to fit it, than to get a good plan matured, and wait for a chance of using it.
>
> Thomas Hardy (1874)
> in *Far from the Madding Crowd*

Review

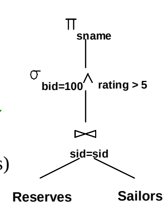
- **Implementation of single Relational Operations**
- **Choices depend on indexes, memory, stats,...**
- **Joins**
  - Blocked nested loops:
    - simple, exploits extra memory
  - Indexed nested loops:
    - best if 1 rel small and one indexed
  - Sort/Merge Join
    - good with small amount of memory, bad with duplicates
  - Hash Join
    - fast (enough memory), bad with skewed data

Query Optimization Overview

- **Query can be converted to relational algebra**
- **Rel. Algebra converted to tree, joins as branches**
- **Each operator has implementation choices**
- **Operators can also be applied in different order!**

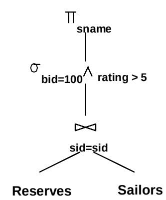
```
SELECT S.sname
FROM  Reserves R, Sailors S
WHERE  R.sid=S.sid AND
   R.bid=100 AND S.rating>5
```

$\pi_{(sname)}\sigma_{(bid=100 \wedge rating > 5)}$ (Reserves $\bowtie$ Sailors)



Iterator Interface

- **A note on implementation:**



•Relational operators at nodes support uniform *iterator* interface:

Open( ), get_next( ), close( )

•Unary Ops – On Open() call Open() on child.

•Binary Ops – call Open() on left child then on right.

•By convention, outer is on left.

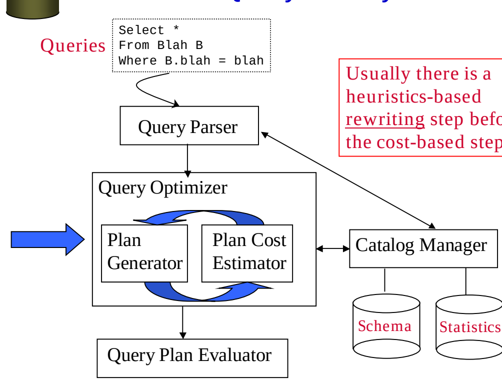
Alternative is pipelining (i.e. a "push"-based approach).

Can combine push & pull using special operators.

Query Optimization Overview (cont)

- ***Plan*: Tree of R.A. ops, with choice of algorithm for each op.**
  - Each operator typically implemented using a `pull' interface: when an operator is `pulled' for the next output tuples, it `pulls' on its inputs and computes them.
- **Two main issues:**
  - For a given query, what plans are considered?
    - Algorithm to search plan space for cheapest (estimated) plan.
  - How is the cost of a plan estimated?
- **Ideally: Want to find best plan.**
- **Reality: Avoid worst plans!**

Cost-based Query Sub-System



Usually there is a heuristics-based rewriting step before the cost-based steps.

Schema for Examples

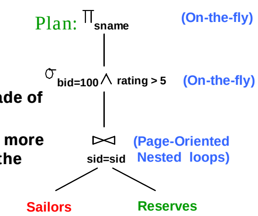
Sailors (sid: integer, sname: string, rating: integer, age: real)
Reserves (sid: integer, bid: integer, day: dates, rname: string)

- **As seen in previous two lectures...**
- **Reserves:**
  - Each tuple is 40 bytes long, 100 tuples per page, 1000 pages.
  - Let's say there are 100 boats.
- **Sailors:**
  - Each tuple is 50 bytes long, 80 tuples per page, 500 pages.
  - Let's say there are 10 different ratings.

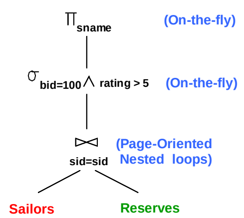
Motivating Example

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

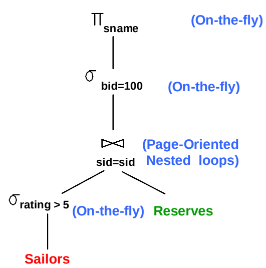
- **Cost: 500+500*1000 I/Os**
- **By no means the best plan!**
- **Misses several opportunities: selections could have been `pushed' earlier, no use is made of any available indexes, etc.**
- ***Goal of optimization:* To find more efficient plans that compute the same answer.**



Alternative Plans – Push Selects (No Indexes)

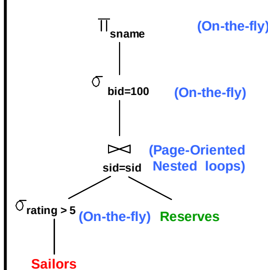


500,500 IOs

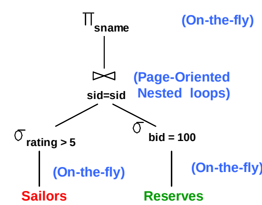


250,500 IOs

Alternative Plans – Push Selects (No Indexes)



250,500 IOs



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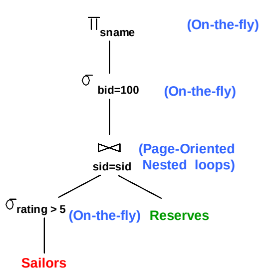
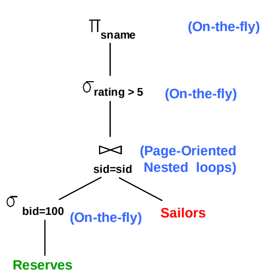
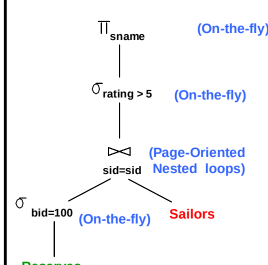


250,500 IOs

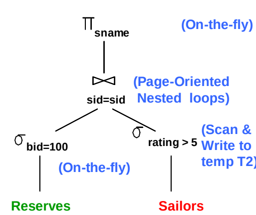


6000 IOs

Alternative Plans – Push Selects (No Indexes)

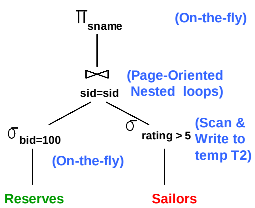


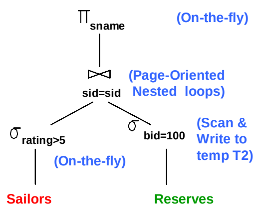
6000 IOs



4250 IOs
1000 + 500+ 250 + (10 * 250)

Alternative Plans – Push Selects (No Indexes)

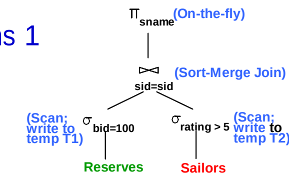




4250 IOs

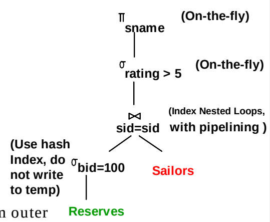
4010 IOs
500 + 1000 +10 +(250 *10)

Alternative Plans 1 (No Indexes)



- *Main difference:* ***Sort Merge Join***
- **With 5 buffers, cost of plan:**
  - Scan Reserves (1000) + write temp T1 (10 pages, if we have 100 boats, uniform distribution).
  - Scan Sailors (500) + write temp T2 (250 pages, if have 10 ratings).
  - Sort T1 (2*2*10), sort T2 (2*3*250), merge (10+250)
  - Total: 3560 page I/Os.
- **If use BNL join, join = 10+4*250, total cost = 2770.**
- **Can also `push' projections, but must be careful!**
  - T1 has only *sid*, T2 only *sid*, *sname*:
  - T1 fits in 3 pgs, cost of BNL under 250 pgs, total < 2000.

Alt Plan 2: Indexes



- **With clustered index on *bid* of Reserves, we get 100,000/100 = 1000 tuples on 1000/100 = 10 pages.**
- **INL with outer not materialized.**
  - Projecting out unnecessary fields from outer doesn't help.
- Join column *sid* is a key for Sailors.
  - At most one matching tuple, unclustered index on *sid* OK.
- Decision not to push *rating*>5 before the join is based on availability of *sid* index on Sailors.
- Cost: Selection of Reserves tuples (10 I/Os); then, for each, must get matching Sailors tuple (1000*1.2); total 1210 I/Os.

What is needed for optimization?

- **Iterator Interface**
- **Cost Estimation**
- **Statistics and Catalogs**
- **Size Estimation and Reduction Factors**

Summary

- **Query optimization is an important task in a relational DBMS.**
- **Must understand optimization in order to understand the performance impact of a given database design (relations, indexes) on a workload (set of queries).**
- **Two parts to optimizing a query:**
  - Consider a set of alternative plans.
    - Must prune search space; typically, 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, indexes, operator implementations.

Query Optimization

- **Query can be dramatically improved by changing access methods, order of operators.**
- **Iterator interface**
- **Cost estimation**
  - Size estimation and reduction factors
- **Statistics and Catalogs**
- **Relational Algebra Equivalences**
- **Choosing alternate plans**
- **Multiple relation queries**
- **Will focus on "System R"-style optimizers**

Highlights of System R Optimizer

- **Impact:**
  - Most widely used currently; works well for < 10 joins.
- **Cost estimation:**
  - Very inexact, but works ok in practice.
  - Statistics, maintained in system catalogs, used to estimate cost of operations and result sizes.
  - Considers combination of CPU and I/O costs.
  - More sophisticated techniques known now.
- **Plan Space: Too large, must be pruned.**
  - Only the space of *left-deep plans* is considered.
  - Cartesian products avoided.

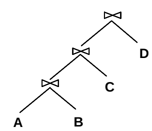
Query Blocks: Units of Optimization

- **An SQL query is parsed into a collection of *query blocks*, and these are optimized one block at a time.**
- **Nested blocks are usually treated as calls to a subroutine, made once per outer tuple. (This is an over-simplification, but serves for now.)**

```
SELECT S.sname
FROM Sailors S
WHERE S.age IN
   (SELECT MAX (S2.age)
    FROM Sailors S2
    GROUP BY S2.rating)
```

Outer block *Nested block*

- For each block, plans considered are:
  - All available access methods, for each reln in FROM clause.
  - All *left-deep join trees* (i.e., all ways to join the relations one-at-a-time, with the inner reln in the FROM clause, considering all reln permutations and join methods.)



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)

- **Reserves:**
  - Each tuple is 40 bytes long, 100 tuples per page, 1000 pages. 100 distinct bids.
- **Sailors:**
  - Each tuple is 50 bytes long, 80 tuples per page, 500 pages. 10 Ratings, 40,000 sids.

Translating SQL to Relational Algebra

```
SELECT S.sid, MIN (R.day)
FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid AND B.color = "red"
AND S.rating = ( SELECT MAX (S2.rating) FROM Sailors S2)
GROUP BY S.sid
HAVING COUNT (*) >= 2
```

For each sailor with the highest rating (over all sailors), and at least two reservations for red boats, find the sailor id and the earliest date on which the sailor has a reservation for a red boat.

Translating SQL to Relational Algebra

```
SELECT S.sid, MIN (R.day)
FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid AND B.color = "red"
AND S.rating = ( SELECT MAX (S2.rating) FROM Sailors S2)
GROUP BY S.sid
HAVING COUNT (*) >= 2
```

Inner Block

$\pi_{\text{S.sid, MIN(R.day)}}$
(HAVING $_{\text{COUNT(*)>2}}$ (
GROUP BY $_{\text{S.Sid}}$ (
$\sigma_{\text{B.color = "red" } \wedge \text{ S.rating = val}}$(
Sailors $\bowtie$ Reserves $\bowtie$ Boats))))

Relational Algebra Equivalences

- **Allow us to choose different join orders and to `push' selections and projections ahead of joins.**
- ***Selections:*** $\sigma_{c1 \wedge \ldots \wedge cn}(R) \equiv \sigma_{c1}(\ldots \sigma_{cn}(R))$ **(*Cascade*)**
  $\sigma_{c1}(\sigma_{c2}(R)) \equiv \sigma_{c2}(\sigma_{c1}(R))$ (*Commute*)
- *Projections:* $\pi_{a1}(R) \equiv \pi_{a1}(\ldots(\pi_{an}(R)))$ (*Cascade*)
- *Joins:* $R \bowtie (S \bowtie T) \equiv (R \bowtie S) \bowtie T$ (*Associative*)
  $(R \bowtie S) \equiv (S \bowtie R)$ (*Commute*)
- **This means we can do joins in any order.**

More Equivalences

- **A projection commutes with a selection that only uses attributes retained by the projection.**
- **Selection between attributes of the two arguments of a cross-product converts cross-product to a join.**
- **A selection on just attributes of R commutes with $R \bowtie S$. (i.e., $\sigma(R \bowtie S) \equiv \sigma(R) \bowtie S$)**
- **Similarly, if a projection follows a join $R \bowtie S$, we can `push' it by retaining only attributes of R (and S) that are needed for the join or are kept by the projection.**

Cost Estimation

- **For each plan considered, must estimate cost:**
  - Must estimate *cost* of each operation in plan tree.
    - Depends on input cardinalities.
    - We've already discussed how to estimate the cost of operations (sequential scan, index scan, joins, etc.)
  - Must estimate *size of result* for each operation in tree!
    - Use information about the input relations.
    - For selections and joins, assume independence of predicates.
  - In System R, cost is boiled down to a single number consisting of #I/O + *factor* * #CPU instructions
  - Q: Is "cost" the same as estimated "run time"?

Statistics and Catalogs

- **Need information about the relations and indexes involved.** *Catalogs* **typically contain at least:**
  - # tuples (**NTuples**) and # pages (**NPages**) per rel'n.
  - # distinct key values (**NKeys**) for each index.
  - low/high key values (**Low/High**) for each index.
  - Index height (**IHeight**) for each tree index.
  - # index pages (**INPages**) for each index.
- **Stats in catalogs updated periodically.**
  - Updating whenever data changes is too expensive; lots of approximation anyway, so slight inconsistency ok.
- **More detailed information (e.g., histograms of the values in some field) are sometimes stored.**

Reduction Factors & Histograms

- **For better estimation, use a histogram**

No. of Values	2	3	3	1	8	2	1
Value	0-.99	1-1.99	2-2.99	3-3.99	4-4.99	5-5.99	6-6.99

equiwidth

No. of Values	2	3	3	3	3	2	4
Value	0-.99	1-1.99	2-2.99	3-4.05	4.06-4.67	4.68-4.99	5-6.99

equidepth

Size Estimation and Reduction Factors

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

- Consider a query block:
- 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.
- *RF is usually called "selectivity".*

Result Size Estimation for Selections

- *Result cardinality =*
  Max # tuples * product of all RF's.
  (Implicit assumption that values are uniformly distributed and *terms* are independent!)
- Term *col=value* (given index I on *col*)
  RF = *1/NKeys(I)*
- Term *col1=col2* (**This is handy for joins too...**)
  RF = *1/MAX(NKeys(I1), NKeys(I2))*
- Term *col>value*
  RF = *(High(I)-value)/(High(I)-Low(I))*
- *Note, if missing indexes, assume* ***1/10****!!!*

Result Size estimation for joins

- **Q: Given a join of R and S, what is the range of possible result sizes (in #of tuples)?**
  - Hint: what if R∩S = ∅?
  - R∩S is a key for R (and a Foreign Key in S)?
- **General case: R∩S = {A} (and A is key for neither)**
  - estimate each tuple r of R generates NTuples(S)/NKeys(A,S) result tuples, so...

    NTuples(R) * NTuples(S)/NKeys(A,**S**)
  - but can also consider it starting with S, yielding:
    NTuples(R) * NTuples(S)/NKeys(A,**R**)
  - If these two estimates differ, take the lower one!
    - Q: Why?

Enumeration of Alternative Plans

- **There are two main cases:**
  - Single-relation plans
  - Multiple-relation plans
- **For queries over a single relation, queries consist of a combination of selects, projects, and aggregate ops:**
  - Each available access path (file scan / index) is considered, and the one with the least estimated cost is chosen.
  - The different operations are essentially carried out together (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 Estimates for Single-Relation Plans

- **Index I on primary key matches selection:**
  - *Cost is Height(I)+1 for a B+ tree, about 1.2 for hash index.*
- **Clustered index I matching one or more selects:**
  - *(NPages(I)+NPages(R)) * product of RF's of matching selects.*
- **Non-clustered index I matching one or more selects:**
  - *(NPages(I)+NTuples(R)) * product of RF's of matching selects.*
- **Sequential scan of file:**
  - *NPages(R).*
  - ***Note:*** *Must also charge for duplicate elimination if requried*

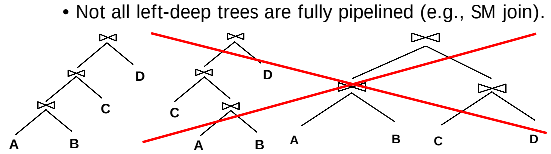
Example

```
SELECT S.sid
FROM  Sailors S
WHERE  S.rating=8
```

- **If we have an index on *rating*:**
  - Cardinality: (1/NKeys(I)) * NTuples(S) = (1/10) * 40000 tuples retrieved.
  - Clustered index: (1/NKeys(I)) * (NPages(I)+NPages(S)) = (1/10) * (50+500) = 55 pages are retrieved.
  - Unclustered index: (1/NKeys(I)) * (NPages(I)+NTuples(S)) = (1/10) * (50+40000) = 4005 pages are retrieved.
- **If we have an index on *sid*:**
  - Would have to retrieve all tuples/pages. With a clustered index, the cost is 50+500, with unclustered index, 50+40000.
- **Doing a file scan:**
  - We retrieve all file pages (500).

Queries Over Multiple Relations

- **Fundamental decision in System R: *only left-deep join trees* are considered.**
  - As the number of joins increases, the number of alternative plans grows rapidly; *we need to restrict the search space.*
  - Left-deep trees allow us to generate all *fully pipelined* plans.
    - Intermediate results not written to temporary files.
    - Not all left-deep trees are fully pipelined (e.g., SM 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.**
  - maximum possible orderings = N! (but no X-products)
- **Enumerated using N passes (if N relations joined):**
  - Pass 1: Find best 1-relation plans for each relation.
  - Pass 2: Find best ways to join result of each 1-relation plan as outer to another relation. *(All 2-relation plans.)*
  - Pass N: Find best ways to join result of a (N-1)-relation plan as outer to the N'th relation. *(All N-relation plans.)*
- **For each subset of relations, retain only:**
  - Cheapest plan overall (possibly unordered), plus
  - Cheapest plan for each *interesting order* of the tuples.

A Note on "Interesting Orders"

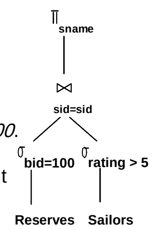
- **An intermediate result has an "interesting order" if it is sorted by any of:**
  - ORDER BY attributes
  - GROUP BY attributes
  - Join attributes of other joins

System R Plan Enumeration (Contd.)

- 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.
- ORDER BY, GROUP BY, aggregates etc. handled as a final step, using either an `interestingly ordered' plan or an additional sorting operator.
- In spite of pruning plan space, this approach is still exponential in the # of tables.
- COST considered is ***#IOs + factor * CPU Inst***

Example

Reserves:
Unclust B+ tree on *bid*
Sailors:
Unclust Hash on *sid*
Unclust B+ tree on *rating*



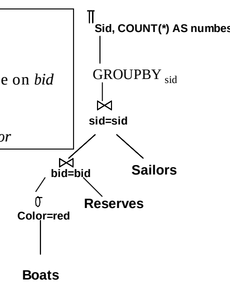
- Pass1:
  - *Reserves*: B+ tree on *bid* matches *bid=100*.
  - *Sailors*: B+ tree matches *rating>5*, but this selection is expected to retrieve a lot of tuples, and index is unclustered, so file scan w/ select is likely cheaper.

Pass 2: We consider each Pass 1 plan as the outer:
Reserves as outer (B+Tree selection on bid):
Use hash index on Sailors.sid for INL
Sailors as outer (File Scan w/select on rating):
Use BNL on result of selection on Reserves.bid

Example

Sailors:
Hash, B+ on *sid*
Reserves:
Clustered B+ tree on *bid*
B+ on *sid*
Boats
B+, Hash on *color*

Select S.sid, COUNT(*) AS numbes
FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid
AND B.color = "red"
GROUP BY S.sid



- **Pass1: Best plan(s) for accessing each relation**
  - Reserves, Sailors: File Scan
  - Q: What about Clustered B+ on Reserves.bid???
  - Boats: B+ tree & Hash on color

Pass 2

- **For each of the plans in pass 1, generate plans joining another relation as the inner, using all join methods**
  - File Scan Reserves (outer) with Boats (inner)
  - File Scan Reserves (outer) with Sailors (inner)
  - File Scan Sailors (outer) with Boats (inner)
  - File Scan Sailors (outer) with Reserves (inner)
  - Boats hash on color with Sailors (inner)
  - Boats Btree on color with Sailors (inner)
  - Boats hash on color with Reserves (inner) (sort-merge)
  - Boats Btree on color with Reserves (inner) (BNL)
- **Retain cheapest plan for each pair of relations plus cheapest plan for each interesting order.**

Pass 3 and beyond

- **For each of the plans retained from Pass 2, taken as the outer, generate plans for the inner join**
  - eg Boats hash on color with Reserves (bid) (inner) (sortmerge)) inner Sailors (B-tree sid) sort-merge
- **Then, add the cost for doing the group by and aggregate:**
  - This is the cost to sort the result by sid, *unless it has already been sorted by a previous operator.*
- **Then, choose the cheapest plan**

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 account.**
- **Implicit ordering 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
```

Points to Remember

- Must understand optimization in order to understand the performance impact of a given database design (relations, indexes) on a workload (set of queries).
- Two parts to optimizing a query:
  - Consider a set of alternative plans.
    - Must prune search space; typically, 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, indexes, operator implementations.

Points to Remember

- **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.

More Points to Remember

- **Multiple-relation queries:**
  - All single-relation plans are first enumerated.
    - Selections/projections considered as early as possible.
  - Next, for each 1-relation plan, all ways of joining another relation (as inner) are considered.
  - Next, for each 2-relation plan that is `retained', all ways of joining another relation (as inner) are considered, etc.
  - At each level, for each subset of relations, only best plan for each interesting order of tuples is `retained'.

Summary

- **Optimization is the reason for the lasting power of the relational system**
- **But it is primitive**
- **New areas: Rule-based optimizers, random statistical approaches (*eg simulated annealing)***