Database Applications (15-415)

DBMS Internals- Part X
Lecture 21, April 7, 2015

Mohammad Hammoud

جامعة كارنيجي ميلون في قطر
Carnegie Mellon University Qatar

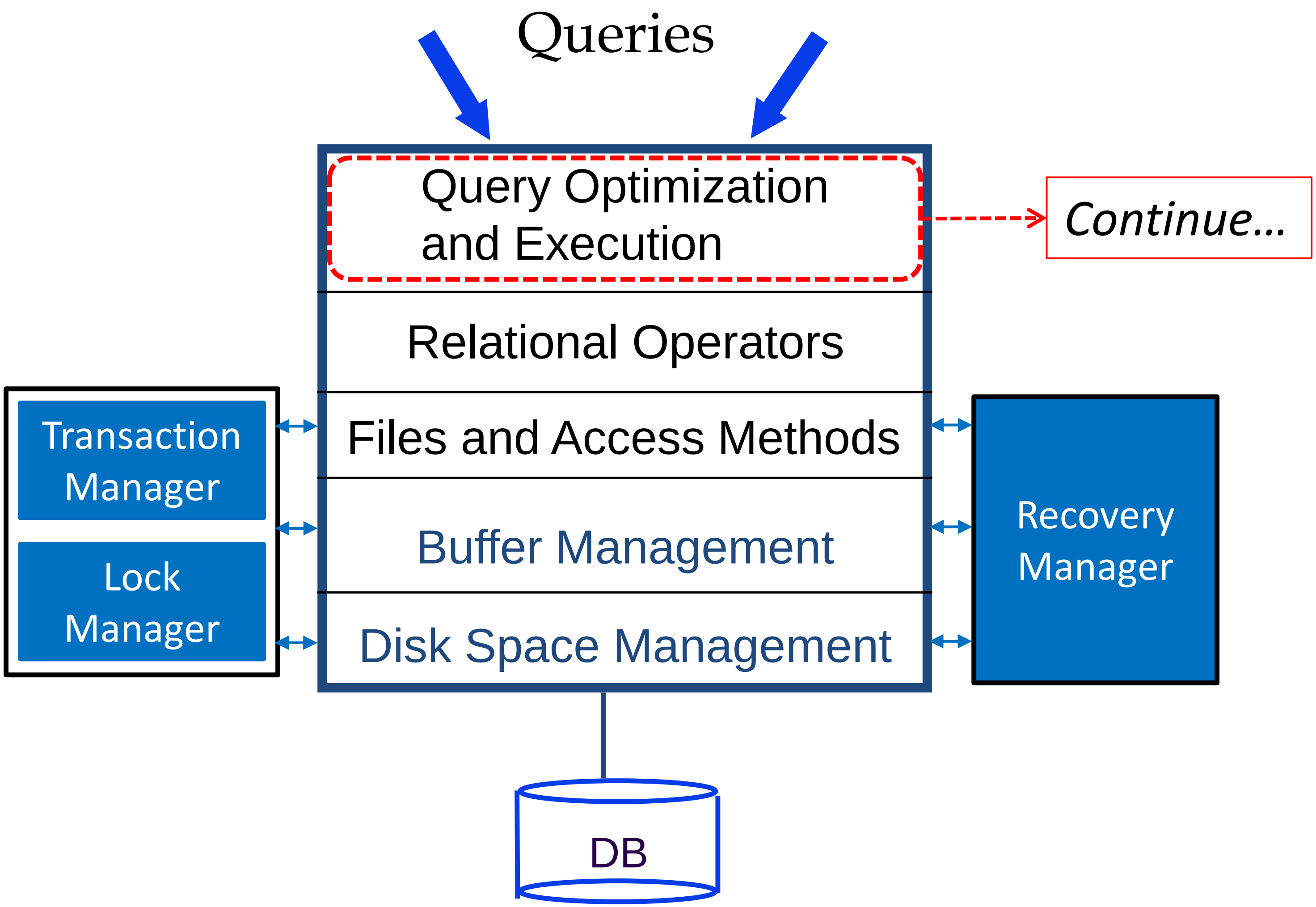
Today…

- Last Session:
  - DBMS Internals- Part IX
    - Query Optimization

- Today's Session:
  - DBMS Internals- Part X
    - Query Optimization (*Cont'd*)

- Announcements:
  - PS4 is due on Sunday, April 12 by midnight
  - Quiz II is on Thursday, April 9th (all concepts covered after the midterm are included)

DBMS Layers


Queries
Query Optimization and Execution
Continue…
Relational Operators
Files and Access Methods
Buffer Management
Disk Space Management
Transaction Manager
Lock Manager
Recovery Manager
DB

Outline

- A Brief Primer on Query Optimization
- Query Evaluation Plans
- Relational Algebra Equivalences
- Estimating Plan Costs ✓
- Enumerating Plans
- Nested Sub-Queries

Last Session

Estimating the Cost of a Plan

- The cost of a plan can be estimated by:
  1. Estimating *the cost of each operation* in the plan tree
     - Already covered last week (e.g., costs of various join algorithms)
  2. Estimating *the size of the result set of each operation* in the plan tree
     - The output *size* and *order* of a child node affects the cost of its parent node

How can we estimate result sizes?

Estimating Result Sizes

- Consider a query block, ***QB***, of the form:

```
SELECT  attribute list
FROM  R1, R2, …., Rn
WHERE  term 1 AND ... AND term k
```

- What is the *maximum* number of tuples generated by ***QB***?
  - NTuples (R1) × NTuples (R2) × .... × NTuples(Rn)

- Every term in the WHERE clause, however, eliminates some of the possible resultant tuples
  - A *reduction factor* can be associated with each term

Estimating Result Sizes (*Cont'd*)

- Consider a query block, ***QB***, of the form:

```
SELECT  attribute list
FROM  R1, R2, …., Rn
WHERE  term 1 AND ... AND term k
```

- The *reduction factor (RF)* associated with each *term* reflects the impact of the *term* in reducing the result size

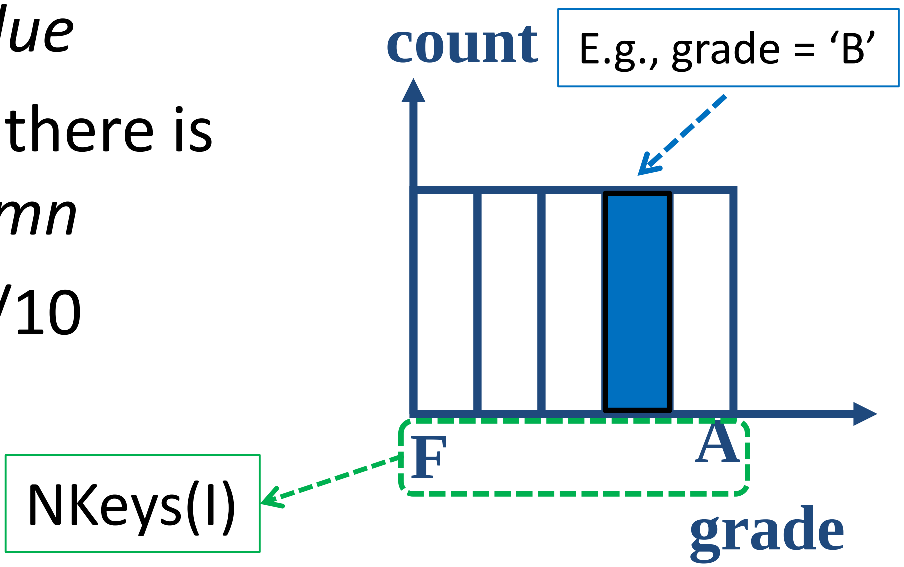
- Final (***estimated***) result cardinality = [NTuples (R1) × ... × NTuples(Rn)] × [RF(term 1) ×... × RF(term k)]
  - ***Implicit assumptions****: terms are independent and distribution is uniform!*

But, how can we compute reduction factors?

Approximating Reduction Factors

- Reduction factors (RFs) can be *approximated* using the statistics available in the DBMS's catalog

- For different ***forms*** of terms, RF is computed differently
  - Form 1: *Column = Value*
    - RF = 1/NKeys(***I***), if there is an index ***I*** on *Column*
    - Otherwise, RF = 1/10

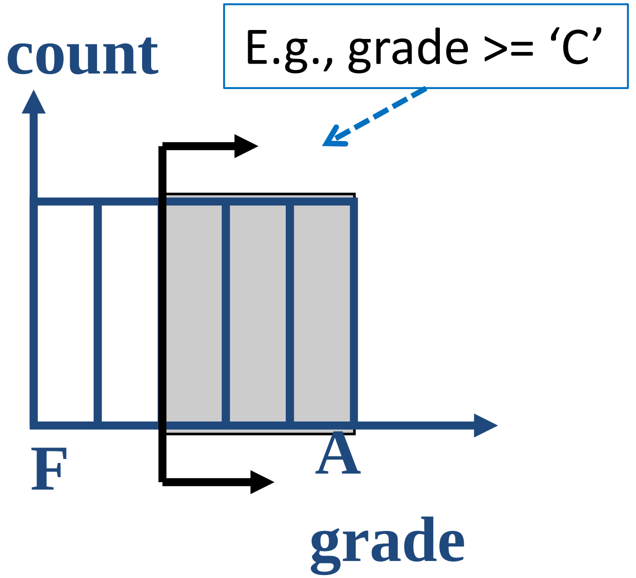


Approximating Reduction Factors (*Cont'd*)

- For different forms of terms, RF is computed differently
  - Form 2: *Column 1 = Column 2*
    - RF = 1/MAX(NKeys(***I1***), NKeys(***I2***)), if there are indices ***I1*** and ***I2*** on *Column 1* and *Column 2*, respectively
    - **Or**: RF = 1/NKeys(***I***), if there is only 1 index on *Column 1* or *Column 2*
    - **Or**: RF = 1/10, if neither *Column 1* nor *Column 2* has an index
  - Form 3: *Column* **IN** (*List of Values*)
    - RF equals to RF of "*Column = Value*" (i.e., Form 1) × # of elements in the *List of Values*

Approximating Reduction Factors (*Cont'd*)

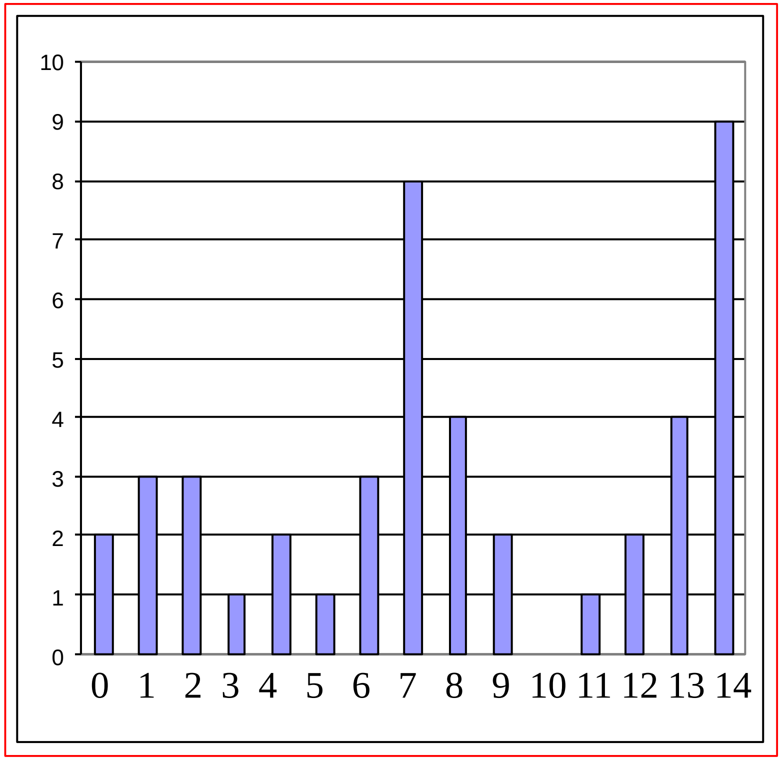
- For different forms of terms, RF is computed differently
  - Form 4: *Column* > *Value*
    - RF = (High(***I***) – *Value*)/(High(***I***) – Low(***I***)), if there is an index ***I*** on *Column*
    - Otherwise, RF equals to any fraction < 1/2



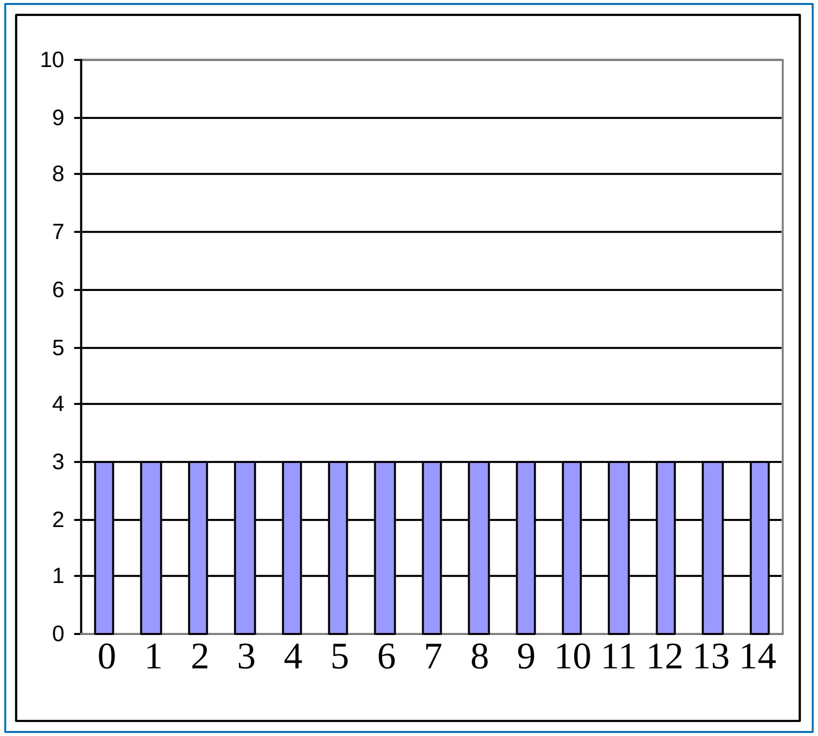
Improved Statistics: Histograms

- Estimates can be improved considerably by maintaining more detailed statistics known as *histograms*

Distribution D



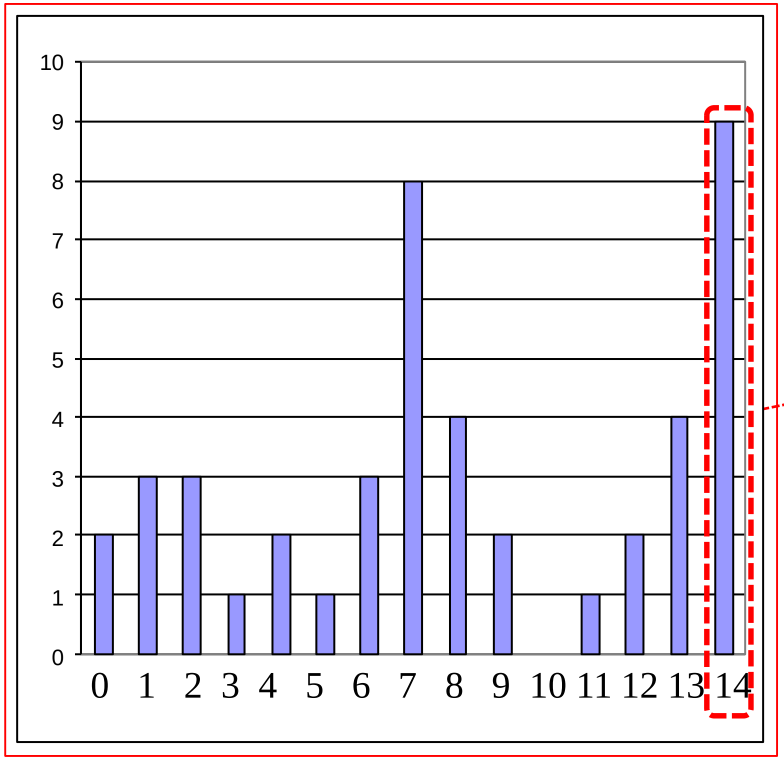
Uniform Distribution Approximating D



Improved Statistics: Histograms

- Estimates can be improved considerably by maintaining more detailed statistics known as *histograms*

Distribution D



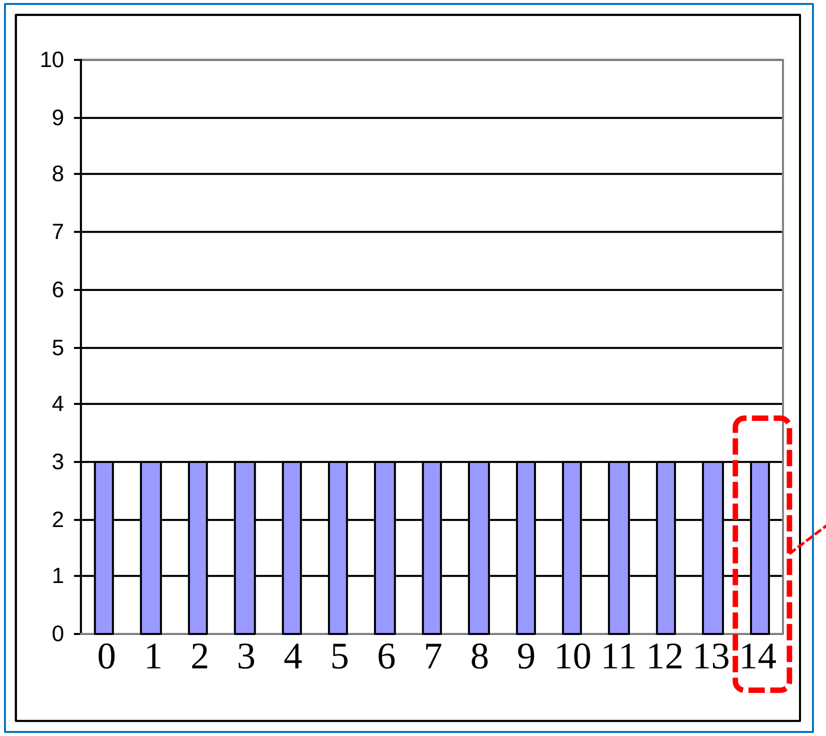
What is the result size of *term* value > 13?

9 tuples

Improved Statistics: Histograms

- Estimates can be improved considerably by maintaining more detailed statistics known as *histograms*

Uniform Distribution Approximating D



What is the (*estimated*) result size of *term* value > 13?

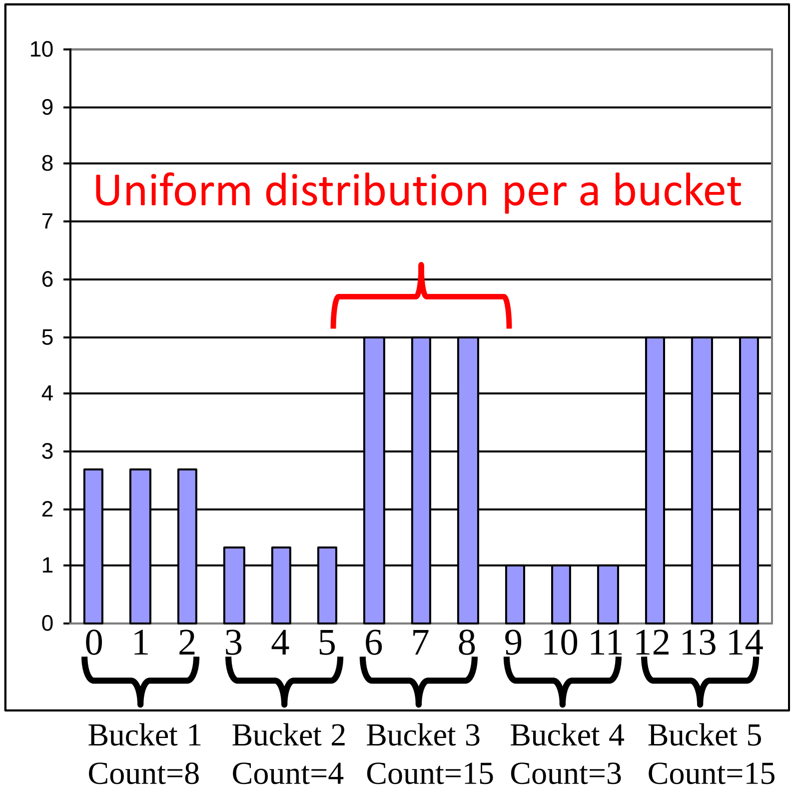
(1/15 × 45) = 3 tuples

Clearly, this is inaccurate!

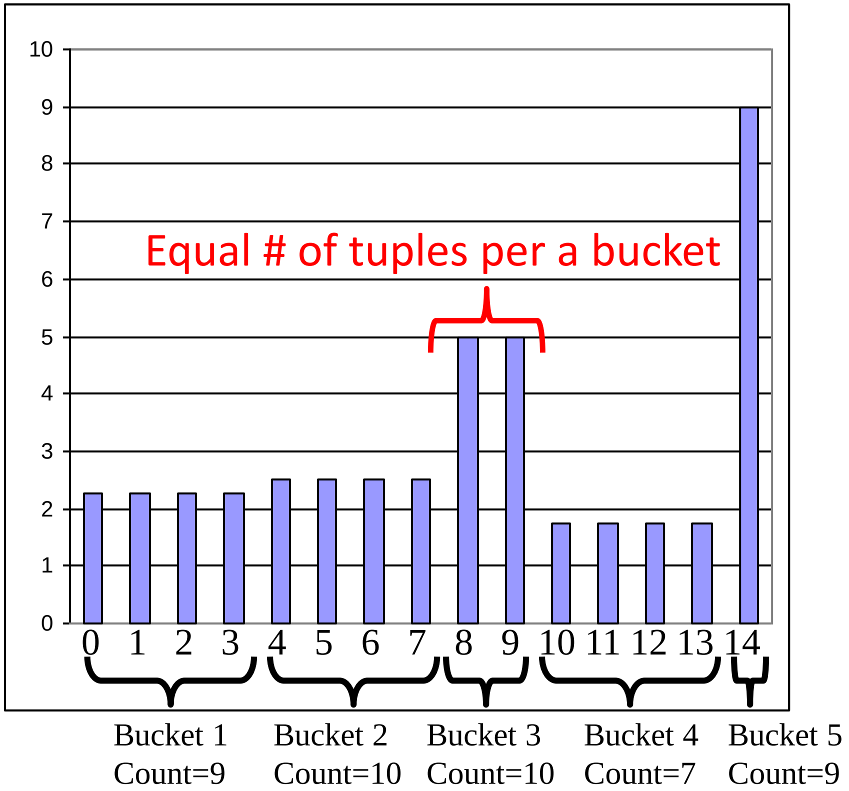
Improved Statistics: Histograms

- We can do better if we divide the range of values into *sub-ranges* called *buckets*

Equiwidth histogram



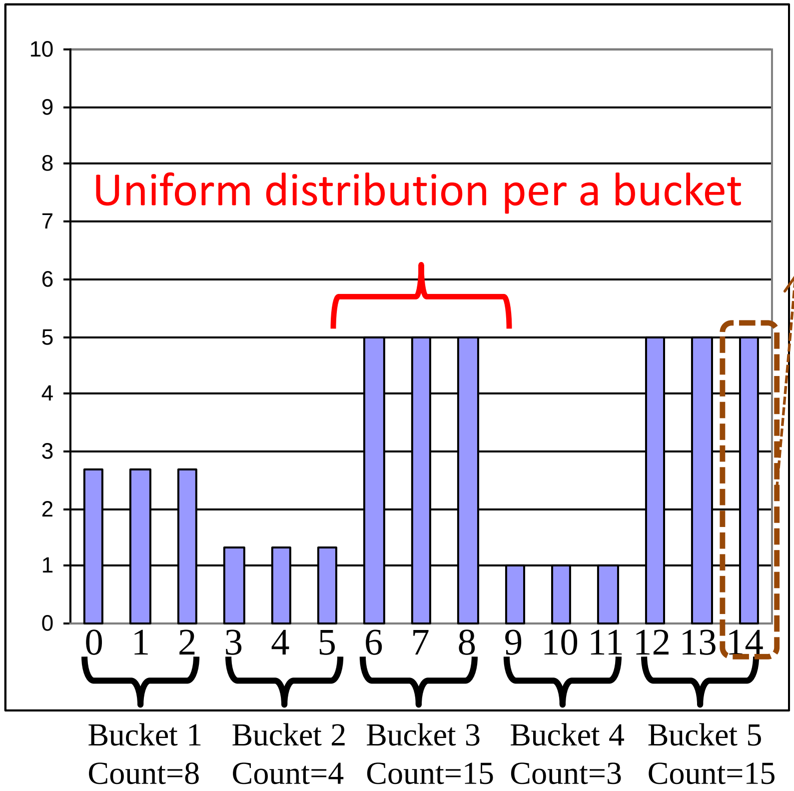
Equidepth histogram



Improved Statistics: Histograms

- We can do better if we divide the range of values into *sub-ranges* called *buckets*

Equiwidth histogram



What is the (*estimated*) result size of *term* value > 13?

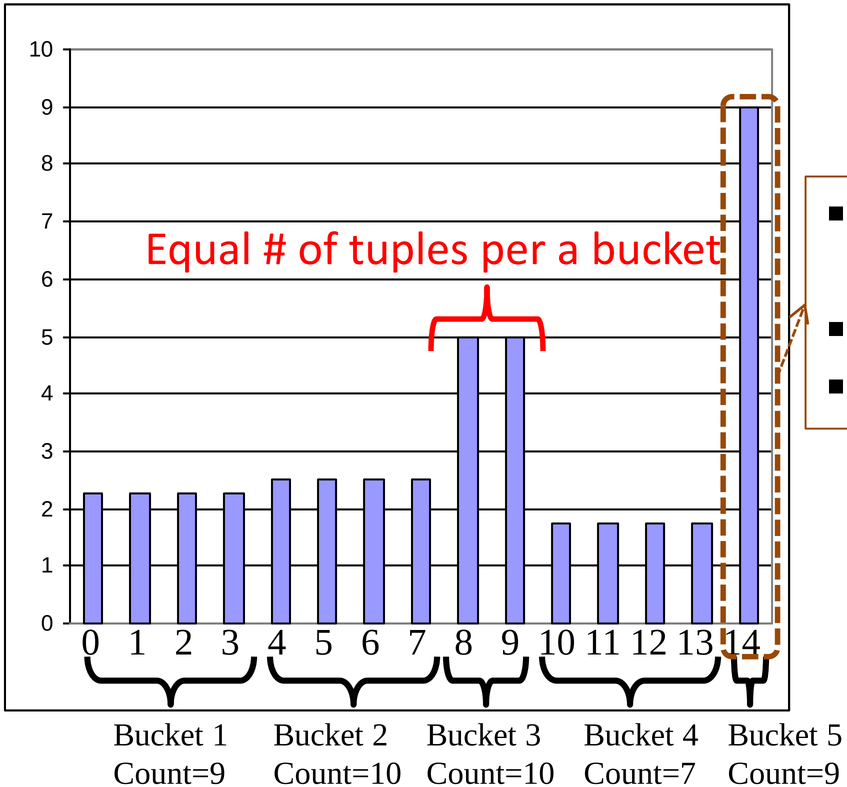
- The selected range = 1/3 of the range for bucket 5
- Bucket 5 represents a total of 15 tuples
- Estimated size = 1/3 × 15 = 5 tuples

Better than regular histograms!

Improved Statistics: Histograms

- We can do better if we divide the range of values into *sub-ranges* called *buckets*

Equidepth histogram



What is the (*estimated*) result size of *term* value > 13?

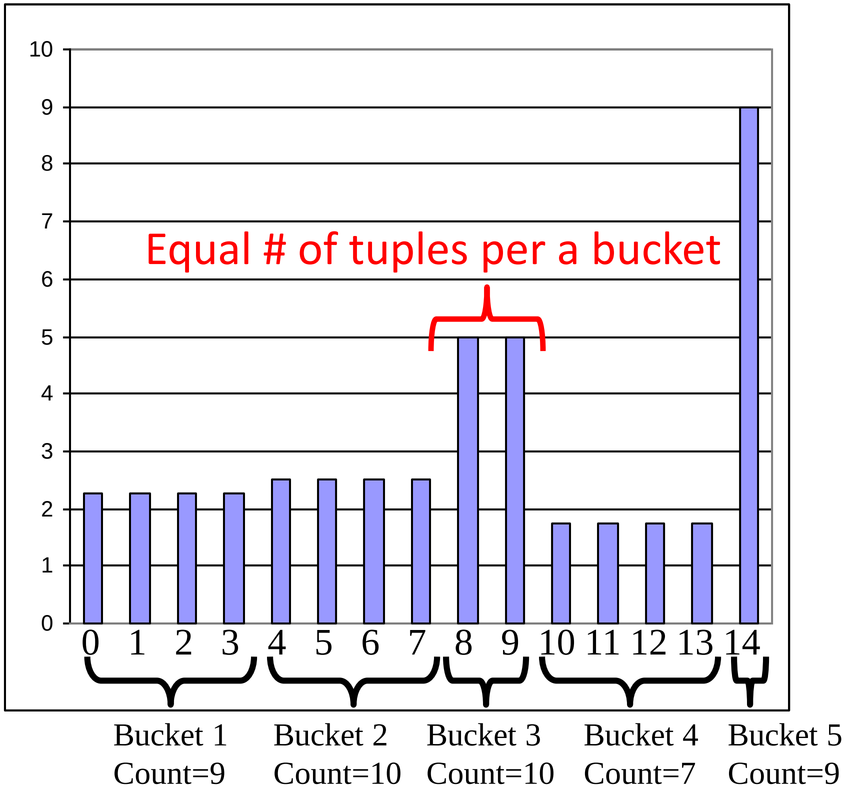
- The selected range = 100% of the range for bucket 5
- Bucket 5 represents a total of 9 tuples
- Estimated size = 1 × 9 = 9 tuples

Better than *equiwidth* histograms! ***Why?***

Improved Statistics: Histograms

- We can do better if we divide the range of values into *sub-ranges* called *buckets*

Equidepth **histogram**



Because, buckets with very frequently occurring values contain fewer slots; hence, the uniform distribution assumption is applied to a smaller range of values!

What about buckets with mostly infrequent values?

They are approximated less accurately!

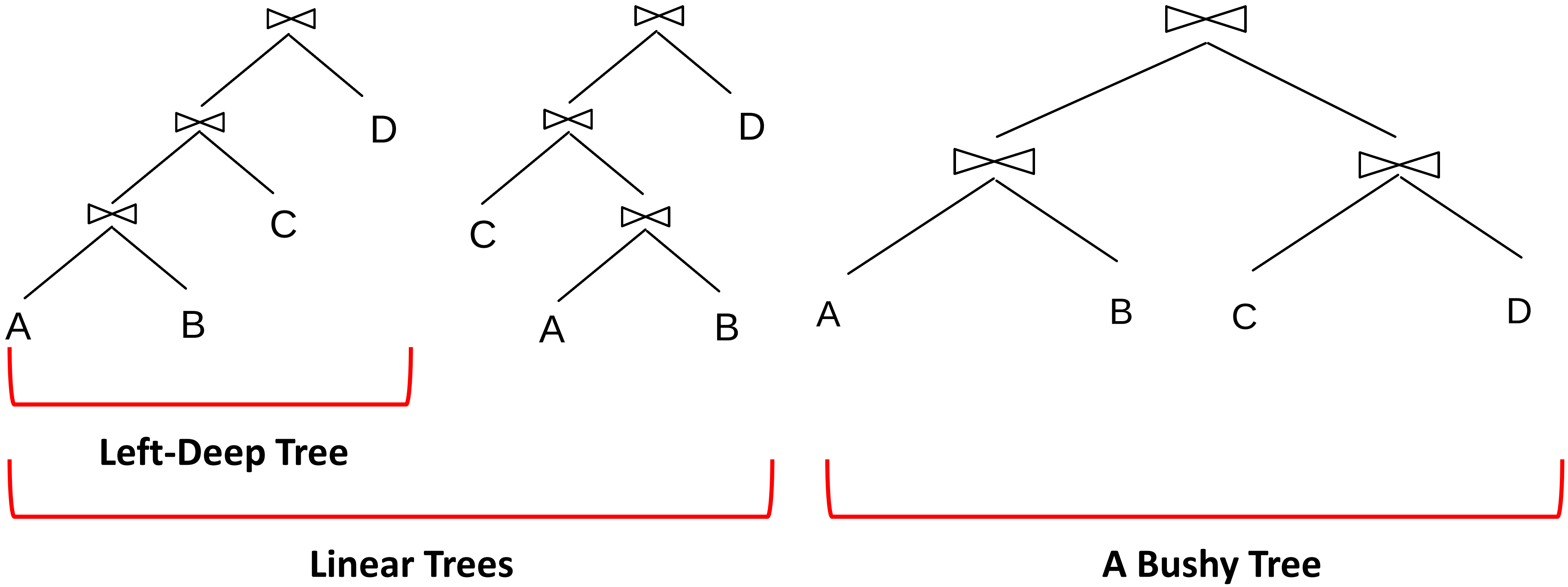
Outline

- A Brief Primer on Query Optimization
- Query Evaluation Plans
- Relational Algebra Equivalences
- Estimating Plan Costs
- Enumerating Plans ✓
- Nested Sub-Queries

Enumerating Execution Plans

- Consider a query ***Q*** = $A \bowtie B \bowtie C \bowtie D$

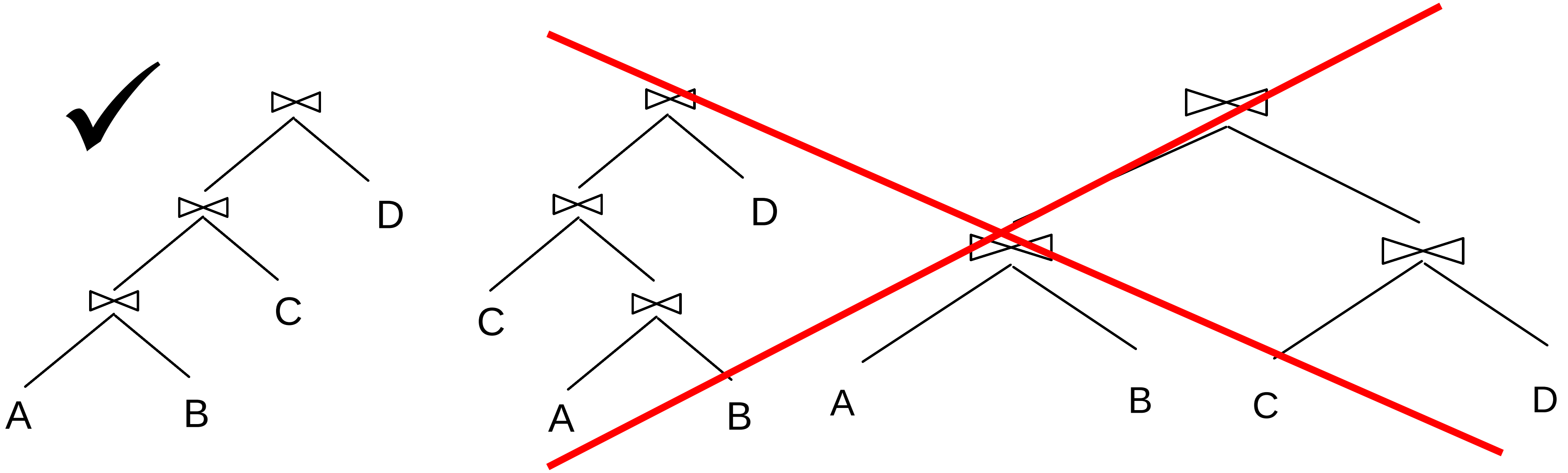
- Here are 3 plans that are *equivalent*:



Enumerating Execution Plans

- Consider a query ***Q*** = $A \bowtie B \bowtie C \bowtie D$

- Here are 3 plans that are *equivalent*:



Why?

Enumerating Execution Plans (*Cont'd*)

- There are two main reasons for concentrating only on left-deep plans:
  - As the number of joins increases, the number of plans increases rapidly; hence, it becomes necessary to prune the space of alternative plans
  - Left-deep trees allow us to generate all ***fully pipelined*** plans

- Clearly, by adding details to left-deep trees (e.g., the join algorithm per each join), several query plans can be obtained

- The query optimizer enumerates *all possible left-deep* plans using typically a *dynamic programming approach* (later), estimates the cost of each plan, and selects the one with the lowest cost!

Enumerating Execution Plans (*Cont'd*)

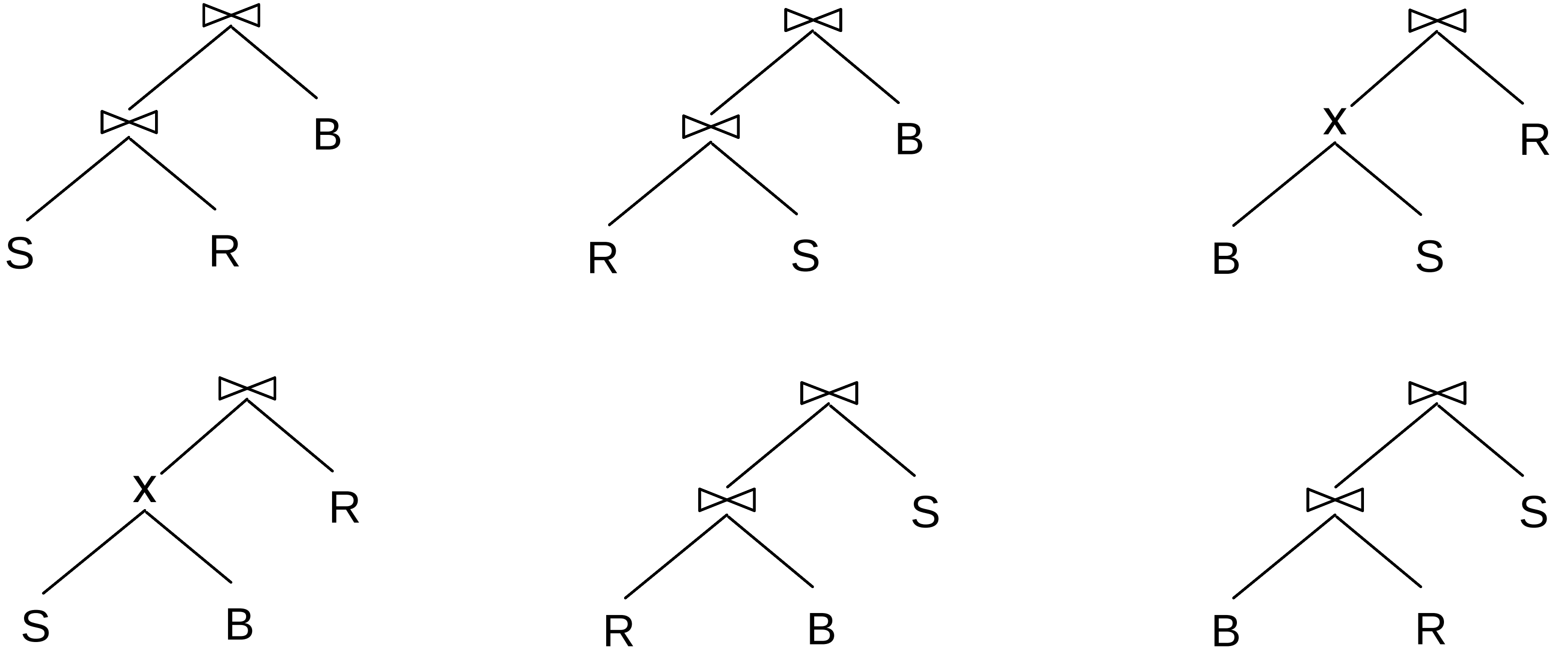
- In particular, the query optimizer enumerates:
  1. All possible left-deep orderings
  2. The different possible ways for evaluating each operator
  3. The different access paths for each relation

- Assume the following query ***Q***:

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

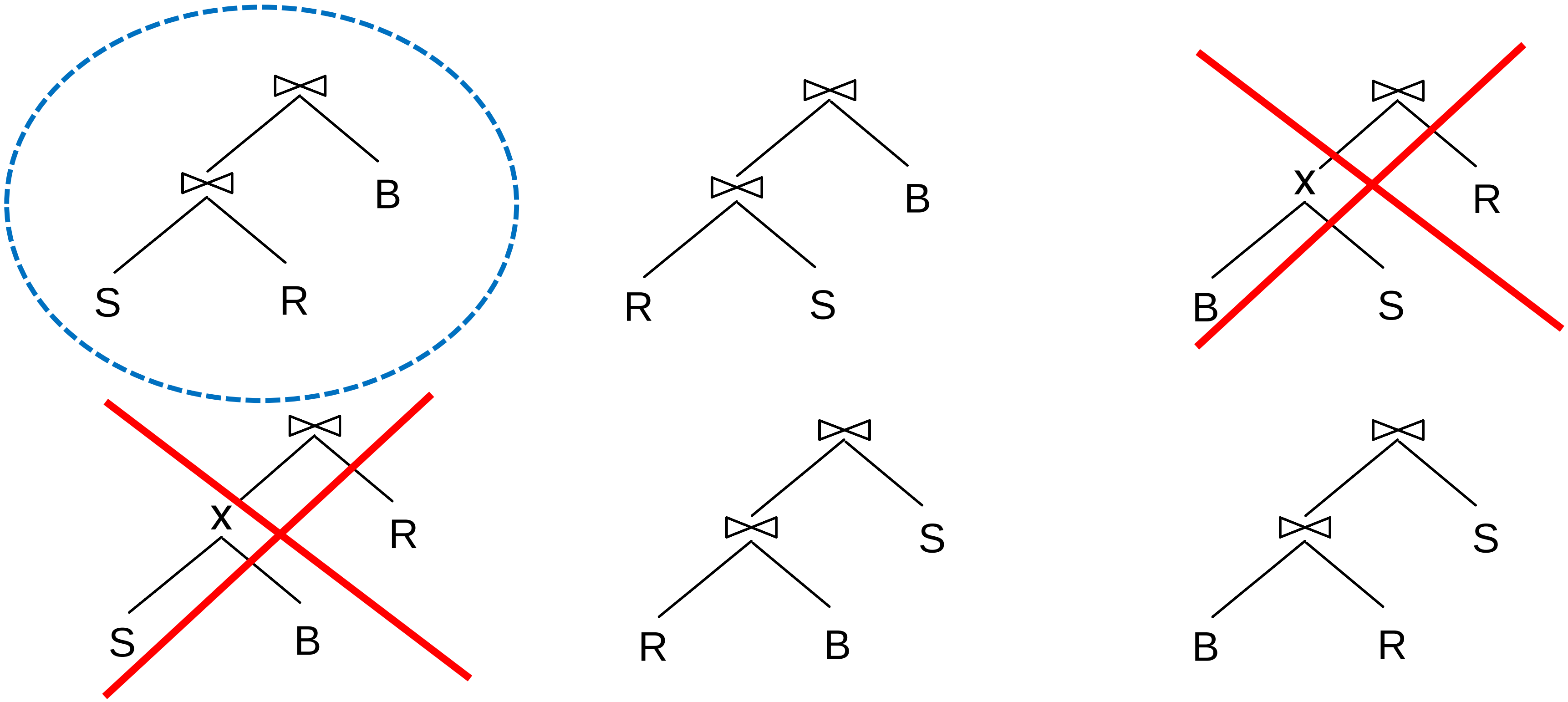
Enumerating Execution Plans (*Cont'd*)

- In particular, the query optimizer enumerates:
  1. All possible left-deep orderings



Enumerating Execution Plans (*Cont'd*)

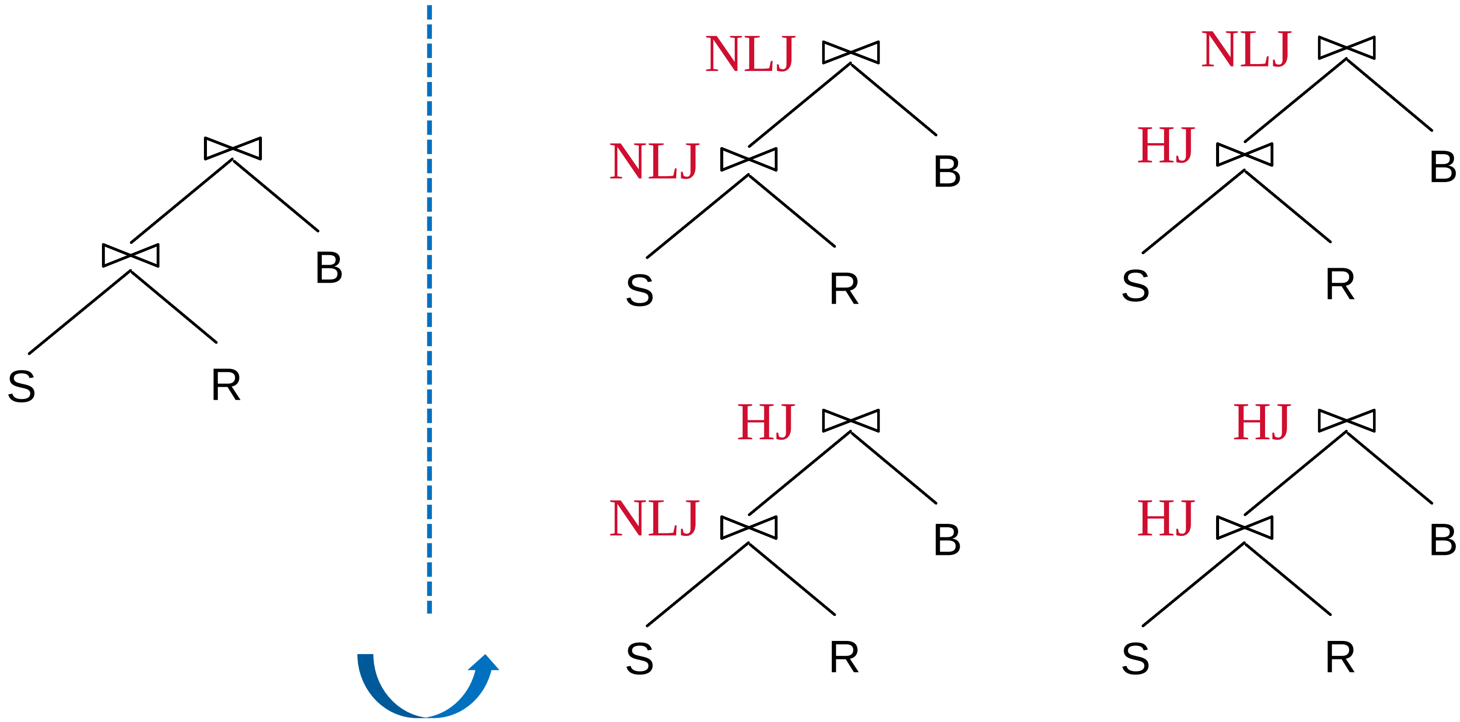
- In particular, the query optimizer enumerates:
  1. All possible left-deep orderings



Prune plans with cross-products immediately!

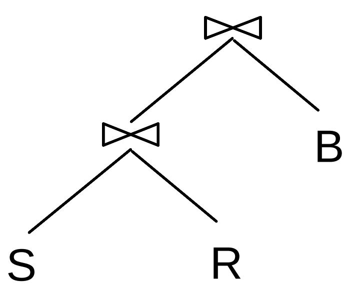
Enumerating Execution Plans (*Cont'd*)

- In particular, the query optimizer enumerates:
  1. All possible left-deep orderings
  2. The different possible ways for evaluating each operator

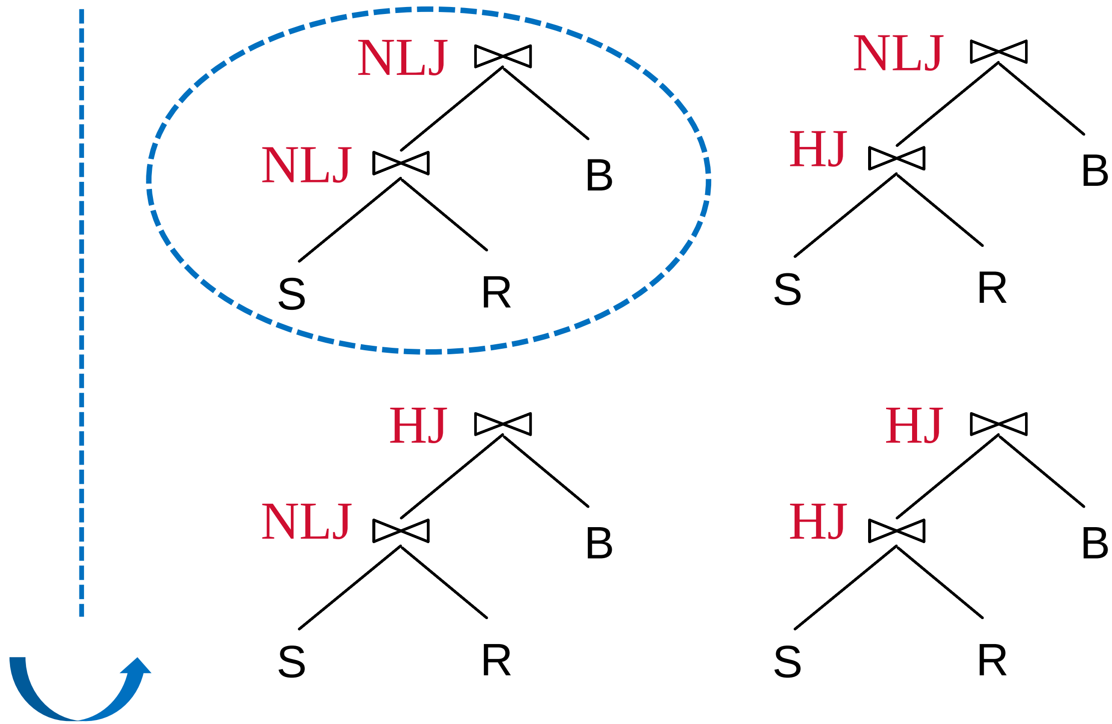


Enumerating Execution Plans (*Cont'd*)

- In particular, the query optimizer enumerates:
  1. All possible left-deep orderings
  2. The different possible ways for evaluating each operator

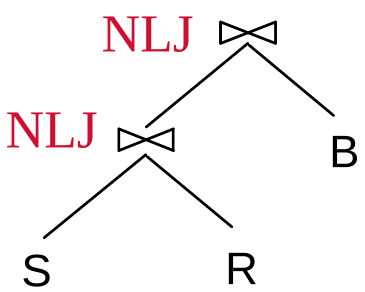


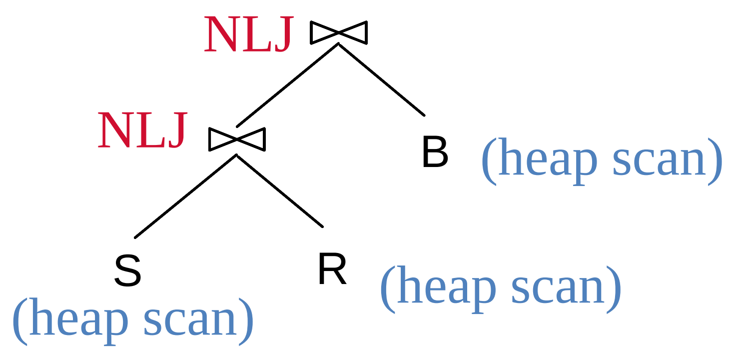
+ do same for
the 3 other plans



Enumerating Execution Plans (*Cont'd*)

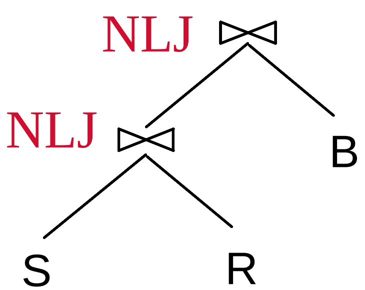
- In particular, the query optimizer enumerates:
  1. All possible left-deep orderings
  2. The different possible ways for evaluating each operator
  3. The different access paths for each relation



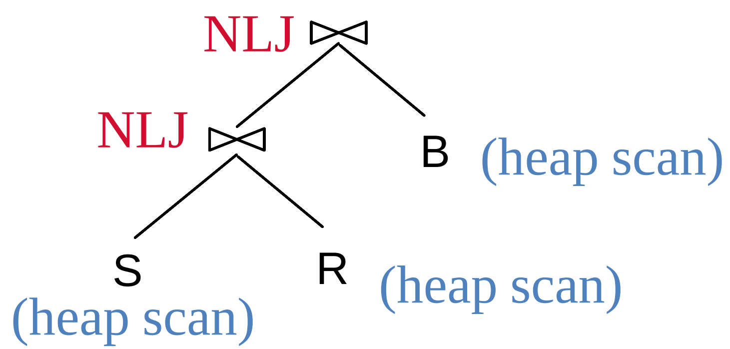


Enumerating Execution Plans (*Cont'd*)

- In particular, the query optimizer enumerates:
  1. All possible left-deep orderings
  2. The different possible ways for evaluating each operator
  3. The different access paths for each relation



+ do same for
the 3 other plans



Enumerating Execution Plans (*Cont'd*)

- In particular, the query optimizer enumerates:
  1. All possible left-deep orderings
  2. The different possible ways for evaluating each operator
  3. The different access paths for each relation

Subsequently, estimate the cost of each plan using *statistics* collected and stored at the system catalog!

Let us now study a *dynamic programming algorithm* to effectively enumerate and estimate cost plans

Towards a Dynamic Programming Algorithm

- There are two main cases to consider:
  - CASE I: Single-Relation Queries
  - CASE II: Multiple-Relation Queries

- CASE I: Single-Relation Queries
  - Only *selection*, *projection*, *grouping* and *aggregate* operations are involved (i.e., no *joins*)
  - Every available access path is considered and the one with the least estimated cost is selected
  - The different operations are carried out together
    - E.g., if an index is used for a selection, projection can be done for each retrieved tuple, and the resulting tuples can be *pipelined* into an aggregate operation (if any)

CASE I: Single-Relation Queries- An Example

- Consider the following SQL query ***Q***:

```
SELECT  S.rating, COUNT (*)
FROM  Sailors S
WHERE  S.rating > 5 AND S.age = 20
GROUP BY S.rating
```

- ***Q*** can be expressed in a relational algebra tree as follows:

$$\pi_{\textbf{rating, COUNT(*)}}$$

$$\text{GROUP BY}_{\textbf{rating}}$$

$$\pi_{\textbf{rating}}$$

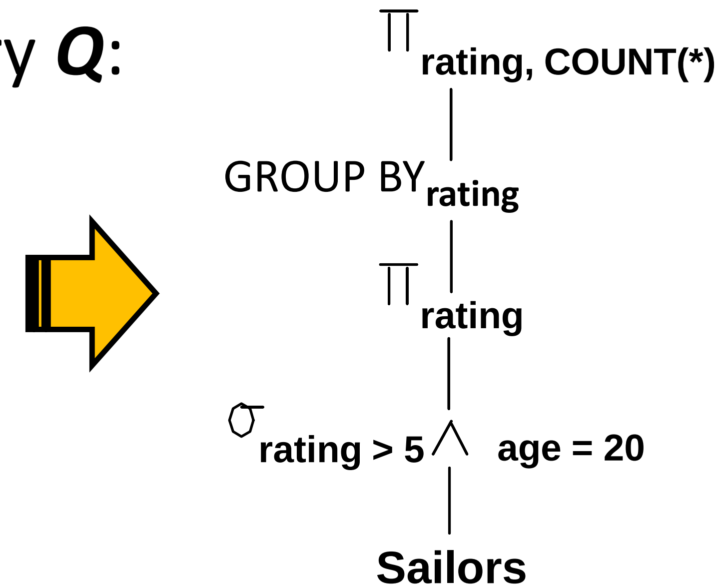
$$\sigma_{\textbf{rating > 5} \wedge \textbf{age = 20}}$$

Sailors

CASE I: Single-Relation Queries- An Example

- Consider the following SQL query ***Q***:

```
SELECT  S.rating, COUNT (*)
FROM  Sailors S
WHERE  S.rating > 5 AND S.age = 20
GROUP BY S.rating
```



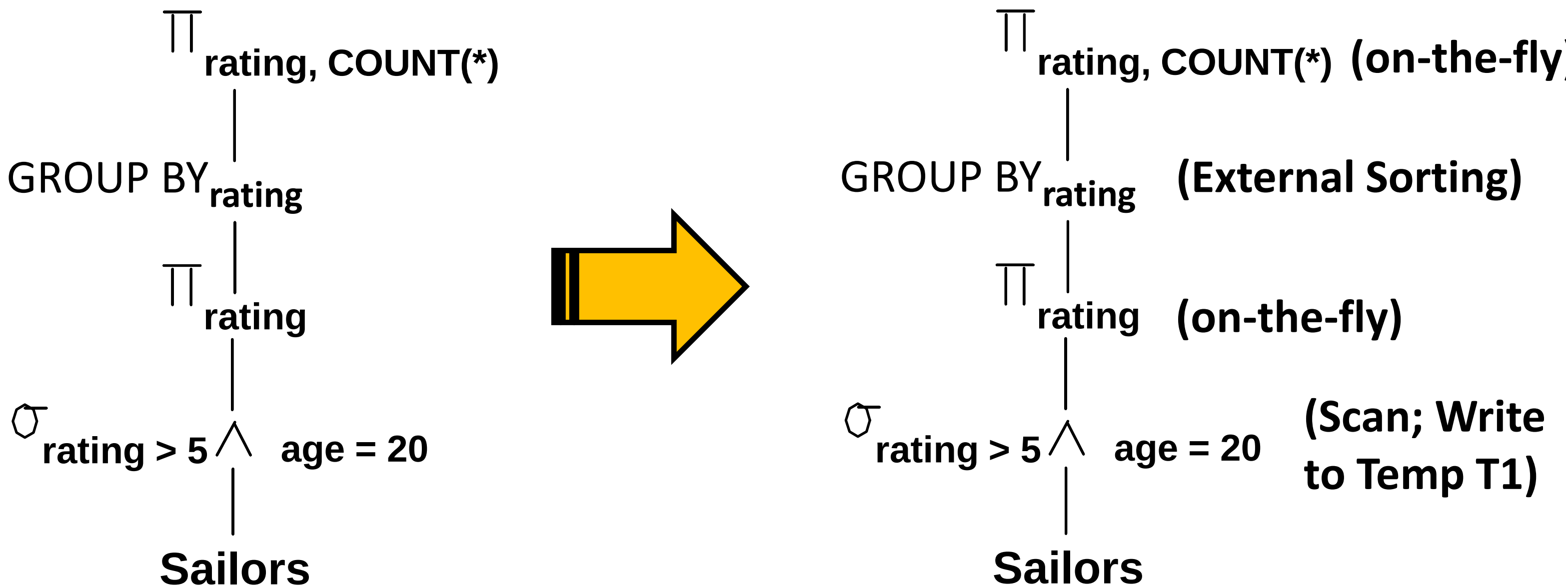
- How can ***Q*** be evaluated?
    - Apply CASE I:
        - Every available access path *for Sailors* is considered and the one with the least estimated cost is selected
        - The selection and projection operations are carried out together

CASE I: Single-Relation Queries- An Example

- Consider the following SQL query ***Q***:

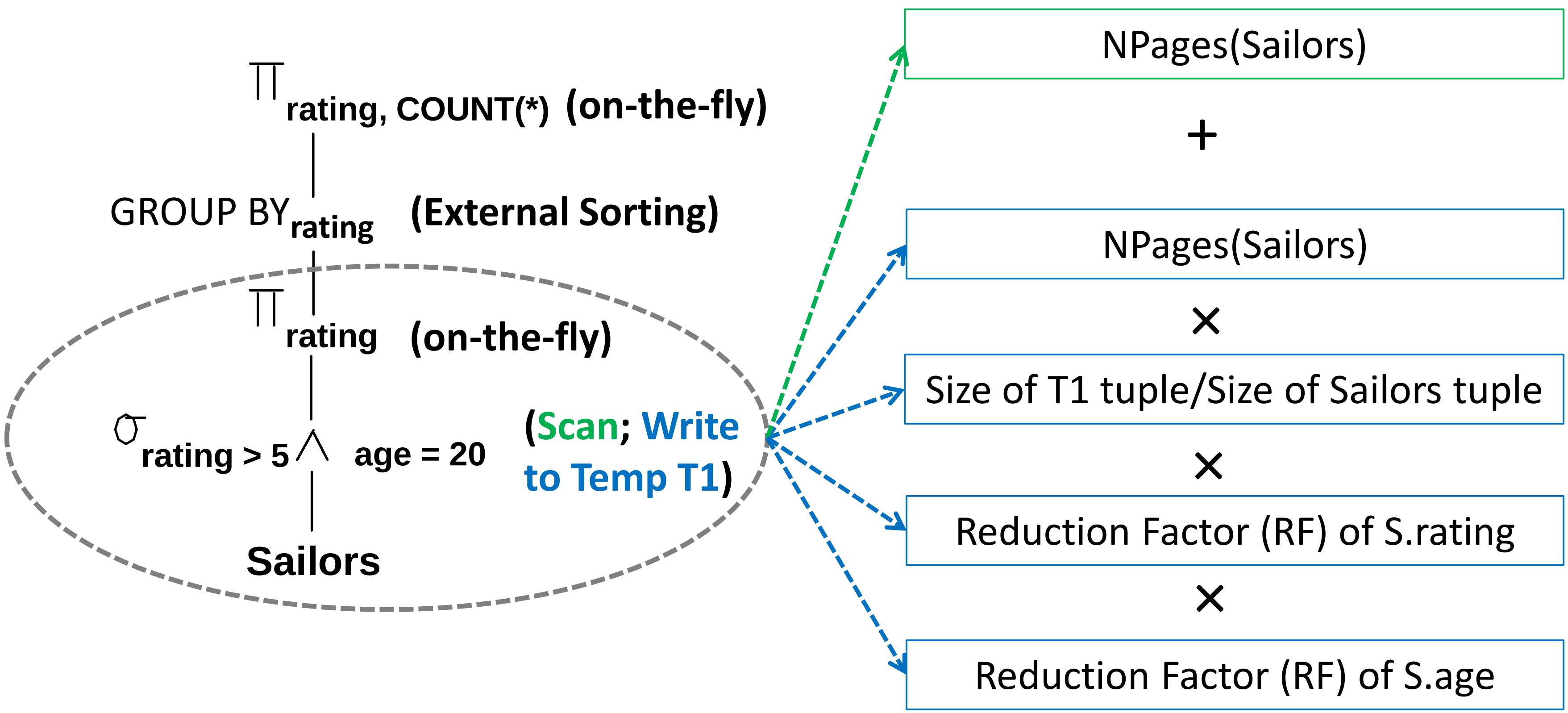
```
SELECT  S.rating, COUNT (*)
FROM  Sailors S
WHERE  S.rating > 5 AND S.age = 20
GROUP BY S.rating
```

- What would be the cost of we assume a <u>file scan</u> for sailors?



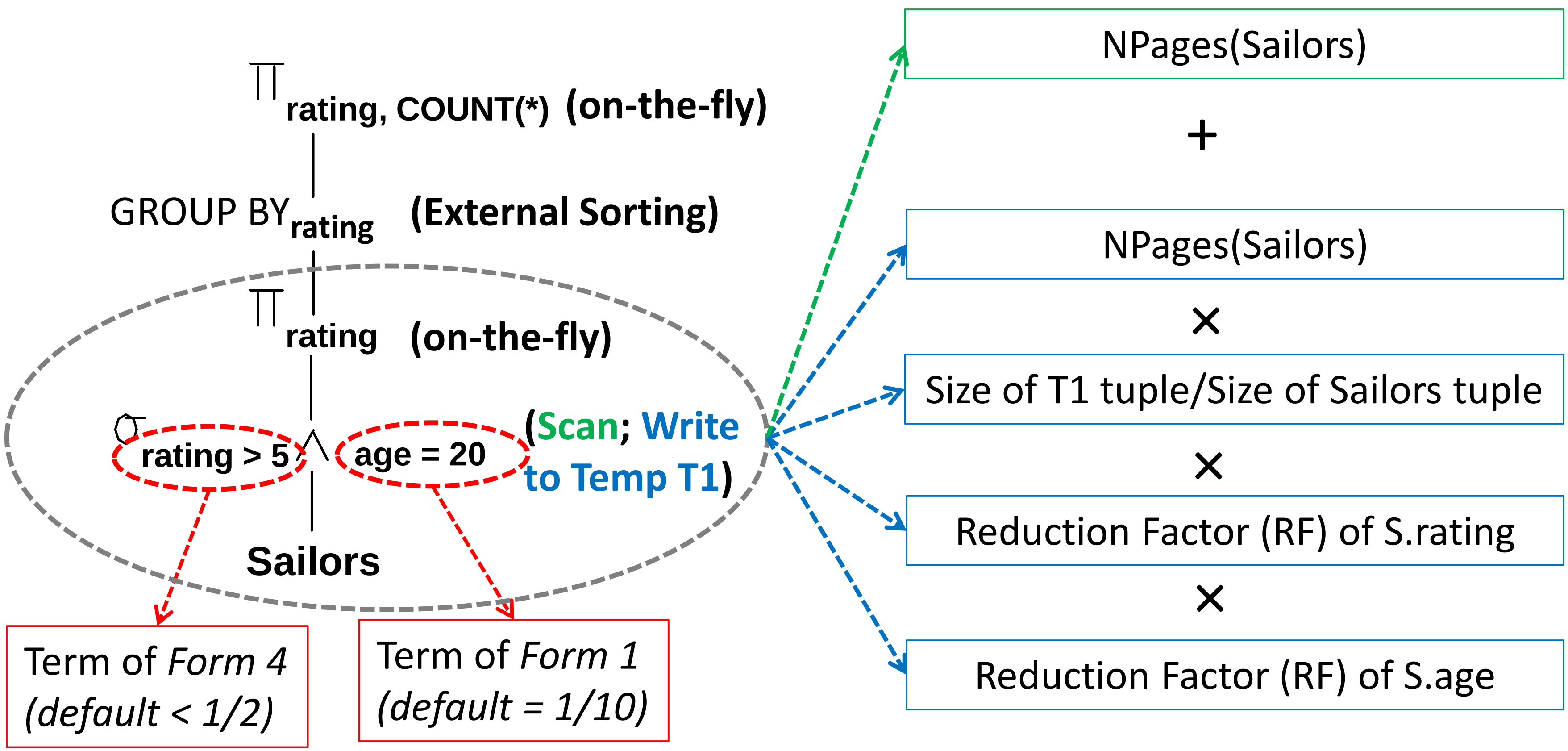
CASE I: Single-Relation Queries- An Example

- What would be the cost of we assume a file scan for sailors?



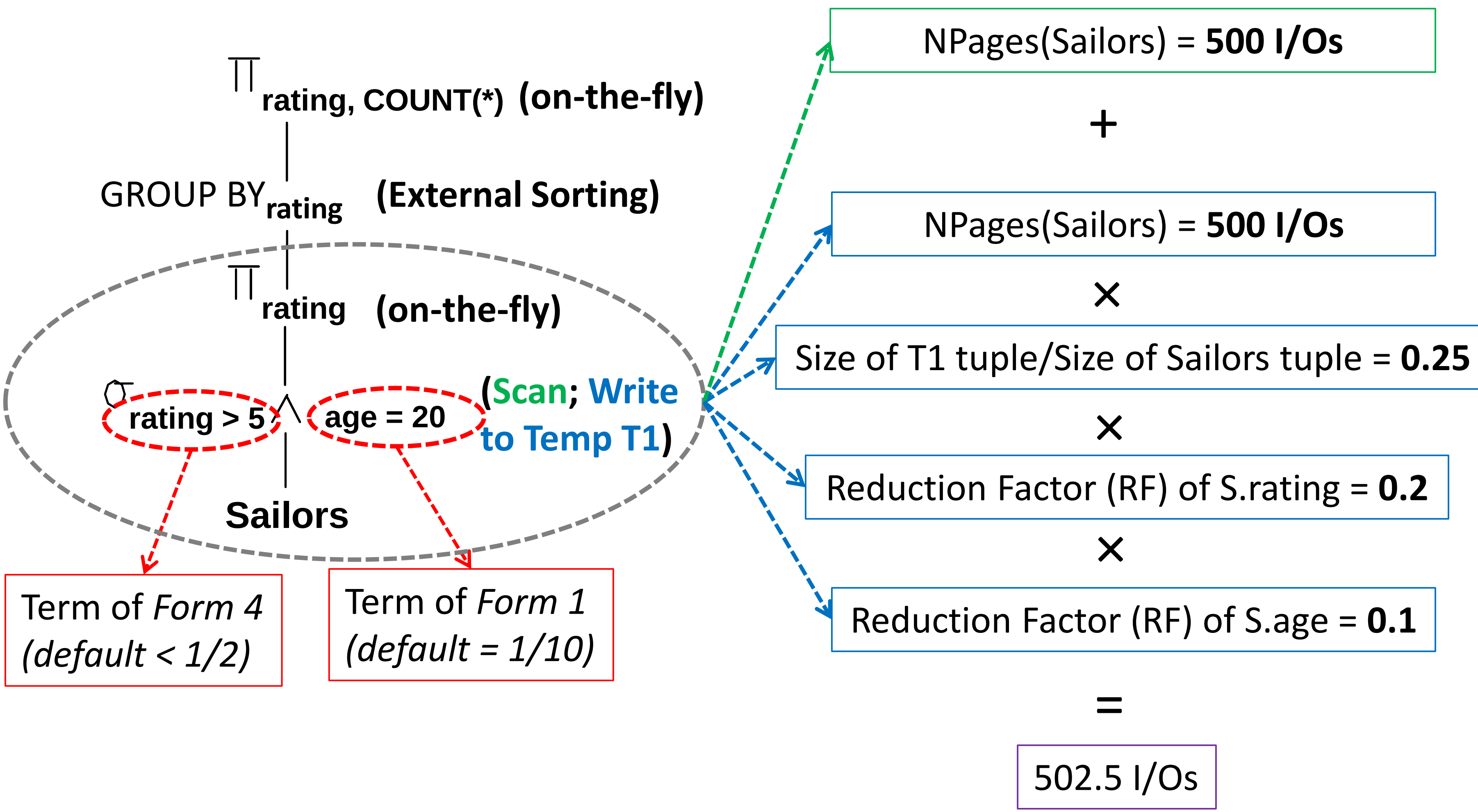
CASE I: Single-Relation Queries- An Example

- What would be the cost of we assume a file scan for sailors?



CASE I: Single-Relation Queries- An Example

- What would be the cost of we assume a <u>file scan</u> for sailors?



CASE I: Single-Relation Queries- An Example

- What would be the cost of we assume a <u>file scan</u> for sailors?

$\pi_{\text{rating, COUNT(*)}}$ **(on-the-fly)**

GROUP BY$_{\text{rating}}$ **(External Sorting)** $\dashrightarrow$ $3 \times \text{NPages(T1)} = 3 \times 2.5 = 7.5$ I/Os

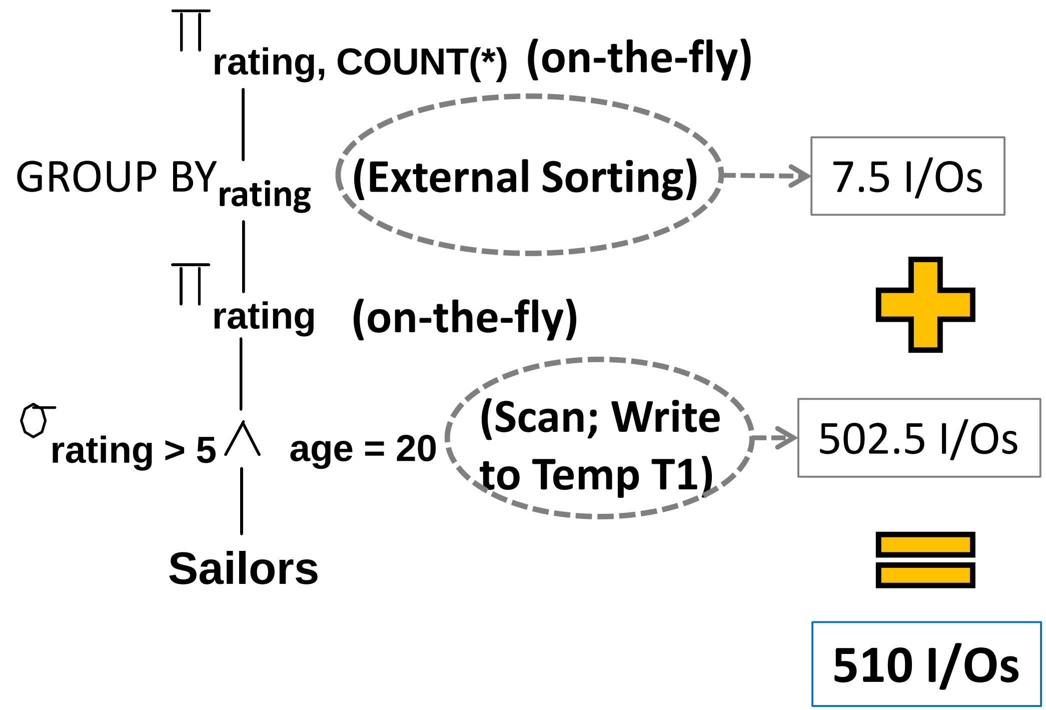
π_{rating} **(on-the-fly)**

$\sigma_{\text{rating} > 5 \wedge \text{age} = 20}$ **(Scan; Write to Temp T1)**

Sailors

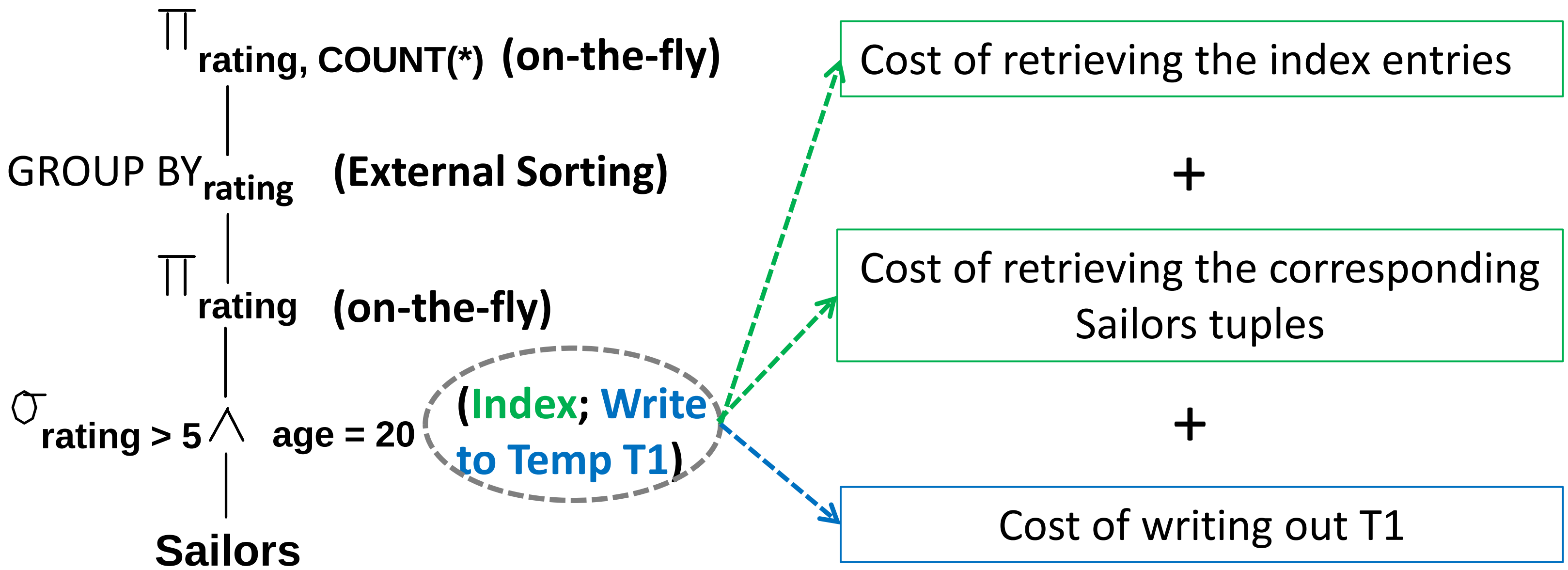
CASE I: Single-Relation Queries- An Example

- What would be the cost of we assume a <u>file scan</u> for sailors?



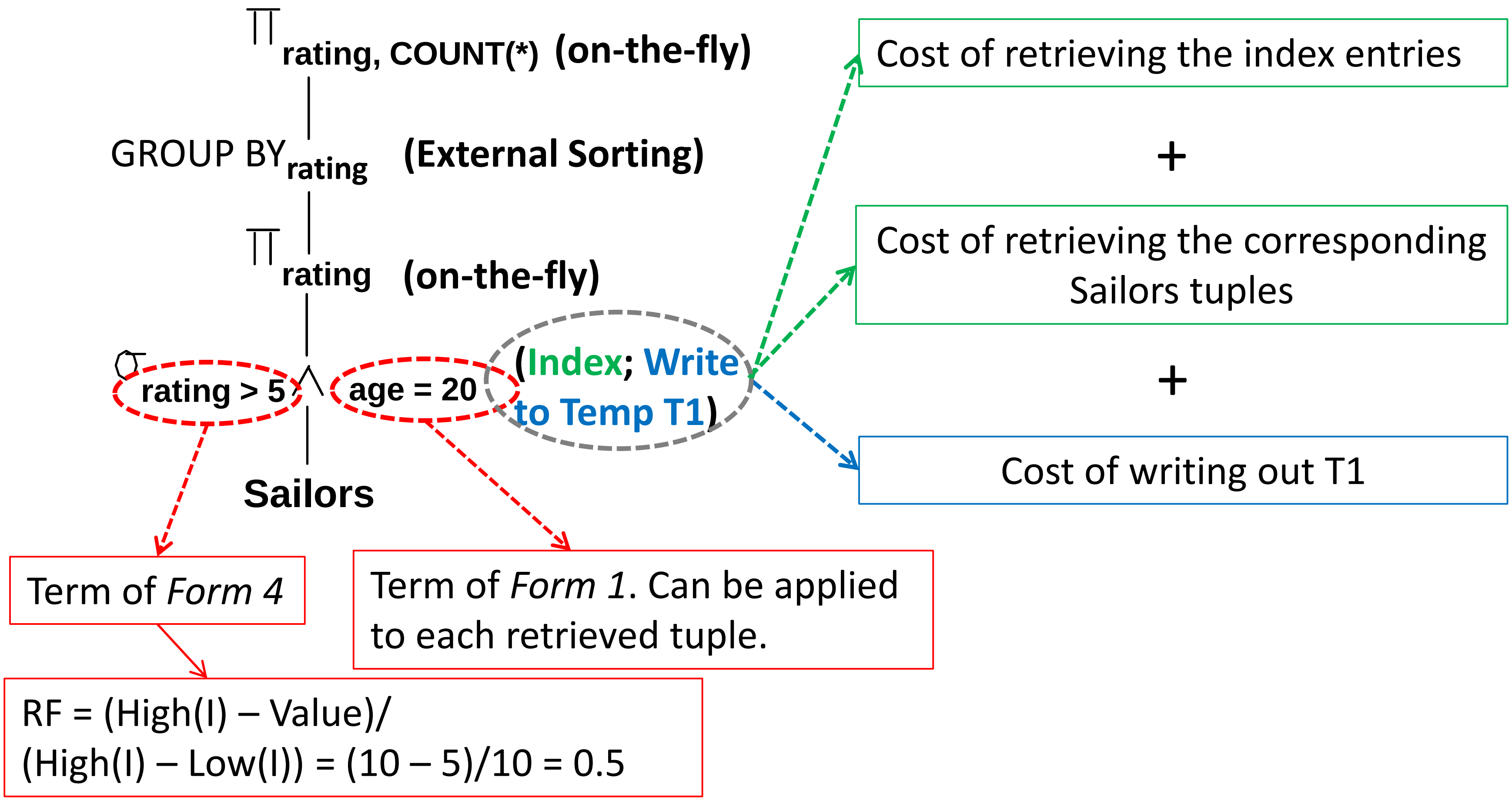
CASE I: Single-Relation Queries- An Example

- What would be the cost of we assume ***a clustered index on rating with A(1)***?



CASE I: Single-Relation Queries- An Example

- What would be the cost of we assume *a clustered index on rating with A(1)*?



CASE I: Single-Relation Queries- An Example

- What would be the cost of we assume *a clustered index on rating with A(1)*?

$\Pi_{\text{rating, COUNT(*)}}$ **(on-the-fly)**

GROUP BY$_{\text{rating}}$ **(External Sorting)**

Π_{rating} **(on-the-fly)**

σ **rating > 5** $\wedge$ **age = 20** **(Index; Write to Temp T1)**

Sailors

Cost of retrieving the index entries

+

Cost of retrieving the corresponding Sailors tuples

=

= 0.5 × 0.1 × NPages(I)
= 0.5 × 0.1 × 600
= 30 I/Os

Term of *Form 4*

RF = (High(I) – Value)/
(High(I) – Low(I)) = (10 – 5)/10 = 0.5

Term of *Form 1*. Can be applied to each retrieved tuple.

CASE I: Single-Relation Queries- An Example

- What would be the cost of we assume *a clustered index on rating with A(1)*?

π **rating, COUNT(*) (on-the-fly)**

GROUP BY**rating** **(External Sorting)**

π **rating** **(on-the-fly)**

σ **rating > 5** $\wedge$ **age = 20** **(Index; Write to Temp T1)**

Sailors

Cost of retrieving the index entries

+

Cost of retrieving the corresponding Sailors tuples

+

Cost of writing out T1

=

2 × 30 = 60 I/Os

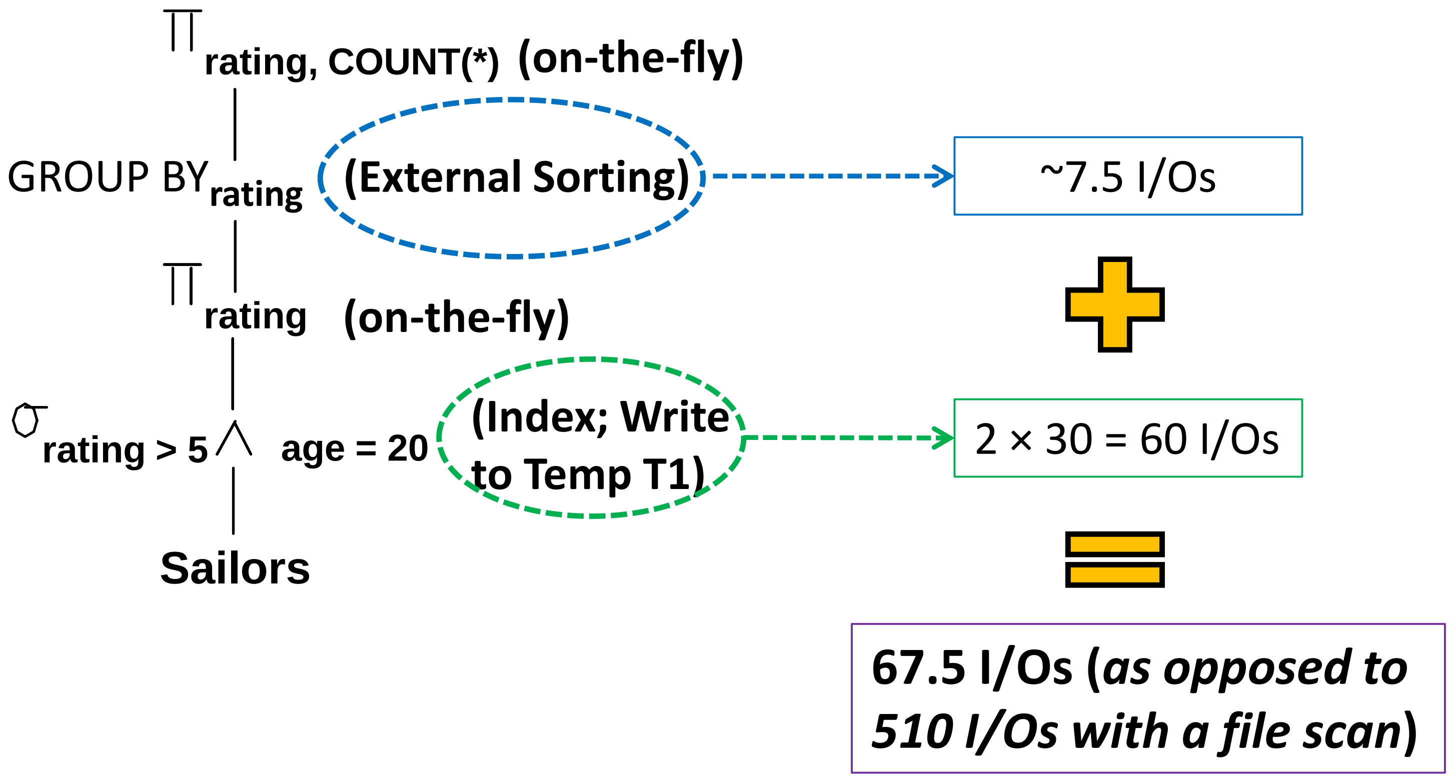
Term of *Form 4*

Term of *Form 1*. Can be applied to each retrieved tuple.

RF = (High(I) – Value)/
(High(I) – Low(I)) = (10 – 5)/10 = 0.5

CASE I: Single-Relation Queries- An Example

- What would be the cost of we assume *a clustered index on rating with A(1)*?



Towards a Dynamic Programming Algorithm

- There are two main cases to consider:
  - CASE I: Single-Relation Queries
  - CASE II: Multiple-Relation Queries

- CASE II: Multiple-Relation Queries
  - Only consider left-deep plans
  - Apply a dynamic programming algorithm

Enumeration of Left-Deep Plans Using Dynamic Programming

- Enumerate using ***N*** passes (if ***N*** relations joined):
  - **Pass 1:**
    - For each relation, enumerate all plans (all ***1***-relation plans)
    - Retain the cheapest plan per each relation
  - **Pass 2:**
    - Enumerate all ***2***-relation plans by considering each ***1***-relation plan retained in Pass 1 (as *outer*) and successively every other relation (as *inner*)
    - Retain the cheapest plan per each ***1***-relation plan
  - **Pass N:**
    - Enumerate all ***N***-relation plans by considering each (***N-1***)-relation plan retained in Pass N-1 (as outer) and successively every other relation (as inner)
    - Retain the cheapest plan per each (***N-1***)-relation plan
  - **Pick the cheapest N-relation plan**

Enumeration of Left-Deep Plans Using Dynamic Programming (*Cont'd*)

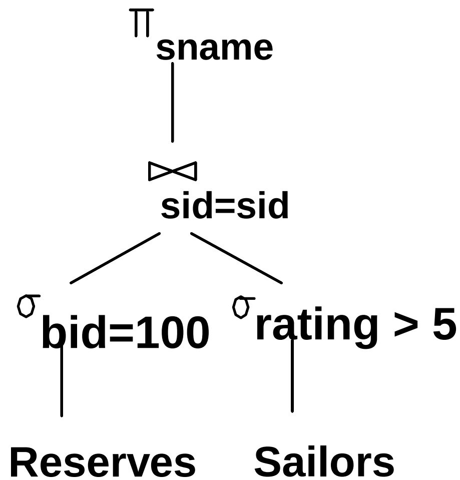
- An ***N-1*** way plan is not combined with an additional relation unless:
  - There is a join condition between them
  - All predicates in the WHERE clause have been used up

- ORDER BY, GROUP BY, and aggregate functions are handled as a final step, using either an `interestingly ordered' plan or an additional sorting operator

- Despite of pruning the plan space, this approach is *still exponential* in the # of tables

CASE II: Multiple-Relation Queries-An Example

- Consider the following relational algebra tree:

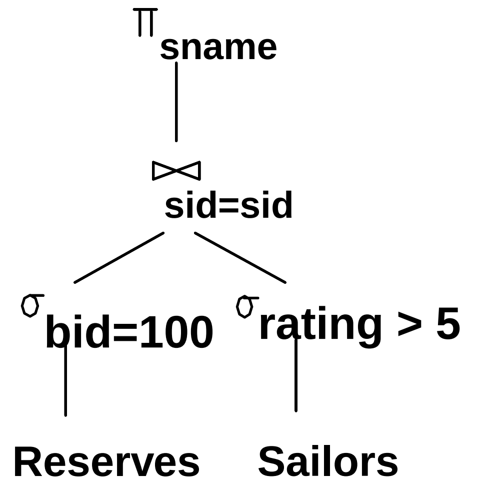


- Assume the following:

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

CASE II: Multiple-Relation Queries-An Example

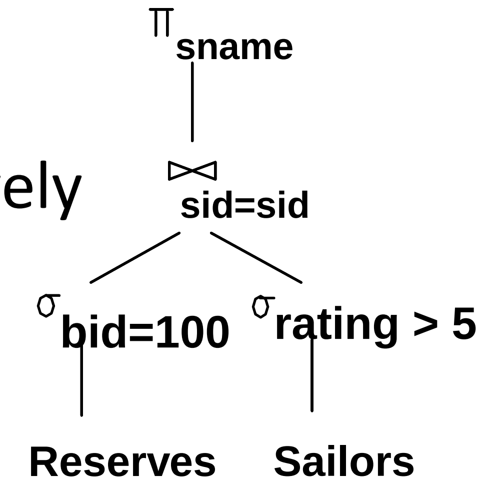
- **Pass 1:**
  - Sailors:
    - B+ tree matches rating>5, and is *probably* the cheapest
    - If this selection is expected to retrieve a lot of tuples, and the index is un-clustered, file scan might be cheaper!
  - Reserves: B+ tree on *bid* matches *bid=500*; *probably* the cheapest



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

CASE II: Multiple-Relation Queries- An Example

- **Pass 2:**
  - Consider each plan retained from **Pass 1** as the outer, and join it effectively with every other relation
  - E.g., Reserves as outer:
    - Hash index can be used to get Sailors tuples that satisfy sid = outer tuple's sid value



- <u>Sailors:</u>
  - B+ tree on *rating*
  - Hash on *sid*
- <u>Reserves:</u>
  - B+ tree on *bid*

Outline

- A Brief Primer on Query Optimization
- Query Evaluation Plans
- Relational Algebra Equivalences
- Estimating Plan Costs
- Enumerating Plans
- Nested Sub-Queries ✓

Nested Sub-queries

- Consider the following nested query ***Q1***:

```
SELECT  S.sname
FROM  Sailors S
WHERE S.rating =
  (SELECT  MAX (S2.rating)
   FROM  Sailors S2)
```

- The nested sub-query can be evaluated *just once*, yielding a <u>single</u> value ***V***

- ***V*** can be incorporated into the top-level query as if it had been part of the original statement of ***Q1***

Nested Sub-queries

- Now, consider the following nested query ***Q2***:

```
SELECT  S.sname
FROM  Sailors S
WHERE EXISTS
  (SELECT  R.sid
   FROM  Reserves R
   WHERE  R.bid=103 )
```

- The nested sub-query can still be evaluated *just once*, but it will yield a <u>collection</u> of *sids*

- Every *sid* value in Sailors must be checked whether it exists in the collection of sids returned by the nested sub-query
  - This entails a join, and the full range of join methods can be explored!

Nested Sub-queries

- Now, consider another nested query ***Q3***:

```
SELECT  S.sname
FROM  Sailors S
WHERE EXISTS
   (SELECT  *
    FROM  Reserves R
    WHERE  R.bid=103
     AND  R.sid=S.sid)
```

- Q3 is *correlated*; hence, we “cannot” evaluate the sub-query just once!

- In this case, the typical evaluation strategy is to evaluate the nested sub-query *for each tuple* of Sailors

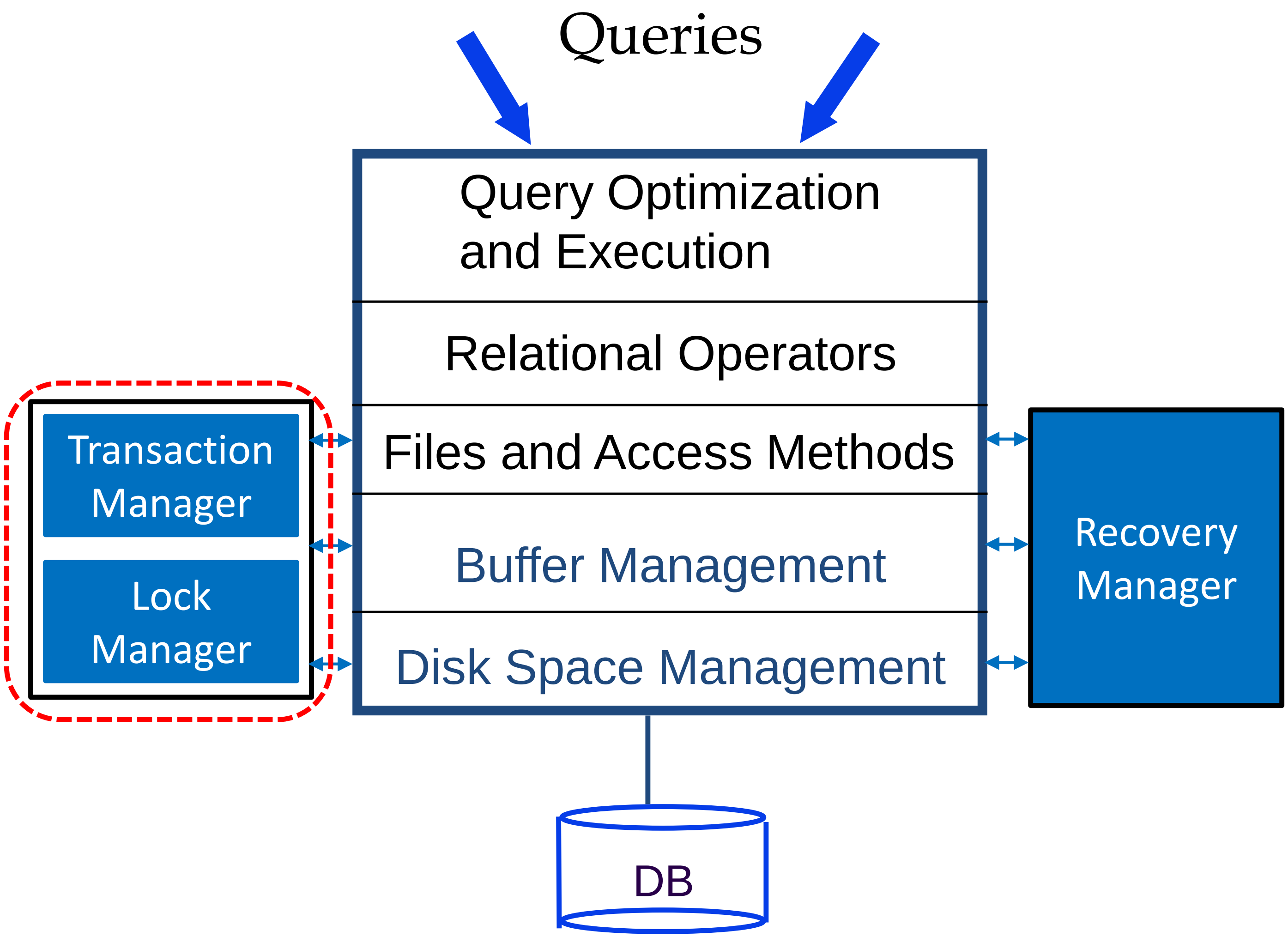
Summary

- Query optimization is a crucial task in relational DBMSs

- We must understand query 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:
  1. Consider a set of alternative plans (e.g., using dynamic programming)
     - Apply selections/projections as early as possible
     - Prune search space; typically, keep left-deep plans only
  2. Estimate the cost of each plan that is considered
     - Must estimate *size of result* and *cost of each tree node*
     - *Key issues*: Statistics, indexes, operator implementations

Next Class



Queries
Query Optimization and Execution
Relational Operators
Files and Access Methods
Buffer Management
Disk Space Management
Transaction Manager
Lock Manager
Recovery Manager
DB