

CMPT 354: Database System I

Lecture 7. Basics of Query Optimization

Why should you care?



<https://databricks.com/glossary/catalyst-optimizer>

At the core of Spark SQL is the Catalyst optimizer, which leverages advanced programming language features (e.g. Scala's pattern matching and quasi quotes) in a novel way to build an extensible query optimizer.



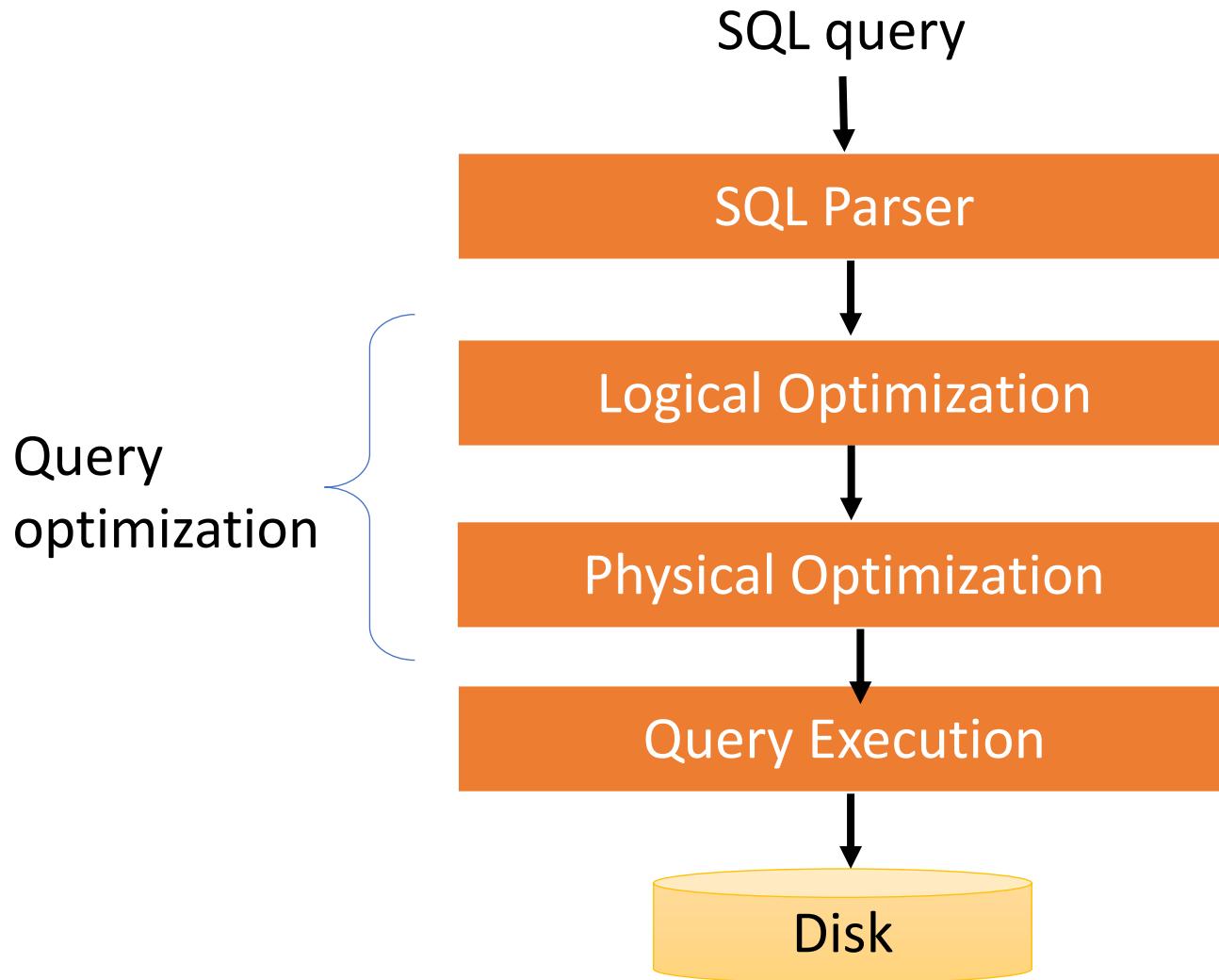
Goetz Graefe

2017 SIGMOD Edgar F. Codd Innovations Award

Professor Goetz Graefe is the recipient of the 2017 ACM SIGMOD Edgar F. Codd Innovations Award for his foundational contributions to the architecture and implementation of database query optimizers.

<https://sigmod.org/sigmod-awards/people/goetz-graefe-2017-sigmod-edgar-f-codd-innovations-award/>

Query Processing Steps



IBM System R Optimizer

- First implementation of a query optimizer
- Make people believe that the DBMS can beat a human developer
- A lot of the concepts are still used today



Access path selection in a relational database management system

<https://dl.acm.org/citation.cfm?id=582099>

by PG Selinger - 1979 - Cited by 2585 - Related articles

In a high level query and data manipulation language such as SQL, requests are stated non-procedurally, without reference to **access paths**. This paper ...

[Abstract](#) · [Authors](#) · [References](#) · [Cited By](#)

How to build a query optimization?

1. Plan Space

- Figure out all possible query plans

Too large, must
be pruned

2. Cost Estimation

- Estimate the cost of each plan

CPU + I/O

3. Search Algorithm

- Find the best plan

don't go for best plan, go
for least worst plan

Outline

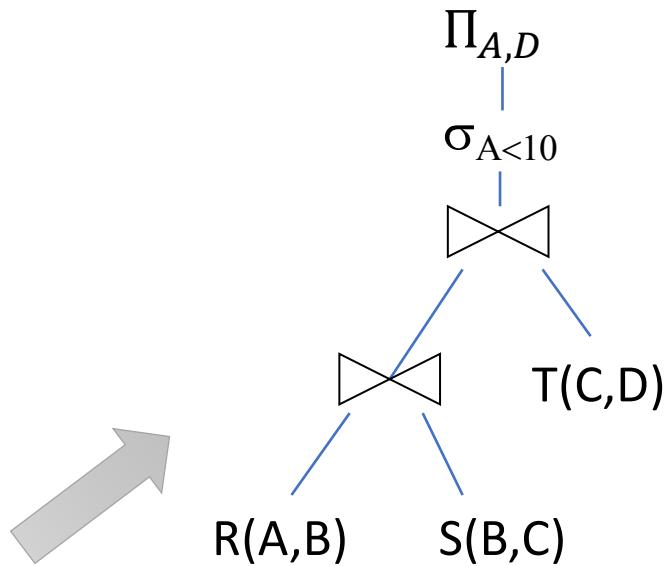
- **Recap of Logical Optimization**
 - Selection Pushdown
 - Projection Pushdown
- **Physical Optimization**
 - Join Algorithms
 - Selectivity Estimation

Translating to RA

R(A,B) S(B,C) T(C,D)

```
SELECT R.A, S.D  
FROM R, S, T  
WHERE R.B = S.B  
AND S.C = T.C  
AND R.A < 10;
```

$\Pi_{A,D}(\sigma_{A<10}(T \bowtie (R \bowtie S)))$

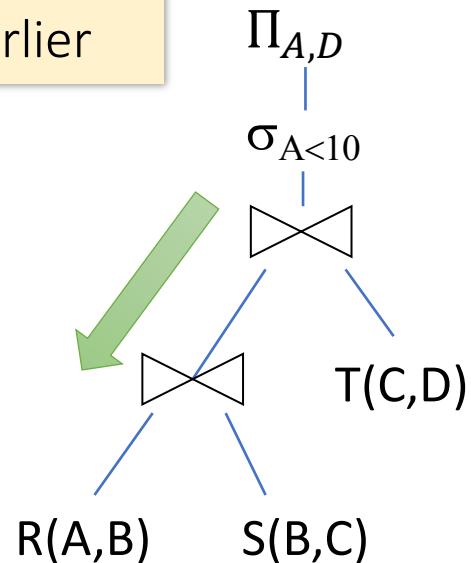


Optimizing RA Plan

R(A,B) S(B,C) T(C,D)

```
SELECT R.A, S.D  
FROM R, S, T  
WHERE R.B = S.B  
AND S.C = T.C  
AND R.A < 10;
```

Push down
selection on A so
it occurs earlier

$$\Pi_{A,D}(\sigma_{A<10}(T \bowtie (R \bowtie S)))$$


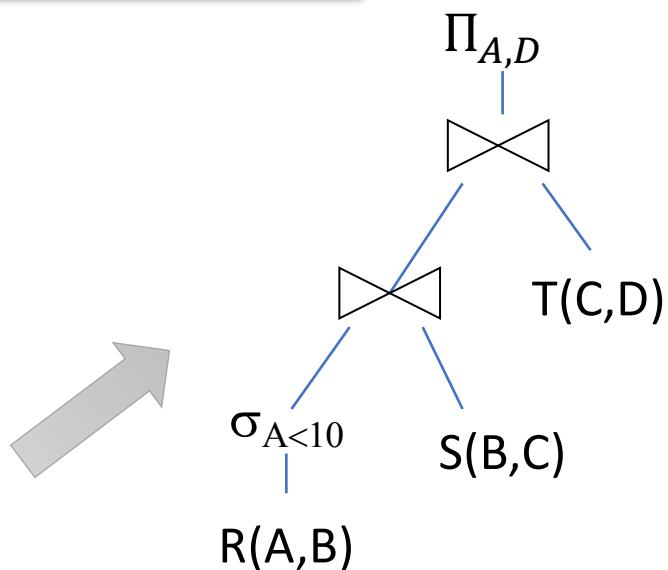
Optimizing RA Plan

R(A,B) S(B,C) T(C,D)

```
SELECT R.A, S.D  
FROM R, S, T  
WHERE R.B = S.B  
AND S.C = T.C  
AND R.A < 10;
```

Push down
selection on A so
it occurs earlier

$\Pi_{A,D}(T \bowtie (\sigma_{A<10}(R) \bowtie S))$



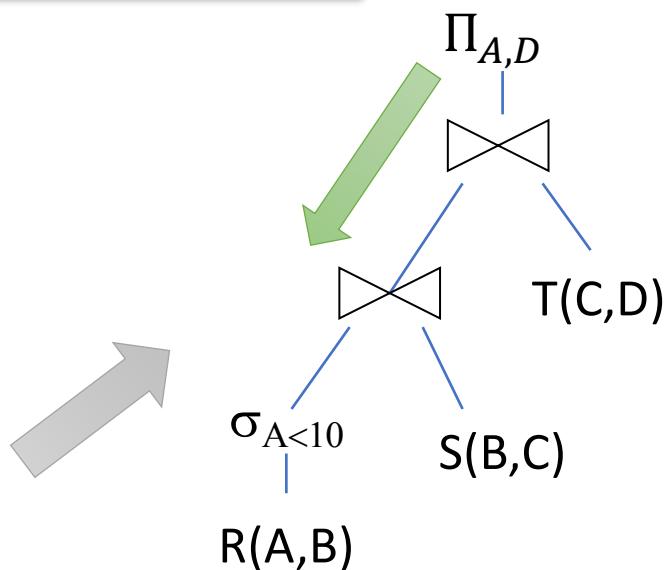
Optimizing RA Plan

R(A,B) S(B,C) T(C,D)

```
SELECT R.A, S.D  
FROM R, S, T  
WHERE R.B = S.B  
AND S.C = T.C  
AND R.A < 10;
```

Push down
projection so it
occurs earlier

$$\Pi_{A,D}(T \bowtie (\sigma_{A<10}(R) \bowtie S))$$



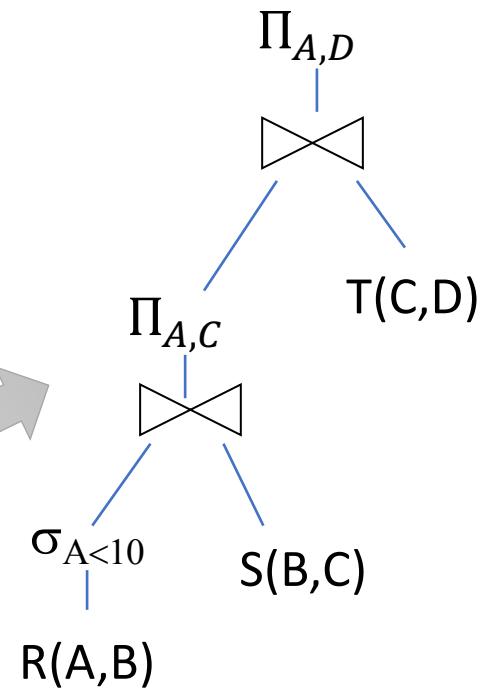
Optimizing RA Plan

R(A,B) S(B,C) T(C,D)

We eliminate B earlier!

```
SELECT R.A, S.D  
FROM R, S, T  
WHERE R.B = S.B  
AND S.C = T.C  
AND R.A < 10;
```

$$\Pi_{A,D} \left(T \bowtie \Pi_{A,C} (\sigma_{A<10}(R) \bowtie S) \right)$$



Outline

- **Recap of Logical Optimization**
 - Selection Pushdown
 - Projection Pushdown
- **Physical Optimization**
 - Join Algorithms
 - Histogram

Join Algorithms

- Nested loop Join
- Hash Join
- Sort-merge join

Student

sname	uID
Mike	0
Joe	1
Alice	0
Marry	1
Bob	0
Tim	2

University

uID	uname
0	SFU
1	UBC
2	UT

Student \bowtie University

Dive into Nested Loop Joins

Notes

- Cost = I/O + CPU + Network

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Page 1

- “IO aware” algorithms
 - We will focus on I/O

30
40	...			

Page 2

- Given a relation R, let:
 - $T(R) = \# \text{ of tuples in } R$
 - $P(R) = \# \text{ of pages in } R$

50				
60				

Page 3

70				
80				

Page 4

Nested Loop Join (NLJ)

Compute $R \bowtie S$ on A :

```
for r in R:  
    for s in S:  
        if r[A] == s[A]:  
            yield (r,s)
```

Nested Loop Join (NLJ)

Compute $R \bowtie S$ on A :

```
for r in R:  
    for s in S:  
        if r[A] == s[A]:  
            yield (r,s)
```

Cost:

$P(R)$

1. Loop over the tuples in R

Note that our IO cost is based on the number of *pages* loaded, not the number of tuples!

Nested Loop Join (NLJ)

Compute $R \bowtie S$ on A :

```
for r in R:  
    for s in S:  
        if r[A] == s[A]:  
            yield (r,s)
```

Cost:

$$P(R) + T(R)*P(S)$$

1. Loop over the tuples in R
2. For every tuple in R , loop over all the tuples in S

Have to read *all of S* from disk for *every tuple in R!*

Nested Loop Join (NLJ)

Compute $R \bowtie S$ on A :

```
for r in R:  
    for s in S:  
        if r[A] == s[A]:  
            yield (r,s)
```

Cost:

$$P(R) + T(R)*P(S)$$

1. Loop over the tuples in R
2. For every tuple in R , loop over all the tuples in S
- 3. Check against join conditions**

Note that NLJ can handle things other than equality constraints... just check in the *if* statement!

Nested Loop Join (NLJ)

Compute $R \bowtie S$ on A :

```
for r in R:  
    for s in S:  
        if r[A] == s[A]:  
            yield (r,s)
```

Cost:

$$P(R) + T(R)*P(S) + OUT$$

1. Loop over the tuples in R
2. For every tuple in R , loop over all the tuples in S
3. Check against join conditions
4. Write out (to page, then when page full, to disk)

Is this the same as a cross product?

Nested Loop Join (NLJ)

Compute $R \bowtie S$ on A :

```
for r in R:  
    for s in S:  
        if r[A] == s[A]:  
            yield (r,s)
```

Cost:

$$P(R) + T(R)*P(S) + OUT$$

What if R ("outer") and S ("inner") switched?



$$P(S) + T(S)*P(R) + OUT$$

Outer vs. inner selection could make a huge difference-
DBMS needs to know which relation is smaller!

IO-Aware Approach

Block Nested Loop Join (BNLJ)

Given $B+1$ pages of memory

Cost:

$P(R)$

Compute $R \bowtie S$ on A :

```
for each  $B-1$  pages pr of R:  
    for page ps of S:  
        for each tuple r in pr:  
            for each tuple s in ps:  
                if  $r[A] == s[A]$ :  
                    yield (r,s)
```

1. Load in $B-1$ pages of R at a time (leaving 1 page each free for S & output)

Note: There could be some speedup here due to the fact that we're reading in multiple pages sequentially however we'll ignore this here!

Block Nested Loop Join (BNLJ)

Given $B+1$ pages of memory

Cost:

$$P(R) + \frac{P(R)}{B-1} P(S)$$

```
Compute R  $\bowtie$  S on A:  
for each B-1 pages pr of R:  
    for page ps of S:  
        for each tuple r in pr:  
            for each tuple s in ps:  
                if r[A] == s[A]:  
                    yield (r,s)
```

1. Load in B-1 pages of R at a time (leaving 1 page each free for S & output)
2. For each (B-1)-page segment of R, load each page of S

Note: Faster to iterate over the *smaller* relation first!

Block Nested Loop Join (BNLJ)

```
Compute R  $\bowtie$  S on A:  
for each B-1 pages pr of R:  
    for page ps of S:  
        for each tuple r in pr:  
            for each tuple s in ps:  
                if r[A] == s[A]:  
                    yield (r,s)
```

Given $B+1$ pages of memory

Cost:

$$P(R) + \frac{P(R)}{B - 1} P(S)$$

1. Load in B-1 pages of R at a time (leaving 1 page each free for S & output)
2. For each (B-1)-page segment of R, load each page of S
3. Check against the join conditions

BNLJ can also handle non-equality constraints

Block Nested Loop Join (BNLJ)

Given $B+1$ pages of memory

Cost:

$$P(R) + \frac{P(R)}{B-1} P(S) + \text{OUT}$$

```
Compute R  $\bowtie$  S on A:  
for each B-1 pages pr of R:  
    for page ps of S:  
        for each tuple r in pr:  
            for each tuple s in ps:  
                if r[A] == s[A]:  
                    yield (r,s)
```

1. Load in B-1 pages of R at a time (leaving 1 page each free for S & output)
2. For each (B-1)-page segment of R, load each page of S
3. Check against the join conditions
4. Write out

BNLJ vs. NLJ: Benefits of IO Aware

- NLJ
 - Read all of S from disk for *every page of R*
- BNLJ
 - Read all of S from disk for *every (B-1)-page segment of R*

NLJ

$$P(R) + T(R)*P(S) + OUT$$



BNLJ

$$P(R) + \frac{P(R)}{B-1} P(S) + OUT$$

BNLJ is faster by roughly $\frac{(B-1)T(R)}{P(R)}$!

BNLJ vs. NLJ: Benefits of IO Aware

- Example:
 - R: 500 pages
 - S: 1000 pages
 - 100 tuples / page
 - We have 12 pages of memory ($B = 11$)
- NLJ: Cost = $500 + 50,000 * 1000 = 50 \text{ Million IOs}$
- BNLJ: Cost = $500 + \frac{500 * 1000}{10} = 50 \text{ Thousand IOs}$

Ignoring OUT here...

A very real difference from a small
change in the algorithm!

Outline

- Recap of Logical Optimization
 - Selection Pushdown
 - Projection Pushdown
- Physical Optimization
 - Join Algorithms
 - Histogram

Motivation

- Imagine you build an index on name, and then run the following queries

```
SELECT sID  
FROM Student  
WHERE name = "Mike"
```

Will query optimizer use the index?
Yes!

- Imagine you build an index on age, and then run the following queries

```
SELECT sID  
FROM Student  
WHERE 10 < age < 15
```

Will query optimizer use the index?
It depends.

How does query optimizer figure these out?

Why Selectivity Estimation?

2014



IS QUERY OPTIMIZATION A "SOLVED" PROBLEM?

≡ Databases

Guy Lohman, IBM DB2 (40 years' experience)

"The root of all evil, the **Achilles Heel** of query optimization, is the estimation of the size of intermediate results, known as **cardinalities**."

2018 - 2021

Multiple research groups consistently reported that learned cardinality estimators show very **impressive** results



Massachusetts
Institute of
Technology

Berkeley
UNIVERSITY OF CALIFORNIA



Microsoft



Technical
University
of Munich

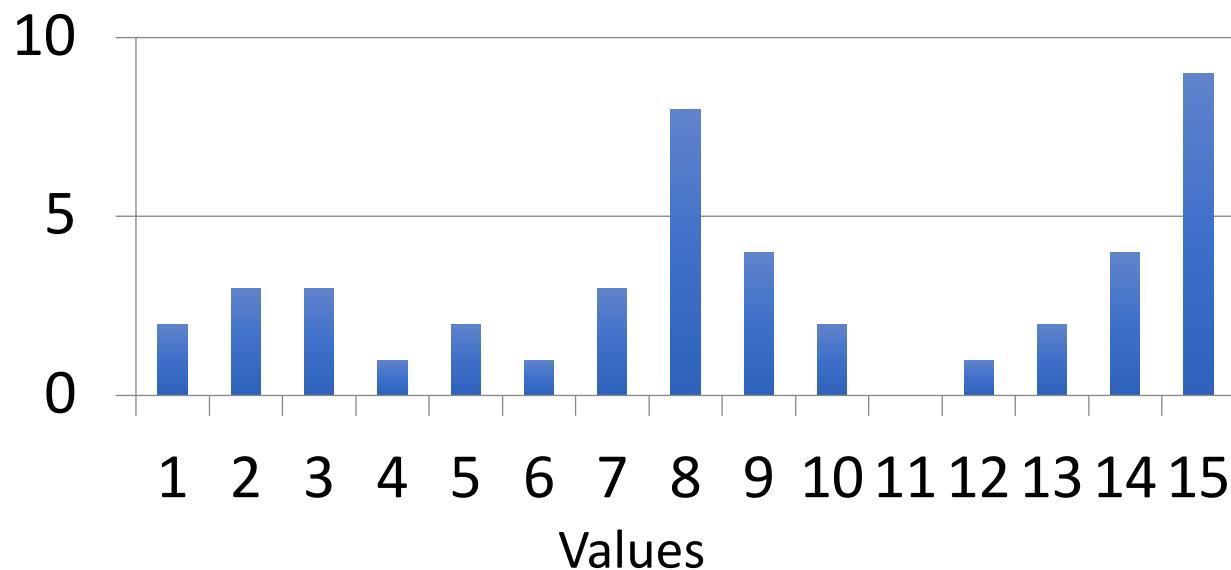


Histograms

- A histogram is a set of value ranges (“buckets”) and the frequencies of values in those buckets occurring
- How to choose the buckets?
 - Equiwidth & Equidepth
- Turns out high-frequency values are **very** important

Example

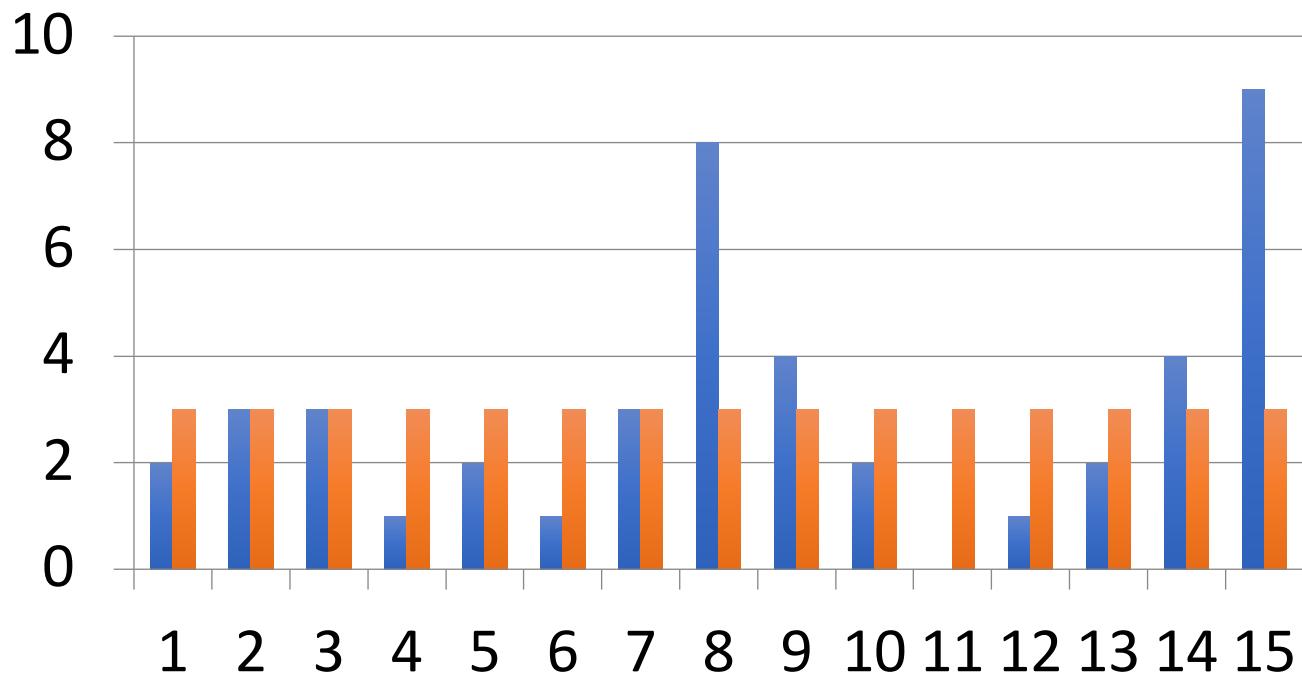
Frequency



How do we compute how many values between 8 and 10?
(Yes, it's obvious)

Problem: counts take up too much space!

Full vs. Uniform Counts



How much space
do the full counts
(`bucket_size=1`)
take?

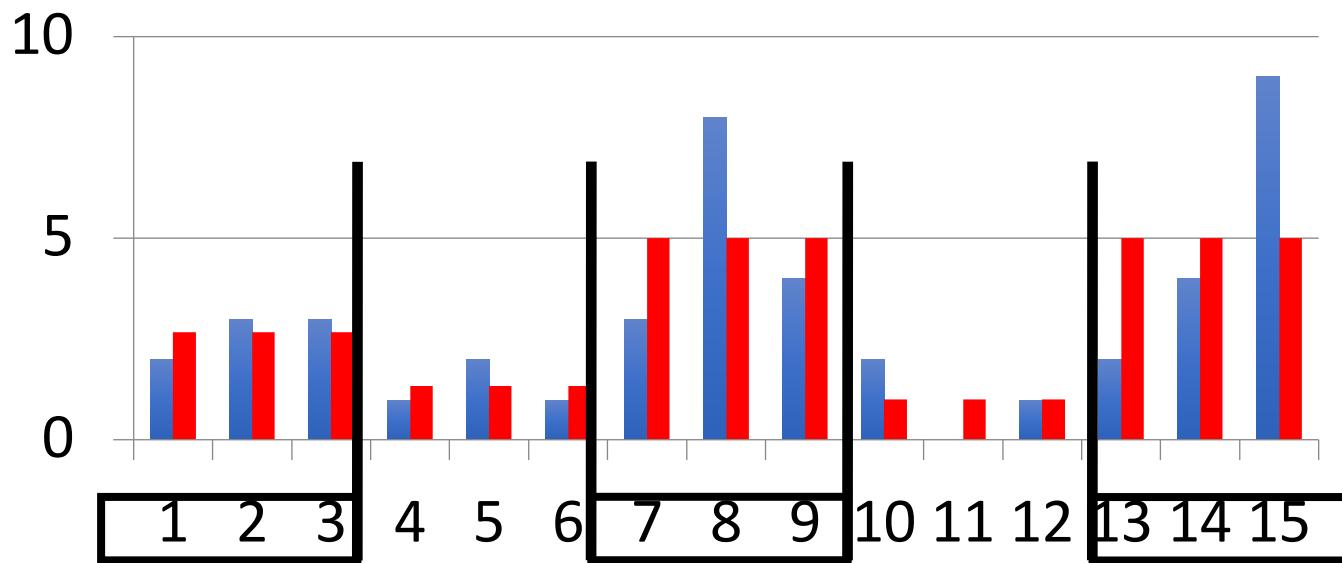
How much space
do the uniform
counts
(`bucket_size=ALL`)
take?

Fundamental Tradeoffs

- Want high resolution (like the full counts)
- Want low space (like uniform)
- Histograms are a compromise!

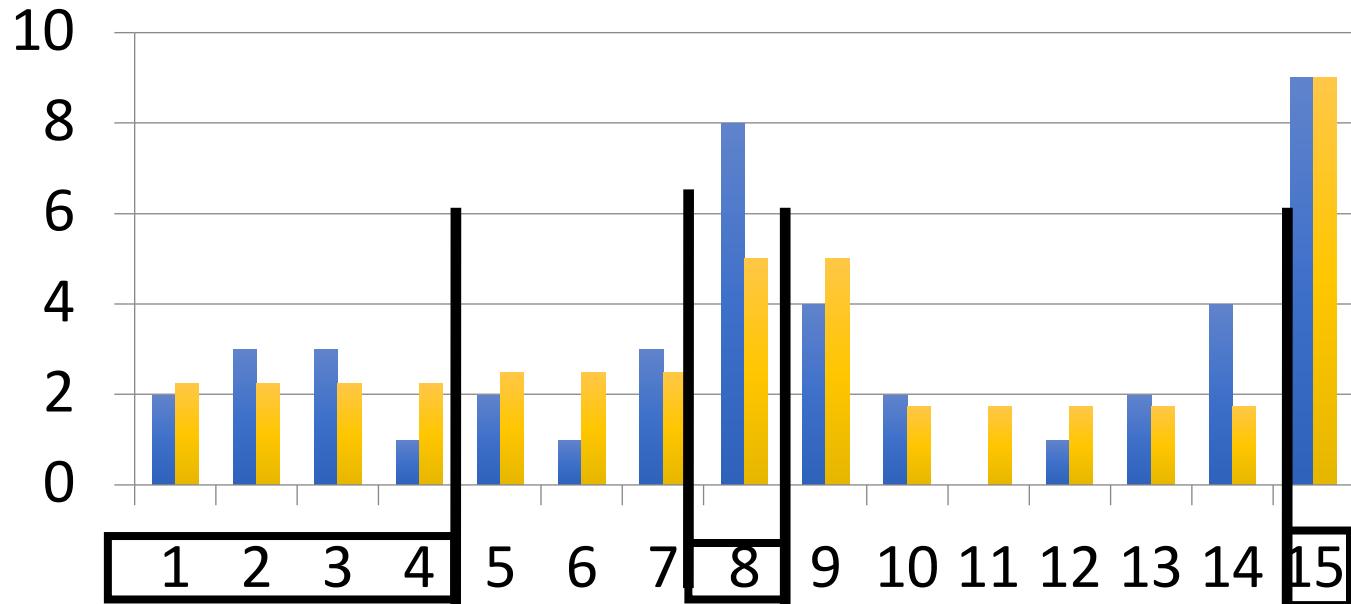
So how do we compute the “bucket” sizes?

Equi-width



All buckets roughly the same width

Equidepth



All buckets contain roughly the same number of items (total frequency)

Histograms

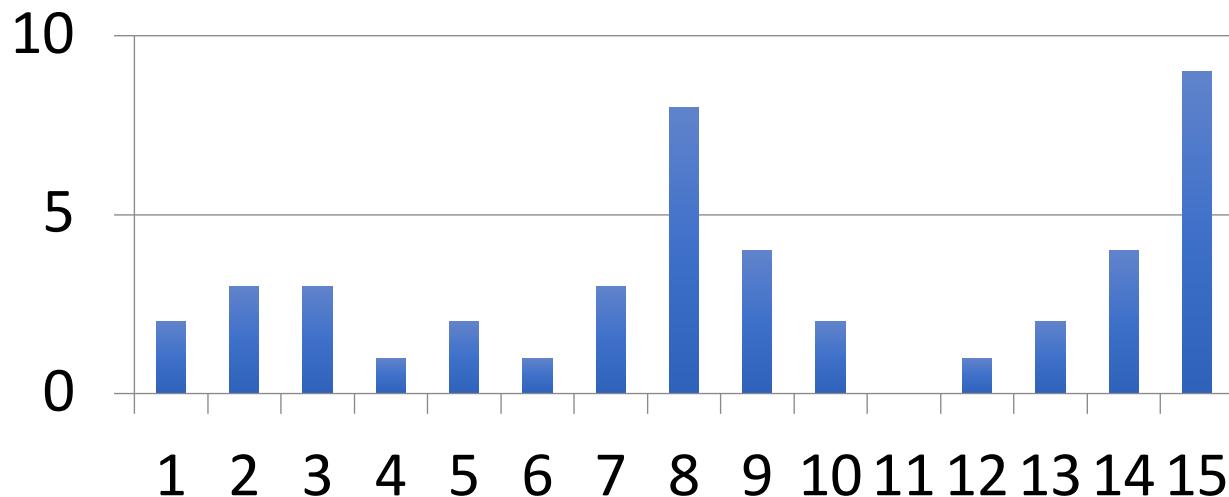
- Simple, intuitive and popular
- Parameters: # of buckets and type
- Can extend to many attributes (multidimensional)

```
SELECT sID  
FROM Student  
WHERE 10 < age < 15 AND gpa > 3.5
```

Maintaining Histograms

- Histograms require that we update them!
 - Typically, you must run/schedule a command to update statistics on the database
 - Out of date histograms can be terrible!
- There is research work on self-tuning histograms and the use of query feedback
 - Oracle 11g

Nasty example



1. we insert many tuples with value > 16
2. we do **not** update the histogram
3. we ask for values > 20?

Compressed Histograms

- One popular approach:
 1. Store the most frequent values and their counts explicitly
 2. Keep an equiwidth or equidepth one for the rest of the values

People continue to try all manner of fanciness here
wavelets, graphical models, entropy models,...

Summary

- **Logical Optimization**
 - SQL -- > RA → RA Tree
 - Selection Pushdown
 - Projection Pushdown
- **Physical Optimization**
 - Nested Loop Join / Hash Join / Sort-Merge Join
 - I/O Aware Algorithm
 - Histogram

Acknowledge

- Some lecture slides were copied from or inspired by the following course materials
 - “W4111: Introduction to databases” by Eugene Wu at Columbia University
 - “CSE344: Introduction to Data Management” by Dan Suciu at University of Washington
 - “CMPT354: Database System I” by John Edgar at Simon Fraser University
 - “CS186: Introduction to Database Systems” by Joe Hellerstein at UC Berkeley
 - “CS145: Introduction to Databases” by Peter Bailis at Stanford
 - “CS 348: Introduction to Database Management” by Grant Weddell at University of Waterloo