Carnegie Mellon University

Query Optimization

Lecture #13

Database Systems
15-445/15-645
Fall 2017

Andy Pavlo
Computer Science Dept.
Carnegie Mellon Univ.

ADMINISTRIVIA

Homework #4 is due TODAY @ 11:59pm

Mid-term Exam is on Wednesday October 18th (in class)

Project #2 is due Wednesday October 25th @ 11:59am

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: 1.3 hours vs. 0.45 seconds

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.

QUERY OPTIMIZATION

Heuristics / Rules

→ Rewrite the query to remove stupid / inefficient things.
→ Does not require a cost model.

Cost-based Search

→ Use a cost model to evaluate multiple equivalent plans and pick the one with the lowest cost.

TODAY'S AGENDA

Relational Algebra Equivalences

Plan Cost Estimation

Plan Enumeration

Nested Sub-queries

Mid-Term

RELATIONAL ALGEBRA EQUIVALENCES

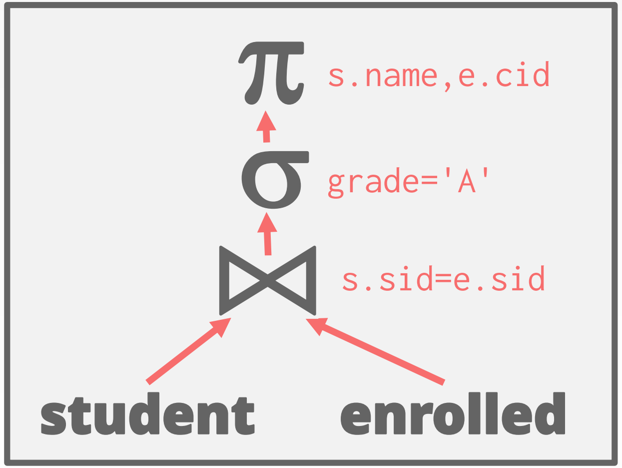
Two relational algebra expressions are equivalent if they generate the same set of tuples.

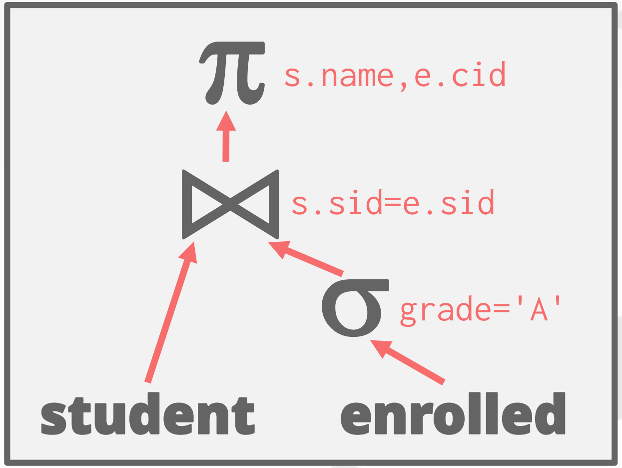
The DBMS can identify better query plans without a cost model.

This is often called **query rewriting**.

PREDICATE PUSHDOWN

```
SELECT s.name, e.cid
  FROM student AS s, enrolled AS e
 WHERE s.sid = e.sid
   AND e.grade = 'A'
```





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RELATIONAL ALGEBRA EQUIVALENCES

```
SELECT s.name, e.cid
  FROM student AS s, enrolled AS e
 WHERE s.sid = e.sid
   AND e.grade = 'A'
```

$$\pi_{\text{name, cid}}(\sigma_{\text{grade='A'}}(\text{student} \bowtie \text{enrolled}))$$

$$=$$

$$\pi_{\text{name, cid}}(\text{student} \bowtie (\sigma_{\text{grade='A'}}(\text{enrolled})))$$

RELATIONAL ALGEBRA EQUIVALENCES

Selections:

→ Perform filters as early as possible

→ Break a complex predicate, and push down

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

Simplify a complex predicate

→ `(X=Y AND Y=3) → X=3 AND Y=3`

RELATIONAL ALGEBRA EQUIVALENCES

Projections:

→ Perform them early to create smaller tuples and reduce intermediate results (if duplicates are eliminated)

→ Project out all attributes except the ones requested or required (e.g., joining attr.)

This is not important for a column store…

PROJECTION PUSHDOWN

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SELECT s.name, e.cid
  FROM student AS s, enrolled AS e
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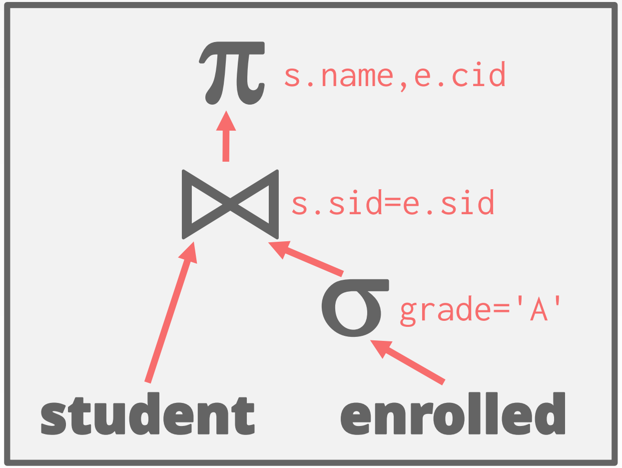
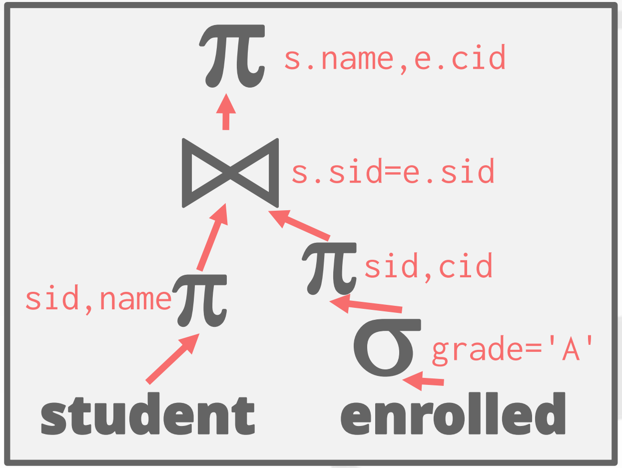
```





MORE EXAMPLES

Impossible / Unnecessary Predicates

```
SELECT * FROM table WHERE 1 = 0
```

```
SELECT * FROM table WHERE 1 = 1
```

Join Elimination

```
SELECT A1.*
  FROM A AS A1 JOIN A AS A2
    ON A1.id = A2.id
```

Source: Lukas Eder

MORE EXAMPLES

Ignoring Projections

```
SELECT * FROM A AS A1
 WHERE EXISTS(SELECT * FROM A AS A2
               WHERE A1.id = A2.id)
```

Merging Predicates

```
SELECT * FROM A
 WHERE val BETWEEN 1 AND 100
   AND val BETWEEN 50 AND 150
```

Source: Lukas Eder

RELATIONAL ALGEBRA EQUIVALENCES

Joins:

→ Commutative, associative

$R \bowtie S = S \bowtie R$

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

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

RELATIONAL ALGEBRA EQUIVALENCES

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

Catalan number $\approx 4^n$

→ Exhaustive enumeration will be too slow.

We'll see in a second how an optimizer limits the search space...

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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 be read/written?

What statistics do we need to keep?

STATISTICS

The DBMS stores internal statistics about tables, attributes, and indexes in its internal catalog.

Different systems update them at different times.

Manual invocations:

→ Postgres/SQLite: `ANALYZE`

→ MySQL: `ANALYZE TABLE`

STATISTICS

For each relation **R**, the DBMS maintains the following information:

→ N_R → # tuples
→ `V(A,R)` → # of distinct values of attribute **A**

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DERIVABLE STATISTICS

The **selection cardinality** (`SC(A,R)`)is the average number of records with a value for an attribute `A` given N_R / `V(A,R)`

Note that this assumes **data uniformity**

→ 10,000 students, 10 colleges – how many students in SCS?

SELECTION STATISTICS

Equality predicates on unique keys are easy to estimate.

```
SELECT * FROM A
 WHERE id = 123
```

What about more complex predicates? What is their selectivity?

```
SELECT * FROM A
 WHERE val > 1000
```

```
SELECT * FROM A
 WHERE age = 30
   AND status = 'Lit'
```

COMPLEX PREDICATES

The **selectivity** (`sel`) of a predicate `P` is the fraction of tuples that qualify.

Formula depends on type of predicate:

→ Equality
→ Range
→ Negation
→ Conjunction
→ Disjunction

COMPLEX PREDICATES

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SELECTIONS – COMPLEX PREDICATES

Assume that V(age, people) has 5 distinct values (0–4) and N_R = 5

Equality Predicate: A=constant

→ sel(A=constant) = SC(P) / V(A,R)

```
SELECT * FROM people
 WHERE age = 2
```

SELECTIONS – COMPLEX PREDICATES

Assume that `V(age, people)` has 5 distinct values (0–4) and N_R = 5

Equality Predicate: `A=constant`

→ `sel(A=constant) = SC(P) / V(A,R)`

→ Example: `sel(age=2) =`

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SELECT * FROM people
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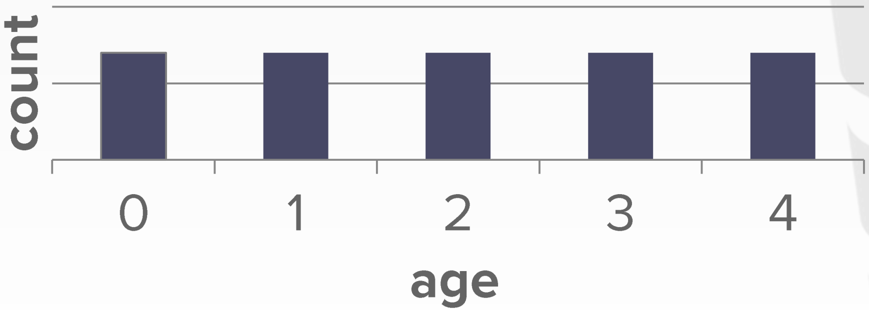

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SELECTIONS – COMPLEX PREDICATES

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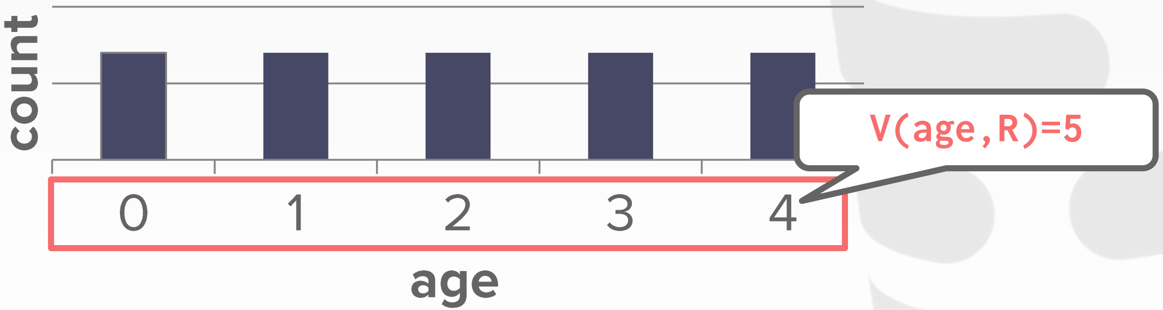

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SELECTIONS – COMPLEX PREDICATES

Assume that `V(age, people)` has 5 distinct values (0–4) and N_R = 5

Equality Predicate: `A=constant`

→ `sel(A=constant) = SC(P) / V(A,R)`

→ Example: `sel(age=2) = 1/5`

```
SELECT * FROM people
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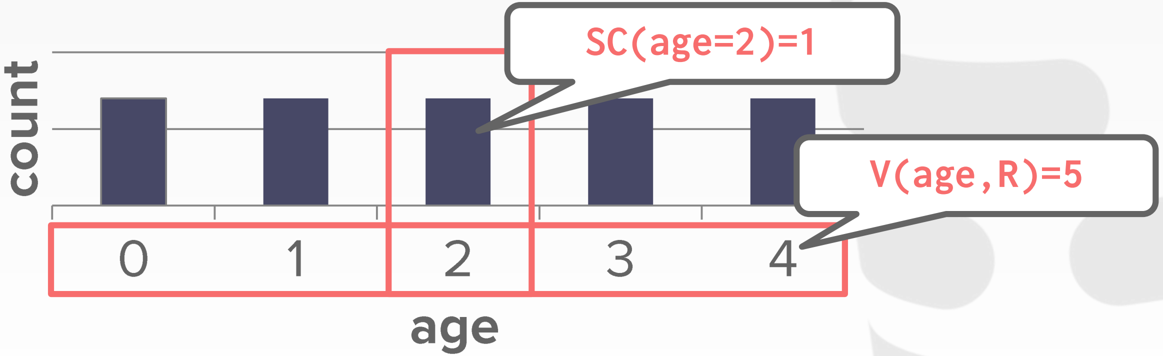

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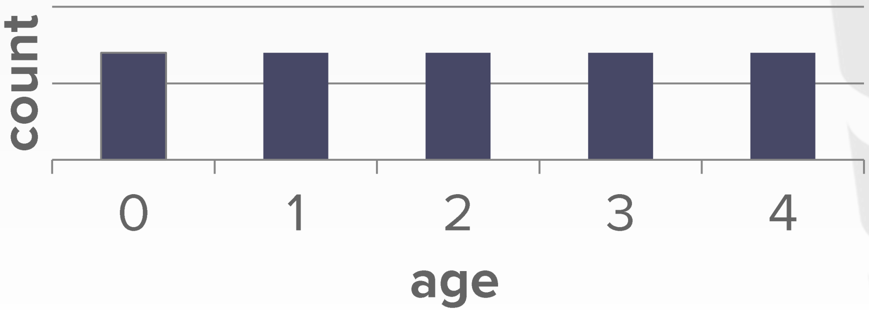
SELECTIONS – COMPLEX PREDICATES

Range Query:

→ $sel(A \geq a) = (A_{max} - a) / (A_{max} - A_{min})$
→ Example: `sel(age>=2)`

```
SELECT * FROM people
 WHERE age >= 2
```



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SELECTIONS – COMPLEX PREDICATES

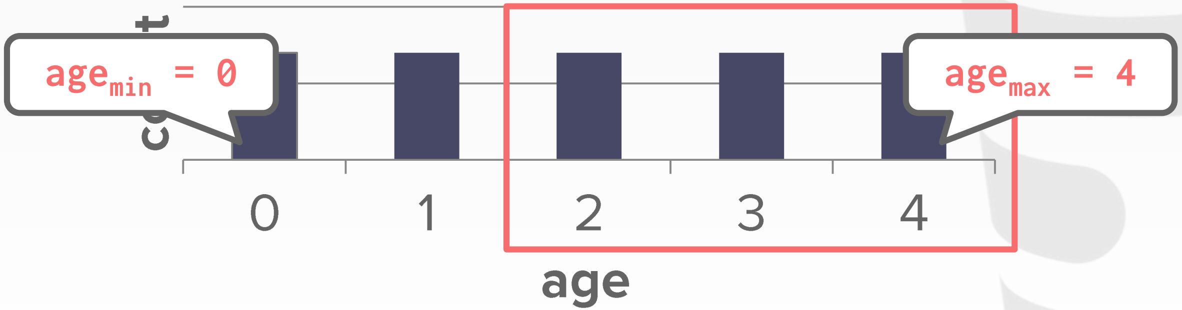
Range Query:

→ $sel(A>=a) = (A_{max} - a) / (A_{max} - A_{min})$

→ Example: $sel(age>=2) = (4 - 2) / (4 - 0)$

$= 1/2$

```
SELECT * FROM people
 WHERE age >= 2
```

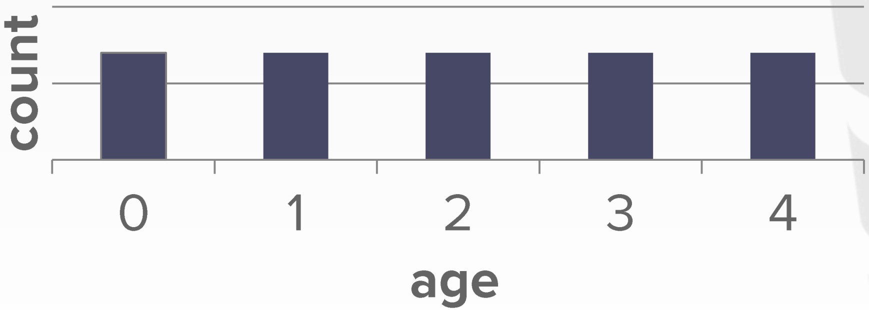


SELECTIONS – COMPLEX PREDICATES

Negation Query:

→ `sel(not P) = 1 - sel(P)`
→ Example: `sel(age != 2)`

```
SELECT * FROM people
 WHERE age != 2
```



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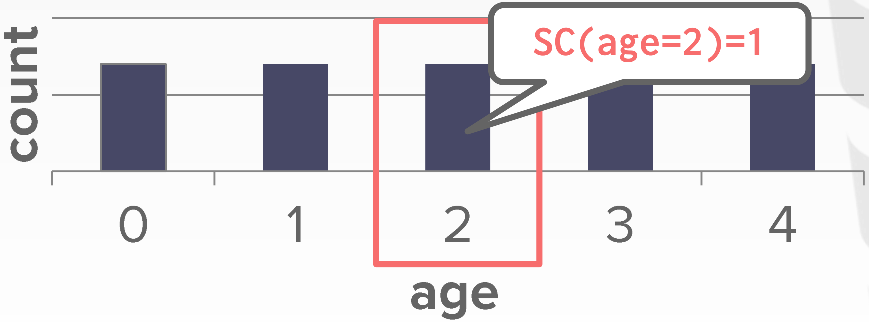

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SELECTIONS – COMPLEX PREDICATES

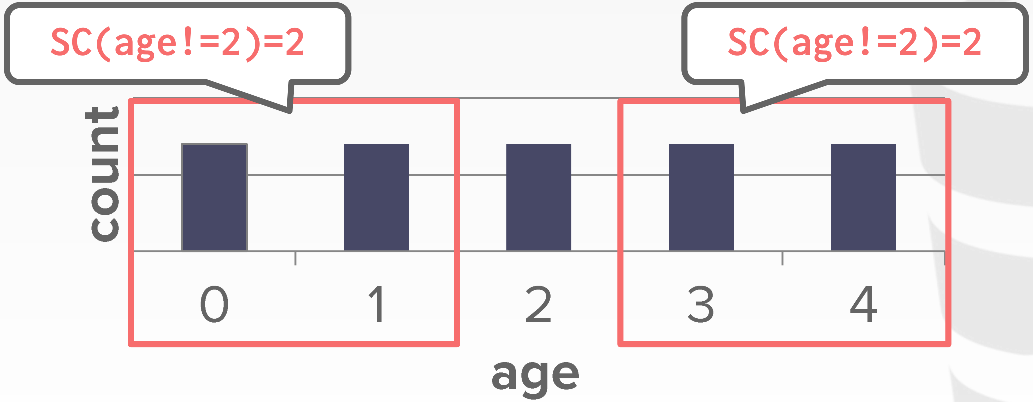
Negation Query:

→ `sel(not P) = 1 - sel(P)`

→ Example: `sel(age != 2) = 1 - (1/5) = 4/5`

Observation: selectivity ≈ probability

```
SELECT * FROM people
 WHERE age != 2
```



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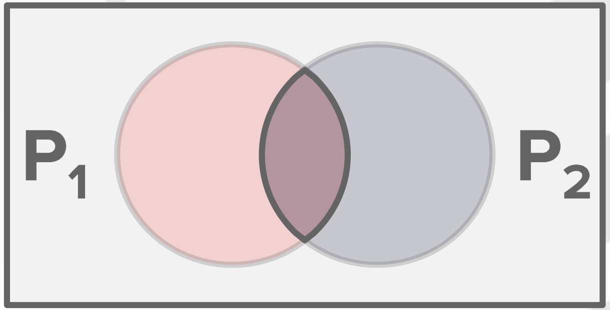
SELECTIONS – COMPLEX PREDICATES

Conjunction:

→ sel(P1 ∧ P2) = sel(P1) • sel(P2)
→ sel(age=2 ∧ name LIKE 'A%')

```
SELECT * FROM people
 WHERE age = 2
   AND name LIKE 'A%'
```

This assumes that the predicates are independent.



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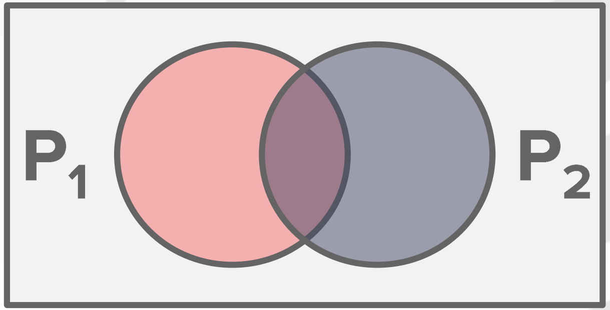
SELECTIONS – COMPLEX PREDICATES

Disjunction:

→ sel(P1 V P2)
  = sel(P1) + sel(P2) - sel(P1 V P2)
  = sel(P1) + sel(P2) - sel(P1) • sel(P2)
→ sel(age=2 OR name LIKE 'A%')

```
SELECT * FROM people
 WHERE age = 2
    OR name LIKE 'A%'
```



This again assumes that the selectivities are independent.

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SELECTIONS – COMPLEX PREDICATES

Disjunction:

→ sel(P1 V P2)
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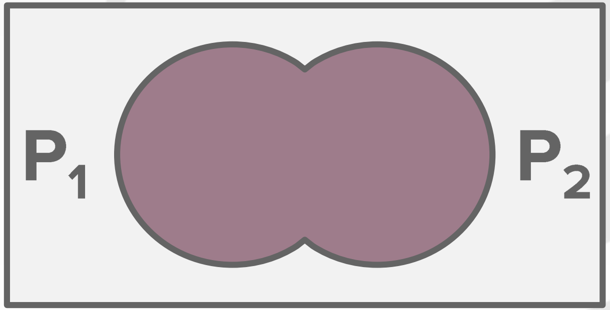


This again assumes that the selectivities are independent.

RESULT SIZE ESTIMATION FOR JOINS

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

In other words, for a given tuple of R, how many tuples of S will it match?

RESULT SIZE ESTIMATION FOR JOINS

General case: $R_{cols} \cap S_{cols} = \{A\}$ where A is not a key for either table.

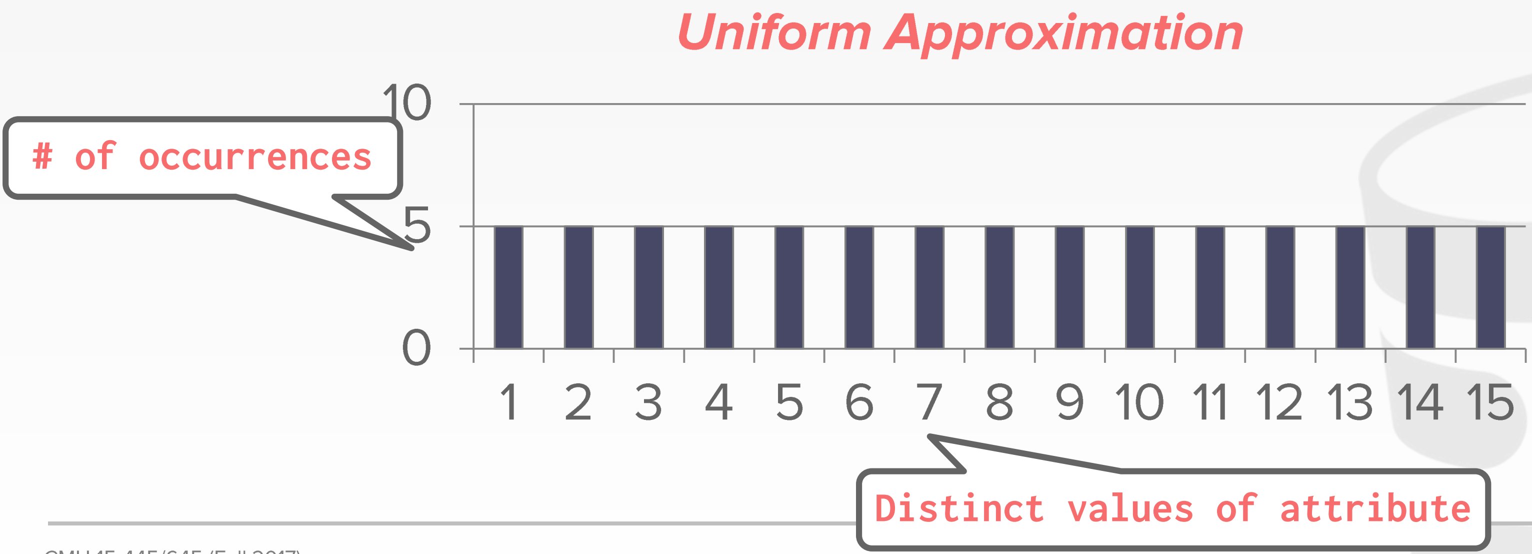
→ Match each R-tuple with S-tuples:
  $estSize \approx N_R \bullet N_S / V(A,S)$
→ Symmetrically, for S:
  $estSize \approx N_R \bullet N_S / V(A,R)$

Overall:

→ $estSize \approx N_R \bullet N_S / \max(\{V(A,S), V(A,R)\})$

COST ESTIMATIONS

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



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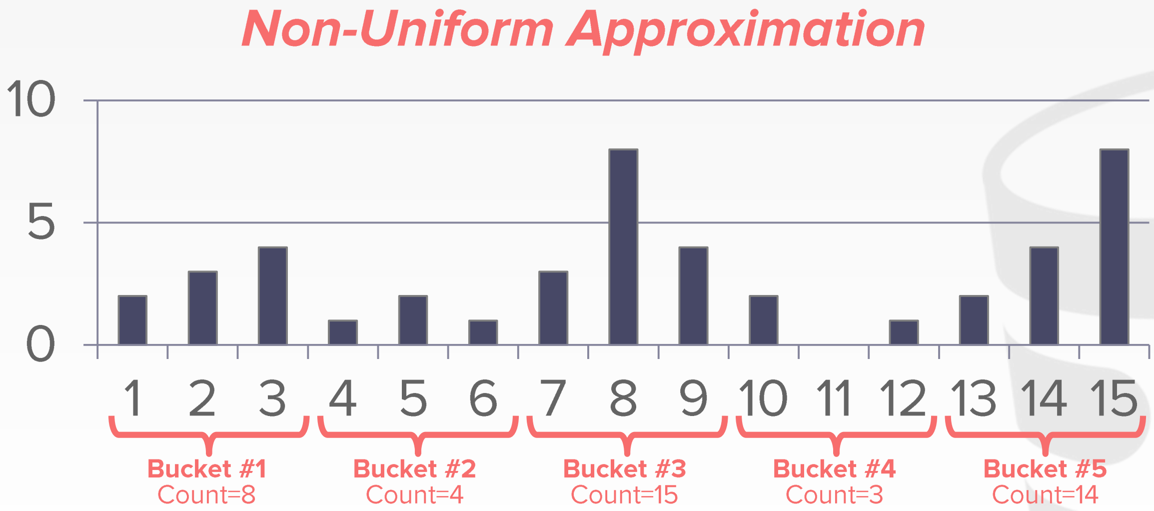

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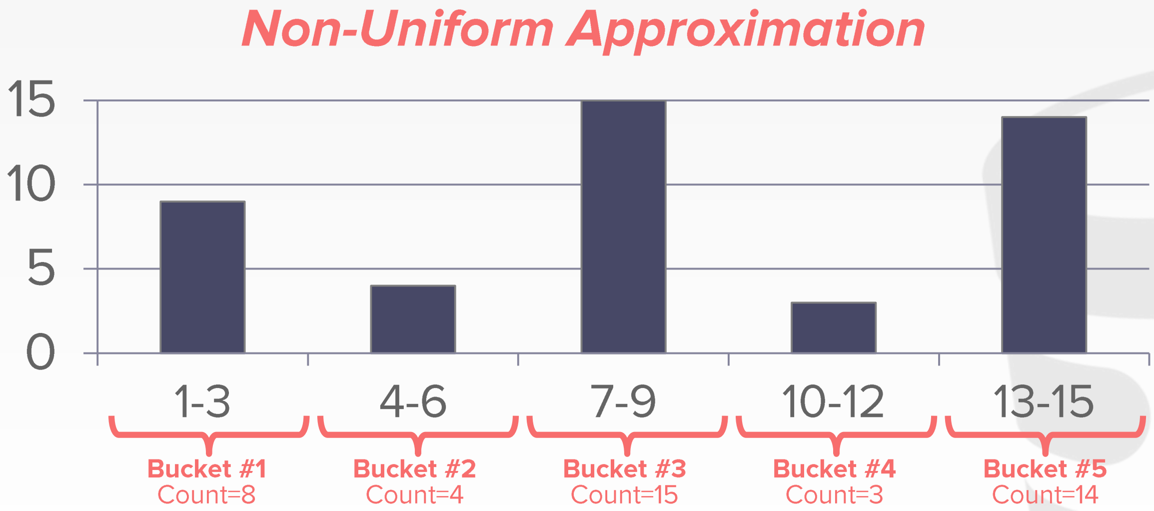
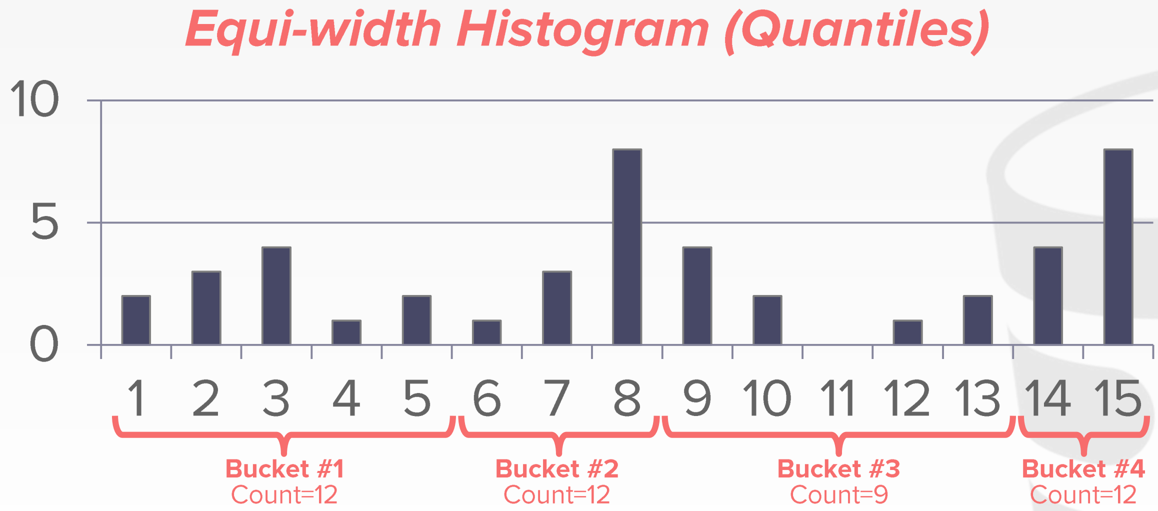


HISTOGRAMS WITH QUANTILES

A histogram type wherein the "spread" of each bucket is same.



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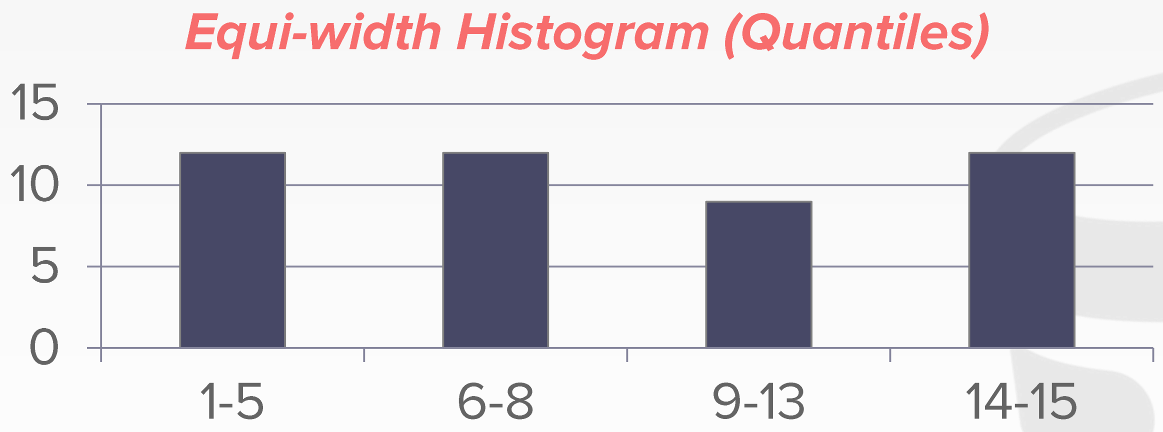

SAMPLING

Modern DBMSs also employ sampling to estimate predicate selectivities.

```
SELECT AVG(age)
  FROM people
 WHERE age > 50
```

id	name	age	status
1001	Obama	56	Rested
1002	Kanye	40	Weird
1003	Tupac	25	Dead
1004	Bieber	23	Crunk
1005	Andy	36	Lit

⋮

1 billion tuples

SAMPLING

Modern DBMSs also employ sampling to estimate predicate selectivities.

```
SELECT AVG(age)
  FROM people
 WHERE age > 50
```

sel(age>50) =

1001	Obama	56	Rested
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1005	Andy	36	Lit

= 1/3

id	name	age	status
1001	Obama	56	Rested
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⋮

1 billion tuples

OBSERVATION

Now that we can (roughly) estimate the selectivity of predicates, what can we actually do with them?

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.

SINGLE-RELATION QUERY PLANNING

Pick the best access method.

→ Sequential Scan
→ Binary Search (clustered indexes)
→ Index Scan

Simple heuristics are often good enough for this.

OLTP queries are especially easy.

OLTP QUERY PLANNING

Query planning for OLTP queries is easy because they are **sargable**.

→ **S**earch **Arg**ument **Able**
→ It is usually just picking the best index.
→ Joins are almost always on foreign key relationships with a small cardinality.
→ Can be implemented with simple heuristics.

MULTI-RELATION QUERY PLANNING

As number of joins increases, number of alternative plans grows rapidly

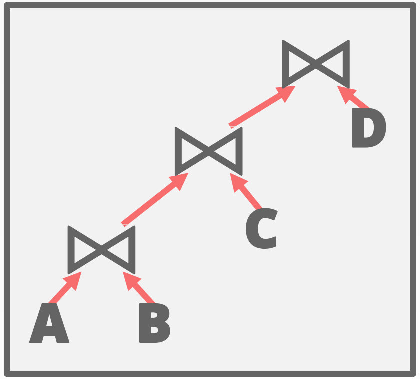
→ We need to restrict search space.

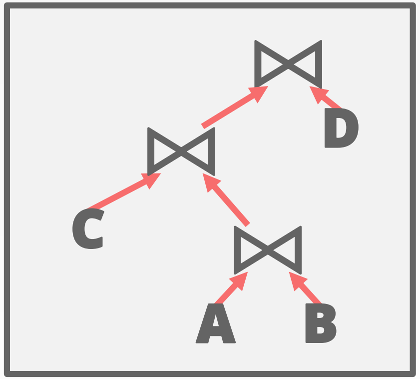
Fundamental decision in System R: only left-deep join trees are considered.

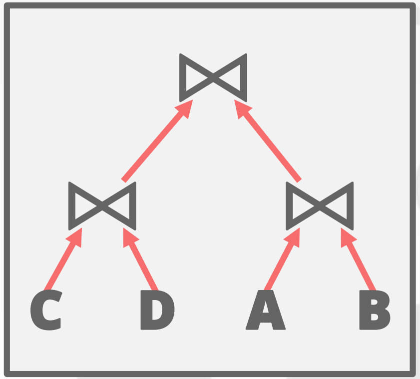
→ Modern DBMSs do not always make this assumption anymore.

MULTI-RELATION QUERY PLANNING

Fundamental decision in **System R**:
Only consider left-deep join trees.







MULTI-RELATION QUERY PLANNING

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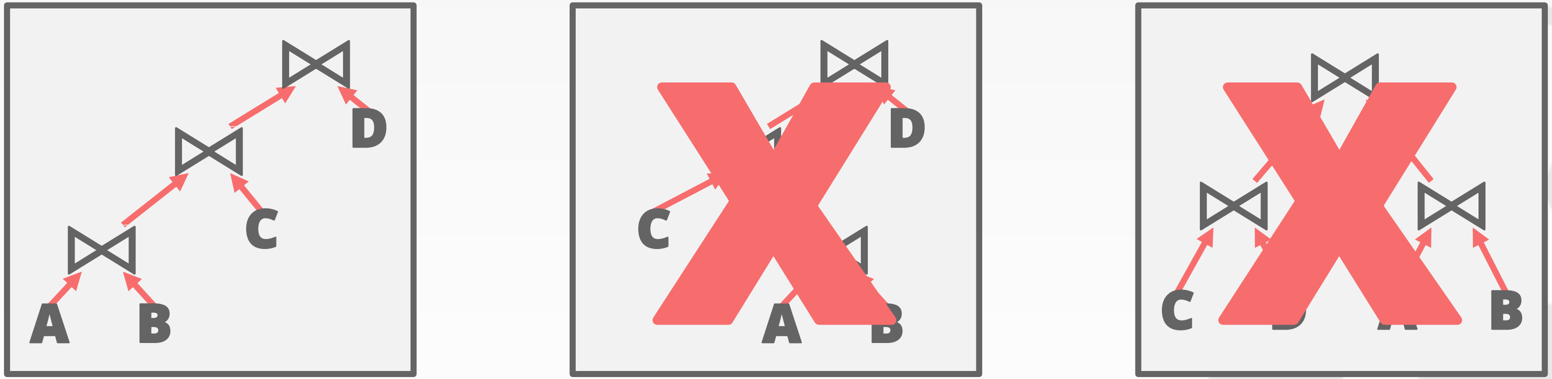

MULTI-RELATION QUERY PLANNING

Fundamental decision in **System R**:
Only consider left-deep join trees.

Allows for fully pipelined plans where intermediate results are not written to temp files.
→ Not all left-deep trees are fully pipelined.

MULTI-RELATION QUERY PLANNING

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…

MULTI-RELATION QUERY PLANNING

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.

DYNAMIC PROGRAMMING

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

$R \bowtie S$
T

R
S
T

$R \bowtie S \bowtie T$

$T \bowtie S$
R

⋮

DYNAMIC PROGRAMMING

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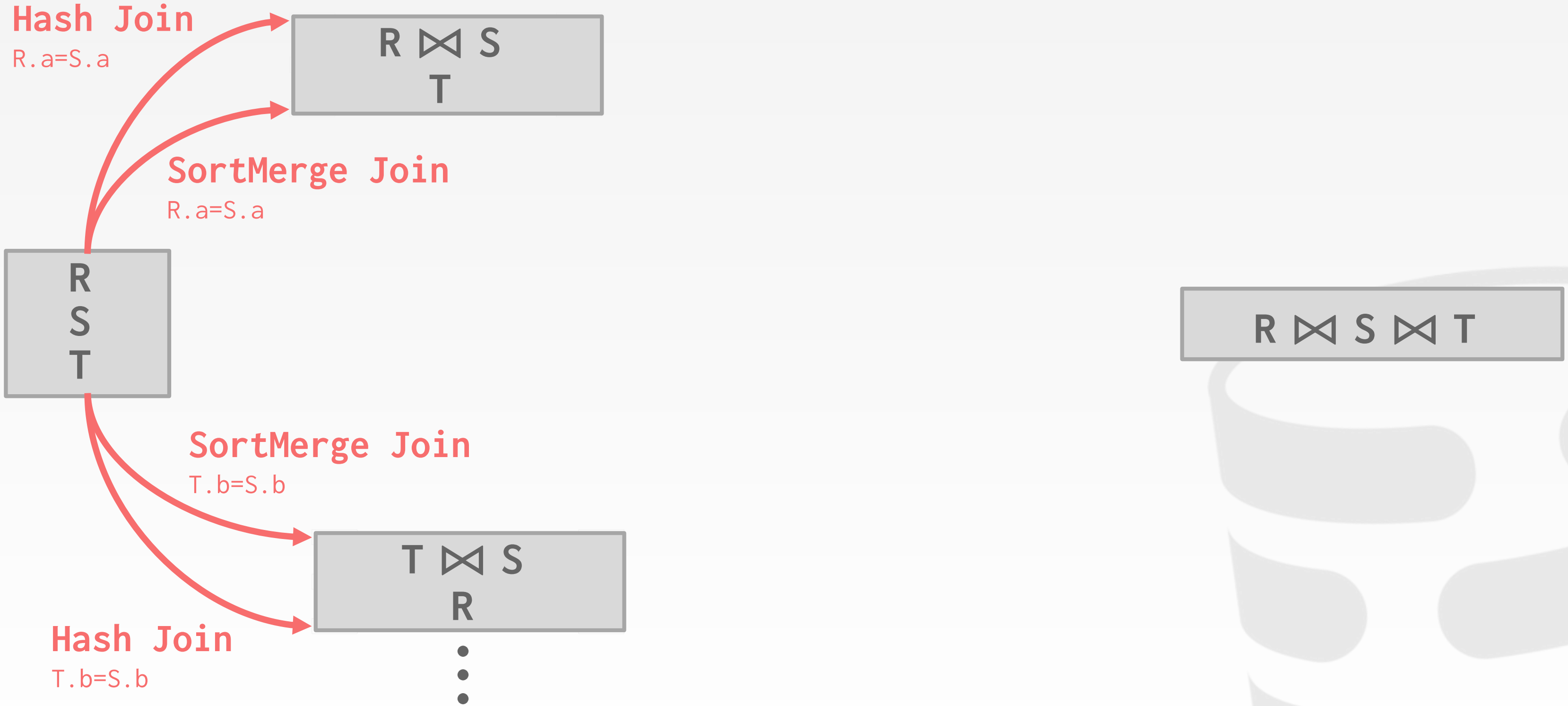

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DYNAMIC PROGRAMMING

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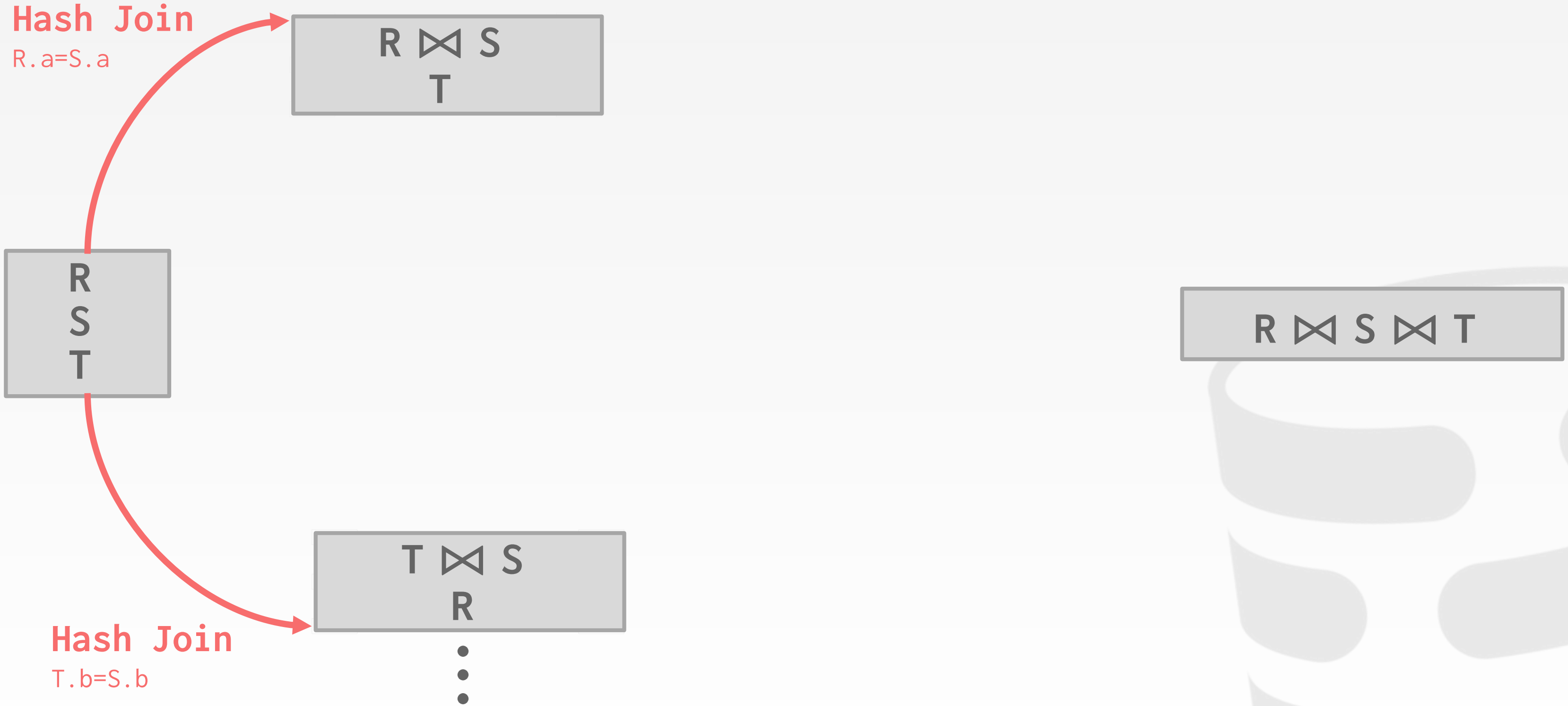

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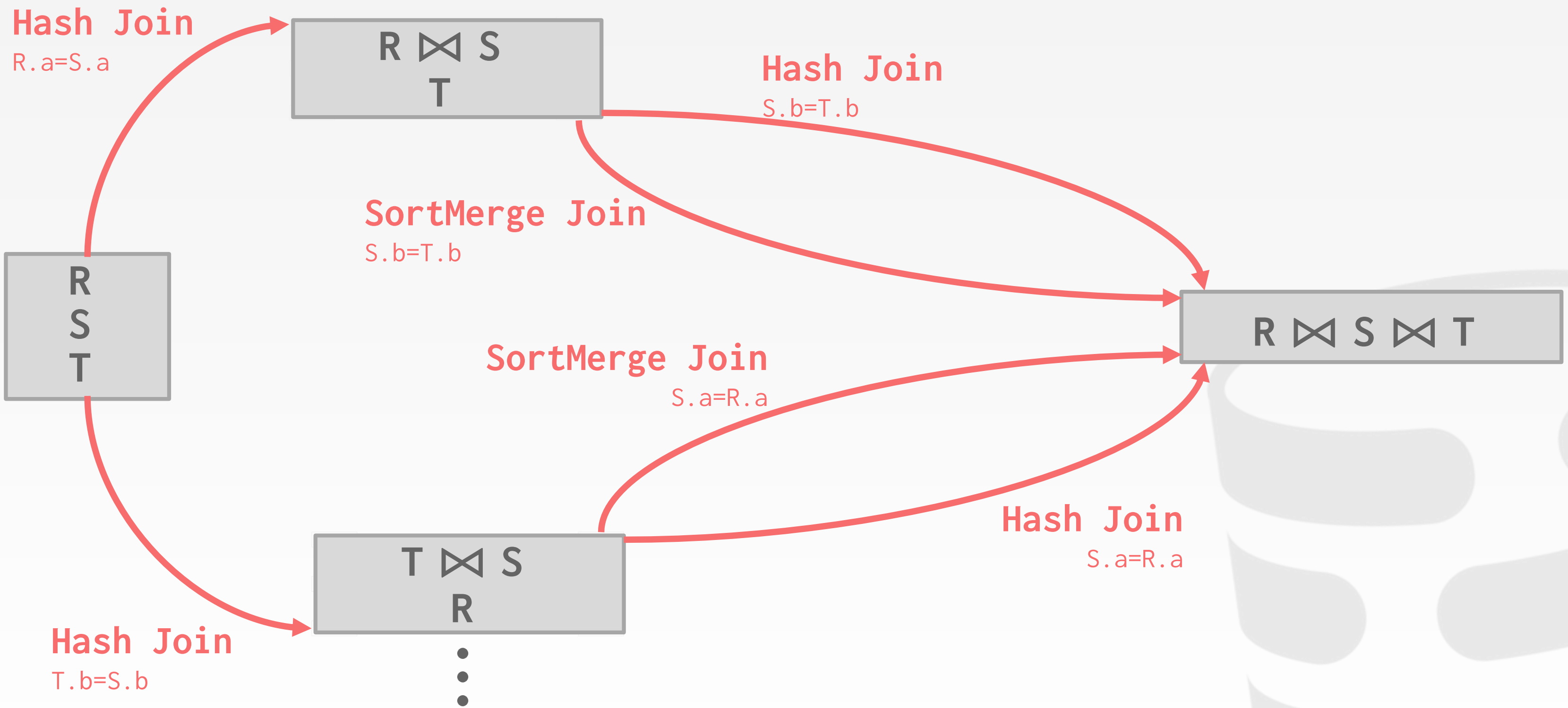

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DYNAMIC PROGRAMMING

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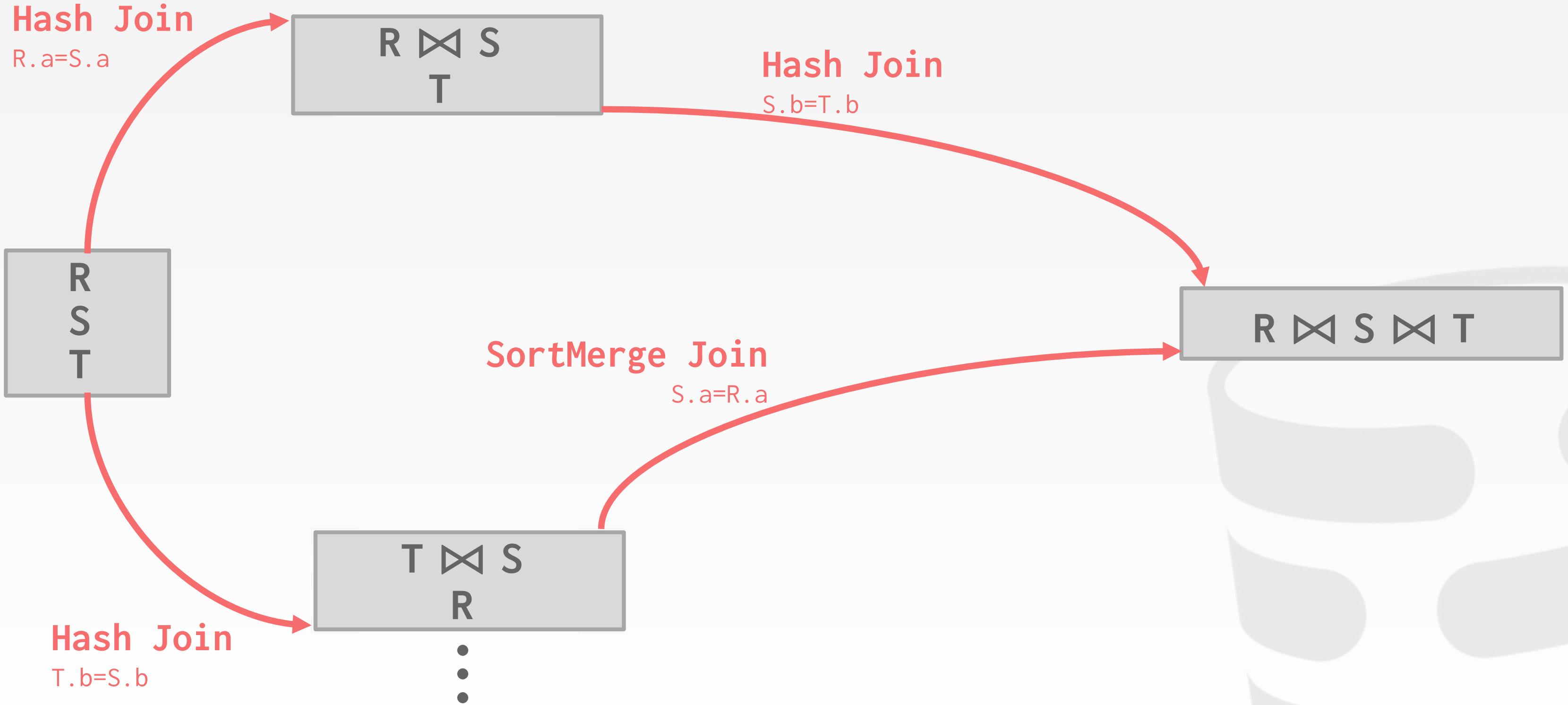

DYNAMIC PROGRAMMING

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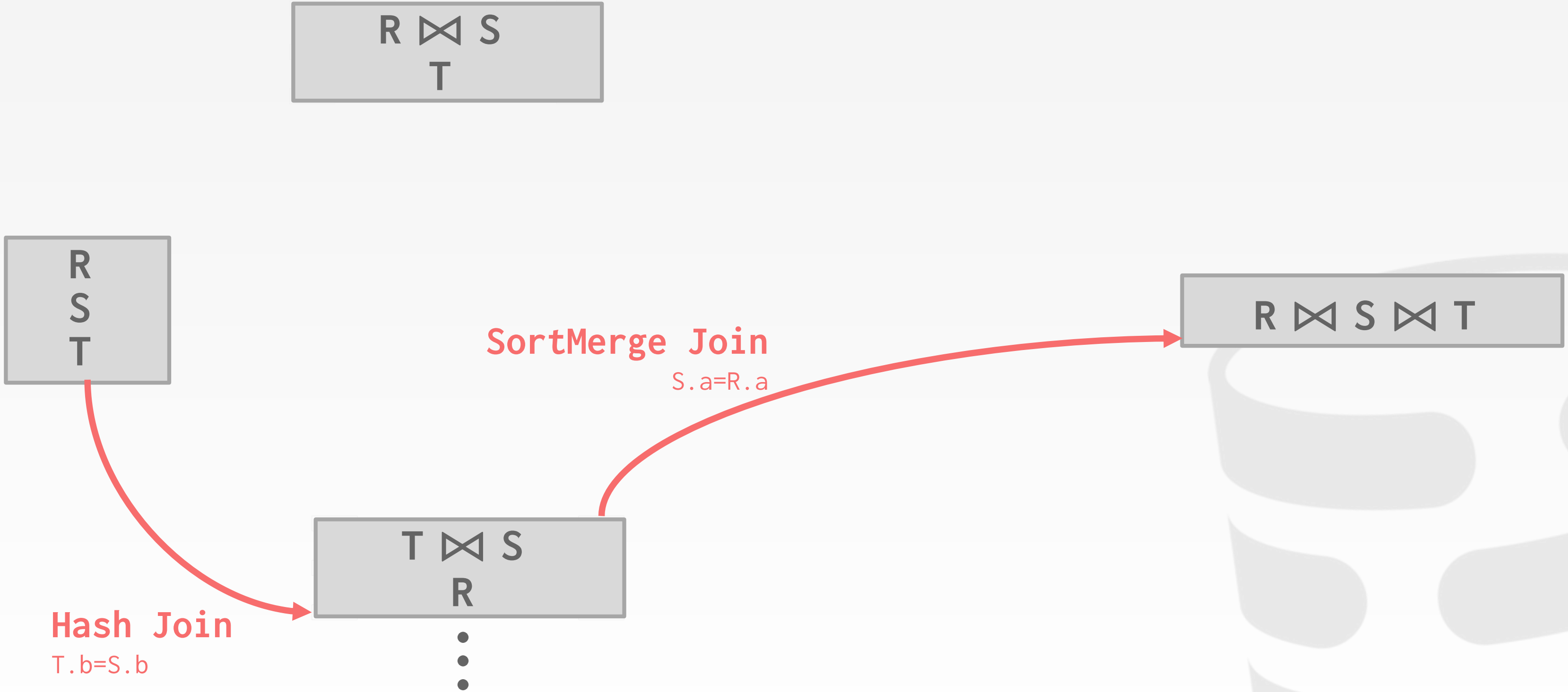


CANDIDATE PLAN EXAMPLE

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

How to generate plans for search algorithm:

→ Enumerate relation orderings
→ Enumerate join algorithm choices
→ Enumerate access method choices

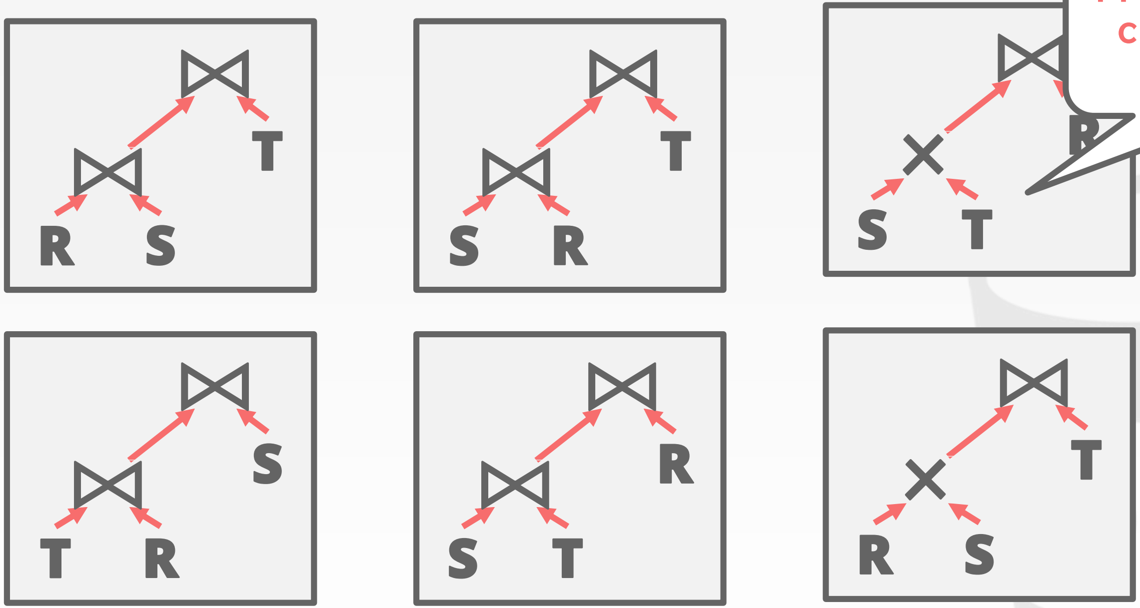
No real DBMSs does it this way.
It's actually more messy...

CANDIDATE PLANS

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

Step #1: Enumerate relation orderings

Prune plans with cross-products immediately!



CANDIDATE PLANS

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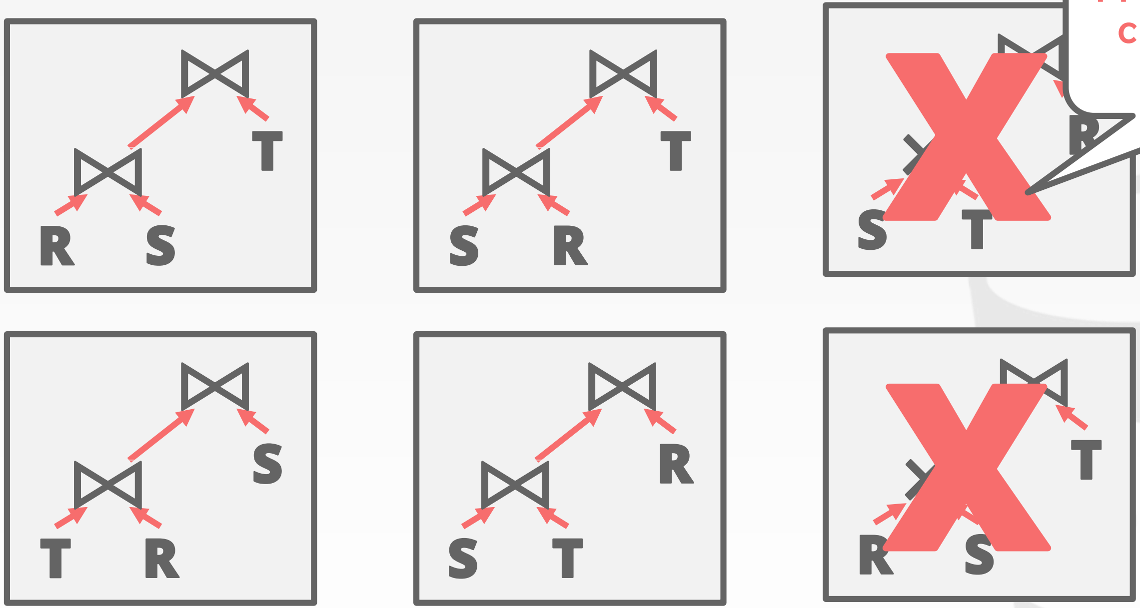
Step #1: Enumerate relation orderings



Prune plans with cross-products immediately!

CARNEGIE MELLON DATABASE GROUP

CANDIDATE PLANS

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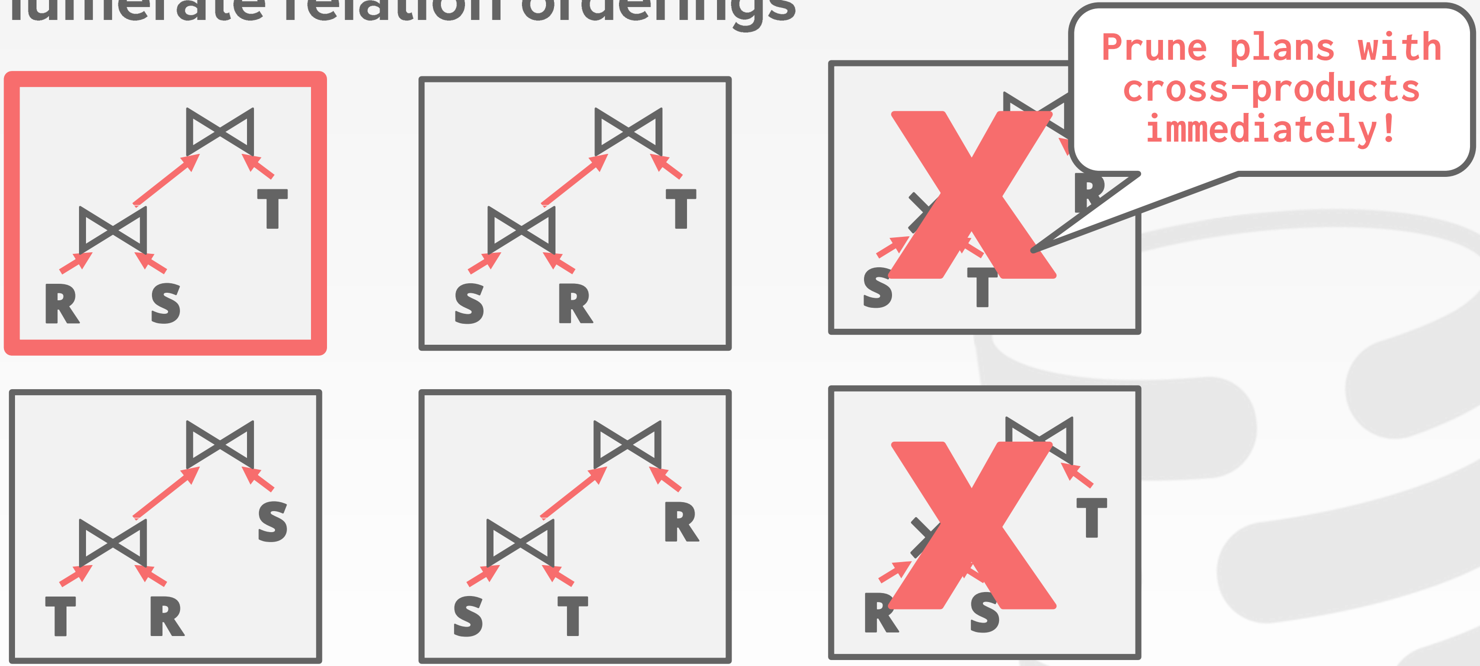
   AND S.b = T.b
```

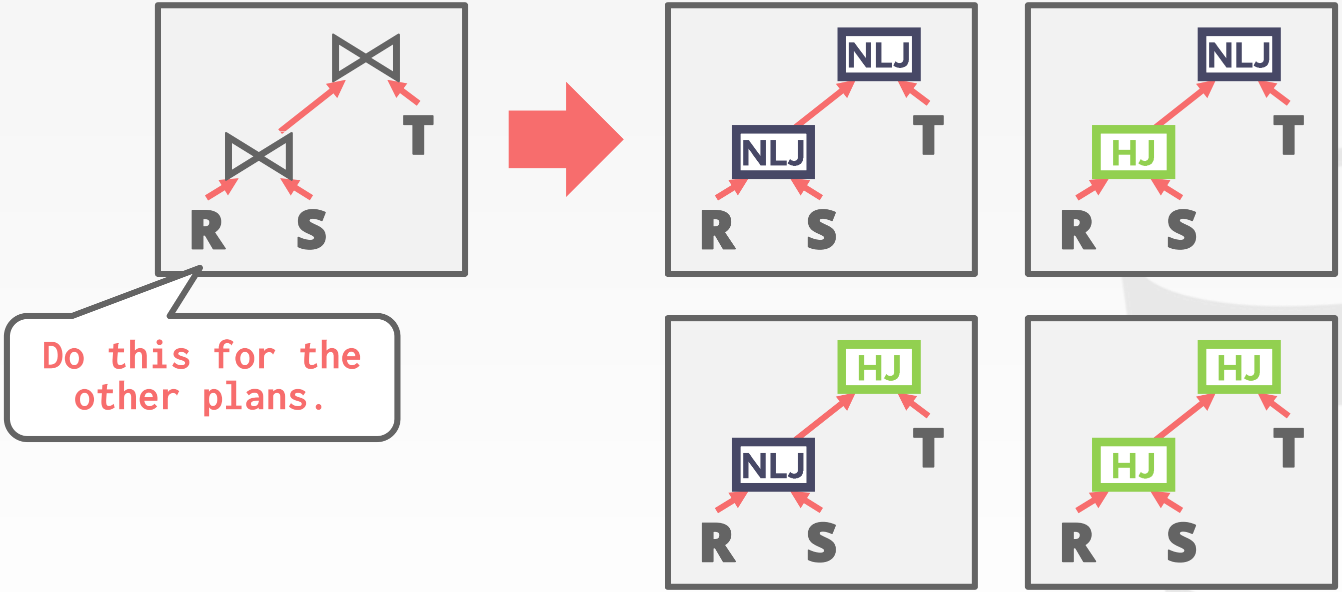
Step #1: Enumerate relation orderings



CANDIDATE PLANS

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

Step #2: Enumerate join algorithm choices

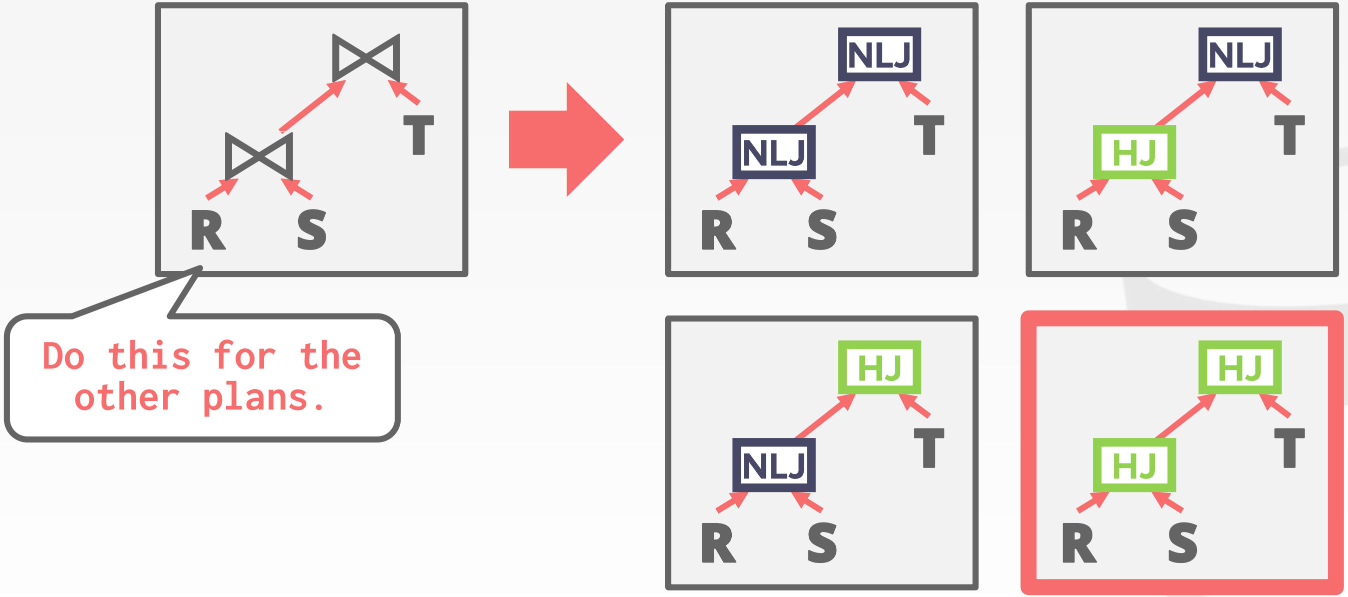


CARNEGIE MELLON DATABASE GROUP

CANDIDATE PLANS

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

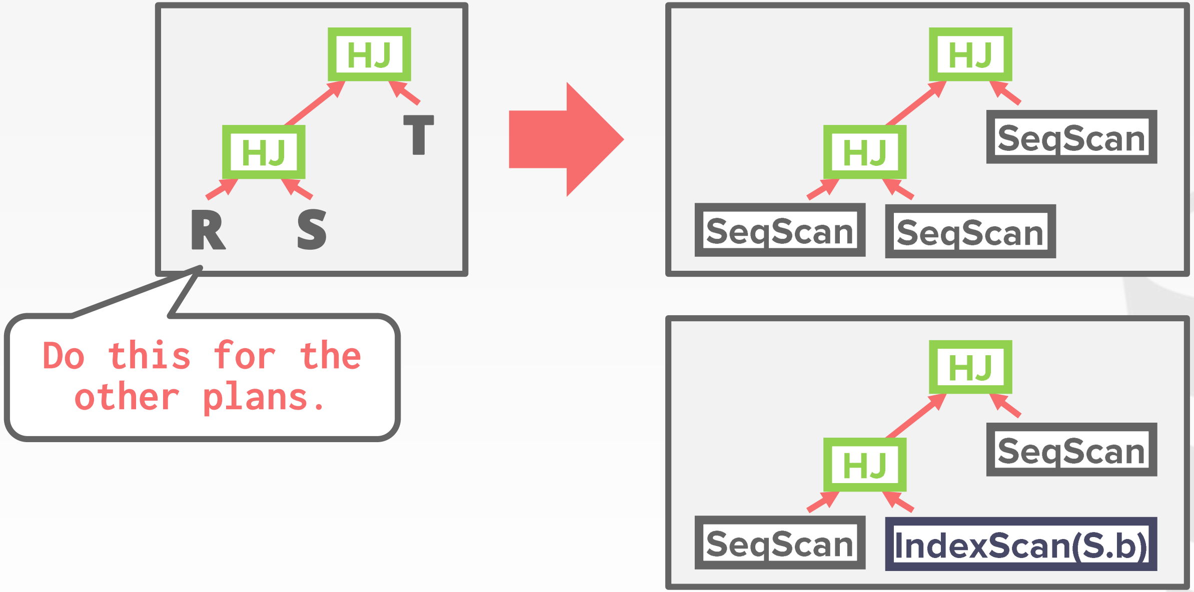
Step #2: Enumerate join algorithm choices



Candidate Plans

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

Step #3: Enumerate access method choices



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

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 = '2017-10-11'
 )
```

```
SELECT name
  FROM sailors AS S, reserves AS R
 WHERE S.sid = R.sid
   AND R.day = '2017-10-11'
```


CARNEGIE MELLON DATABASE GROUP

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.

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.

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
```

Nested Block

DECOMPOSING QUERIES

```
SELECT MAX(rating) FROM sailors
```

```
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
```

Nested Block

DECOMPOSING QUERIES

```
SELECT MAX(rating) FROM sailors
```

```
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 =  ###

 GROUP BY S.sid
HAVING COUNT(*) > 1
```


CARNEGIE MELLON
DATABASE GROUP

DECOMPOSING QUERIES

```
SELECT MAX(rating) FROM sailors
```

```
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 = ###

 GROUP BY S.sid
HAVING COUNT(*) > 1
```

Outer Block

CONCLUSION

Filter early as possible.

Selectivity estimations

- → Uniformity
- → Independence
- → Histograms
- → Join selectivity

Dynamic programming for join orderings

Rewrite nested queries

Query optimization is really hard…

Midterm Exam

Who: You

What: Midterm Exam

When: Wed Oct 18th 12:00pm - 1:20pm

Where: Scaife Hall 125

Why: https://youtu.be/xgMiaIPxSlc

MIDTERM

What to bring:

→ CMU ID
→ Calculator
→ One 8.5x11" page of notes (double-sided)

What not to bring:

→ Live animals

MIDTERM

Covers up to Query Optimization (inclusive).

→ Closed book, one sheet of notes (double-sided)

→ Please email Andy if you need special accommodations.

http://cmudb.io/f17-midterm

RELATIONAL MODEL

Integrity Constraints

Relation Algebra

SQL

Basic operations:

→ SELECT / INSERT / UPDATE / DELETE
→ WHERE predicates
→ Output control

More complex operations:

→ Joins
→ Aggregates
→ Common Table Expressions

STORAGE

Buffer Management Policies

→ LRU / MRU / CLOCK

On-Disk File Organization

→ Heaps

→ Linked Lists

Understand high-level trade-offs of different approaches.

HASHING

Extendible Hashing
→ Global Depth vs. Local Depth
→ Overflow Chains

Linear Hashing
→ Insertion / Splitting
→ Overflow Chains

Comparison with B+Trees

TREE INDEXES

B+Tree
→ Insertions / Deletions
→ Splits / Merges
→ Difference with B-Tree

Radix Trees

Skip Lists

SORTING

Two-way External Merge Sort

General External Merge Sort

Cost to sort different data sets with different number of buffers.

QUERY PROCESSING

Processing Models
→ Advantages / Disadvantages

Join Algorithms
→ Nested Loop
→ Sort-Merge
→ Hash

Query Optimization & Planning

NEXT CLASS

Parallel Query Execution