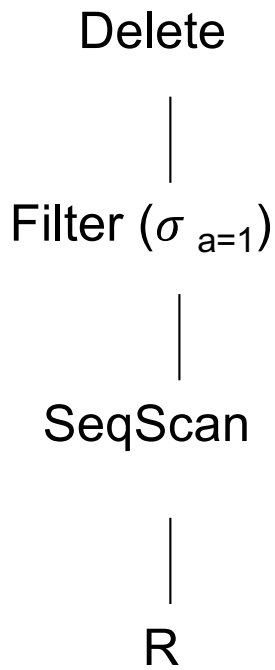


# Before We Go Into Query Plan Costs... How do Updates Work? (Insert/Delete)

# Example Using Delete

`delete from R where a=1;`

## Query plan



In SimpleDB, the Delete Operator calls `BufferPool.deleteTuple()`

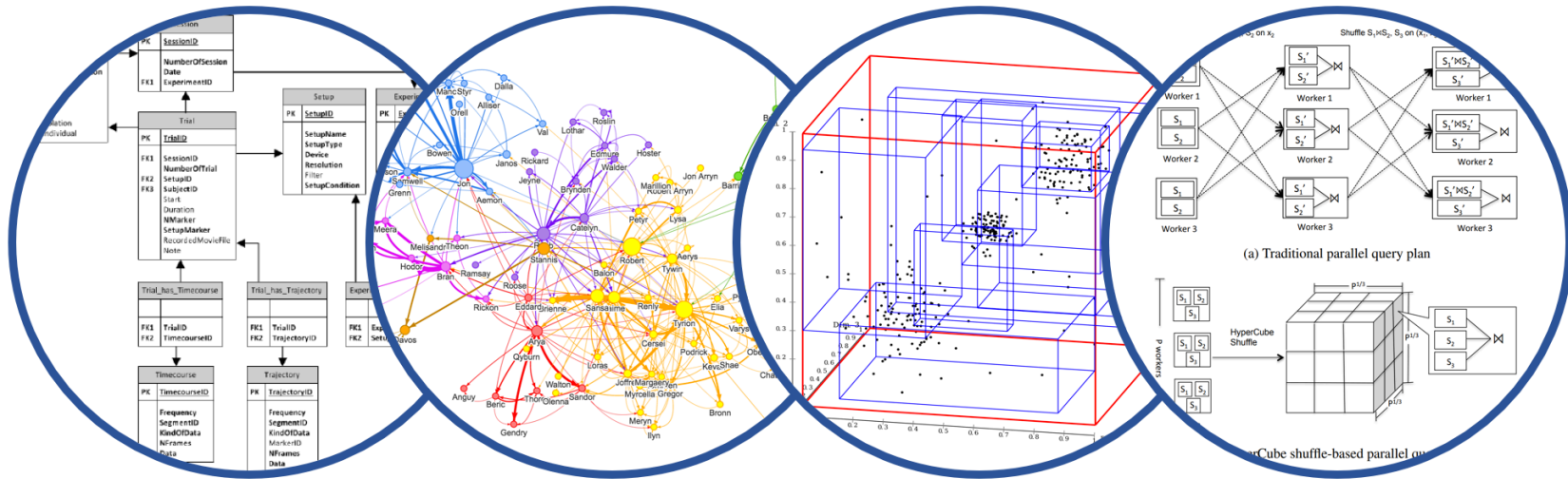
Why not call `HeapFile.deleteTuple()` directly?

Because there could also be indexes.  
Need some entity that will decide all the structures from where tuple needs to be deleted

`BufferPool` then calls `HeapFile.deleteTuple()`

# Pushing Updates to Disk

- When **inserting a tuple**, HeapFile inserts it on a page but does not write the page to disk
- When **deleting a tuple**, HeapFile deletes tuple from a page but does not write the page to disk
- The buffer manager worries when to write pages to disk (and when to read them from disk)
- When need to **add new page** to file, HeapFile adds page to file on disk and then reads it through buffer manager



# Database System Internals

## Query Plan Costs

Paul G. Allen School of Computer Science and Engineering  
University of Washington, Seattle

# Query Optimizer

Three components:

- Cost estimation
  - Cardinality estimation  $T(R)$  each intermediate result
  - Cost = CPU + I/O + Network, all depend on  $T(R)$
- Search space
  - Which plans do we consider?
- Search algorithm
  - How do we search the space?

# Summary of External Join Algorithms

- Block Nested Loop:  $B(S) + B(R) \cdot B(S) / (M-1)$
- Index Join:  $B(R) + T(R)B(S)/V(S,a)$   
(unclustered)
- Partitioned Hash:  $3B(R) + 3B(S)$ ;
  - $\min(B(R), B(S)) \leq M^2$
- Merge Join:  $3B(R) + 3B(S)$ 
  - $B(R) + B(S) \leq M^2$

# Summary of Query Execution

- For each logical query plan
  - There exist many physical query plans
  - Each plan has a different cost
  - Cost depends on the data
- Additionally, for each query
  - There exist several logical plans
- Next lecture: query optimization
  - How to compute the cost of a complete plan?
  - How to pick a good query plan for a query?

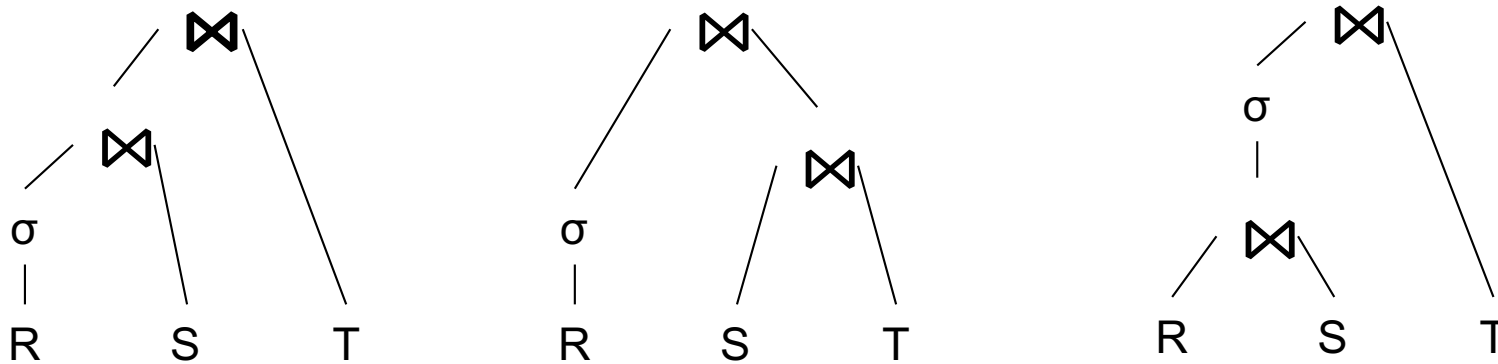
# A Note About Skew

- Previously shown 2 pass join algorithms do not work for heavily skewed data
- For a sort-merge join, the maximum number of tuples with a particular join attribute should be the number of tuples per page:
  - This often isn't the case: would need multiple passes



# Query Optimization Summary

Goal: find a physical plan that has minimal cost



What is the cost of a plan?

For each operator, cost is function of CPU, IO, network bw

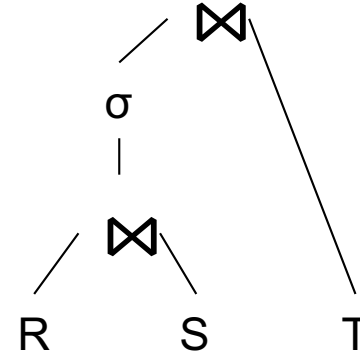
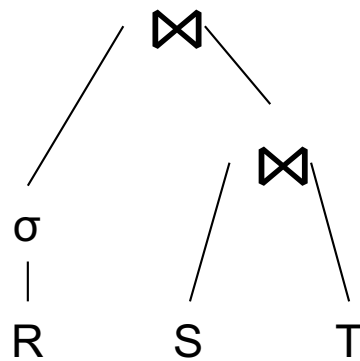
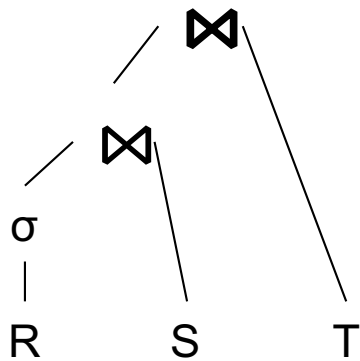
$$\text{Total\_Cost} = \text{CPUCost} + w_{\text{IO}} \text{IOCost} + w_{\text{BW}} \text{BWCost}$$

Cost of plan is total for all operators

In this class, we look only at IO

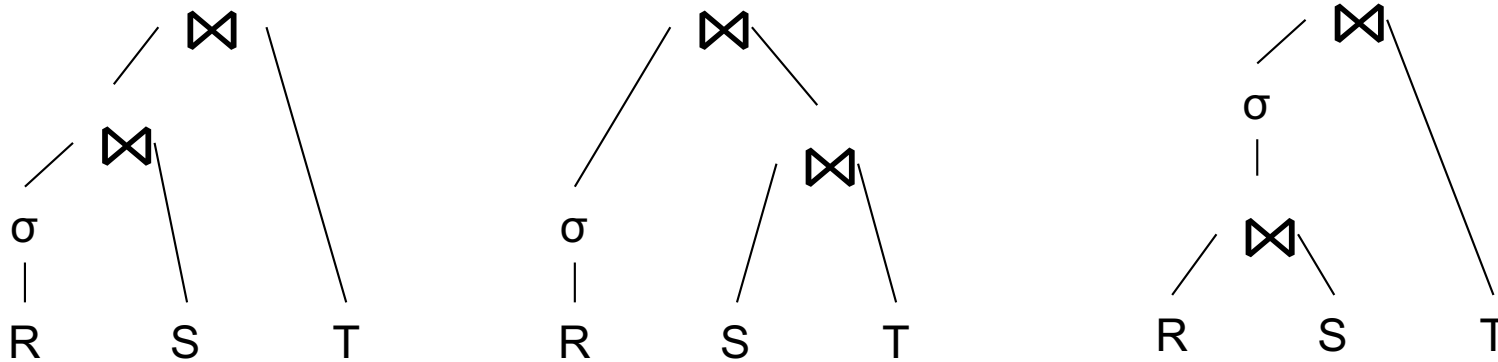
# Query Optimization Summary

Goal: find a physical plan that has minimal cost



# Query Optimization Summary

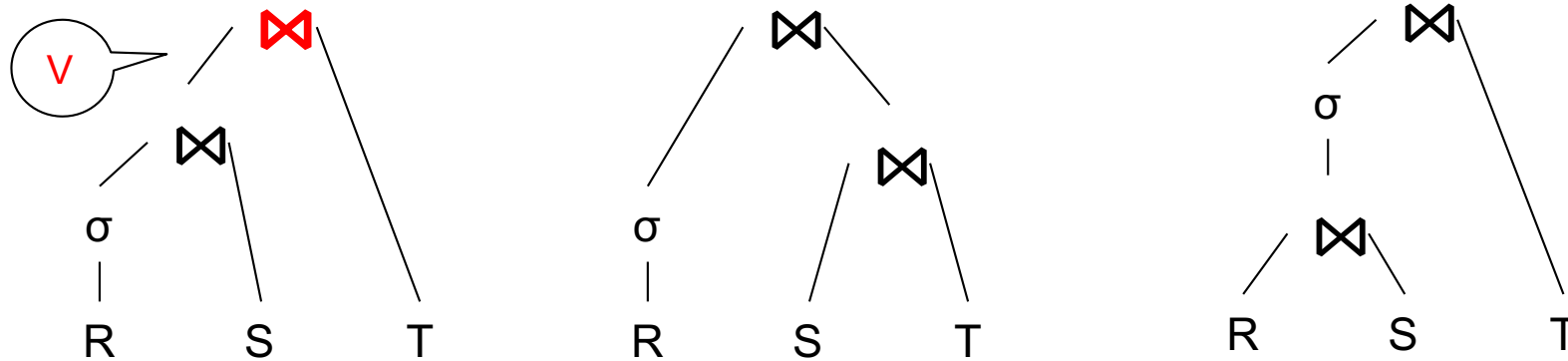
Goal: find a physical plan that has minimal cost



Know how to compute cost if know cardinalities

# Query Optimization Summary

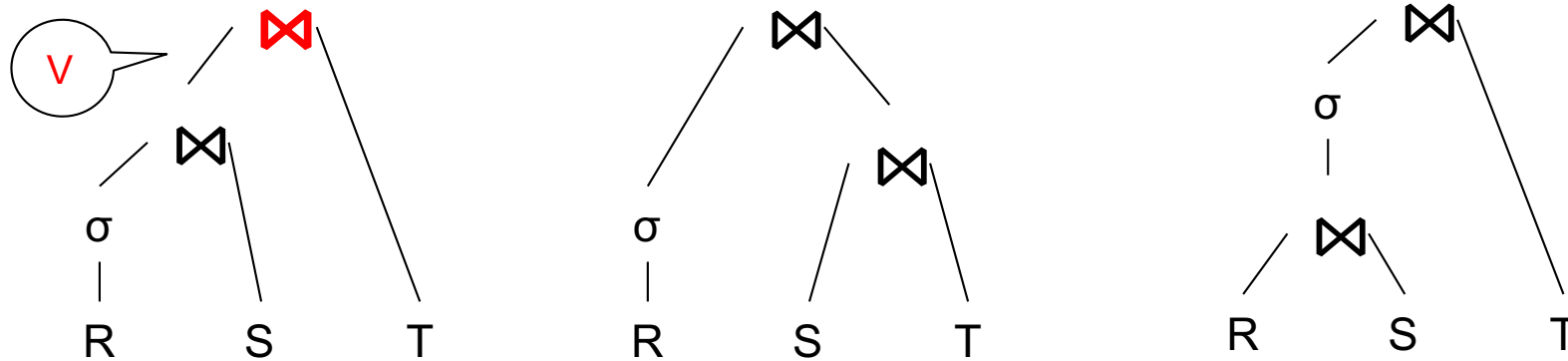
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Know how to compute cost if know cardinalities

# Query Optimization Summary

Goal: find a physical plan that has minimal cost

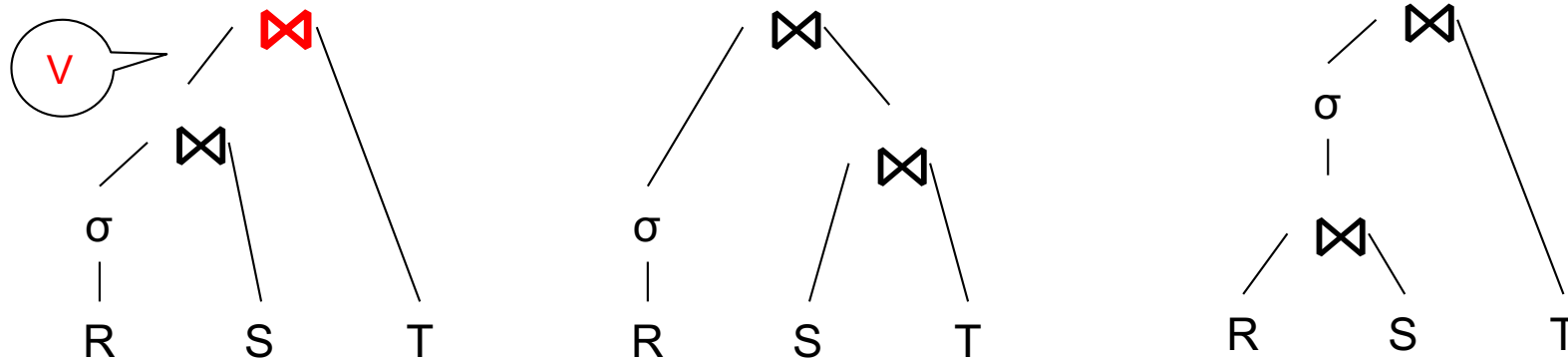


Know how to compute cost if know cardinalities

- Eg.  $\text{Cost}(V \bowtie T) = 3B(V) + 3B(T)$
- $B(V) = T(V) / \text{PageSize}$
- $T(V) = T(\sigma(R) \bowtie S)$

# Query Optimization Summary

Goal: find a physical plan that has minimal cost



Know how to compute cost if know cardinalities

- Eg.  $\text{Cost}(V \bowtie T) = 3B(V) + 3B(T)$
- $B(V) = T(V) / \text{PageSize}$
- $T(V) = T(\sigma(R) \bowtie S)$

Cardinality estimation problem: e.g. estimate  $T(\sigma(R) \bowtie S)$

# Database Statistics

- **Collect** statistical summaries of stored data
- **Estimate size** (=cardinality) in a bottom-up fashion
  - This is the most difficult part, and still inadequate in today's query optimizers
- **Estimate cost** by using the estimated size
  - Hand-written formulas, similar to those we used for computing the cost of each physical operator

# Database Statistics

- Number of tuples (cardinality)  $T(R)$
- Indexes, number of keys in the index  $V(R,a)$
- Number of physical pages  $B(R)$
- Statistical information on attributes
  - Min value, Max value,  $V(R,a)$
- Histograms
  
- Collection approach: periodic, using sampling



# Size Estimation Problem

```
Q = SELECT list  
    FROM R1, ..., Rn  
    WHERE cond1 AND cond2 AND . . . AND condk
```

Given  $T(R_1), T(R_2), \dots, T(R_n)$   
Estimate  $T(Q)$

How can we do this ? Note: doesn't have to be exact.

# Size Estimation Problem

```
Q = SELECT list  
    FROM R1, ..., Rn  
    WHERE cond1 AND cond2 AND . . . AND condk
```

Remark:  $T(Q) \leq T(R1) \times T(R2) \times \dots \times T(Rn)$

# Size Estimation Problem

```
Q = SELECT list  
    FROM R1, ..., Rn  
    WHERE cond1 AND cond2 AND ... AND condk
```

Remark:  $T(Q) \leq T(R1) \times T(R2) \times \dots \times T(Rn)$

**Key idea:** each condition reduces the size of  $T(Q)$  by some factor, called **selectivity factor**

# Selectivity Factor

- Each condition **cond** reduces the size by some factor called **selectivity factor**
- Assuming independence, **multiply** the selectivity factors

# Example

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

```
Q = SELECT *  
    FROM R, S, T  
    WHERE R.B=S.B and S.C=T.C and R.A<40
```

$T(R) = 30k$ ,  $T(S) = 200k$ ,  $T(T) = 10k$

Selectivity of  $R.B = S.B$  is  $1/3$

Selectivity of  $S.C = T.C$  is  $1/10$

Selectivity of  $R.A < 40$  is  $1/2$

Q: What is the estimated size of the query output  $T(Q)$  ?

# Example

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Selectivity of  $R.A < 40$  is  $1/2$

Q: What is the estimated size of the query output  $T(Q)$  ?

A:  $T(Q) = 30k * 200k * 10k * 1/3 * 1/10 * 1/2 = 10^{12}$

# Selectivity Factors for Conditions

- $A = c$  /\*  $\sigma_{A=c}(R)$  \*/
  - Selectivity =  $1/V(R,A)$

# Selectivity Factors for Conditions

■  $A = c$  /\*  $\sigma_{A=c}(R)$  \*/

• Selectivity =  $1/V(R,A)$

■  $A < c$  /\*  $\sigma_{A<c}(R)$  \*/

• Selectivity =  $(c - \text{Low}(R, A)) / (\text{High}(R,A) - \text{Low}(R,A))$



# Selectivity Factors for Conditions

- $A = c$   $/* \sigma_{A=c}(R) */$ 
  - Selectivity =  $1/V(R,A)$
- $A < c$   $/* \sigma_{A < c}(R) */$ 
  - Selectivity =  $(c - \text{Low}(R, A)) / (\text{High}(R, A) - \text{Low}(R, A))$
- $A = B$   $/* R \bowtie_{A=B} S */$ 
  - Selectivity =  $1 / \max(V(R,A), V(S,A))$
  - (will explain next)

# Assumptions

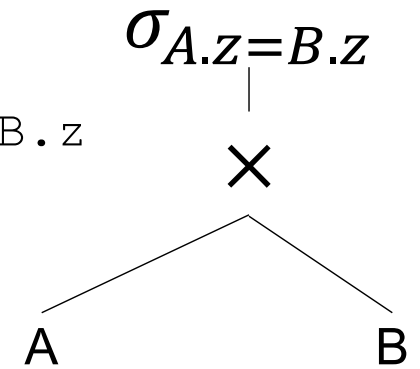
- Containment of values: if  $V(R,A) \leq V(S,B)$ , then all values  $R.A$  occur in  $S.B$ 
  - Note: this indeed holds when  $A$  is a foreign key in  $R$ , and  $B$  is a key in  $S$
- Preservation of values: for any other attribute  $C$ ,  
 $V(R \bowtie_{A=B} S, C) = V(R, C)$  (or  $V(S, C)$ )
  - Note: we don't need this to estimate the size of the join, but we need it in estimating the next operator

# Cardinality Estimation: JOIN

1.  $T(A) * T(B)$  tuples in Cartesian product
2. Suppose  $z_0$  exists in the join
3. How many times does  $z_0$  occur?

- Like the selection condition  $\sigma_{A.z=z_0 \text{ AND } B.z=z_0}$

```
SELECT *
FROM A, B
WHERE A.z = B.z
```



4. How many distinct  $z_0$ s exist in the join?

- $\geq 0$  [if no overlap]
- $\leq \min\{V(A, z), V(B, z)\}$  [if full overlap]
- For this class, ASSUME full overlap
  - As if one is a subset of the other (containment assumption)

Selectivity Factor  
 $1/V(A, z) * 1/V(B, z)$

5. Multiply by estimate # of distinct  $z_0$ s

$$\frac{T(A) * T(B)}{V(A, z) * V(B, z)} * \min\{V(A, z), V(B, z)\} = \frac{T(A) * T(B)}{\max\{V(A, z), V(B, z)\}}$$

# Complete Example

Supplier(sno, sname, scity, sstate)  
Supply(sno, pno, quantity)

- Some statistics Supply.sno references Supplier.sno
  - T(Supplier) = 1000 records
  - T(Supply) = 10,000 records
  - B(Supplier) = 100 pages
  - B(Supply) = 100 pages
  - V(Supplier,scity) = 20, V(Suppliers,state) = 10
  - V(Supply,pno) = 2,500
  - Both relations are clustered
- M = 11

```
SELECT sname
FROM Supplier x, Supply y
WHERE x.sno = y.sno
      and y.pno = 2
      and x.scity = 'Seattle'
      and x.sstate = 'WA'
```

# Physical Query Plan 1

T(Supplier) = 1000  
T(Supply) = 10,000

B(Supplier) = 100  
B(Supply) = 100

V(Supplier,scity) = 20  
V(Supplier,state) = 10  
V(Supply,pno) = 2,500

M = 11  
Supply.sno references  
Supplier.sno

(On the fly)

$\pi_{\text{sname}}$

Selection and project on-the-fly  
-> No additional cost.

(On the fly)

$\sigma_{\text{scity}='Seattle' \wedge \text{sstate}='WA' \wedge \text{pno}=2}$

Total cost of plan is thus cost of join:  
= B(Supplier)+B(Supplier)\*B(Supply)  
= 100 + 100 \* 100 / (11-1)  
**= 1,100 I/Os**

(Nested loop  
memory optimized)

sno = sno

Supplier

Supply

(File scan)

(File scan)

# Physical Query Plan 2

T(Supplier) = 1000  
T(Supply) = 10,000

B(Supplier) = 100  
B(Supply) = 100

V(Supplier,scity) = 20  
V(Supplier,state) = 10  
V(Supply,pno) = 2,500

M = 11  
Supply.sno references  
Supplier.sno

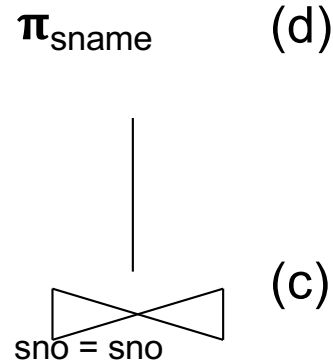
(On the fly)

(Sort-merge join  
In memory if possible)

(Scan  
write to T1)

(a)  $\sigma_{\text{scity}='Seattle' \wedge \text{sstate}='WA'}$

Supplier  
(File scan)



(b)  $\sigma_{\text{pno}=2}$

Supply  
(File scan)

Total cost  
= 100 + 100 \* 1/20 \* 1/10 (a)  
+ 100 + 100 \* 1/2500 (b)  
+ 1 + 1 (c)  
+ 0 (d)

Total cost  $\approx$  **204 I/Os**

(Scan  
write to T2)

# Plan 2 with Different Numbers

$V(\text{Supplier}, \text{scity}) = 20$   $V(\text{Supplier}, \text{state}) = 10$   $V(\text{Supply}, \text{pno}) = 2,500$

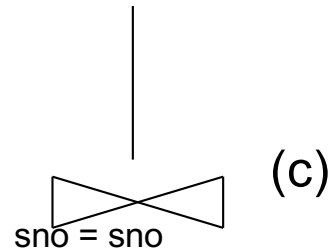
$M = 11$

Supply.sno references  
Supplier.sno

What if we had:

10K pages of Supplier  $\pi_{\text{sname}}$  (d)  
10K pages of Supply

(Sort-merge join  
In memory if possible)



Total cost  
= 10000 + 50 (a)  
+ 10000 + 4 (b)  
+ 3\*50 + 4 (c)  
+ 0 (d)

Total cost  $\approx 20,208$  I/Os

(Scan  
write to T1)

(a)  $\sigma_{\text{scity}='Seattle' \wedge \text{sstate}='WA'}$

Supplier  
(File scan)

(Scan write to T2)

(b)  $\sigma_{\text{pno}=2}$

Supply  
(File scan)

Need to do a two-pass sort algorithm for Supplier since 50 blocks  $> M$

# Physical Query Plan 3

T(Supplier) = 1000  
T(Supply) = 10,000

B(Supplier) = 100  
B(Supply) = 100

V(Supplier,scity) = 20  
V(Supplier,state) = 10  
V(Supply,pno) = 2,500

M = 11  
Supply.sno references  
Supplier.sno

(On the fly)

(d)  $\pi_{\text{sname}}$

(On the fly)

(c)  $\sigma_{\text{scity}='Seattle' \wedge \text{sstate}='WA'}$

Total cost

= 1 (a)

+ 4 (b)

+ 0 (c)

+ 0 (d)

Total cost  $\approx$  5 I/Os

(b)

sno = sno

(Index nested loop)

Remember: Supply.sno references  
Supplier.sno

(Use hash index)

4 tuples

(a)  $\sigma_{\text{pno}=2}$

Supply

Supplier

(Hash index on pno)

Assume: clustered

(Hash index on sno)

Clustering does not matter



# Histograms

- Statistics on data maintained by the RDBMS
- Makes size estimation much more accurate (hence, cost estimations are more accurate)

# Histograms

Employee(ssn, name, age)

$T(\text{Employee}) = 25000$ ,  $V(\text{Employee}, \text{age}) = 50$   
 $\min(\text{age}) = 19$ ,  $\max(\text{age}) = 68$

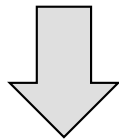
$\sigma_{\text{age}=48}(\text{Employee}) = ?$      $\sigma_{\text{age}>28 \text{ and } \text{age}<35}(\text{Employee}) = ?$

# Histograms

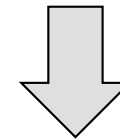
## Employee(ssn, name, age)

$T(\text{Employee}) = 25000$ ,  $V(\text{Employee}, \text{age}) = 50$   
 $\min(\text{age}) = 19$ ,  $\max(\text{age}) = 68$

$\sigma_{\text{age}=48}(\text{Employee}) = ?$      $\sigma_{\text{age}>28 \text{ and } \text{age}<35}(\text{Employee}) = ?$



Uniform Estimate =  $25000 / 50 = 500$



Uniform Estimate =  $25000 * 6 / 50 = 3000$

# Histograms

## Employee(ssn, name, age)

$T(\text{Employee}) = 25000$ ,  $V(\text{Employee}, \text{age}) = 50$   
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Age:	0-20	20-29	30-39	40-49	50-59	> 60
Tuples	200	800	5000	12000	6500	500

# Histograms

## Employee(ssn, name, age)

$T(\text{Employee}) = 25000$ ,  $V(\text{Employee, age}) = 50$   
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Age:	0..20	20..29	30-39	40-49	50-59	> 60
Tuples	200	800	5000	12000	6500	500

Histogram Estimate = 1200

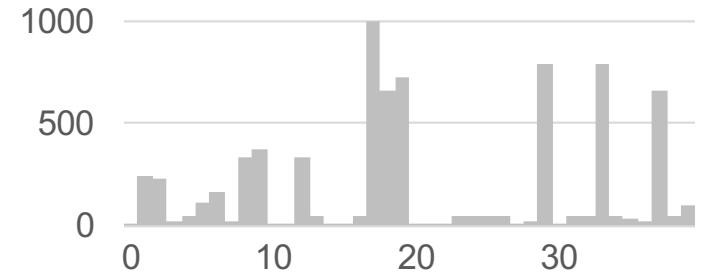
Histogram Estimate =  $1 \cdot 80 + 5 \cdot 500 = 2580$

# Types of Histograms

- How should we determine the bucket boundaries in a histogram?

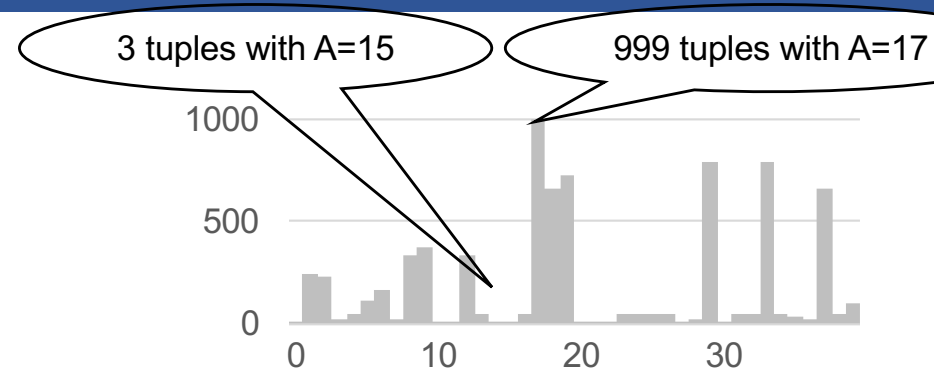
# Types of Histograms

- Eqwidth
- Eqdepth
- V-optimal: minimize error



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- Eqwidth
- Eqdepth
- V-optimal: minimize error





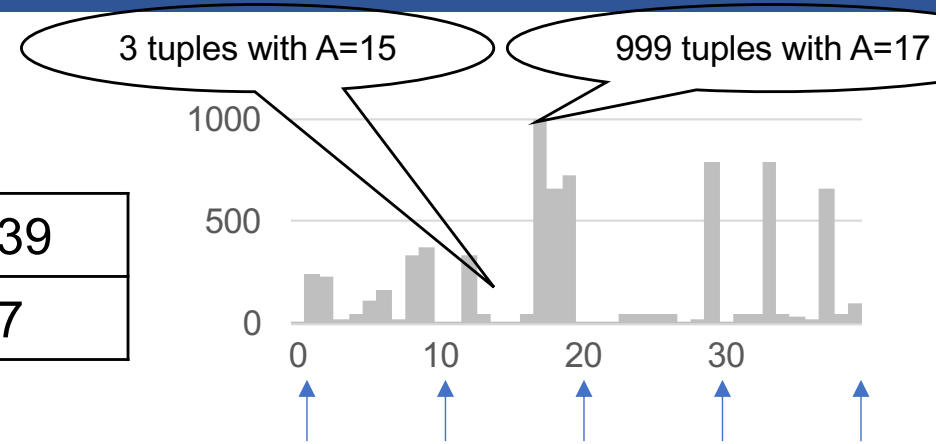
# Types of Histograms

- Eqwidth

Attr =	0..9	10..19	20..29	30..39
#tuples	1585	2860	1039	1827

- Eqdepth

- V-optimal: minimize error



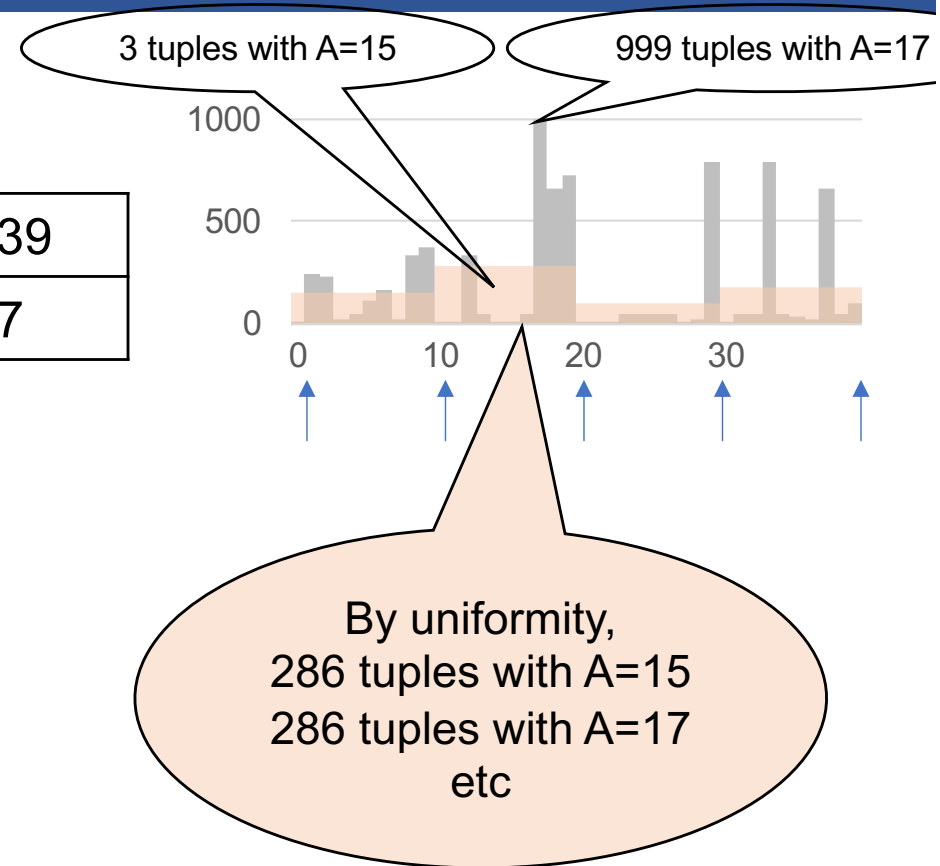
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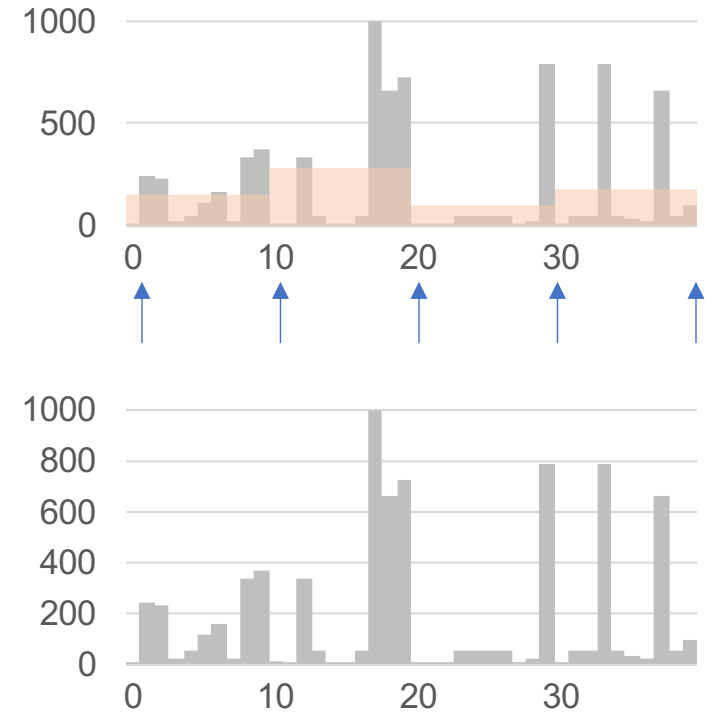
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# Types of Histograms

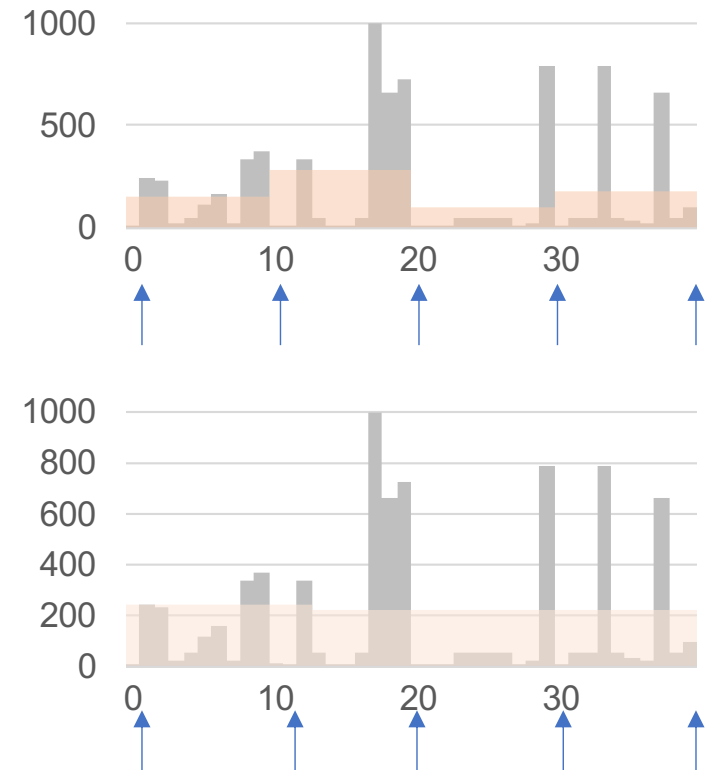
## ■ Eqwidth

Attr =	0..9	10..19	20..29	30..39
#tuples	1585	2860	1039	1827

## ■ Eqdepth

Attr =	0..12	13..18	19..31	32..39
#tuples	1943	1779	1822	1767

## ■ V-optimal: minimize error



# Types of Histograms

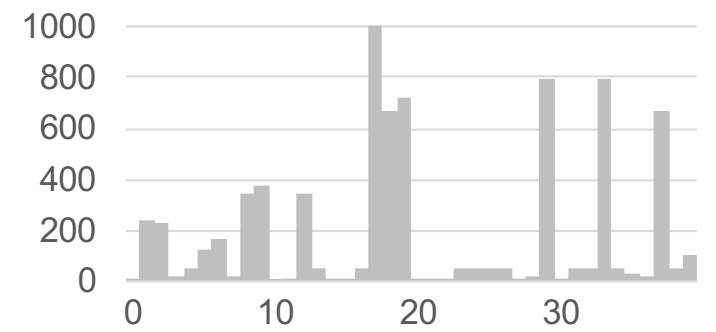
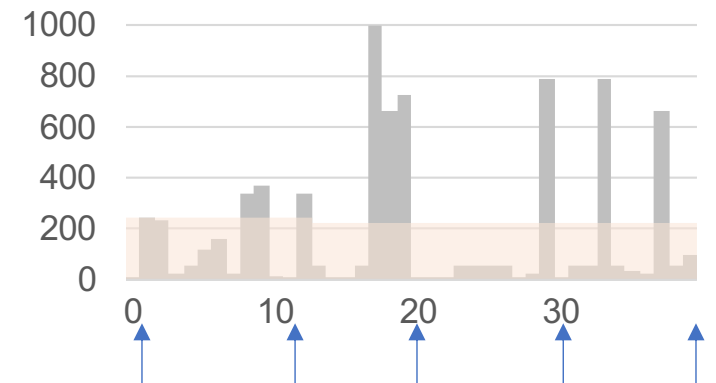
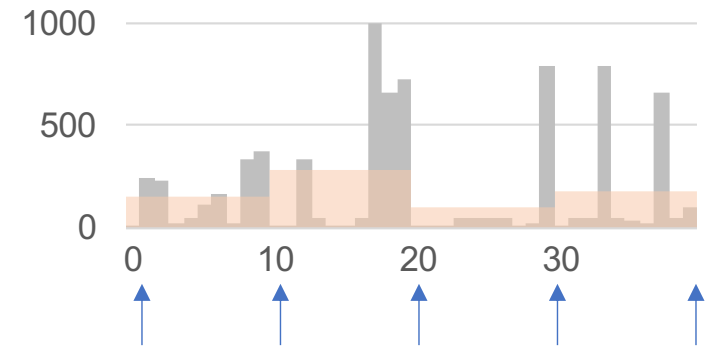
## ■ Eqwidth

Attr =	0..9	10..19	20..29	30..39
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## ■ V-optimal: minimize error



# Types of Histograms

## ■ Eqwidth

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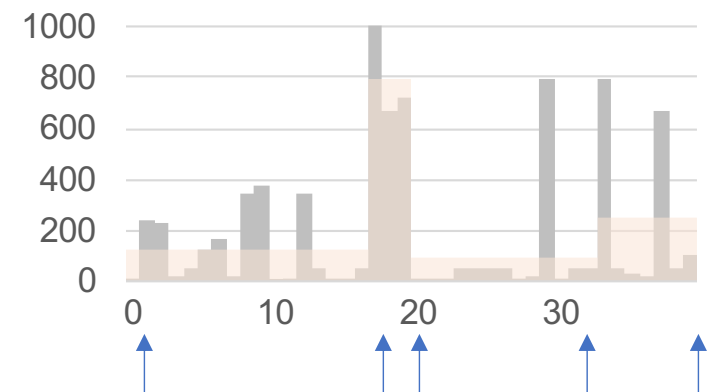
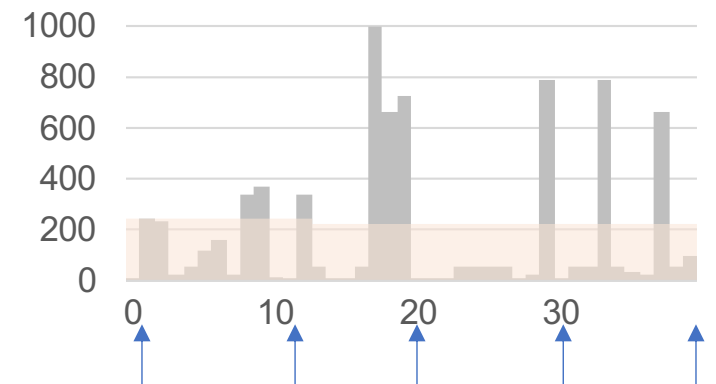
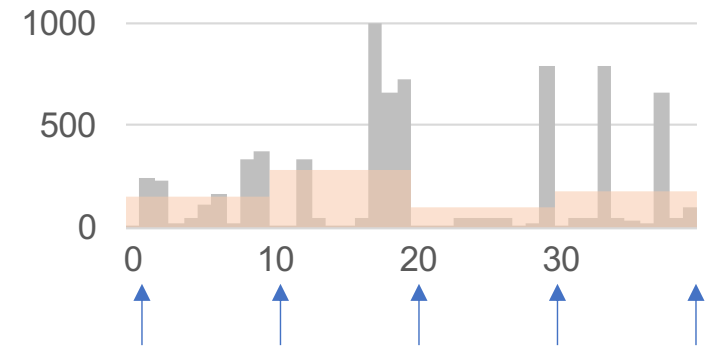
## ■ Eqdepth

Attr =	0..12	13..18	19..31	32..39
#tuples	1943	1779	1822	1767

## ■ V-optimal: minimize error

Attr =	0..16	17..19	20..34	35..39
#tuples	2056	2389	1152	1714

Minimizes  $\sum_a |\text{true-#tuples}(a) - \text{estimate-#tuples}(a)|^2$



# Difficult Questions on Histograms

- Small number of buckets
  - Hundreds, or thousands, but not more
  - WHY?
- *Not* updated during database update, but recomputed periodically
  - WHY?
- Multidimensional histograms rarely used
  - WHY?

# Difficult Questions on Histograms

- Small number of buckets
  - Hundreds, or thousands, but not more
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# Difficult Questions on Histograms

- Small number of buckets
  - Hundreds, or thousands, but not more
  - WHY? All histograms are kept in main memory during query optimization; plus need fast access
- *Not* updated during database update, but recomputed periodically
  - WHY? Histogram update creates a write conflict; would dramatically slow down transaction throughput
- Multidimensional histograms rarely used
  - WHY?

# Difficult Questions on Histograms

- Small number of buckets
  - Hundreds, or thousands, but not more
  - WHY? All histograms are kept in main memory during query optimization; plus need fast access
- *Not* updated during database update, but recomputed periodically
  - WHY? Histogram update creates a write conflict; would dramatically slow down transaction throughput
- Multidimensional histograms rarely used
  - WHY? Too many possible multidimensional histograms, unclear which ones to choose and how to use