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Carnegie Mellon Univ.
Dept. of Computer Science
15-415/615 - DB Applications

C. Faloutsos – A. Pavlo

Lecture#15: Query Optimization

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Administrivia

- HW5 is due **Wed Oct 28th**.
- Mid-terms are available for **viewing**
  - Marilyn Walgora's office (GHC 8120)
  - 9:00am-11:45am and 1:00pm-4:15pm
  - Bring your CMU id

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Today's Class

- History & Background
- Relational Algebra Equivalences
- Plan Cost Estimation
- Plan Enumeration

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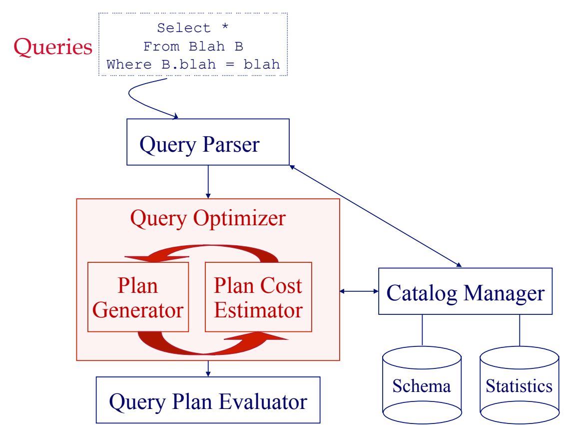
Cost-based Query Sub-System



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Query Optimization

- Remember that SQL is declarative.
  - User tells the DBMS *what* answer they want, not *how* to get the answer.
- There can be a big difference in performance based on plan is used:
  - See last week: 5.7 days vs. 45 seconds

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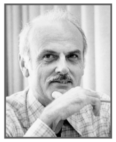
1970s – Relational Model


Codd

- Ted Codd saw the maintenance overhead for IMS/Codasyl.
- Proposed database abstraction based on relations:
  - Store database in simple data structures.
  - Access it through high-level language.
  - Physical storage left up to implementation.

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IBM System R

- Skunkworks project at IBM Research in San Jose to implement Codd's ideas.
- Had to figure out all of the things that we are discussing in this course themselves.
- IBM never commercialized System R.

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IBM System R

- First implementation of a query optimizer.
- People argued that the DBMS could never choose a query plan better than what a human could write.
- A lot of the concepts from System R's optimizer are still used today.

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Today's Class

- History & Background
- Relational Algebra Equivalences
- Plan Cost Estimation
- Plan Enumeration
- Nested Sub-queries

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Relational Algebra Equivalences

- A query can be expressed in different ways.
- The optimizer considers variations and choose the one with the lowest cost.
- How do we know whether two queries are equivalent?

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Relational Algebra Equivalences

- Two relational algebra expressions are ***equivalent*** if they generate the same set of tuples.

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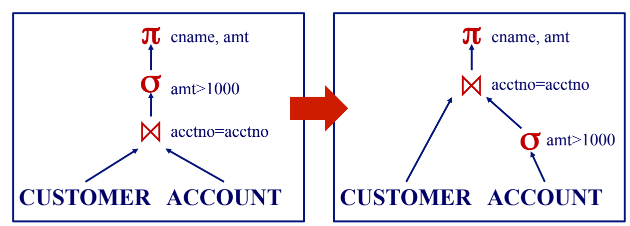
Predicate Pushdown

```
SELECT cname, amt
  FROM customer, account
 WHERE customer.acctno =
       account.acctno
   AND account.amt > 1000
```



Relational Algebra Equivalences

```
SELECT cname, amt
 FROM customer, account
WHERE customer.acctno =
      account.acctno
  AND account.amt > 1000
```

$$\pi_{\text{cname, amt}}(\sigma_{\text{amt>1000}}(\text{customer} \bowtie \text{account}))$$

$$=$$

$$\pi_{\text{cname, amt}}(\text{customer} \bowtie (\sigma_{\text{amt>1000}}(\text{account}))$$

Relational Algebra Equivalences

- **Selections:**
  - Perform them early
  - Break a complex predicate, and push

$$\sigma_{p1\wedge p2\wedge \ldots pn}(R) = \sigma_{p1}(\sigma_{p2}(\ldots\sigma_{pn}(R))\ldots)$$

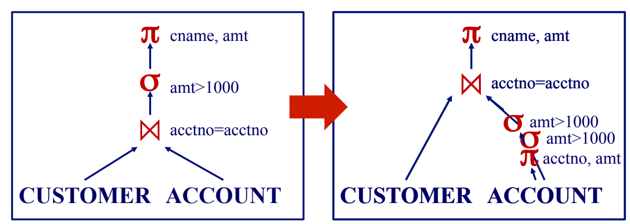
- Simplify a complex predicate
  - **(X=Y AND Y=3)** → **X=3 AND Y=3**

Relational Algebra Equivalences

- **Projections:**
  - Perform them early
    - Smaller tuples
    - Fewer tuples (if duplicates are eliminated)
  - Project out all attributes except the ones requested or required (e.g., joining attr.)

Projection Pushdown

```
SELECT cname, amt
 FROM customer, account
WHERE customer.acctno =
      account.acctno
  AND account.amt > 1000
```



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Relational Algebra Equivalences

- **Joins:**
  - Commutative, associative

$$R \bowtie S = S \bowtie R$$
$$(R \bowtie S) \bowtie T = R \bowtie (S \bowtie T)$$

- Q: How many different orderings are there for an *n*-way join?

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Relational Algebra Equivalences

- **Joins:** How many different orderings are there for an n-way join?
- A: Catalan number ~ 4^n
  - Exhaustive enumeration: too slow.
- We'll see in a second how an optimizer limits the search space...

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Today's Class

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Cost Estimation

- How long will a query take?
  - **CPU**: Small cost; tough to estimate
  - **Disk**: # of block transfers
  - **Memory**: Amount of DRAM used
  - **Network**: # of messages
- How many tuples will qualify?
- What statistics do we need to keep?

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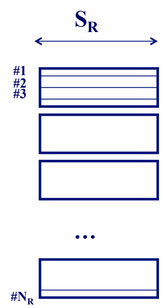
Cost Estimation – Statistics

- For each relation **R** we keep:
  - $\mathbf{N_R}$ → # tuples
  - $\mathbf{S_R}$ → size of tuple in bytes
  - **V(A,R)** → # of distinct values of attribute ‘A’



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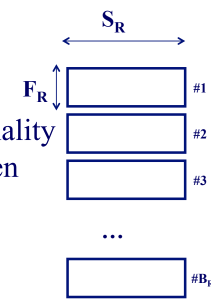
Derivable Statistics

- $\mathbf{F_R}$ → max# records/block
- $\mathbf{B_R}$ → # blocks
- **SC(A,R)** → selection cardinality avg# of records with A=given



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Derivable Statistics

- **SC(A,R)** → Selection Cardinality
  avg# of records with A=given
  → $\mathbf{N_R / V(A,R)}$
- Note that this assumes data uniformity
  - 10,000 students, 10 colleges – how many students in SCS?

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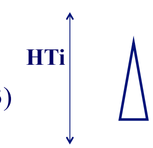
Additional Statistics

- For index **i**:
  - $\mathbf{F_i}$ → average fanout (~50-100)
  - $\mathbf{HT_i}$ → # levels of index **i** (~2-3)
    ~ log(#entries)/log($\mathbf{F_i}$)
  - $\mathbf{LB_i}$ # → blocks at leaf level



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Statistics

- Where do we store them?
- How often do we update them?

- Manual invocations:
  - Postgres: **ANALYZE**
  - MySQL: **ANALYZE TABLE**

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Selection Statistics

- We saw simple predicates (**name="Trump"**)
- How about more complex predicates, like
  - **salary > 10000**
  - **age=30 AND jobTitle="Costermonger"**
- What is their selectivity?

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Selections – Complex Predicates

- Selectivity **sel(P)** of predicate **P**:

  == fraction of tuples that qualify

  sel(P) = SC(P) / N_R

  # of tuples

  Selection Cardinality

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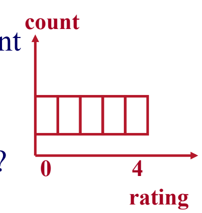
Selections – Complex Predicates

- Assume that **V(rating, SAILORS)** has 5 distinct values (i.e., 0 to 4).
- simple predicate **P**: A=constant
  - **sel(A=constant)** = **1/V(A,R)**
  - eg., **sel(rating='2')** = 1/5
- What if **V(A,R)** is unknown??



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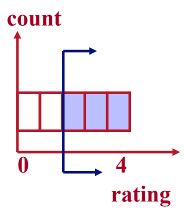
Selections – Complex Predicates

- Range Query: **sel(**rating >= ‘2’**)**
- **sel(**A>a) = **(A$_{max}$ – a) / (A$_{max}$ – A$_{min}$)**



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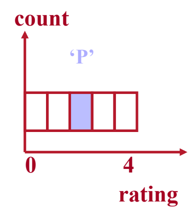
Selections – Complex Predicates

- Negation: **sel(**rating != ‘2’**)**
  - **sel(not** P) = **1 – sel(**P)
- Observation: selectivity ≈ probability



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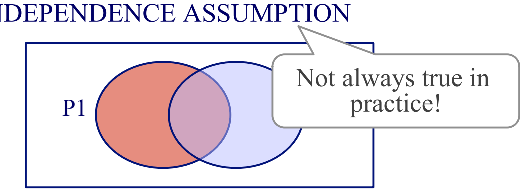
Selections – Complex Predicates

- **Conjunction:**
  - **sel(**rating = ‘2’ **and** name LIKE ‘C%’**)**
  - **sel(**P1 ∧ P2**) = sel(**P1) **· sel(**P2**)**
  - INDEPENDENCE ASSUMPTION



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Selections – Complex Predicates

- **Disjunction**:
  - **sel(**rating = ‘2’ **or** name LIKE ‘C%’**)**
  - **sel(**P1 ∨ P2**)**
    = **sel(**P1) + **sel(**P2) – **sel(**P1 ∧ P2**)**
    = **sel(**P1) + **sel(**P2) – **sel(**P1) **· sel(**P2**)**
  - INDEPENDENCE ASSUMPTION, again

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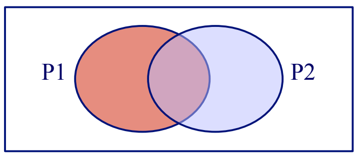
Selections – Complex Predicates

- **Disjunction, in general**:
  - **sel**(P1 **or** P2 **or** … Pn) =
  - 1 - (1- **sel**(P1)) · (1 - **sel**(P2)) · … (1 - **sel**(Pn))



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Joins

- Q: Given a join of **R** and **S**, what is the range of possible result sizes in #of tuples?

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Result Size Estimation for Joins

- General case: $\mathbf{R_{cols}} \cap \mathbf{S_{cols}}$ = {A} where A is not a key for either table.
- *Hint: for a given tuple of R, how many tuples of S will it match?*

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Result Size Estimation for Joins

- General case: $\mathbf{R_{cols}} \cap \mathbf{S_{cols}}$ = {A} where A is not a key for either table.
  - Match each **R**-tuple with **S**-tuples: estSize ≈ $\mathbf{N_R \cdot N_S / V(A,S)}$
  - Symmetrically, for **S**: estSize ≈ $\mathbf{N_R \cdot N_S / V(A,R)}$
- Overall:
  - estSize ≈ $\mathbf{N_R \cdot N_S / max(\{V(A,S), V(A,R)\})}$

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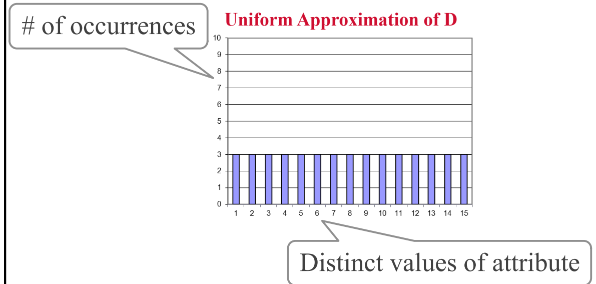
Cost Estimations

- Our formulas are nice but we assume that data values are uniformly distributed.



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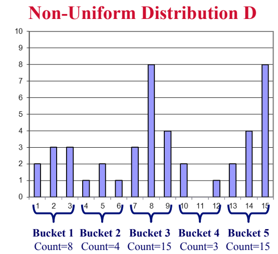
Cost Estimations

- Our formulas are nice but we assume that data values are uniformly distributed.



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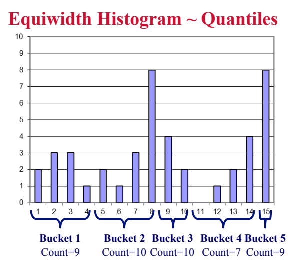
Histograms w/ Quantiles

- Allows the DBMS to have leverage better statistics about the data.



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Today's Class

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Query Optimization

- Bring query in internal form into "canonical form" (syntactic q-opt)
- Generate alternative plans.
  - Single relation.
  - Multiple relations.
  - Nested sub-queries.
- Estimate cost for each plan.
- Pick the best one.

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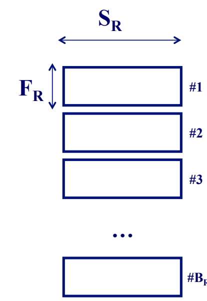
Plan Generation

```
SELECT *
 FROM SAILORS
WHERE rating = 10
```

- What are our plan options?



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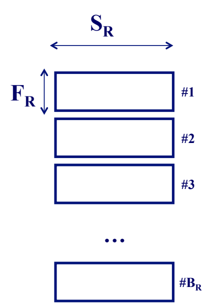
Plan Generation

```
SELECT *
 FROM SAILORS
WHERE rating = 10
```

- Sequential Scan
- Binary Search
  - *if sorted & consecutive*
- Index Search
  - *if an index exists*



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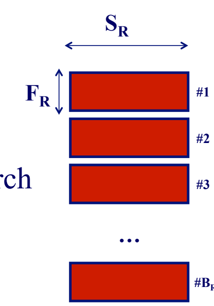
Sequential Scan

```
SELECT *
 FROM SAILORS
WHERE rating = 10
```

- **B_R** (worst case)
- **B_R /2** (on average, if we search for primary key)



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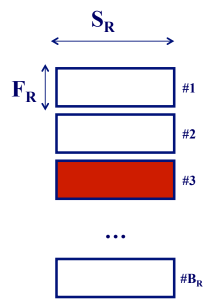
Binary Search

```
SELECT *
 FROM SAILORS
WHERE rating = 10
```

- **~log(B_R) + SC(A,R)/ F_R**
- Extra blocks are ones that contain qualifying tuples



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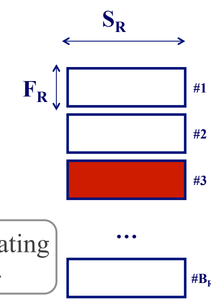
Binary Search

```
SELECT *
 FROM SAILORS
WHERE rating = 10
```

- **~log(B_R) + SC(A,R)/ F_R**
- Extra blocks are ones that contain qualifying tuples

We showed that estimating this is non-trivial.



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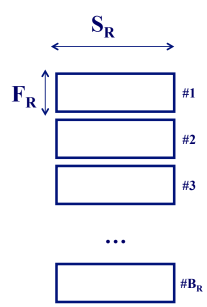
Index Search

```
SELECT *
 FROM SAILORS
WHERE rating = 10
```

- Index Search:
  - levels of index + blocks w/ qual. tuples

Case#1: Primary Key
Case#2: Secondary key – clustering index
Case#3: Secondary key – non-clust. index



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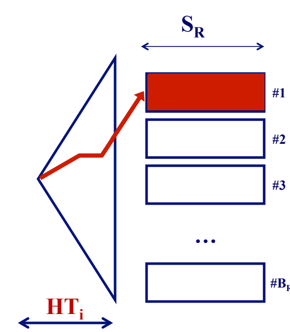
Index Search: Case #1

```
SELECT *
 FROM SAILORS
WHERE rating = 10
```

- Primary Key
  - **cost: HT_i + 1**



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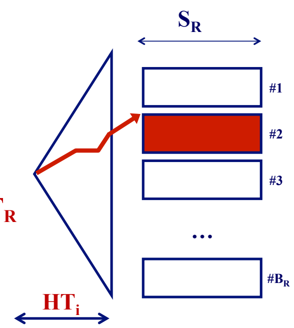
Index Search: Case #2

SELECT *
FROM SAILORS
WHERE rating = 10

- Secondary key with clustering index:
  - **cost: $HT_i + SC(A,R)/F_R$**



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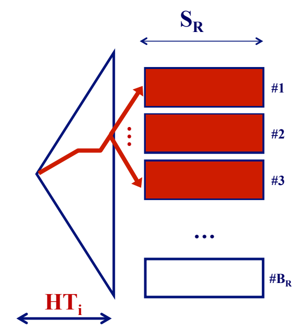
Index Search: Case #3

SELECT *
FROM SAILORS
WHERE rating = 10

- Secondary key with non-clustering index:
  - **cost: $HT_i + SC(A,R)$**



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Query Optimization

- Bring query in internal form into "canonical form" (syntactic q-opt)
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  - Nested sub-queries.
- Estimate cost for each plan.
- Pick the best one.

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Queries over Multiple Relations

- As number of joins increases, number of alternative plans grows rapidly
  - We need to restrict search space.
- **Fundamental decision in System R:** only left-deep join trees are considered.

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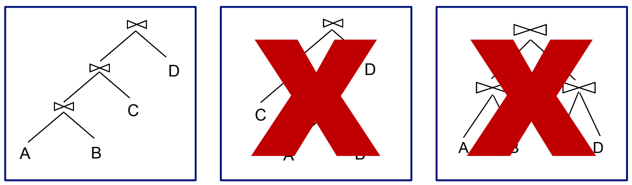
Queries over Multiple Relations

- **Fundamental decision in System R:** only left-deep join trees are considered.



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Queries over Multiple Relations

- **Fundamental decision in System R:** only left-deep join trees are considered.
  - Allows for fully pipelined plans where intermediate results not written to temp files.
  - Not all left-deep trees are fully pipelined.

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Queries over Multiple Relations

- **Enumerate the orderings**
  - *Example: Left-deep tree #1, Left-deep tree #2…*
- **Enumerate the plans for each operator**
  - *Example: Hash, Sort-Merge, Nested Loop…*
- **Enumerate the access paths for each table**
  - *Example: Index #1, Index #2, Seq Scan…*
- Use **dynamic programming** to reduce the number of cost estimations.

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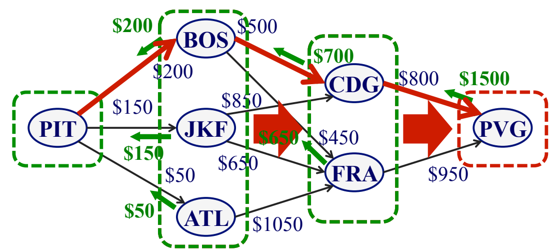
Dynamic Programming Example



Compute the cheapest flight PIT -> PVG

Solution: Compute partial optimal, left-to-right

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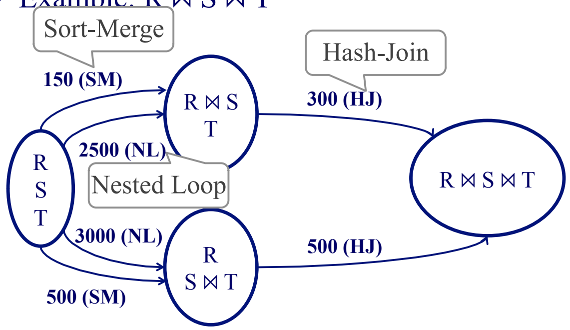
Q-Opt + Dynamic Programming

- Example: R $\bowtie$ S $\bowtie$ T



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Q-Opt + Dynamic Programming

- How to plan a query where **R** is sorted on **R.a**?
- Consider the following query:

```
SELECT *
 FROM R, S, T
WHERE R.a = S.a AND S.b = T.b
ORDER BY R.a
```


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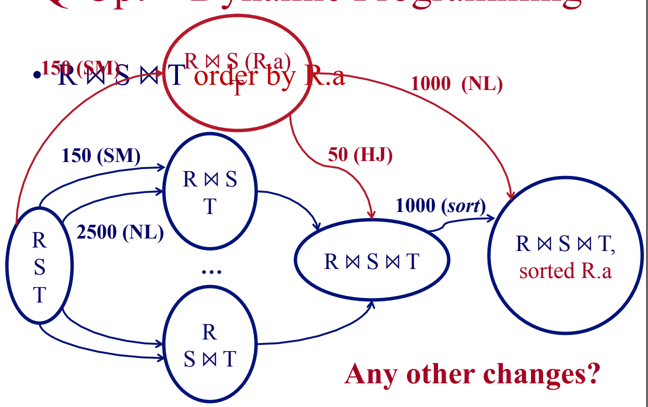
Q-Opt + Dynamic Programming

- R $\bowtie$ S $\bowtie$ T order by R.a



Any other changes?

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Candidate Plan Example

```
SELECT sname, bname, day
 FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid
```

1. Enumerate relation orderings
2. Enumerate join algorithm choices
3. Enumerate access method choices

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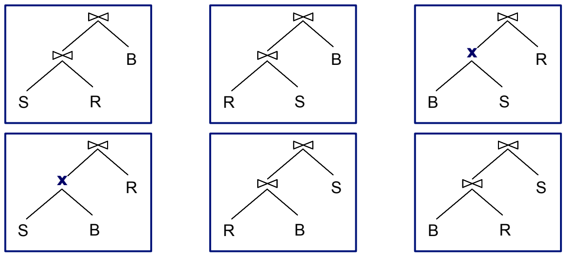
Candidate Plans

```
SELECT sname, bname, day
 FROM Sailors S, Reserves R, Boats B
 WHERE S.sid = R.sid AND R.bid = B.bid
```

1. Enumerate relation orderings:



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Candidate Plans

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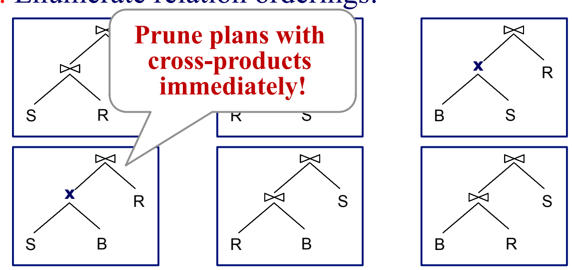
1. Enumerate relation orderings:



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Candidate Plans

```
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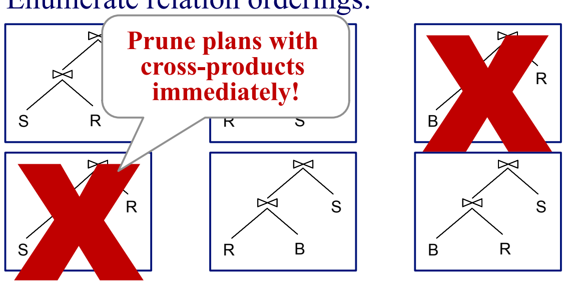
```

1. Enumerate relation orderings:



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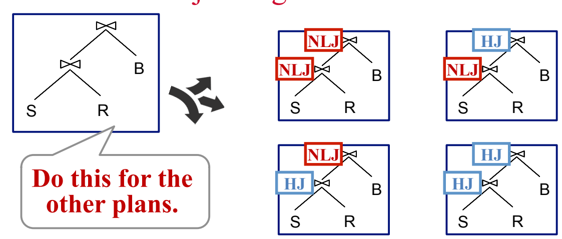
Candidate Plans

```
SELECT sname, bname, day
 FROM Sailors S, Reserves R, Boats B
 WHERE S.sid = R.sid AND R.bid = B.bid
```

2. Enumerate join algorithm choices:



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Candidate Plans

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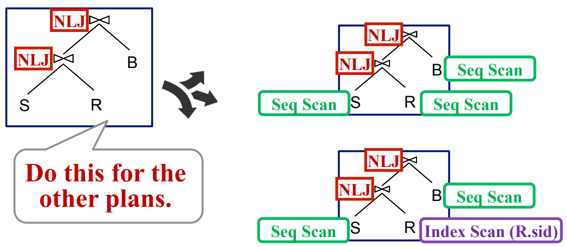
SELECT sname, bname, day
 FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid
```

3. Enumerate access method choices:



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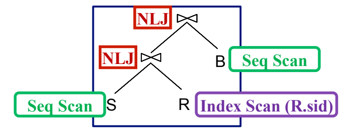
Candidate Plans

```
SELECT sname, bname, day
 FROM Sailors S, Reserves R, Boats B
WHERE S.sid = R.sid AND R.bid = B.bid
```

4. Now we can estimate the cost of each plan.



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Query Optimization

- Bring query in internal form into “canonical form” (syntactic q-opt)
- Generate alternative plans.
  - Single relation.
  - Multiple relations.
  - Nested sub-queries.
- Estimate cost for each plan.
- Pick the best one.

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Nested Sub-Queries

- The DBMS treats nested sub-queries in the where clause as functions that take parameters and return a single value or set of values.
- Two Approaches:
  - Rewrite to de-correlate and/or flatten them
  - Decompose nested query and store result to temporary table

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Nested Sub-Queries: Rewrite

```
SELECT name FROM Sailors AS S
 WHERE EXISTS (
   SELECT * FROM Reserves AS R
    WHERE S.sid = R.sid
      AND R.day = "2015-10-18"
 )
```

```
SELECT name
  FROM Sailors AS S, Reserves AS R
 WHERE S.sid = R.sid
   AND R.day = "2015-10-18"
```


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Nested Sub-Queries: Decompose

```
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(*) > 1
```

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.

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Decomposing Queries

- For harder queries, the optimizer breaks up queries into blocks and then concentrates on one block at a time.
- Sub-queries are written to a temporary table that are discarded after the query finishes.

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Decomposing Queries

```
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(*) > 1
```

Outer Block **Nested Block**

What Optimizers are Still Bad At

- Cardinality estimations are still hard.
- Problem Areas:
  - Prepared Statements
  - Correlated Columns
  - Plan Stability

More Information: Guy Lohman, *Is Query Optimization a "Solved" Problem?* SIGMOD Blog (April 2014), http://wp.sigmod.org/?p=1075

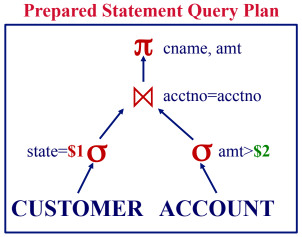
Prepared Statements

```
PREPARE myQuery (varchar, int) AS
SELECT cname, amt
 FROM customer AS C, account AS A
 WHERE C.acctno = A.acctno
  AND C.state = $1
  AND A.amt > $2
```

```
EXECUTE myQuery ('PA', 1000);
```


Prepared Statements

Prepared Statement Query Plan



- What should be the join order for **CUSTOMER** and **ACCOUNT**?

Prepared Statements

- **Solution #1** – Rerun optimizer each time the query is invoked.
- **Solution #2** – Generate multiple plans for different values of the parameters.
- **Solution #3** – Choose the average value for a parameter and use that for all invocations.

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Correlated Columns

- We showed how selectivities are modeled as probabilities on whether a predicate on any given row will be satisfied.
- We then multiply these individual selectivities together.

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Correlated Columns

- Consider a database of automobiles:
  - # of Makes = 10, # of Models = 100
- And the following query:
  - **make="Honda" AND model="Accord"**
- With the independence and uniformity assumption, the selectivity is:
  - **1/10 * 1/100 = 0.001**
- But since only Honda makes Accords the real selectivity is **1/100 = 0.01**.

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Column Group Statistics

- Tell the DBMS that it should keep track of statistics for groups of columns together rather than just treating them all as independent variables.
- Only supported in commercial systems.

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Plan Stability

- We want to deploy a new version of a DBMS but need to make sure that there are no performance regressions.
- What if 99% of the query plans are faster on the newer DBMS version, but 1% are slower?

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Plan Stability

- **Solution #1 –** Allow tuning hints in plans.
- **Solution #2 –** Set the optimizer version number and migrate queries one-by-one to the new optimizer.
- **Solution #3 –** Save query plan from old version and provide it to the new DBMS.

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Query Optimizer Overview

- System R:
  - Break query in query blocks
  - Simple queries (ie., no joins): look at stats
  - n-way joins: left-deep join trees; ie., only one intermediate result at a time
    - *Pros: smaller search space; pipelining*
    - *Cons: may miss optimal*
  - 2-way joins: NL and sort-merge

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Conclusions

- Ideas to remember:
  - Syntactic q-opt – do selections early
  - Selectivity estimations (uniformity, indep.; histograms; join selectivity)
  - Hash join (nested loops; sort-merge)
  - Left-deep joins
  - Dynamic programming

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Next Class

- How to refine database schemas through normalization and functional dependencies to remove redundancies and prevent loss data.

Equivalence of Expressions

- Q: How to prove a transformation rule?
- Use relational tuple calculus to show that LHS = RHS:

$$\underbrace{\sigma_P(R1 \cup R2)}_{\textbf{LHS}} = \underbrace{\sigma_P(R1) \cup \sigma_P(R2)}_{\textbf{RHS}}$$

Equivalence of Expressions

$$\sigma_P(R1 \cup R2) = \sigma_P(R1) \cup \sigma_P(R2)$$

$$t \in LHS \Leftrightarrow$$
$$t \in (R1 \cup R2) \wedge P(t) \Leftrightarrow$$
$$(t \in R1 \vee t \in R2) \wedge P(t) \Leftrightarrow$$
$$(t \in R1 \wedge P(t)) \vee (t \in R2) \wedge P(t)) \Leftrightarrow$$

Equivalence of Expressions

$$\sigma_P(R1 \cup R2) = \sigma_P(R1) \cup \sigma_P(R2)$$

...

$$(t \in R1 \wedge P(t)) \vee (t \in R2) \wedge P(t)) \Leftrightarrow$$
$$(t \in \sigma_P(R1)) \vee (t \in \sigma_P(R2)) \Leftrightarrow$$
$$t \in \sigma_P(R1) \cup \sigma_P(R2) \Leftrightarrow$$
$$t \in RHS$$
$$QED$$

Equivalence of Expressions

- Q: How to disprove a rule?

$$\pi_A(R1 - R2) = \pi_A(R1) - \pi_A(R2)$$

R1

A	B
Trump	squirrels

R2

A	B
Trump	knifefights

A	B
Trump	squirrels

$\neq$ Ø