Relational Query Optimization II: Costing and Searching

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Reading: R & G Chapter 15

What is needed for query optimization?

- Given: A closed set of operators
  - Relational ops (table in, table out)
  - Physical implementations (of those ops and a few more)

1. **Plan space**
   - Based on relational equivalences, different implementations
2. **Cost Estimation** based on
   - Cost formulas
   - Size estimation, in turn based on
     - Catalog information on base tables
     - Selectivity (Reduction Factor) estimation
3. **A search algorithm**
   - To sift through the plan space and find lowest cost option!

Reminder

- We’ll focus on “System R” (“Selinger”) optimizers
  - Many of the details have been refined over time
  - We’ll see some refinements today
  - This remains an area of ongoing research!

A Naïve Query Optimizer

- Given an input query Q:
  1. Enumerate all possible plans for Q
     - Too many plans to consider!
  2. Estimate the cost of each plan
     - Hard to estimate cost accurately given caches etc
  3. Pick plan with the lowest cost
     - How? Keep all plans in memory?

Query plan space

```
Select o_year,
sum(case
 when nation = 'BRAZIL' then volume
 else 0
end) / sum(volume)
from
(
 select YEAR(O_ORDERDATE) as o_year,
  L_EXTENDEDPRICE * (1 - L_DISCOUNT) as volume,
  n2.N_NAME as nation
 from PART, SUPPLIER, LINEITEM, ORDERS, CUSTOMER, NATION n1,
 NATION n2, REGION
 where
    P_PARTKEY = L_PARTKEY and S_SUPPKEY = L_SUPPKEY
    and L_ORDERKEY = O_ORDERKEY and O_CUSTKEY = C_CUSTKEY
    and C_NATIONKEY = n1.N_NATIONKEY and n1.N_REGIONKEY = R_REGIONKEY
    and R_NAME = 'AMERICA' and S_NATIONKEY = n2.N_NATIONKEY
    and O_ORDERDATE between '1995-01-01' and '1996-12-31'
    and P_TYPE = 'ECONOMY ANODIZED STEEL'
    and S_ACCTBAL <= constant-1
    and L_EXTENDEDPRICE <= constant-2
) as all_nations
group by o_year  order by o_year
```

There about 22 million alternative ways of executing this query!

Slide from D Dewitt

Big Picture of System R Optimizer

- Plan Space
  - Many plans have the same high cost subtree that can be pruned
  - Heuristics (aka tricks that usually work):
    - Consider only left-deep plans
    - Avoid Cartesian products
    - Don’t optimize the entire query at once
- Cost estimation
  - Inexact is fine as long as we can compare plans
    - Better estimators have been developed
- Search Algorithm
  - Dynamic Programming

Query Optimization

1. **Plan Space**
2. Cost Estimation
3. Search Algorithm

Query Blocks: Units of Optimization

- Break query into query blocks
- Optimize one block at a time
- Uncorrelated nested blocks computed once
- Correlated nested blocks are like function calls
  - But sometimes can be "decorrelated"
  - Recall relational algebra lecture

```
SELECT S.sname
  FROM Sailors S
 WHERE S.age IN
```

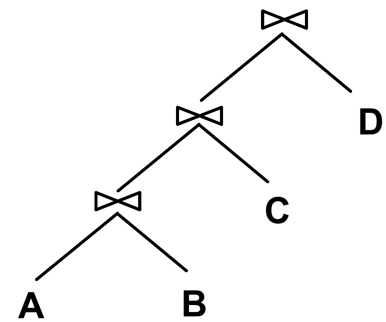
Outer block

```
   (SELECT MAX (S2.age)
       FROM  Sailors S2
GROUP BY  S2.rating)
```

Nested block

Query Blocks: Units of Optimization Pt 2

- For each block, the plans considered are:
  - All relevant access methods, for each relation in `FROM` clause.
  - All left-deep join trees
    - right branch always a base table
    - consider all join orders and join methods

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  FROM Sailors S
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```

Outer block

```
  (SELECT MAX (S2.age)
     FROM   Sailors S2
GROUP BY   S2.rating)
```

Nested block

Schema for Examples

```
Sailors (sid: integer, sname: text, rating: integer,
         age: float)
Reserves (sid: integer, bid: integer, day: date,
          rname: text)
```

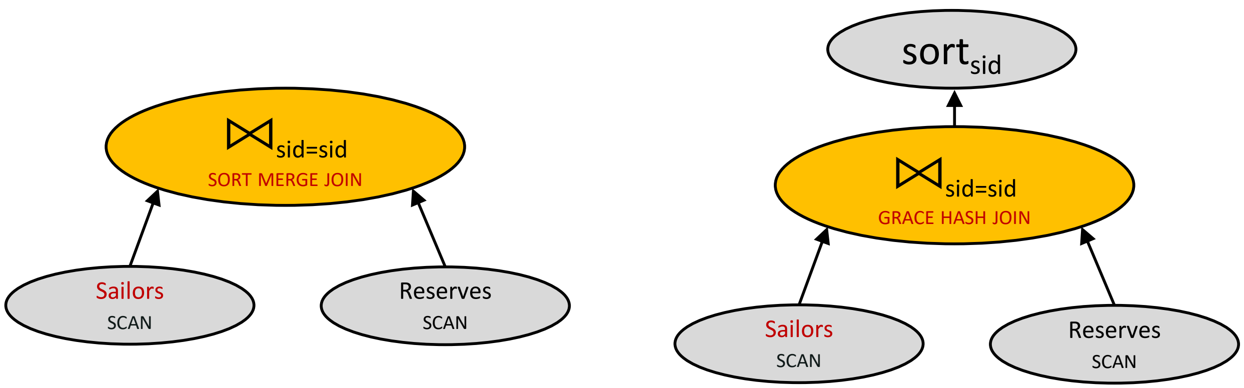
- Reserves:
  - Each tuple is 40 bytes long, 100 tuples per page, 1000 pages.
  - 100 distinct bids.
- Sailors:
  - Each tuple is 50 bytes long,
  - 80 tuples per page, 500 pages.
  - 10 ratings, 40,000 sids.

“Physical” Properties

- Two common “physical” properties of an output:
  - Sort order
  - Hash Grouping
- Certain operators produce these properties in output
  - E.g. Index scan (result is sorted)
  - E.g. Sort (result is sorted)
  - E.g. Hash (result is grouped)
- Certain operators require these properties at input
  - E.g. MergeJoin requires sorted input
- Certain operators preserve these properties from inputs
  - E.g. MergeJoin preserves sort order of inputs
  - E.g. Index nested loop join (INLJ) preserves sort order of outer (left) input

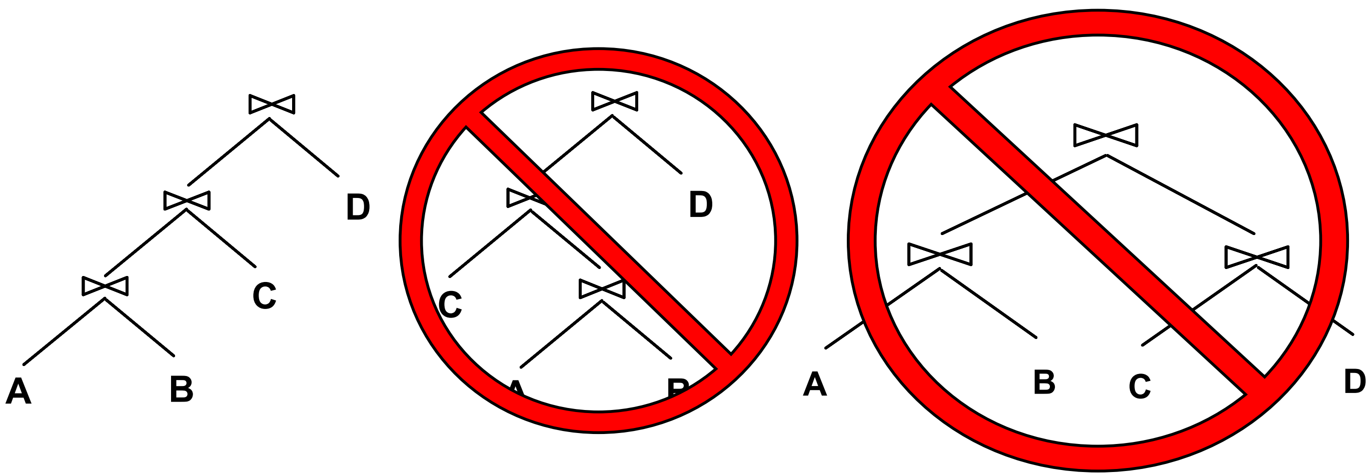
Recall: Physically Equivalent Plans

- Same content and same physical properties



Queries Over Multiple Relations

- A System R heuristic: only left-deep join trees considered.
  - Restricts the search space
  - Left-deep trees allow us to generate all fully pipelined plans.
    - i.e., intermediate results not written to temporary files.
    - Not all left-deep trees are fully pipelined (e.g., SM join).



Plan Space Review

- For a SQL query, full plan space:
  - All equivalent relational algebra expressions
    - Based on the equivalence rules we learned
  - All mixes of physical implementations of those algebra expressions
- We might prune this space:
  - Selection/Projection pushdown
  - Left-deep trees only
  - Avoid Cartesian products
- Along the way we may care about physical properties like sorting
  - Because downstream ops may depend on them
  - And enforcing them later may be expensive

Query Optimization: Cost Estimation

1. Plan Space
2. **Cost Estimation**
3. Search Algorithm

Cost Estimation

- For each plan considered, must estimate total cost:
  - Must estimate ***cost*** of each operation in plan tree.
    - Depends on input cardinalities.
    - We've already discussed this for various operators
      - sequential scan, index scan, joins, etc.
  - Must estimate ***size of result*** for each operation in tree!
    - Because it determines downstream input cardinalities!
    - 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 + ***CPU-factor*** * #tuples
  - Second term estimate the cost of tuple processing

Statistics and Catalogs

- Need info on relations and indexes involved.
- **Catalogs** typically contain at least:

Statistic	Meaning
NTuples	# of tuples in a table (cardinality)
NPages	# of disk pages in a table
Low/High	min/max value in a column
Nkeys	# of distinct values in a column
IHeight	the height of an index
INPages	# of disk pages in an index

- Catalogs updated periodically.
  - Too expensive to do continuously
  - Lots of approximation anyway, so a little slop here is ok.
- Modern systems do more
  - Especially keep more detailed statistical information on data values
    - e.g., histograms

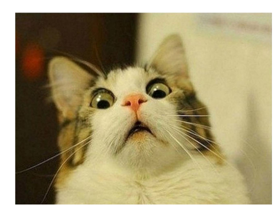
Size Estimation and Selectivity

- Max output cardinality = product of input cardinalities
- **Selectivity (sel)** associated with each **term**
  - reflects the impact of the term in reducing result size.
  - selectivity = |output| / |input|
  - Book calls selectivity "Reduction Factor" (RF)
  - Always between 0 and 1
- Avoid confusion:
  - "highly selective" in common English is opposite of a high selectivity value (|output|/|input| high!)

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

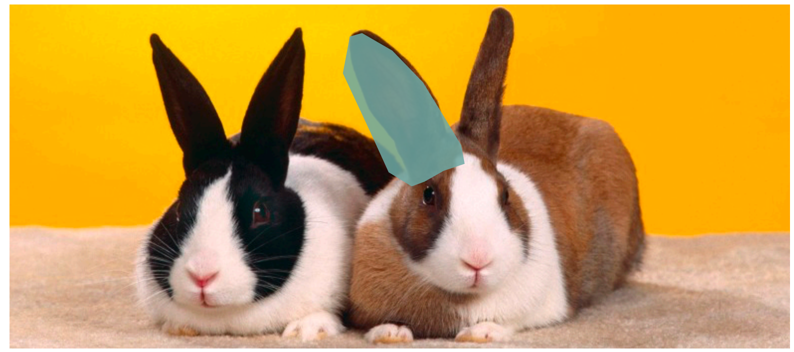
Result Size Estimation

- Result cardinality = Max # tuples * **product** of all selectivities.
- Term col=value (given Nkeys(col) unique values of col)
  - sel = 1/NKeys(col)
- Term col1=col2 (handy for joins too…)
  - sel = 1/MAX(NKeys(col1), NKeys(col2))
  - Why MAX?
- Term col>value
  - sel = (High(col)-value)/(High(col)-Low(col) + 1)
- Note, if missing the needed stats, assume 1/10!!!



P(leftEar = rightEar)

- 100 bunnies
- 2 distinct LeftEar colors
  - {C1, C2}
- 10 distinct RightEar colors
  - {C1, C2, …, C10}
- Independent ears
- What's the probability of matching ears?



$$
\begin{aligned}
&P(L = R) \\
&= \Sigma_i \, P(C_i, C_i) \\
&= P(C_1, C_1) + P(C_2, C_2) + P(C_3, C_3) + \ldots \\
&= (1/2 * 1/10) + (1/2 * 1/10) + (0 * 1/10) + \ldots \\
&= 1/10 = 1/MAX(2,10)
\end{aligned}
$$

Postgres 10.0: src/include/utils/selfuncs.h

```
/* default selectivity estimate for equalities such as "A = b" */
   #define DEFAULT_EQ_SEL  0.005

   /* default selectivity estimate for inequalities such as "A < b" */
   #define DEFAULT_INEQ_SEL  0.3333333333333333

   /* default selectivity estimate for range inequalities "A > b AND A < c" */
   #define DEFAULT_RANGE_INEQ_SEL  0.005

/* default selectivity estimate for pattern-match operators such as LIKE */
   #define DEFAULT_MATCH_SEL 0.005

   /* default number of distinct values in a table */
   #define DEFAULT_NUM_DISTINCT  200

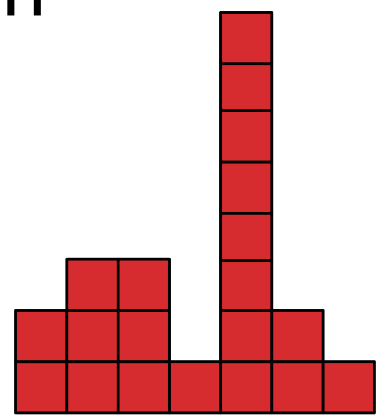
   /* default selectivity estimate for boolean and null test nodes */
   #define DEFAULT_UNK_SEL     0.005
   #define DEFAULT_NOT_UNK_SEL   (1.0 - DEFAULT_UNK_SEL)
```

Reduction Factors & Histograms

- For better estimation, use a histogram

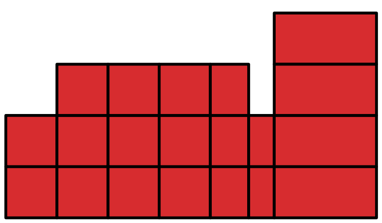
equiwidth

# values	2	3	3	1	8	2	1
Value	0-0.99	1-1.99	2-2.99	3-3.99	4-4.99	5-5.99	6-6.99



equidepth

# values	2	3	3	3	3	2	4
Value	0-0.99	1-1.99	2-2.99	3-4.05	4.06-4.67	4.68-4.99	5-6.99

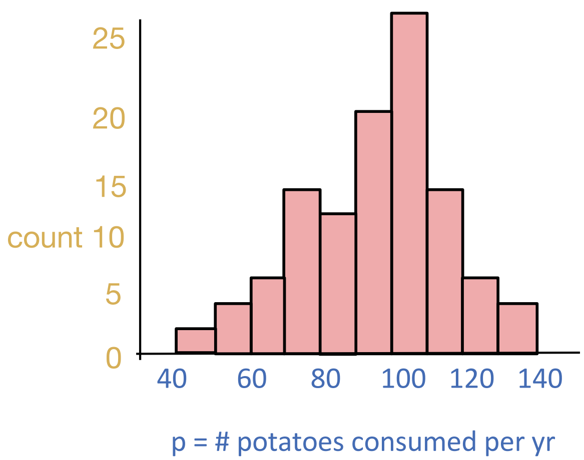


Note: 10-bucket equidepth histogram divides the data into *deciles*

- akin to quantiles, median, etc.

Computing selectivity with histograms

- 100 rows
- $\sigma_{p > 99}$?



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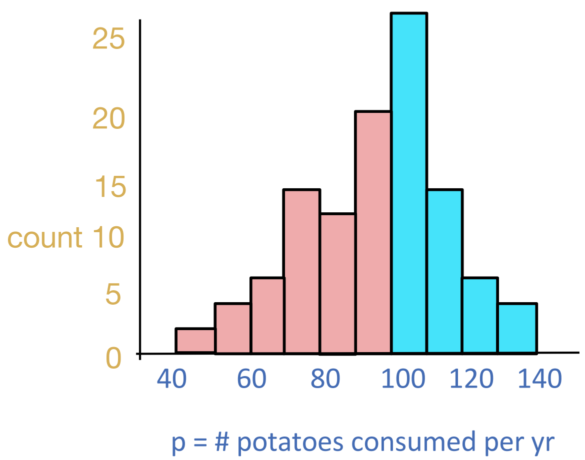
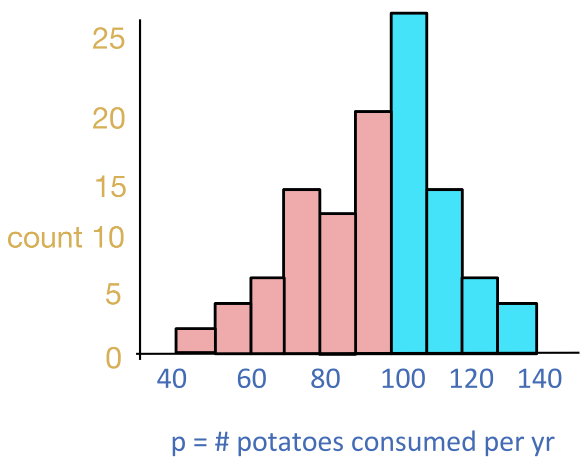


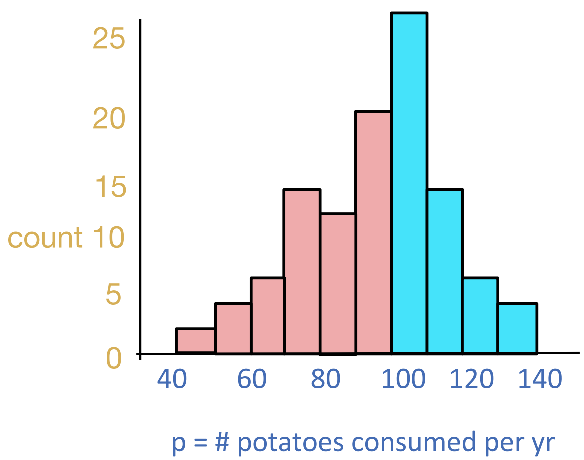
Computing selectivity with histograms

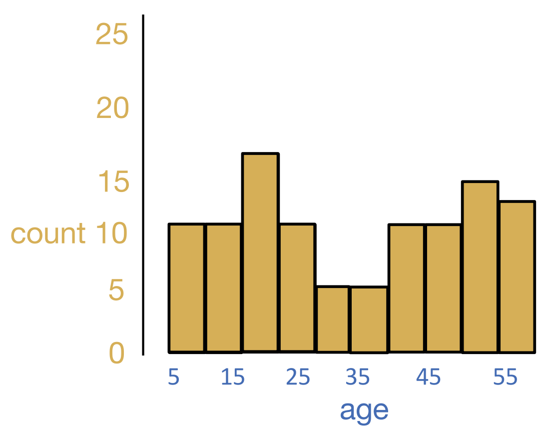
- 100 rows
- $\sigma_{p > 99}$? 50/100 = 50%.



Computing selectivity with histograms

- 100 rows
- $\sigma_{age < 26}$?





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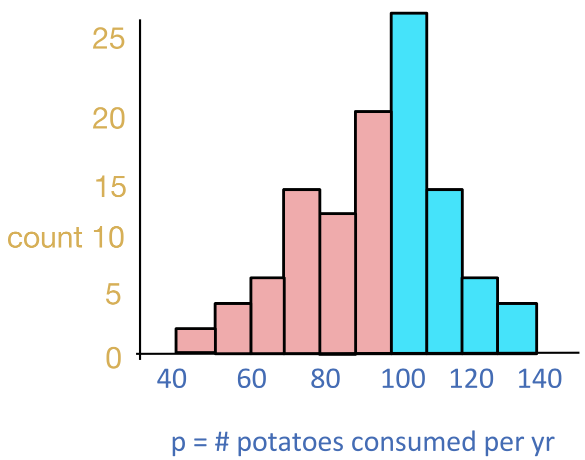
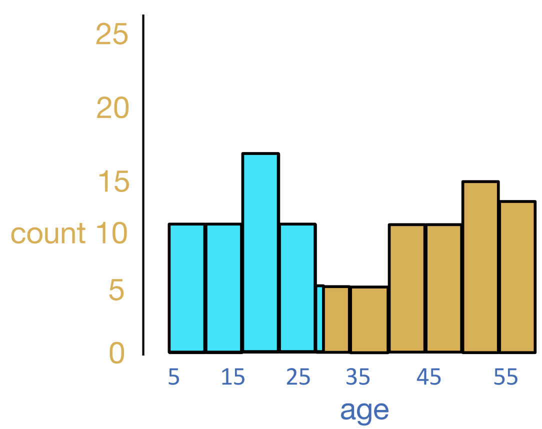
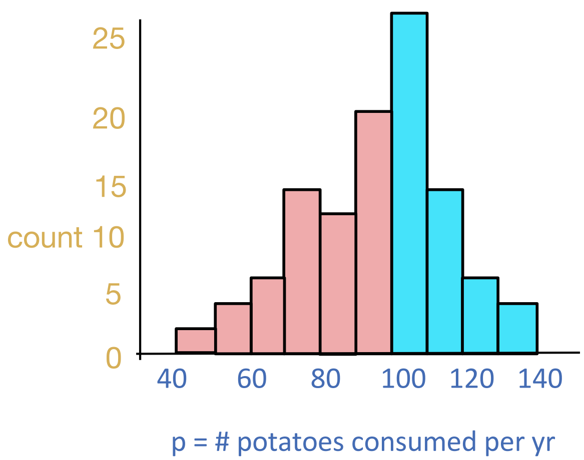


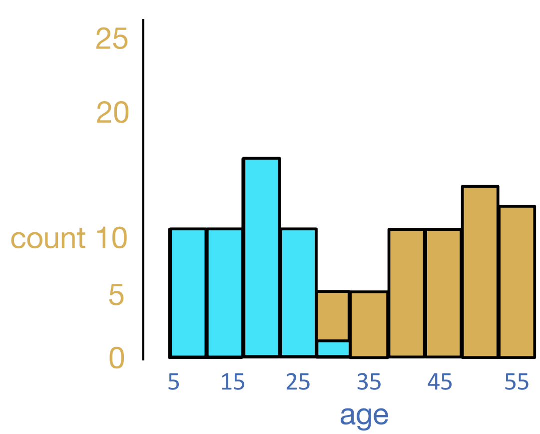


Computing selectivity with histograms

- 100 rows
- $\sigma_{age < 26}$?

- **Uniformity assumption:**
  Uniform distribution within each bin
  Each vertical slice the same
  Hence ⅕ of the population of bin [25,30) has age < 26.
  10 + 10 + 15 + 10 + (⅕ * 5) = 46/100 **= 46%**

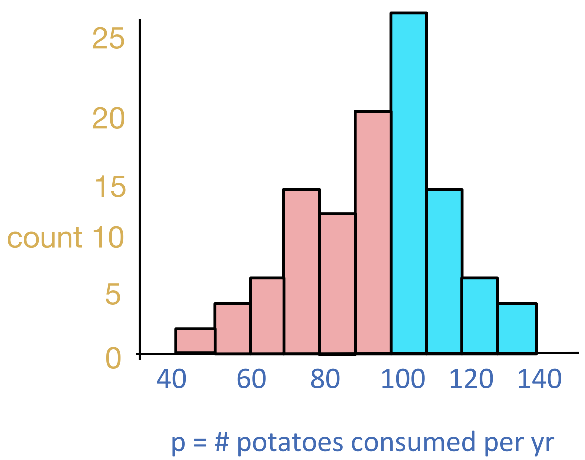


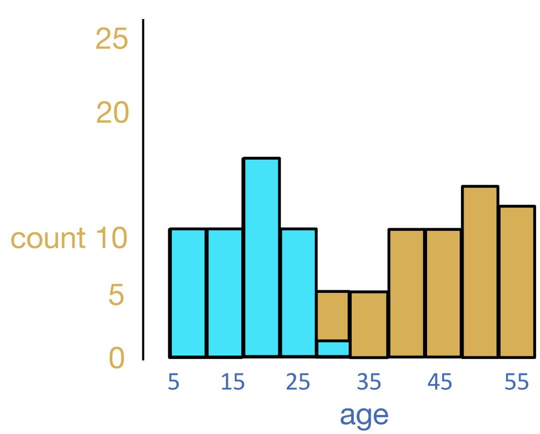


Selectivity of Conjunction

- 100 rows
- $\sigma_{p > 99 \wedge age < 26}$?

  50% 46%





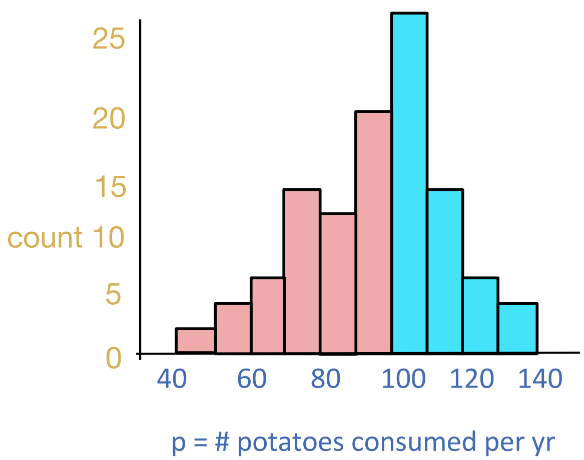
- **Independence assumption:**
  - Age and potato consumption are independent
- Selectivity: 50% × 46% = **23%**

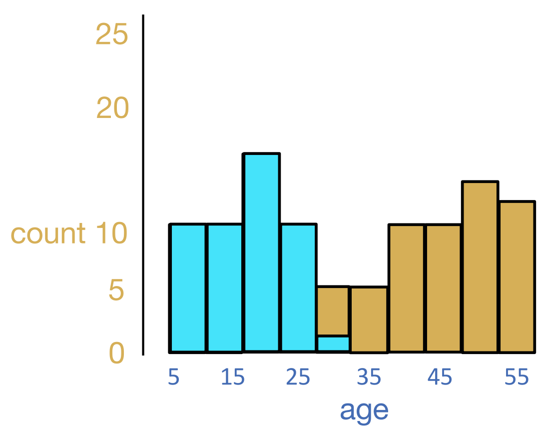
Selectivity of Disjunction

- 100 rows
- $\sigma_{p > 99 \vee age < 26}$?

  50% 46%

- Answer tuples satisfy one or both predicates
- By independence assumption:
  - Satisfy the first predicate: 50%
  - Satisfy the second predicate: 46%
  - Satisfy both: 50% × 46%
    - **Don't double-count!**





- Selectivity:
  50% + 46% - (50% × 46%) = **73%**

Selectivity for more complicated queries?

- $R \bowtie_p \sigma_q(S)$
  - Selectivity of join predicate p is s_p
  - Selectivity of selection predicate q is s_q
  - How to think about overall selectivity?

Join Selectivity

- Recall algebraic equivalence: $R \bowtie_p S \equiv \sigma_p(R \times S)$
- Hence join selectivity is "just" selectivity s_p
  - Over a big input: $|R| \times |S|$!
- Total rows: $s_p \times |R| \times |S|$

Selectivity for our earlier query?

- Recall from algebraic equivalences

  $$R \bowtie_p \sigma_q(S) \equiv \sigma_p(R \times \sigma_q(S)) \equiv \sigma_{p \wedge q}(R \times S))$$

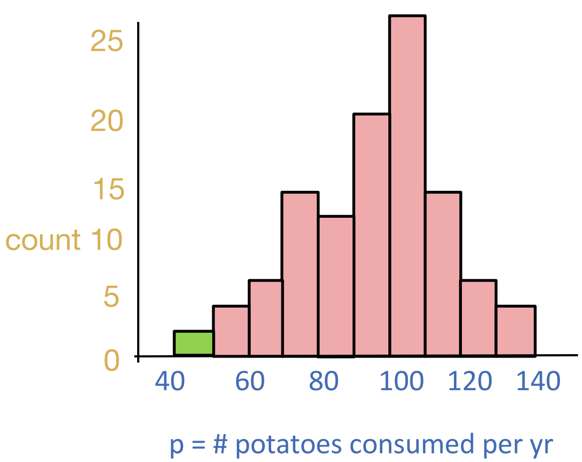
  - Hence selectivity just $s_p s_q$
    - Applied to $|R| \times |S|$!

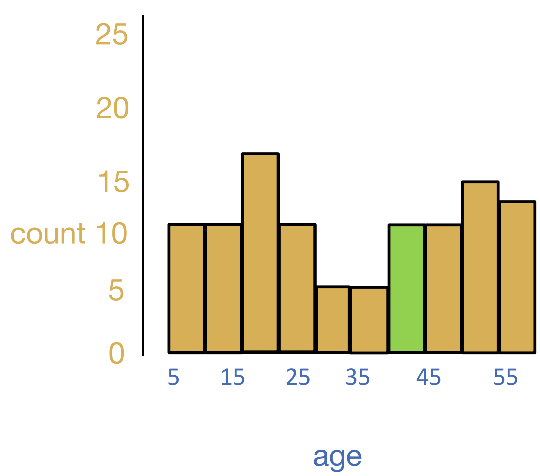
- Total rows: $s_p s_q |R||S|$

Column Equality?

T.p = T.age ??

Idea: scan over all values of p and age, and check when they are equal





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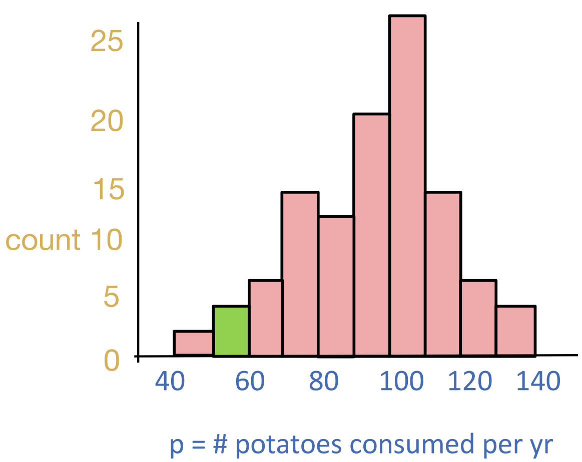
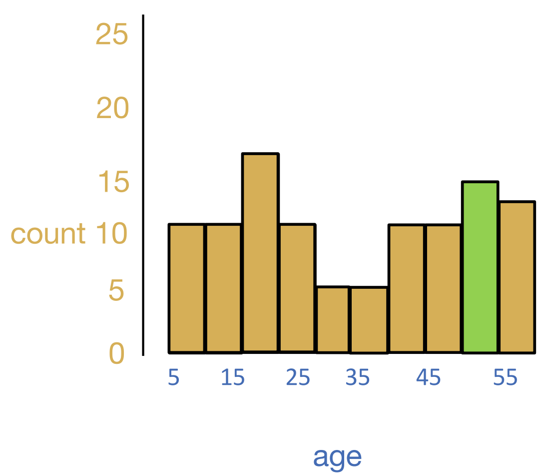




Column Equality?

T.p = T.age ??

Idea: scan over all values of p and age, and check when they are equal

T.p = T.age

= (T.p = 40 ∧ T.age = 40) ∨ (T.p = 41 ∧ T.age = 41) ∨ (T.p = 42 ∧ T.age = 42) …

= (T.p = 40 ∧ T.age = 40) + (T.p = 41 ∧ T.age = 41) + (T.p = 42 ∧ T.age = 42) …

= (T.p = 40 * T.age = 40) + (T.p = 41 * T.age = 41) + (T.p = 42 * T.age = 42) …

Independence assumption

(T.p = 40)

$$= \frac{\text{height(binp(40))}}{\text{width(binp(40))} * n}$$

(T.age = 40)

$$= \frac{\text{height(binage(40))}}{\text{width(binage(40))} * n}$$

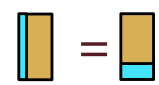
Uniform assumption

Just add up all the values…

What you need to know

- Know how to compute selectivities for basic predicates
  - The original Selinger version
  - The histogram version

- Assumption 1: uniform distribution within histogram bins
  - Within a bin, fraction of range = fraction of count



- Assumption 2: independent predicates
  - Selectivity of AND = product of selectivities of predicates
  - Selectivity of OR = sum of selectivities of predicates - product of selectivities of predicates
  - Selectivity of NOT = 1 – selectivity of predicates

- Joins are not a special case
  - Simply compute the selectivity of all predicates
  - And multiply by the product of the table sizes

Summary: Selectivity Estimation

- We need a way to estimate the size of the intermediate tables
  - Recall cost of each operator =
    I/Os (to bring in input) + *CPU-factor* * # tuples processed
- Output size = input size * operator selectivity

Summary: Selectivity Estimation

System R

- col=value
  - 1/uniq-keys(col)
- col1=col2
  - 1/MAX(uniq-keys(col1), uniq-keys(col2))
- col>value

$$\frac{\text{High(col)} - \text{value}}{\text{High(col)} - \text{Low(col)} + 1}$$

Histogram

- col=value

Uniform assumption

$$\frac{\text{bar height containing value}}{\text{(\# values contained in bar)} * n}$$

- col1=col2
  - Breakdown into (col1 = v1 ∧ col2 = v1) ∨ (col1 = v2 ∧ col2 = v2) ∨ …
- col>value

$$\frac{\text{sum of bar heights >value}}{\text{total number of rows}}$$

See discussion for floating-point-valued columns!

Summary: Selectivity Estimation

- In both cases, for more complex predicates:
  - $p1 \wedge p2$
    - selectivity(p1) * selectivity(p2)
  - $p1 \vee p2$
    - selectivity(p1) + selectivity(p2) – (selectivity(p1) * selectivity(p2))
    - Last term is 0 if p1 and p2 are non-overlapping (e.g., `age>60 OR age<21`)
  - not p1 = 1 – selectivity(p1)

  - This stems from our independence assumption

Query Optimization

1. Plan Space

2. Cost Estimation

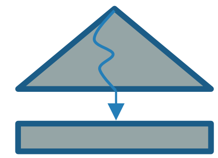
3. Search Algorithm

Enumeration of Alternative Plans

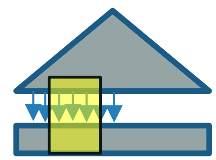
- There are two main cases:
  - **Single-table plans (base case)**
  - **Multiple-table plans (induction)**
- Single-table queries include selects, projects, and groupBy/agg:
  - Consider each available access path (file scan / index)
    - Choose the one with the least estimated cost

Cost Estimates for Single-Relation Plans

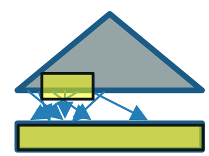
- Index I on primary key matches selection:
  - Cost is (Height(I) + 1) + 1 for a B+ tree.



- Clustered index I matching selection:
  - (NPages(I)+**NPages**(R)) * selectivity (approximately)



- Non-clustered index I matching selection:
  - (NPages(I)+**NTuples**(R)) * selectivity (approximately)



- Sequential scan of file:
  - NPages(R).

- Recall: Must also charge for duplicate elimination if required

Example

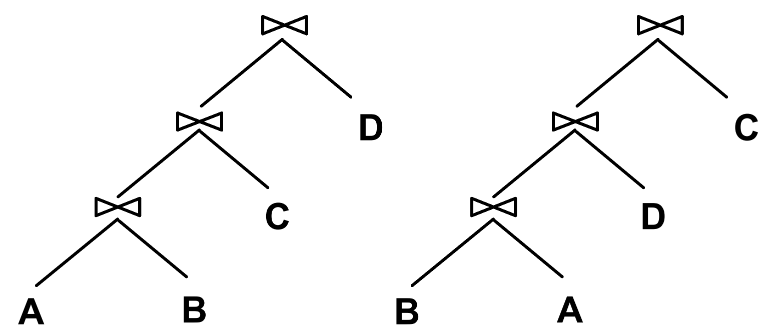
```
SELECT S.sid
  FROM Sailors S
 WHERE S.rating=8
```

- If we have an index on rating:
  - **Cardinality** = (1/NKeys(I)) * NTuples(R) = (1/10) * 40000 tuples
  - **Clustered index:** (1/NKeys(I)) * (NPages(I)+NPages(R))
    = (1/10) * (50+500) = **55 pages are retrieved.**
  - **Unclustered index**: (1/NKeys(I)) * (NPages(I)+NTuples(R))
    = (1/10) * (50+40000) = **4005 pages are retrieved**.
  - (costs on indexes are approximate as we might not need to retrieve all index pages)

- If we have an index on sid:
  - Would have to (roughly) retrieve all tuples/pages. With a clustered index, the cost is ~ 50+500, with unclustered index, ~ 50+40000.

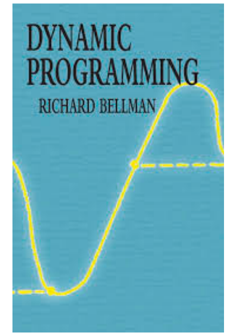
- Doing a file scan:
  - We retrieve all file pages (500).

Joins: Enumeration of Left-Deep Plans



- Left-deep plans differ in
  - the order of relations
  - the access method for each leaf operator
  - the join method for each join operator
- Enumerated using N passes (if N relations joined):
  - **Pass 1:** Find best 1-relation plan for each relation
  - **Pass i:** Find best way to join result of an (i -1)-relation plan (as outer) to the i' th relation. (i between 2 and N.)
- For each subset of relations, retain only:
  - Cheapest plan overall, plus
  - Cheapest plan for each *interesting order* of the tuples.

The Principle of Optimality



- Bellman ’57 (slightly adapted to our setting)
- The best overall plan is composed of best decisions on the subplans
  - Optimal result has optimal substructure
- For example, the best left-deep plan to join tables A, B, C is either:
  - (The best plan for joining A, B) $\bowtie$ C
  - (The best plan for joining A, C) $\bowtie$ B
  - (The best plan for joining B, C) $\bowtie$ A
- This is great!
  - When optimizing a subplan (e.g. A $\bowtie$ B), we don’t have to think about how it will be used later (e.g. when dealing with C)!
  - When optimizing a higher-level plan (e.g. A $\bowtie$ B $\bowtie$ C) we can reuse the best results of subroutines (e.g. A $\bowtie$ B)!

Dynamic Programming Algorithm for System R

- Principle of optimality allows us to build best subplans "bottom up"
  - Pass 1: Find best plans of height 1 (base table accesses), and record them in a table
  - Pass 2: Find best plans of height 2 (joins of base tables) by combining plans of height 1, record them in a table
  - …
  - Pass i: Find best plans of height i by combining plans of height i - 1 with plans of height 1, record them in a table
  - …
  - Pass *n:* Find best plan overall by combining plans of height *n-1* with plans of height 1.

The Basic Dynamic Programming Table

Table keyed on 1st column

Subset of tables in FROM clause	Best plan	Cost
{R, S}	hashjoin(R,S)	1000
{R, T}	mergejoin(R,T)	700

A Note on "Interesting Orders"

- Physical property: Order.
  When should we care? When is it "interesting"?

- An intermediate result has an "interesting order" if it is sorted by anything we can use later in the query (i.e., "downstream" op):
  - ORDER BY attributes
  - GROUP BY attributes
  - Join attributes of yet-to-be-added joins
    - subsequent merge join might be good

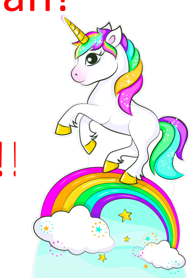
The Dynamic Programming Table

Table keyed on concatenation of first two columns

Subset of tables in FROM clause	Interesting-order columns	Best plan	Cost
{R, S}	<none>	hashjoin(R,S)	1000
{R, S}	<R.a, S.b>	sortmerge(R,S)	1500

← Higher cost, but may lead to global optimal plan!

TINSTAFL!!



Enumeration of Plans

- First figure out the scans and joins (select-project-join) using dynamic programming
  - **Avoid Cartesian Products** in dynamic programming as follows:
    When matching an i -1 way subplan with another table, only consider it if
    - There is a join condition between them, **or**
    - All predicates in WHERE have been "used up" in the i -1 way subplan.

- Then handle ORDER BY, GROUP BY, aggregates etc. as a post-processing step
  - Via "interestingly ordered" plan if chosen (free!)
  - Or via an additional sort/hash operator

- Despite pruning, this System R dynamic programming algorithm is **exponential** in #tables.

Example

```
SELECT S.sid, COUNT(*) AS number
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
```

<u>Sailors:</u>
B+ tree indexes on *sid*
<u>Reserves:</u>
Clustered B+ tree on *bid*
B+ on *sid*
<u>Boats</u>
B+ on *color*

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Pass 1: Best plan(s) for each relation

- Sailors, Reserves: File Scan

- Also B+ tree on Reserves.bid as interesting order (output sorted on bid)
- Also B+ tree on Reserves.sid as interesting order (output sored on sid)
- Also B+ tree on Sailors.sid as interesting order (output sorted on sid)

- Boats: B+ tree on color as interesting order (output sorted on color)

Best plans after pass 1

Subset of tables in FROM clause	Interesting-order columns	Best plan	Cost
{Sailors}	n/a	filescan	…
{Reserves}	n/a	Filescan	…
{Boats}	(color)	B-tree on color	…
{Reserves}	(bid)	B-tree on bid	…
{Reserves}	(sid)	B-tree on sid	…
{Sailors}	(sid)	B-tree on sid	…

Pass 2

```
// for each left-deep logical plan
for each plan P in pass 1
  for each FROM table T not in P
    // for each physical plan
    for each access method M on T
      for each join method
        generate P ⋈ M(T)
```

- File Scan Reserves (outer) with Boats (inner)
- File Scan Reserves (outer) with Sailors (inner)
- Reserves Btree on bid (outer) with Boats (inner)
- Reserves Btree on bid (outer) with Sailors (inner)
- File Scan Sailors (outer) with Boats (inner)
- File Scan Sailors (outer) with Reserves (inner)
- Boats Btree on color with Sailors (inner)
- Boats Btree on color with Reserves (inner)

- Retain cheapest plan for each (pair of relations, order)

Best plans after pass 2

Subset of tables in FROM clause	Interesting-order columns	Best plan	Cost
{Sailors}	n/a	filescan	…
{Reserves}	n/a	Filescan	…
{Boats}	n/a	B-tree on color	…
{Reserves}	(bid)	B-tree on bid	…
{Sailors}	(sid)	B-tree on sid	…
{Boats, Reserves}	(B.bid) (R.bid)	SortMerge(B-tree on Boats.color, filescan Reserves)	…
Etc…			

Pass 3 and beyond

- Using Pass 2 plans as outer relations, generate plans for the next join in the same way as Pass 2
  - E.g. {SortMerge(B-tree on Boats.color, filescan Reserves)} (outer) | with Sailors (B-tree sid) (inner)
- Then, add cost for groupby/aggregate:
  - This is the cost to sort the result by sid, *unless it has already been sorted by a previous operator.*

- Finally, choose the cheapest plan

Now you understand the optimizer!

- Benefit #1: You could build one.
  - And you will in project 3!
- Benefit #2: You can influence one
  - People who write non-trivial SQL often get frustrated with the optimizer
    - It picked a crummy plan!
    - It didn't use the index I built!
    - Etc.
  - Understanding the optimizer can lead you to:
    - Design your DB & Indexes better
    - Avoid "weak spots" in your optimizer's implementation
    - Coax your optimizer to do what you want

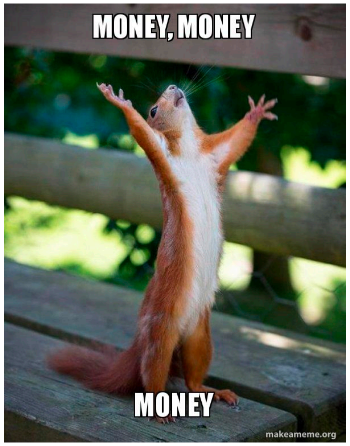
Relational Query Optimization III: Physical Database Design

Alvin Cheung
Aditya Parameswaran

Reading: R & G Chapter 20

Physical DB Design

- Query optimizer does what it can to use indices, clustering etc.
- DataBase Administrator (DBA)
  - expected to set up physical design well
- Good DBAs understand query optimizers very well



One Key Decision: Indexes

- Which tables
- Which field(s) should be the search key?
- Multiple indexes?
- Clustering?

Index Selection

- A greedy approach:
  - Consider most important queries in turn.
  - Consider best plan using the current indexes
  - See if better plan is possible with an additional index.
  - If so, create it.
- But consider impact on updates!
  - Indexes can make queries go faster, updates slower.
  - Require disk space, too.

Issues to Consider in Index Selection

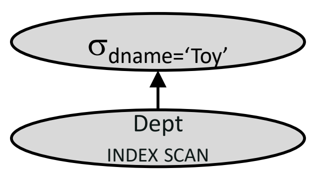
- Attributes mentioned in a WHERE clause are candidates for index search keys.
  - Range conditions are sensitive to clustering
  - Exact match conditions don't require clustering
    - Or do they????
    - What if you have a lot of duplicate values? Then just like range search!

- Choose indexes that benefit many queries
- NOTE: only one index can be clustered per relation!
  - So choose it wisely!

Example 1, Part 1

```
SELECT E.ename, D.mgr
  FROM Emp E, Dept D
 WHERE E.dno=D.dno
   AND D.dname='Toy'
```

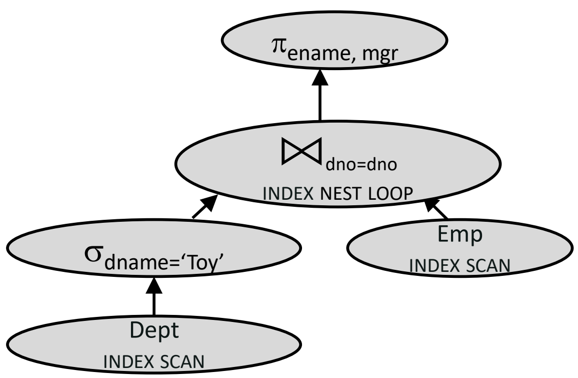
- B+ tree index on D.dname supports 'Toy' selection.
  - Given this, index on D.dno isn't important.



Example 1, Part 2

```
SELECT E.ename, D.mgr
  FROM Emp E, Dept D
 WHERE E.dno=D.dno
   AND D.dname='Toy'
```

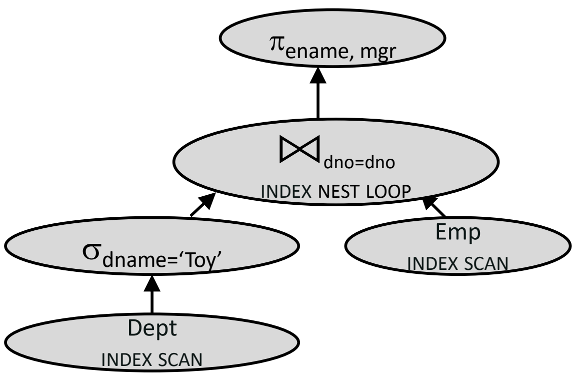
- B+ tree index on D.dname supports 'Toy' selection.
  - Given this, index on D.dno isn't important:
    D is already filtered prior to join.
- B+ tree index on E.dno allows us to get matching (inner) Emp tuples for each selected (outer) Dept tuple.

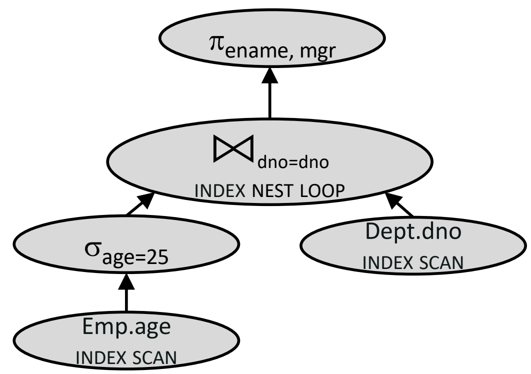


Example 1, Part 3

```
SELECT E.ename, D.mgr
  FROM Emp E, Dept D
 WHERE E.dno=D.dno
   AND D.dname='Toy'
```

- What if `WHERE` included: "… `AND E.age=25`" ?
  - Could retrieve Emp tuples using index on Emp.age, then join with Dept tuples satisfying dname selection.
    - Comparable performance to strategy that used E.dno index.
  - So, if Emp.age index is already created, this query provides much less motivation for adding an Emp.dno index.





Index Tuning "Wizards"

- A number of RDBMSs now have automated index advisors
  - Some info in Section 20.6 of the book
- Basic idea:
  - Train on a workload of queries
    - Possibly based on logging what's been going on
  - Use the optimizer cost metrics to estimate the cost of the workload over different choices of sets of indexes
  - Enormous # of different choices of sets of indexes:
    - Heuristics to help this go faster

Tuning Queries and Views

- If a query runs slower than expected:
  - check if an index needs to be re-clustered, or if statistics are too old.

- Sometimes, the DBMS may not be executing the plan you had in mind.
- Common areas where optimizers are sub-par:
  - Selections involving **null values** (bad selectivity estimates)
  - Selections involving **arithmetic or string expressions** (ditto)
  - Selections involving **OR** conditions (ditto)
  - Complex **subqueries** (lack of flattening)
  - Failed **cost estimation** (a common problem in large queries)
  - **Lack of evaluation features** like index-only strategies or certain join methods.

- Check the plan that is being used!
- Then adjust the choice of indexes or **rewrite the query/view.**
  - E.g. check via SQL `EXPLAIN` command
  - Many systems rewrite for you under the covers (e.g. DB2)
    - Can be confusing and/or helpful!

Points to Remember

- Want to understand DB design (tables, indexes)?
  - Must understand query optimization
- Three parts to optimizing a query:
  - Plan space
    - E.g., left-deep plans only
    - avoid Cartesian products.
    - Prune plans with interesting orders separate from unordered plans
  - Cost Estimation
    - Output cardinality and cost for each plan node.
    - Key issues: Statistics, indexes, operator implementations.
  - Search Strategy
    - we learned “bottom-up” dynamic programming

Points to Remember, cont

- Single-relation queries:
  - All access paths considered, cheapest is chosen.
  - Issues:
    - Selections that *match* index
    - Whether index key has all needed fields
    - Whether index provides tuples in an interesting order.

More Points to Remember

- Multiple-relation (aka Join) queries:
  - All single-relation plans are first enumerated.
    - Selections/projections considered as early as possible.
  - Use best 1-way plans to form 2-way plans. Prune losers.
  - Use best (i-1)-way plans and best 1-way plans to form i-way plans
  - At each level, for each subset of relations, retain:
    - Best plan for each interesting order (including no order)

Summary

- Optimization is the reason for the lasting power of the relational system
- Active area of research!
  - Smarter statistics (fancy histograms, "sketches")
  - Auto-tuning statistics
  - Adaptive runtime re-optimization (e.g. *Eddies*)
  - Multi-query optimization
  - Parallel scheduling issues