DATA516/CSED516
Scalable Data Systems and Algorithms

Lecture 2 Query Execution and Optimization

Announcements

- Project teams due on Wednesday (October 18)
  - Fill out even if you are doing it solo

- Proposals due next Friday (October 27)

- HW1 is due Monday (October 23)
  - SQL Queries for Q1, Q4

Administrivia

- Paper Reading #1: Graded, released tonight
  - Address all papers, ~1 page, Avoid Copy-Paste

- Gitlab access should be resolved

- Gitlab README
  1. git remote add upstream git@gitlab.cs.washington.edu:jackkhuu/csed516-2023au.git
  2. git pull upstream main

Outline for Today

- Discuss *Goes Around* paper

- Discuss query optimization
  - Major paper to read for next time
  - We continue query optimization next time
    - (Maybe)

Discussion of the paper

- M. Stonebraker and J. Hellerstein. What Goes Around Comes Around. In "Readings in Database Systems" (aka the Red Book). 4th ed.

Data Model

- Enables a user to define the data using high-level constructs without worrying about many low-level details of how data will be stored on disk

- Examples:
  - Relational data model
  - Semi-structured data model
  - Graph data model
  - Key-value pairs data model

Data Independence

What is it?

Data Independence

What is it?

- **Physical data independence**: Applications are insulated from changes in **physical storage details**

- **Logical data independence**: Applications are insulated from changes to **logical structure of the data**

Paper Discussion

- Early data models: IMS, CODASYL

- Relational data model

- Semistructured data model

Early Proposal 1: IMS*

- What is it?

* IBM Information Management System

Early Proposal 1: IMS*

- What is it?

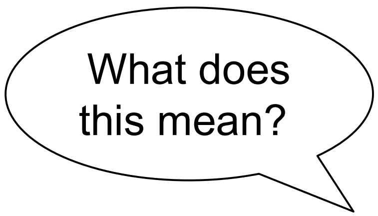
- **Hierarchical data model**

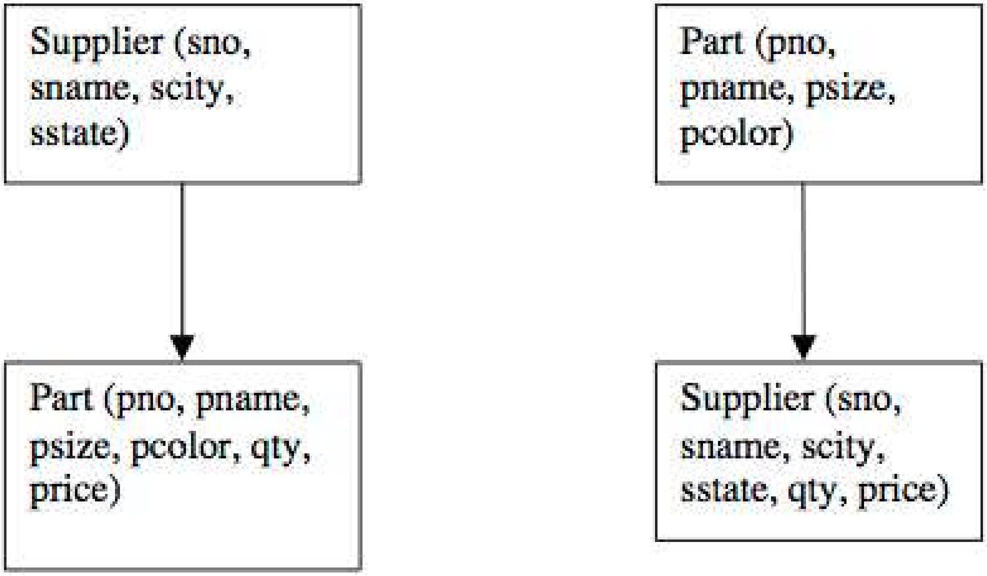
- **Record**
  - Record type, record instance
  - Each instance has a **key**
  - Arranged in a **tree**

* IBM Information Management System

IMS Example

Figure 2 from “What goes around comes around”

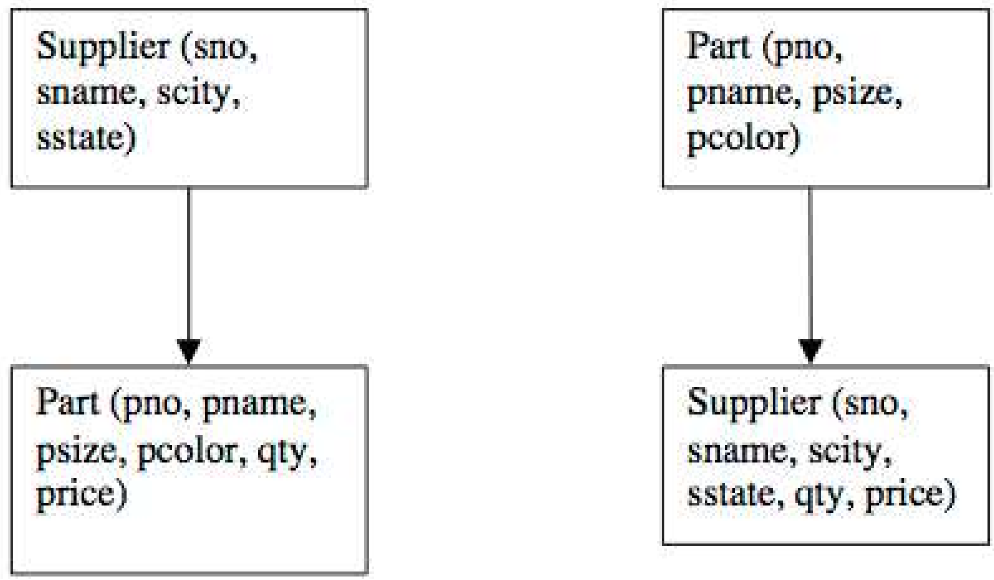




IMS Example

Figure 2 from “What goes around comes around”

What does this mean?

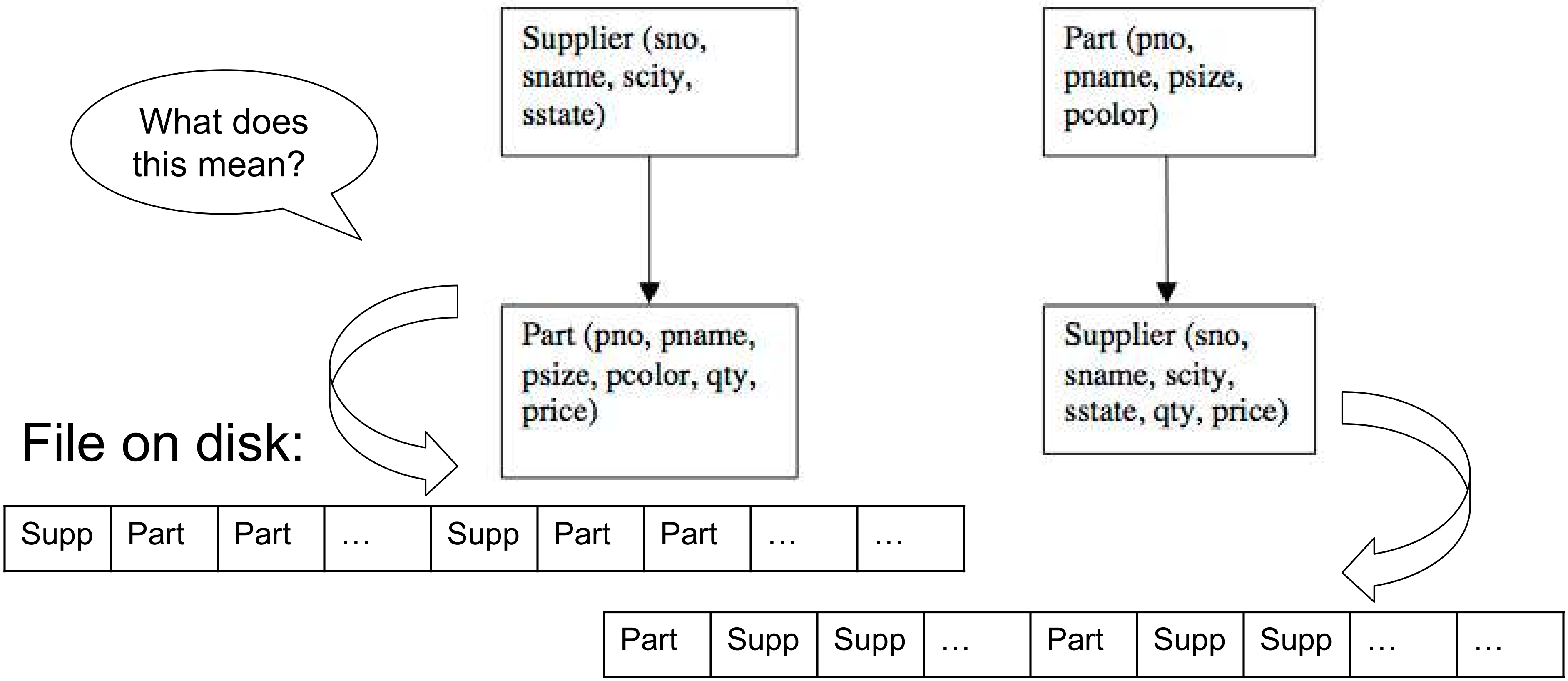


File on disk:

Supp	Part	Part	…	Supp	Part	Part	…	…

IMS Example

Figure 2 from “What goes around comes around”



IMS Limitations

IMS Limitations

- Tree-structured: redundant; existence depends on parent
- Record-at-a-time interface
- Very limited physical independence
- Some logical independence but limited

Data Manipulation Language: DL/1

How does a programmer retrieve data in IMS?

Data Manipulation Language: DL/1

How does a programmer retrieve data in IMS?

- Each record has a hierarchical sequence key (HSK)
- get_next; get_next_within_parent
- Programmers need to worry about optimization

DL/1 is a record-at-a-time language

Data storage

How is data physically stored in IMS?

Data storage

How is data physically stored in IMS?

- Root records
  - Stored sequentially (sorted on key), or
  - Indexed in a B-tree using the key of the record, or
  - Hashed using the key of the record
- Dependent records: various forms of pointers
- Selected organizations restrict DL/1 commands

Early Proposal 2: CODASYL

What is it?

Early Proposal 2: CODASYL

What is it?

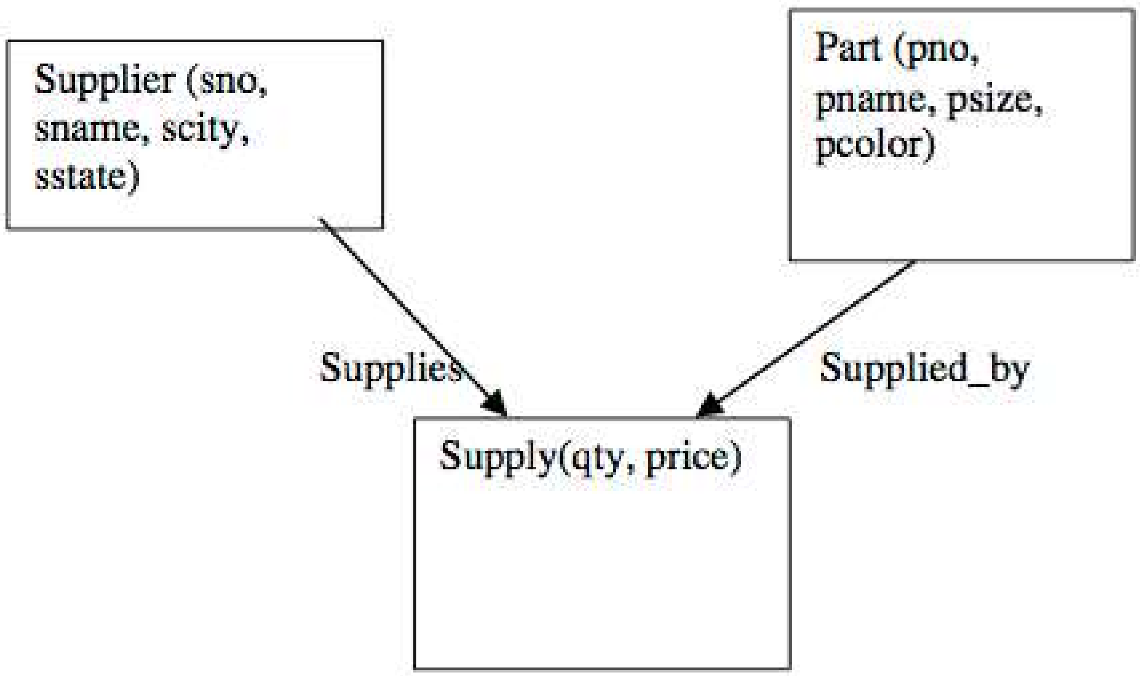
- **Networked data model**

- Organized into **network**
- Multiple parents; arcs = “sets”

- **Record-at-a-time** data manipulation language

CODASYL Example

- Figure 5 from “What goes around comes around”



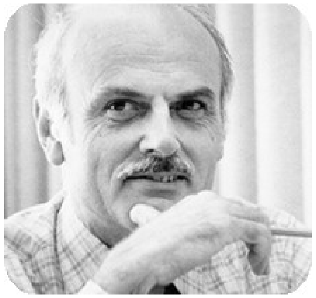
Paper Discussion

- Early data models: IMS, CODASYL
- Relational data model
- Semistructured data model

Relational Model Overview

Ted Codd 1970

- What was the motivation? What is the model?



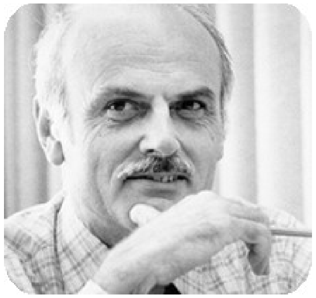
Relational Model Overview

Ted Codd 1970

- What was the motivation? What is the model?

- Logical and physical data independence

- Store data in a **simple data structure** (table)
- Access data through **set-at-a-time** language
- **No need for physical storage proposal**



Great Debate

- Pro relational
  - What were the arguments?
- Against relational
  - What were the arguments?
- How was it settled?

Great Debate

- Pro relational
  - CODASYL is too complex
  - No data independence
  - Record-at-a-time hard to optimize
  - Trees/networks not flexible enough

- Against relational
  - COBOL programmers cannot understand relational languages
  - Impossible to implement efficiently

- Ultimately settled by the market place

Recap

- Physical data independence:
  - SQL: *what* data we want
  - Optimizer: figures out *how* to get it
- Logical data independence
  - Realized in SQL through *views*

Paper Discussion

- Early data models: IMS, CODASYL
- Relational data model
- Semistructured data model

Other Data Models

- Entity-Relationship: 1970’s
  - Successful in logical database design
- Extended Relational: 1980’s
- Semantic: late 1970’s and 1980’s
- Object-oriented: late 1980’s and early 1990’s
  - Address impedance mismatch: relational dbs ←→ OO languages
  - Interesting but ultimately failed (several reasons, see references)
- Object-relational: late 1980’s and early 1990’s
  - User-defined types, ops, functions, and access methods
- Semi-structured: late 1990’s to the present

Semi-structured Data Model

- Main idea: *schema-last*

- Examples:
  - XML
  - Json
  - Protobuf

- All use a *tree data model*

XML Syntax

```
<article mdate="2011-01-11" key="journals/acta/GoodmanS83">
   <author>Nathan Goodman</author>
   <author>Oded Shmueli</author>
   <title>NP-complete Problems Simplified on Tree Schemas.</title>
   <pages>171-178</pages>
   <year>1983</year>
   <journal>Acta Inf.</journal>
   <url>db/journals/acta/acta20.html#GoodmanS83</url>
</article>
```

Semi-structured, self-describing schema

JSon

Example from: http://www.jsonexample.com/

```
myObject = {
  "first": "John",
  "last": "Doe",
  "salary": 70000,
  "registered": true,
  "interests": [ "Reading", “Biking”, "Hacking" ]
}
```

Semi-structured, self-describing schema

Discussion of Semi-structured

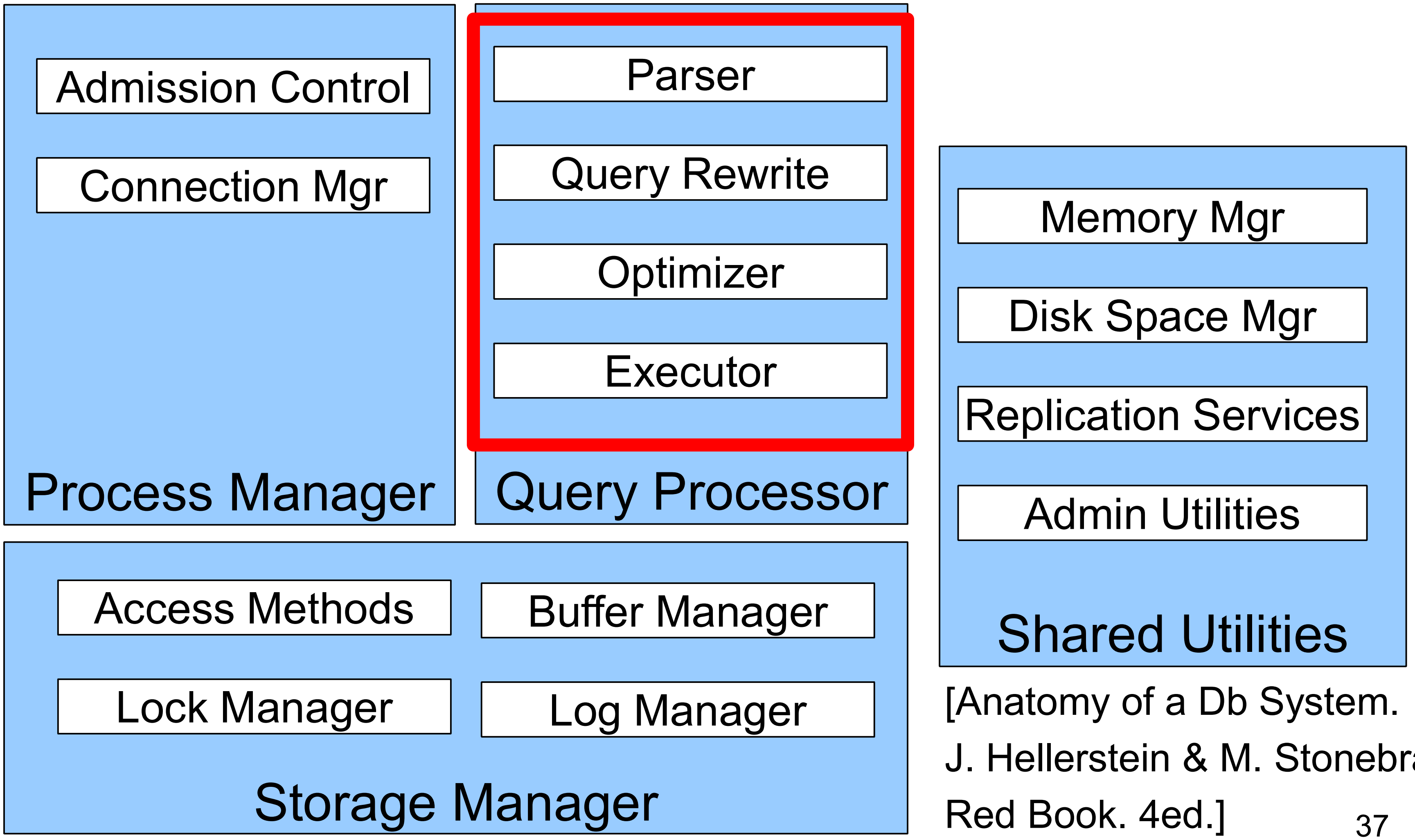
- Stonebraker (circa 1998): niche market
- Today (circa 2020): Json is common
- What changed? Data Science!

Outline for Today

- Discuss *Goes Around* paper

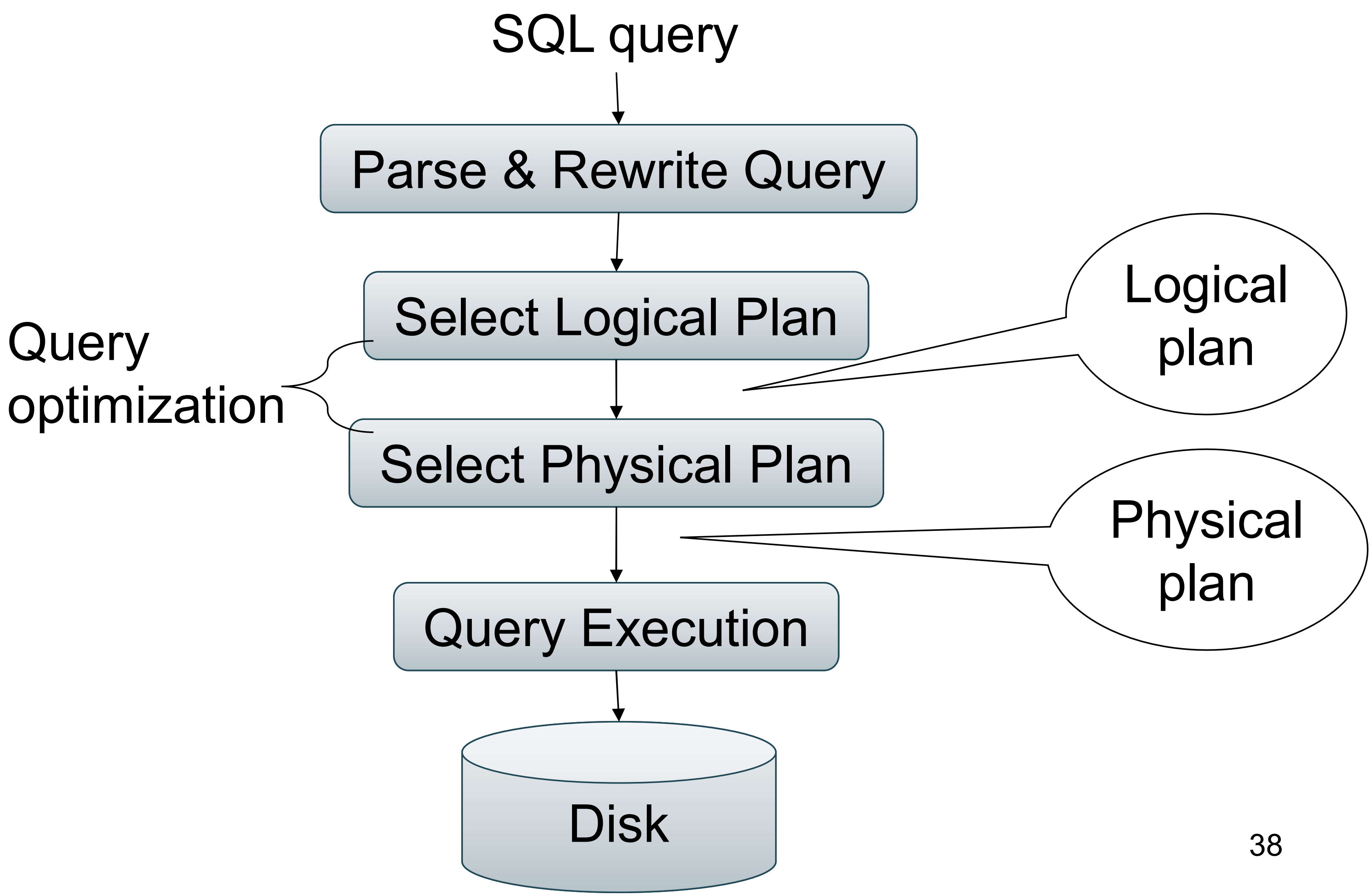
- Discuss query optimization
  - Major paper to read for next time
  - We continue query optimization next time

DBMS Architecture



[Anatomy of a Db System.
J. Hellerstein & M. Stonebraker.
Red Book. 4ed.]

Lifecycle of a Query



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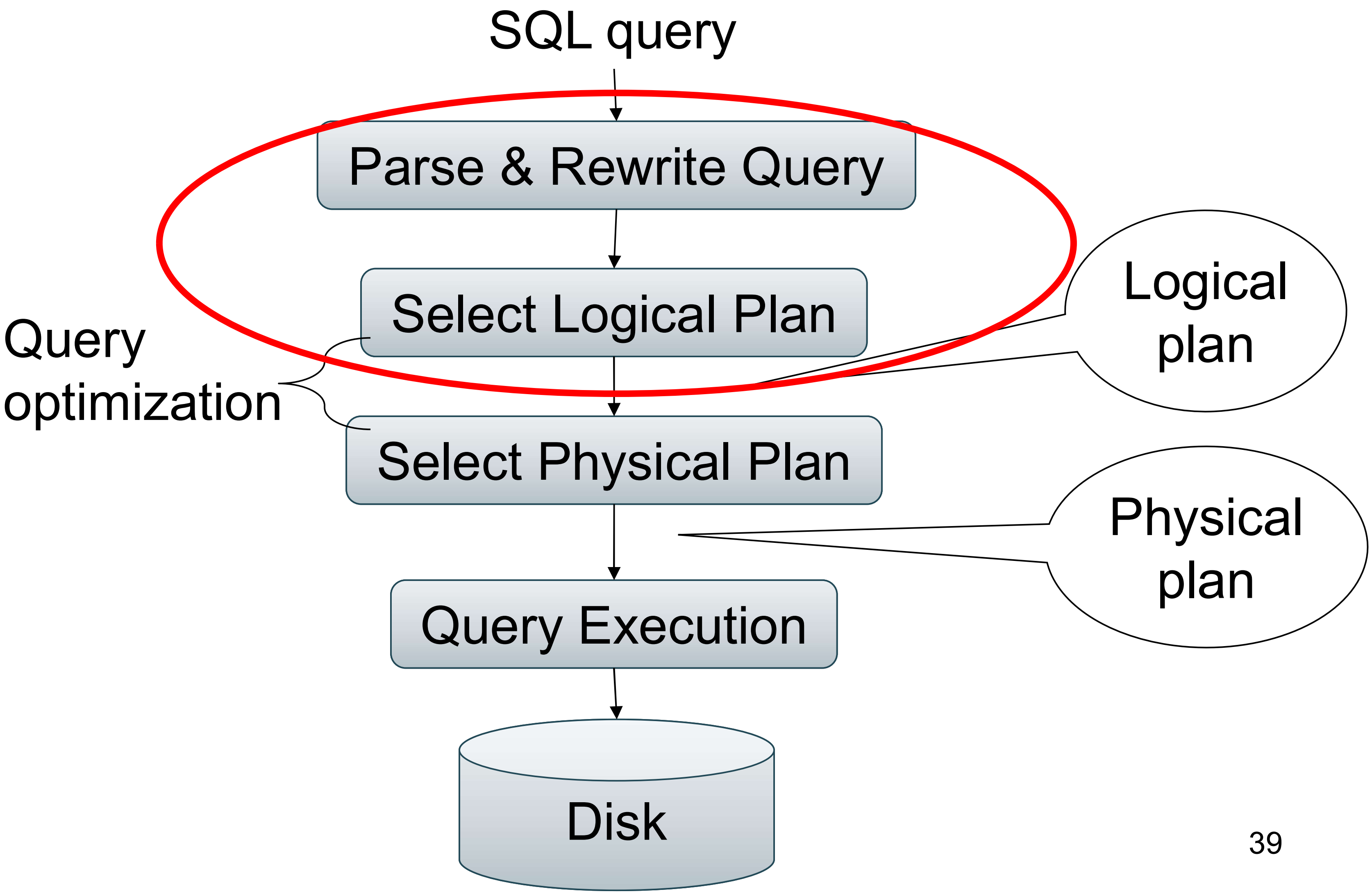

Relational Algebra

Relational Algebra

- A *set-at-a-time* algebra
- Inputs: relations; Output: relation
- E.g. join: R ⋈ S

RA details on next slides

Five Basic Relational Operators

- Selection: $\sigma_{\text{condition}}(S)$
- Projection: $\pi_{\text{list-of-attributes}}(S)$
- Union $(\cup)$
- Set difference $(-)$,
- Cross-product/cartesian product $(\times)$,
  Join: $R \bowtie_{\theta} S = \sigma_{\theta}(R \times S)$

Extended Operators of Relational Algebra

- Duplicate elimination (δ)
- Group-by/aggregate (ɣ)
- Sort operator (τ)

Supplier(sno,sname,scity,sstate)

Supply(sno,pno,price)

Part(pno,pname,psize,pcolor)

Logical Query Plan

- Is an expression in RA
- It specifies in which order to execute the operators

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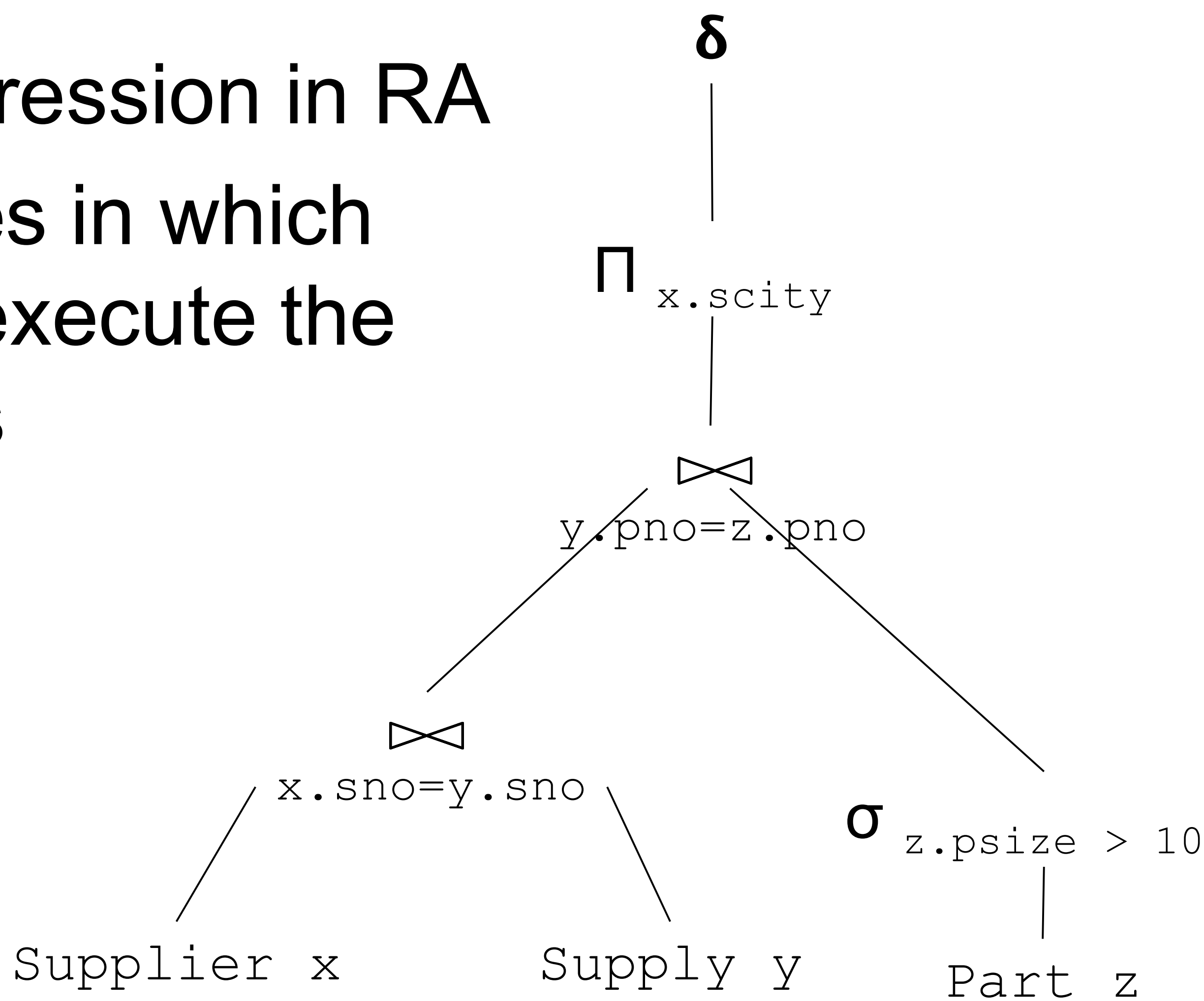

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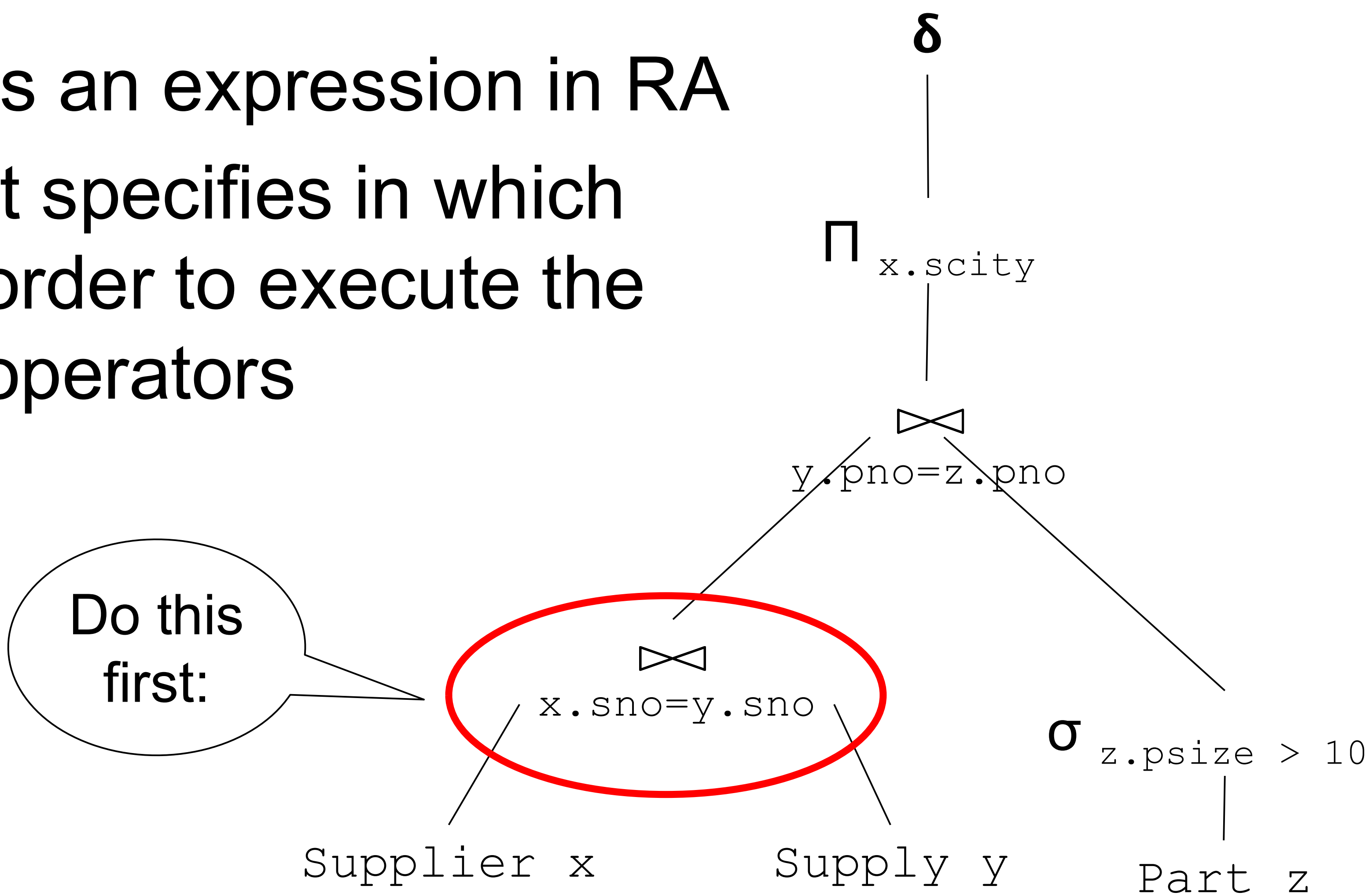

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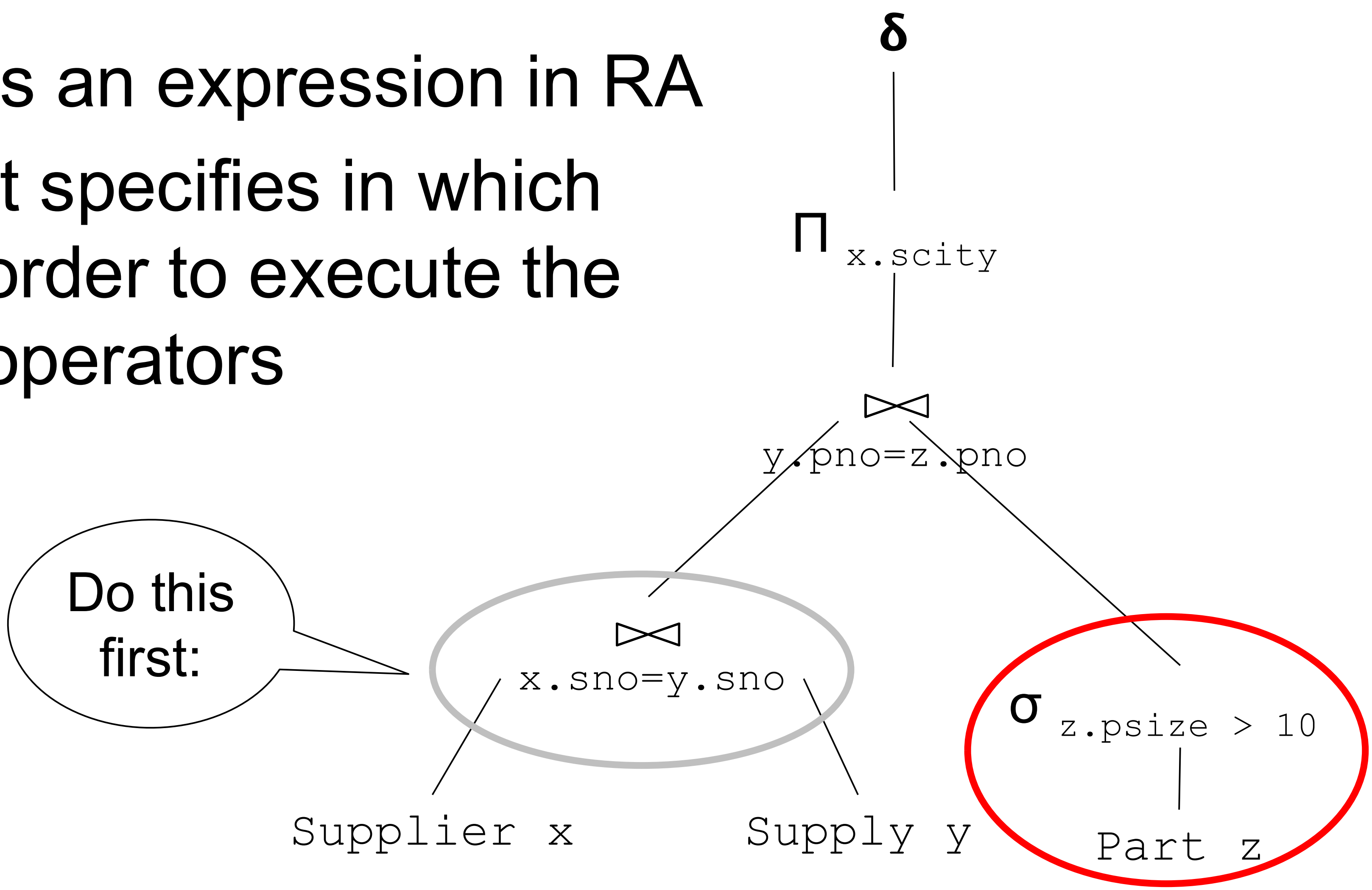

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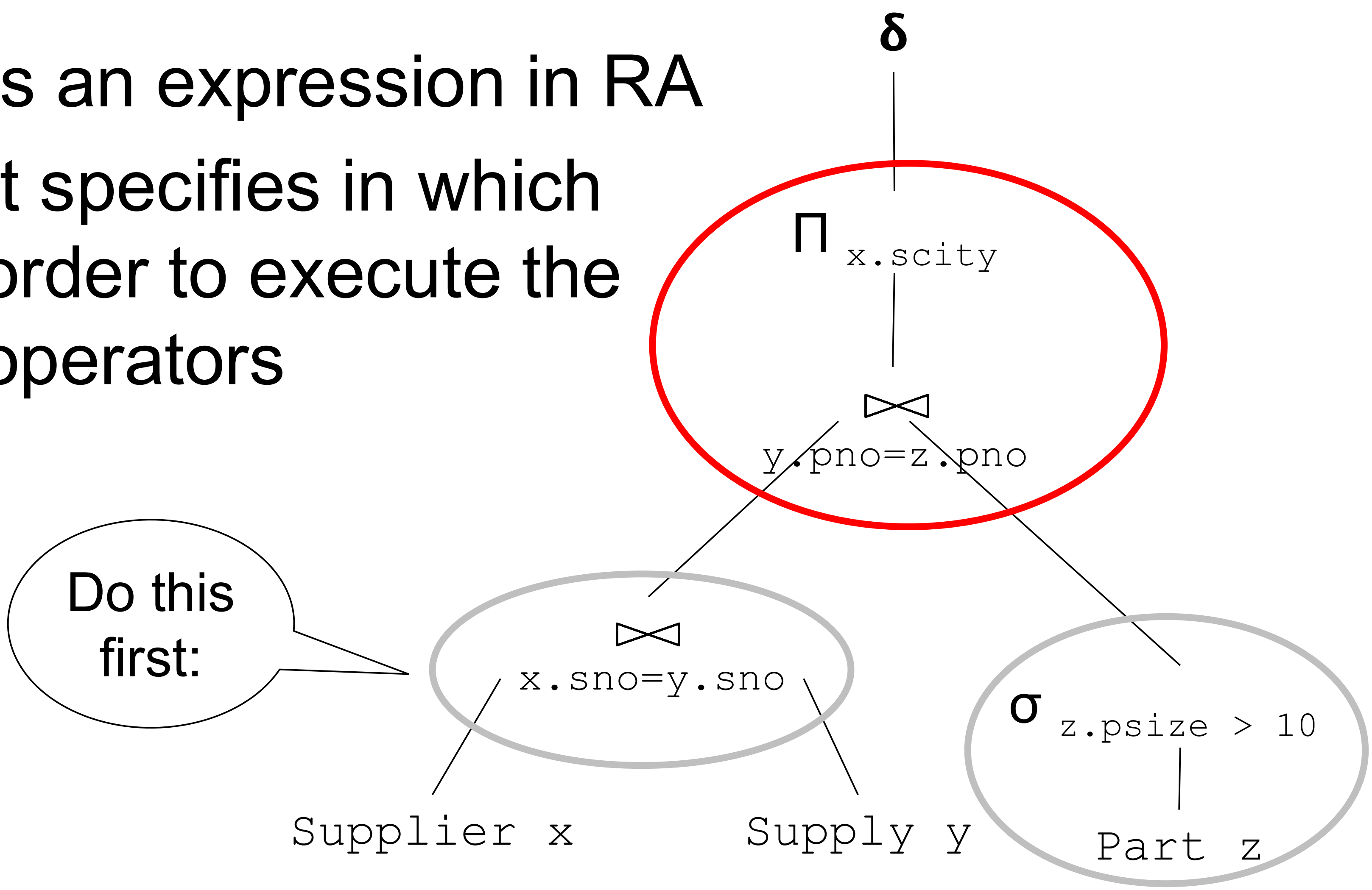

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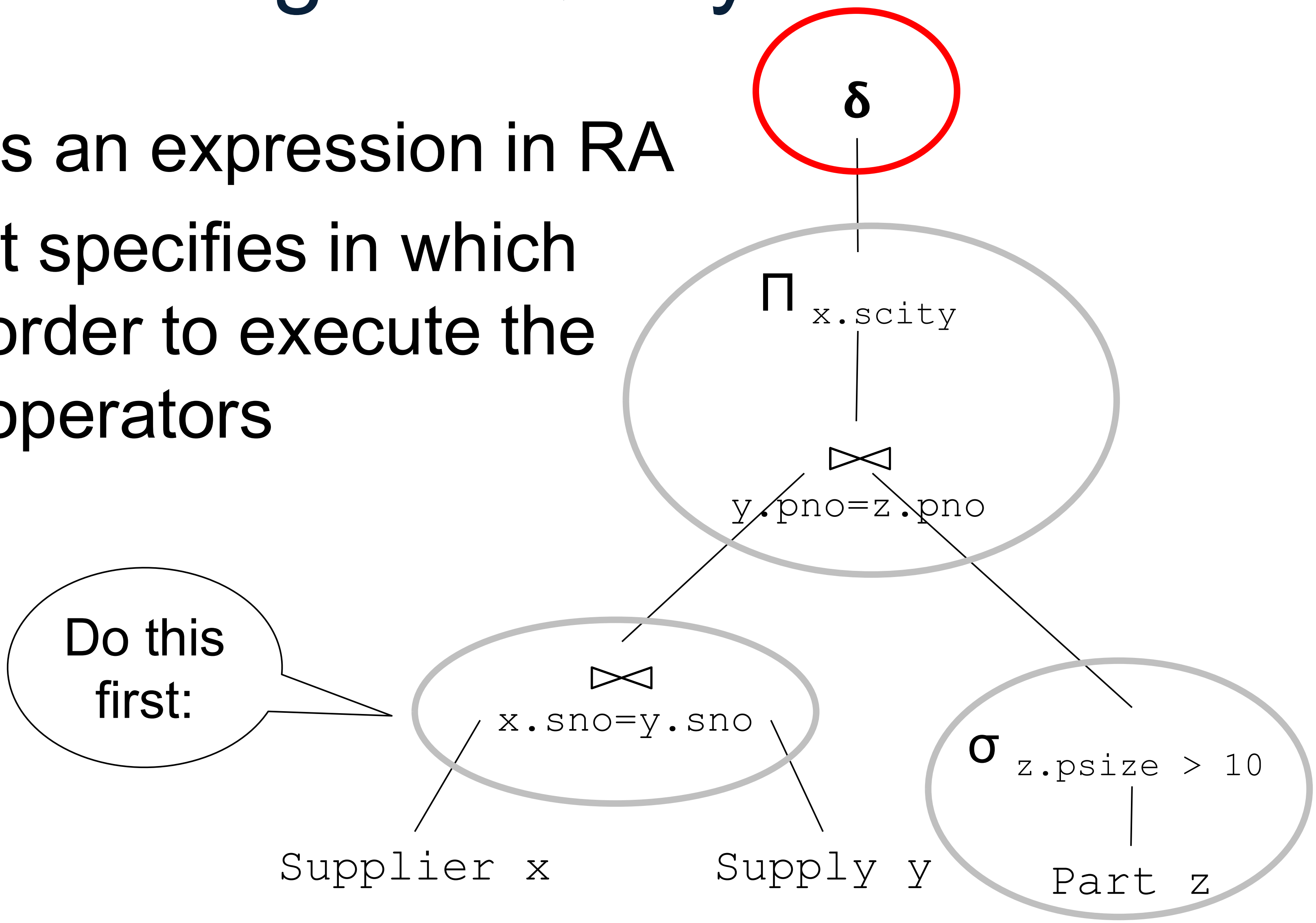


Converting SQL to RA

1. Convert FROM-WHERE to $\bowtie$ and σ

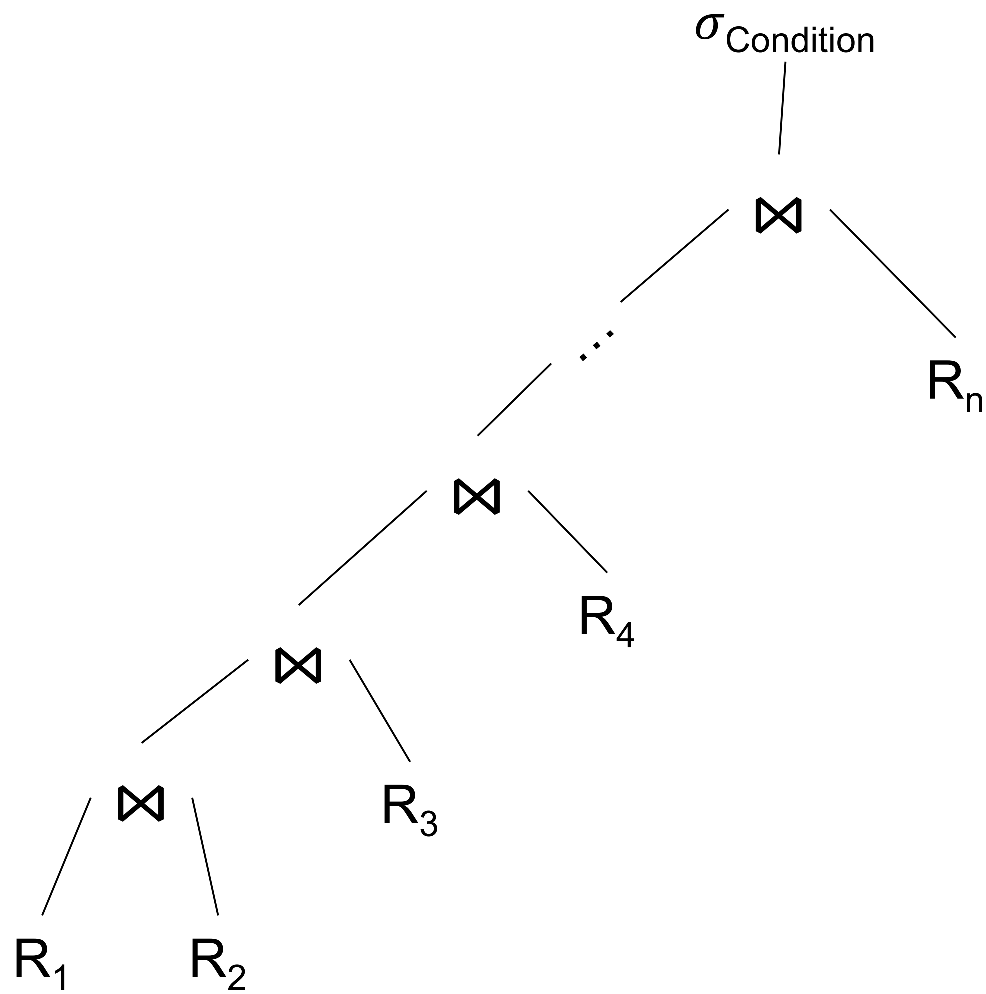
2. Convert GROUP-BY to γ

3. Convert HAVING to σ, SELECT to $\mathbf{\Pi}$

Note: Decorrelate queries (done first)

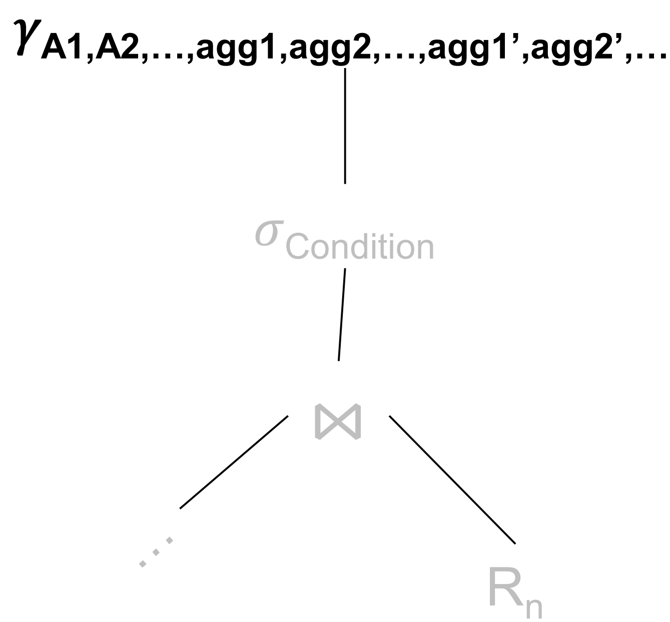
1. FROM-WHERE to ⋈-σ

SELECT …
FROM R1, R2, …
WHERE Condition
GROUP BY …
HAVING …



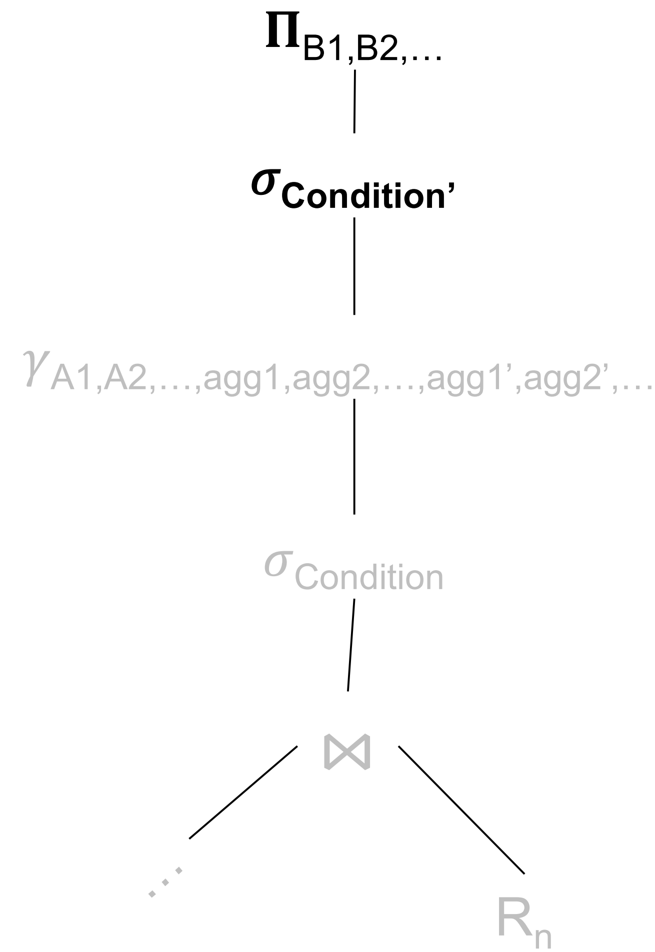
2. GROUP-BY to γ

SELECT …, agg_1,agg_2,…
FROM R1, R2, …
WHERE Condition
GROUP BY A_1, A_2,
HAVING …agg'_1, agg'_2,…



3. HAVING to σ, SELECT to Π

SELECT B1, B2,…, agg_1,…
FROM R1, R2, …
WHERE Condition
GROUP BY A_1, A_2,
HAVING Condition’



Supplier(sno,sname,scity,sstate)

Supply(sno,pno,price)

Part(pno,pname,psize,pcolor)

Example

Find max price of red products for each city that sold > 100 parts

Supplier(sno,sname,scity,sstate)

Supply(sno,pno,price)

Part(pno,pname,psize,pcolor)

Example

Find max price of red products for each city that sold > 100 parts

```
SELECT x.city, max(y.price)
FROM Supplier x, Supply y, Part z,
WHERE x.sno=y.sno and y.pno=z.pno
      and z.pcolor='red'
GROUP BY x.city
HAVING count(*) > 100
```

Supplier(sno,sname,scity,sstate)

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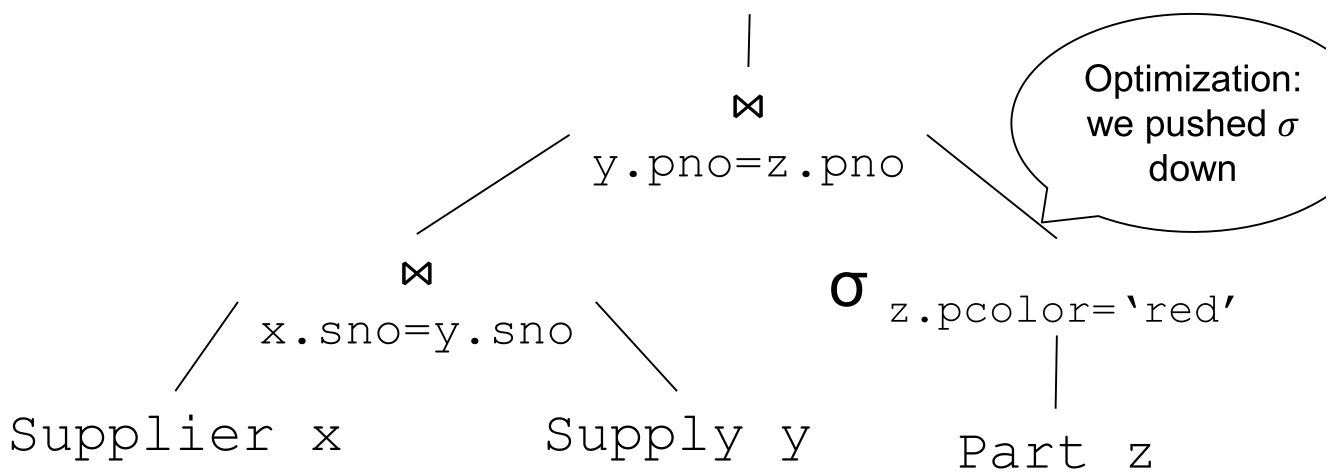

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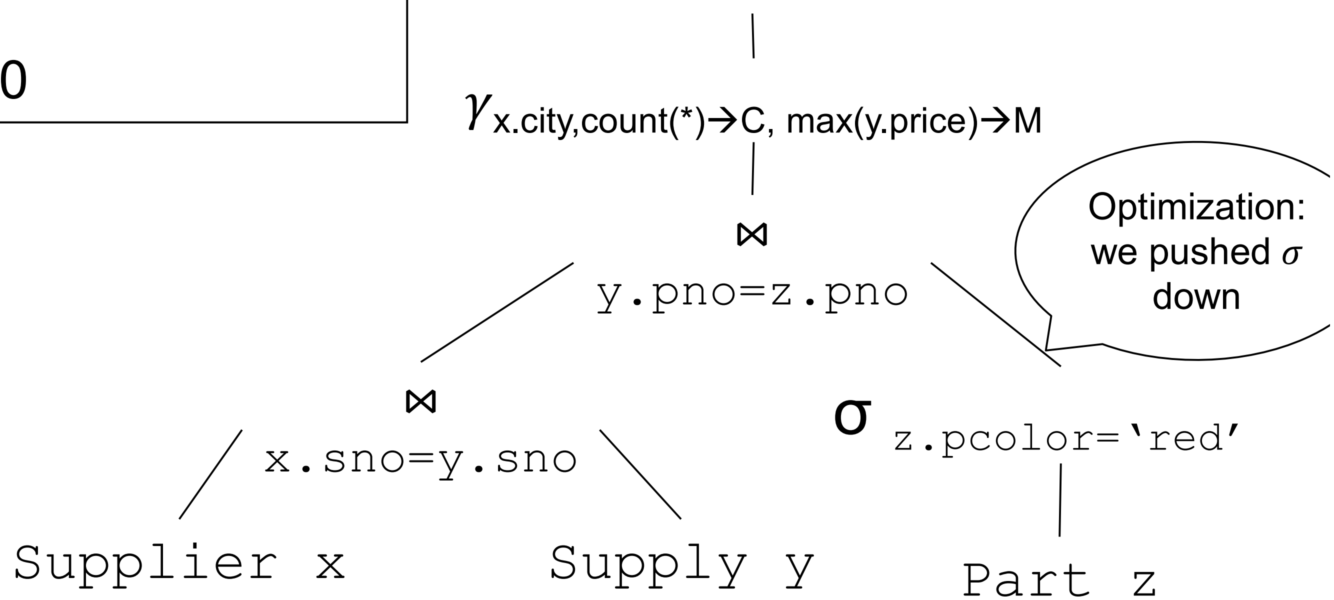

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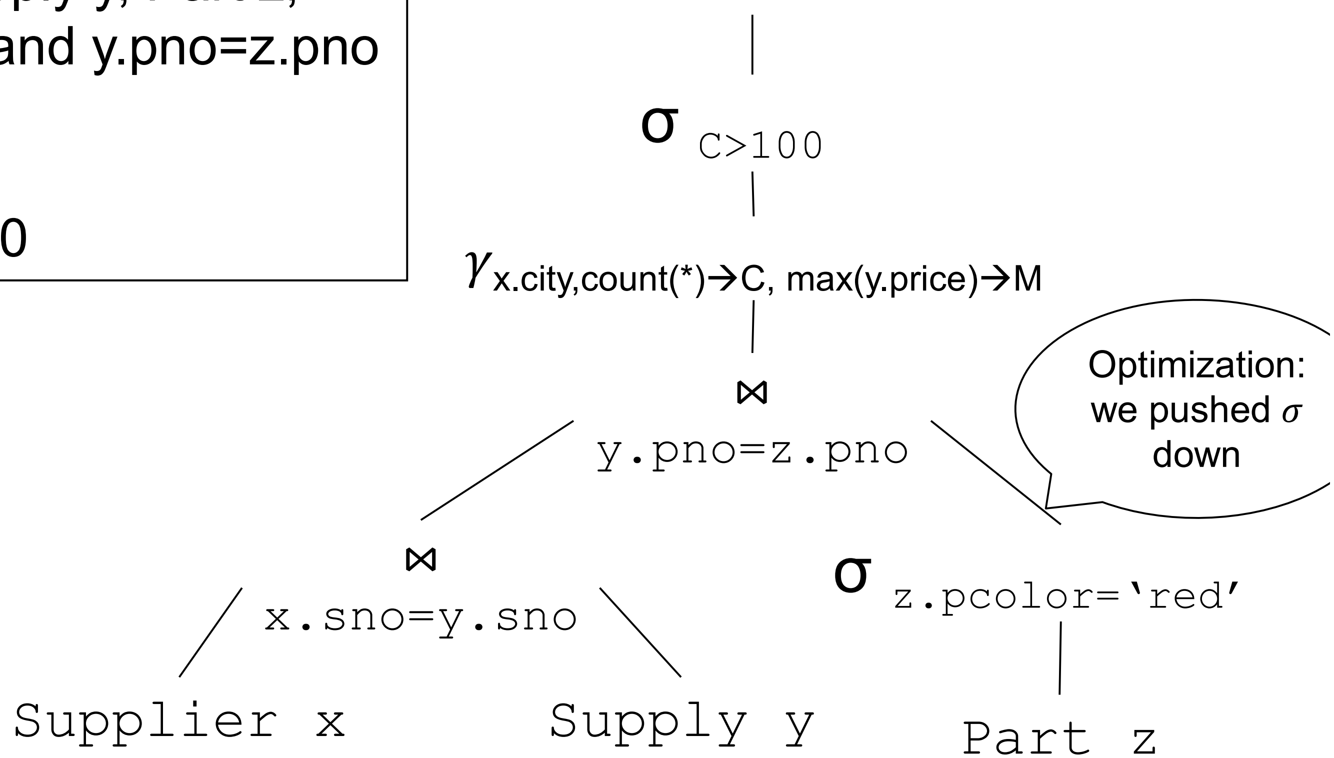

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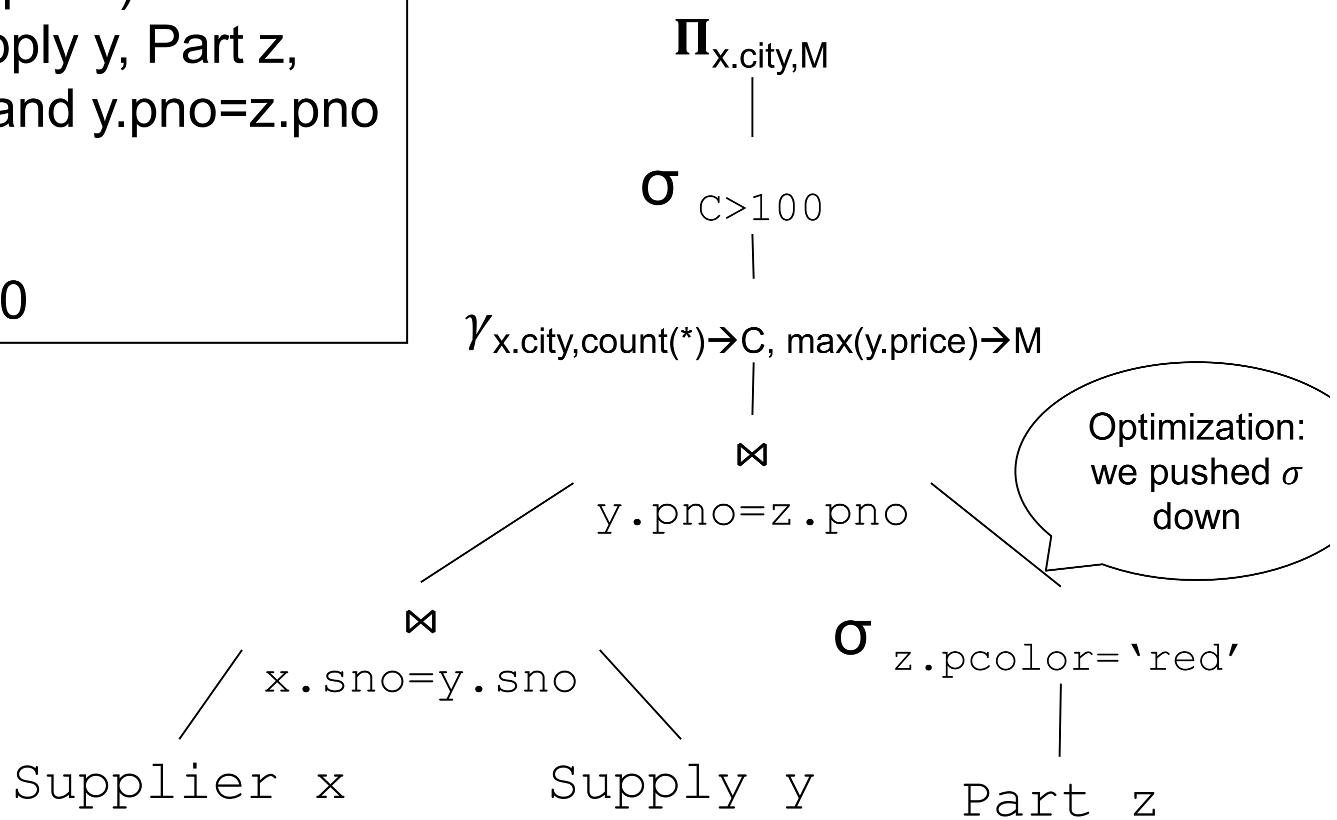

Decorrelation

- A *correlated SQL subquery* is one that depends on a variable of outer query
- This cannot be converted to RA, because does not have variables
- Solution: decorrelation

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

4.Decorrelation

Find all suppliers in ‘WA’ that supply only parts under $100

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

4.Decorrelation

```
SELECT  Q.sno
FROM Supplier Q
WHERE  Q.sstate = 'WA'
    and not exists
      (SELECT *
       FROM Supply P
       WHERE P.sno = Q.sno
           and P.price > 100)
```

Find all suppliers in 'WA' that supply only parts under $100

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

4.Decorrelation

```
SELECT  Q.sno
FROM Supplier Q
WHERE  Q.sstate = ‘WA’
    and not exists
       (SELECT *
        FROM Supply P
        WHERE P.sno = Q.sno
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```

Correlation !

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

4.Decorrelation

```
SELECT  Q.sno
FROM Supplier Q
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    and not exists
      (SELECT *
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       WHERE P.sno = Q.sno
             and P.price > 100)
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De-Correlation

```
SELECT  Q.sno
FROM Supplier Q
WHERE  Q.sstate = 'WA'
    and Q.sno not in
      (SELECT P.sno
       FROM Supply P
       WHERE P.price > 100)
```

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

4.Decorrelation

Un-nesting

```
SELECT  Q.sno
FROM Supplier Q
WHERE  Q.sstate = 'WA'
    and Q.sno not in
       (SELECT P.sno
        FROM Supply P
        WHERE P.price > 100)
```

```
(SELECT  Q.sno
 FROM Supplier Q
 WHERE  Q.sstate = 'WA')
   EXCEPT
 (SELECT P.sno
  FROM Supply P
  WHERE P.price > 100)
```

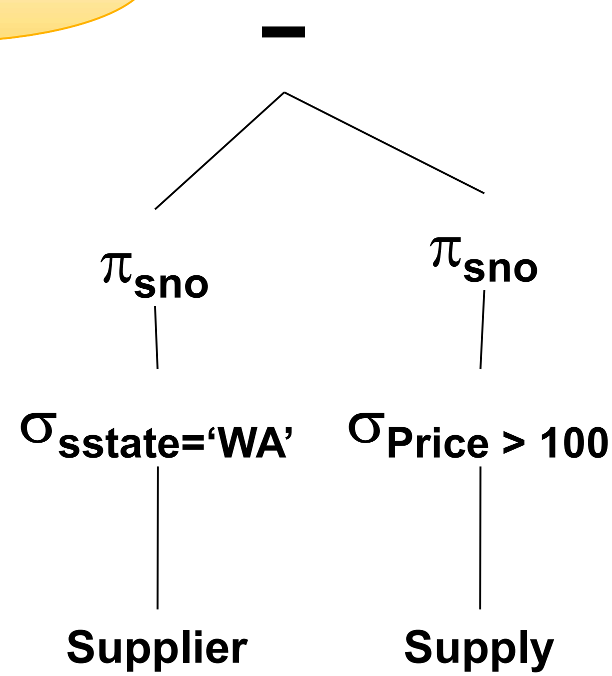
EXCEPT = set difference

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

4.Decorrelation

```
(SELECT  Q.sno
 FROM Supplier Q
 WHERE  Q.sstate = 'WA')
   EXCEPT
 (SELECT P.sno
   FROM Supply P
   WHERE P.price > 100)
```

Finally…

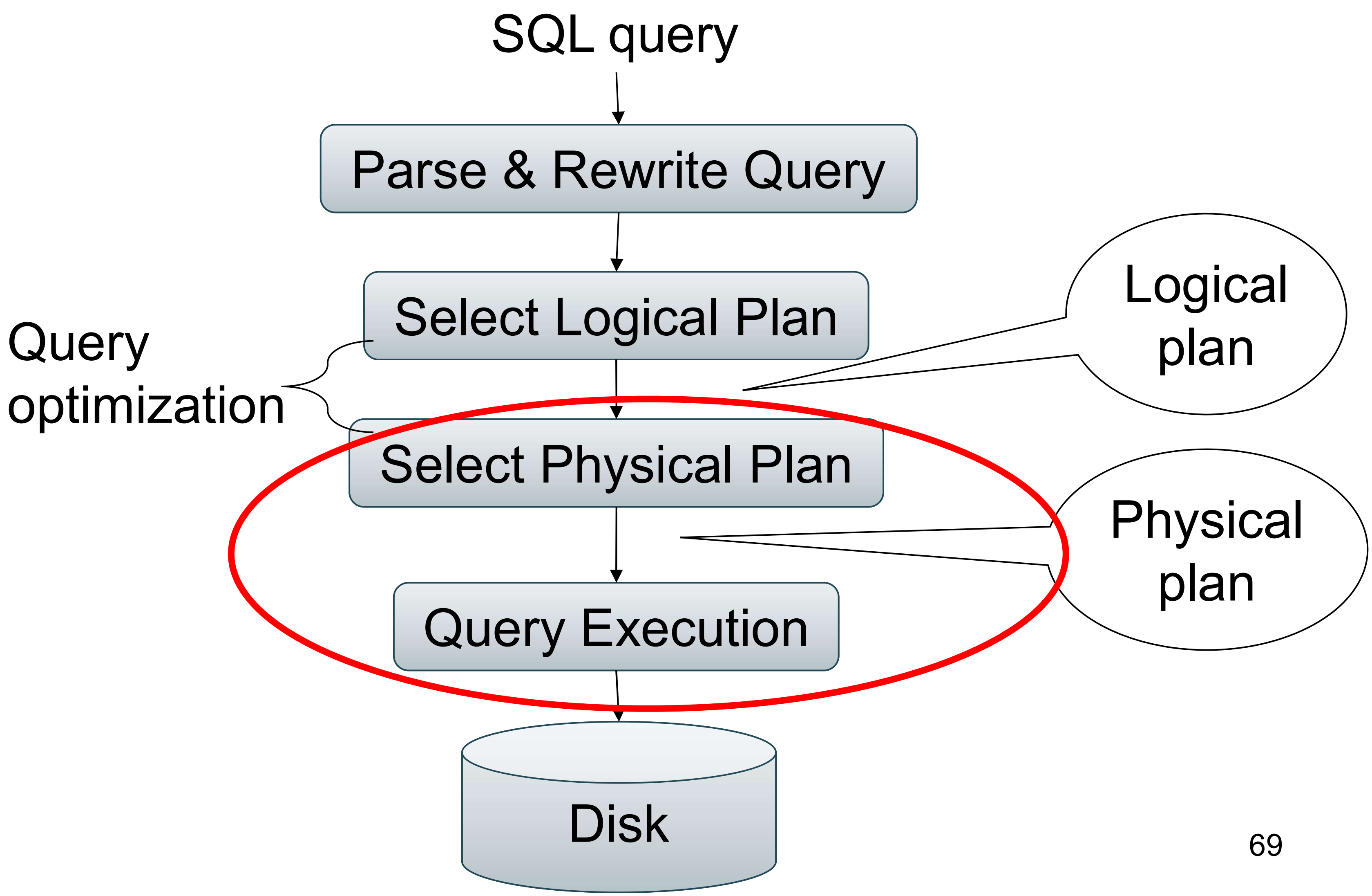


SQL to RA: Summary

- SQL query to Relational Algebra Plan, which is further optimized
- This is a *logical* plan; specifies the order
- Next: *physical* plan; specifies the implementation

Physical Operators

Lifecycle of a Query



Physical Operators

- Each logical operator in RA can be implemented in multiple ways
- An implementation: a *physical operator*

Physical Operators

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  - Physical operators for σ: [in class]
  - Physical operators for ∪: [in class]

Physical Operators

- Each logical operator in RA can be implemented in multiple ways
- An implementation: a *physical operator*
  - Physical operators for σ: [in class]
  - Physical operators for $\cup$: [in class]
  - Physical operators for $\bowtie$: next slides
  - Physical operators for γ, δ: not discussed
  - Physical operators for - : not discussed

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

Join

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

Three algorithms:

1.
2.
3.

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

Join

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

Three algorithms:

1. Nested Loops
2. Hash-join
3. Merge-join

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

1. Nested Loop Join

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

```
for x in Supplier do
   for y in Supply do
      if x.sid = y.sid
         then output(x,y)
```

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

1. Nested Loop Join

Logical operator:

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for x in Supplier do
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If |R|=|S|=n,
what is the runtime?

Supplier(sid, sname, scity, sstate)
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1. Nested Loop Join

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If |R|=|S|=n,
what is the runtime?

$O(n^2)$

Supplier(<u>sid</u>, sname, scity, sstate)
Supply(<u>sid, pno</u>, quantity)

"Hash Tables"

Key/value pairs; e.g. (sid, Supply)

- insert(k, v) duplicate allowed
- find(k) = returns the ***list*** of values v
- Time is O(1), but can become O(n)
- Collisions!
- Don't write your own hash function

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

2. Hash Join

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

Build phase

```
for x in Supplier do
    insert(x.sid, x)
```

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

2. Hash Join

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

Build phase

```
for x in Supplier do
      insert(x.sid, x)
```

Probe phase

```
for y in Supply do
      x = find(y.sid);
      output(x,y);
```

Supplier(<u>sid</u>, sname, scity, sstate)
Supply(<u>sid, pno</u>, quantity)

2. Hash Join

Logical operator:

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for x in Supplier do
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      output(x,y);
```

If |R|=|S|=n,
what is the runtime?

O(n)

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

2. Hash Join

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

Change join order

```
for y in Supply do
      insert(y.sid, y)

for x in Supplier do ??
```

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

2. Hash Join

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

Change join order

```
for y in Supply do
     insert(y.sid, y)

for x in Supplier do
   for y in find(x.sid) do
        output(x,y);
```

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

2. Hash Join

Logical operator:

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Change join order

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Can be $O(n^2)$ why?

Supplier(sid, sname, scity, sstate)
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2. Hash Join

Why would we change the order?

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

2. Hash Join

Why would we change the order?

When |Supply| << |Supplier|

Change join order

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

```
for y in Supply do
     insert(y.sid, y)

for x in Supplier do
    for y in find(x.sid) do
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```

If |R|=|S|=n,
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Can be $O(n^2)$ why?

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

3. Merge Join

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

```
Sort(Supplier); Sort(Supply);
x = Supplier.first();
y = Supply.first();
```

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

3. Merge Join

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

```
Sort(Supplier); Sort(Supply);
x = Supplier.first();
y = Supply.first();
while y != NULL do
  case:
    x.sid < y.sid: ???
    x.sid = y.sid: ???
    x.sid > y.sid: ???
```

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

3. Merge Join

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

```
Sort(Supplier); Sort(Supply);
x = Supplier.first();
y = Supply.first();
while y != NULL do
  case:
    x.sid < y.sid: x = x.next()
    x.sid = y.sid: ???
    x.sid > y.sid: ???
```

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

3. Merge Join

Logical operator:

Supplier $\bowtie_{sid=sid}$ Supply

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    x.sid = y.sid: output(x,y); y = y.next();
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Supply(sid, pno, quantity)

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If |R|=|S|=n,
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    x.sid = y.sid: output(x,y); y = y.next();
    x.sid > y.sid: y = y.next();
```

If |R|=|S|=n,
what is the runtime?

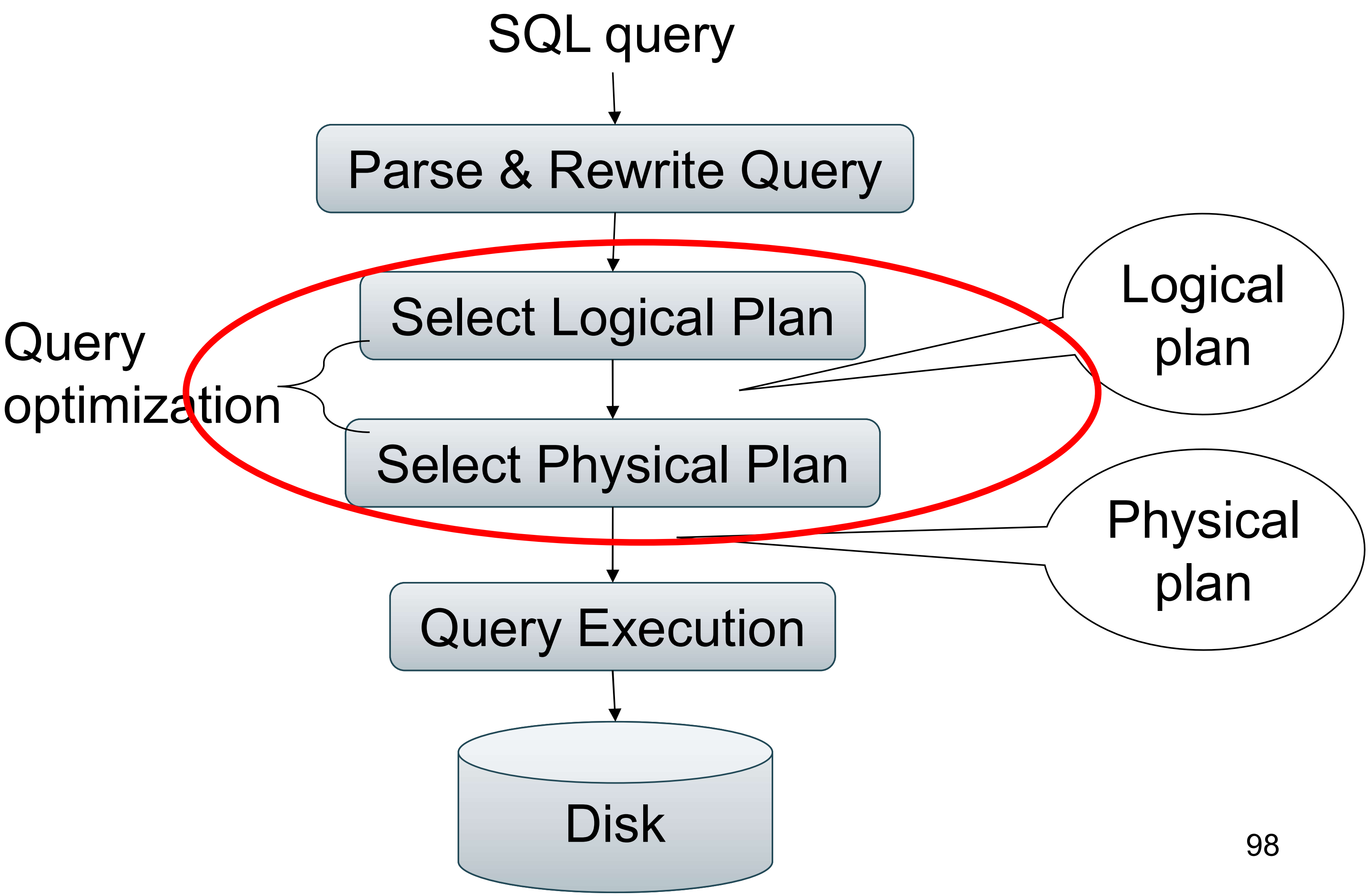
O(n log(n))
(because sorting…)

Summary of Physical Operators

- σ: on-the-fly
- $\cup$: concatenate, then apply δ
- $\bowtie$: nested-loop join, hash-join, merge-join
- γ, δ: nested-loop, hash-based, sort-based
- - : nested-loop, hash-based, sort-based

Query Optimizer

Lifecycle of a Query



Query Optimization

1. Search space

2. Cardinality and cost estimation

3. Plan enumeration algorithms (next time)

Search Space

- Search space = set of rewrite rules that the optimizer implements
- E.g. SQL Server has 400+ rules

We discuss a few basic rewrite rules next

Supplier(<u>sid</u>, sname, scity, sstate)

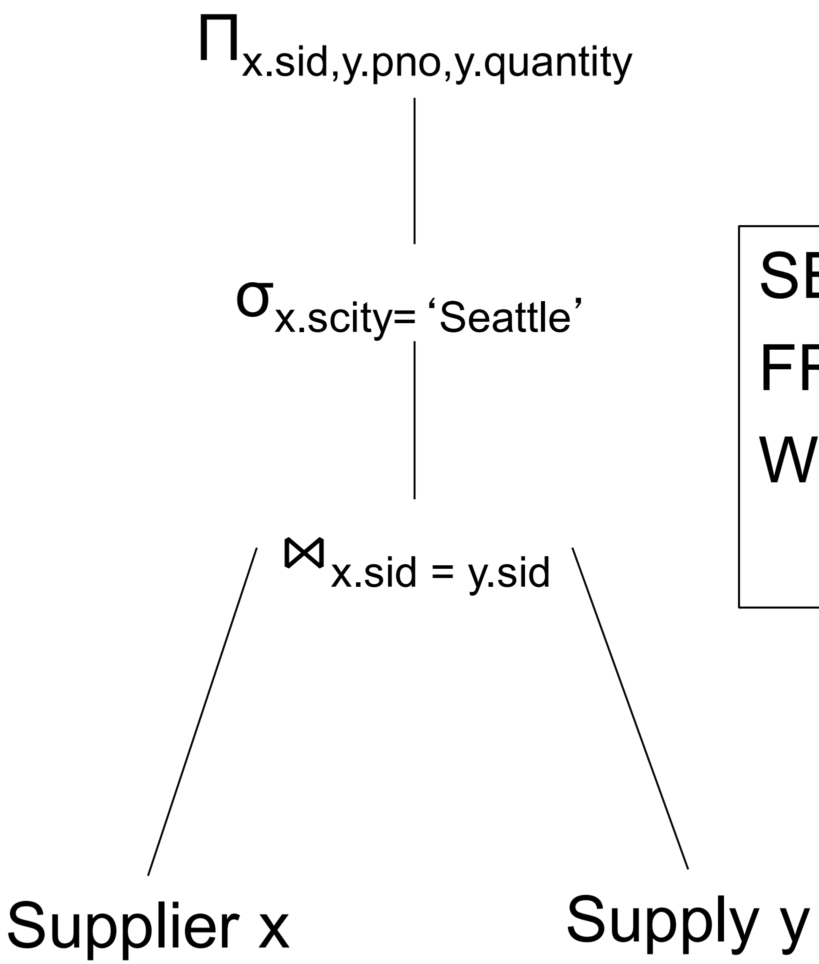
Supply(<u>sid, pno</u>, quantity)

Example Optimization

```
SELECT x.sid, y.pno, y.quantity
FROM.   Supplier x, Supply y
WHERE x.sid = y.sid
        and x.scity = ‘Seattle’
```

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

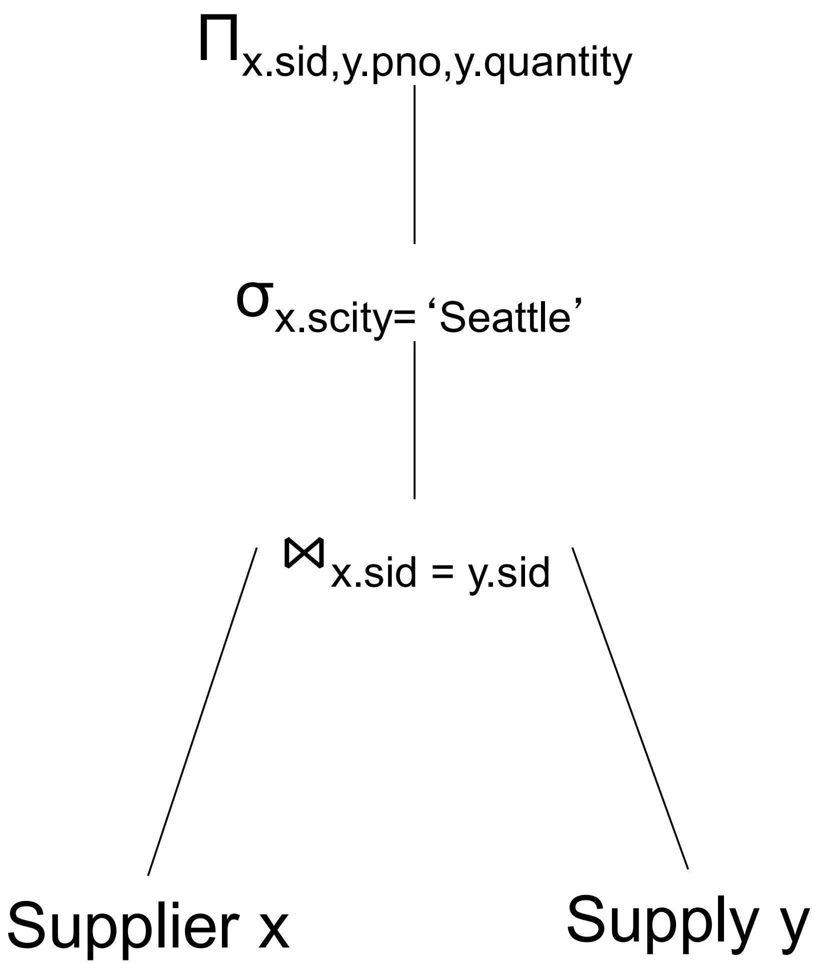
Example Optimization




```
SELECT x.sid, y.pno, y.quantity
FROM.   Supplier x, Supply y
WHERE x.sid = y.sid
      and x.scity = 'Seattle'
```

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

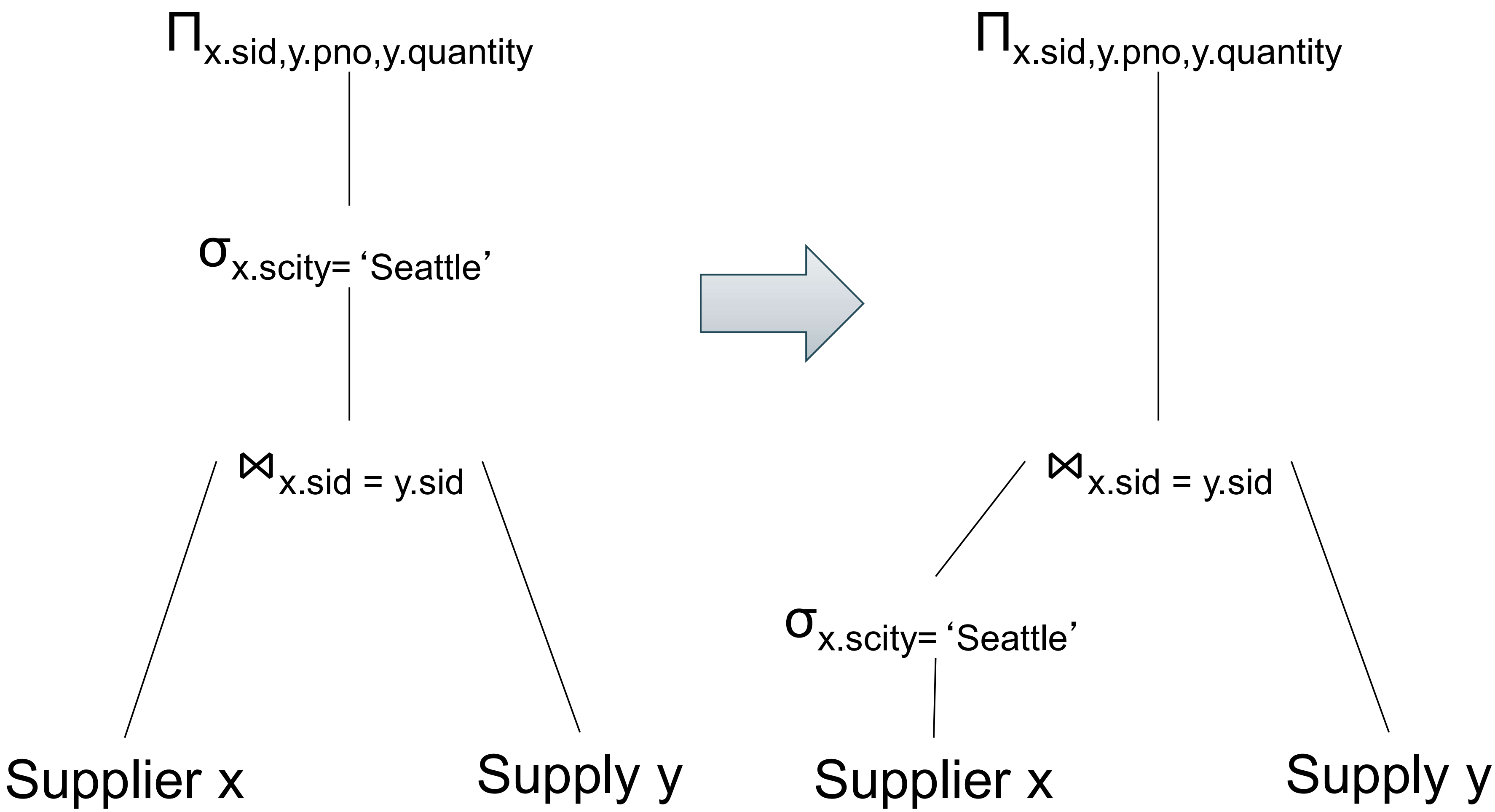
Push Selections Down



Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Push Selections Down



Supplier(<u>sid</u>, sname, scity, sstate)

Supply(<u>sid, pno</u>, quantity)

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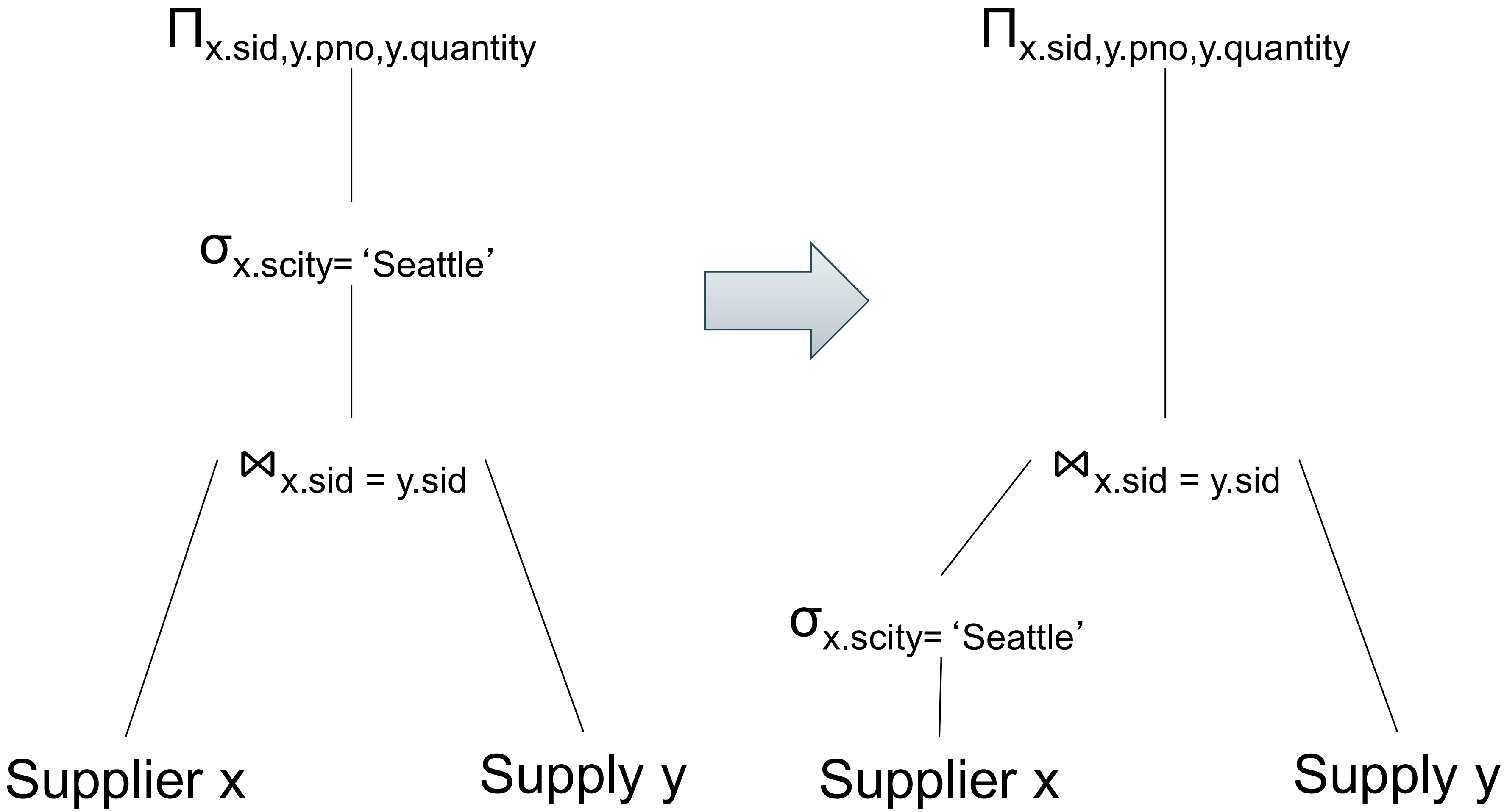
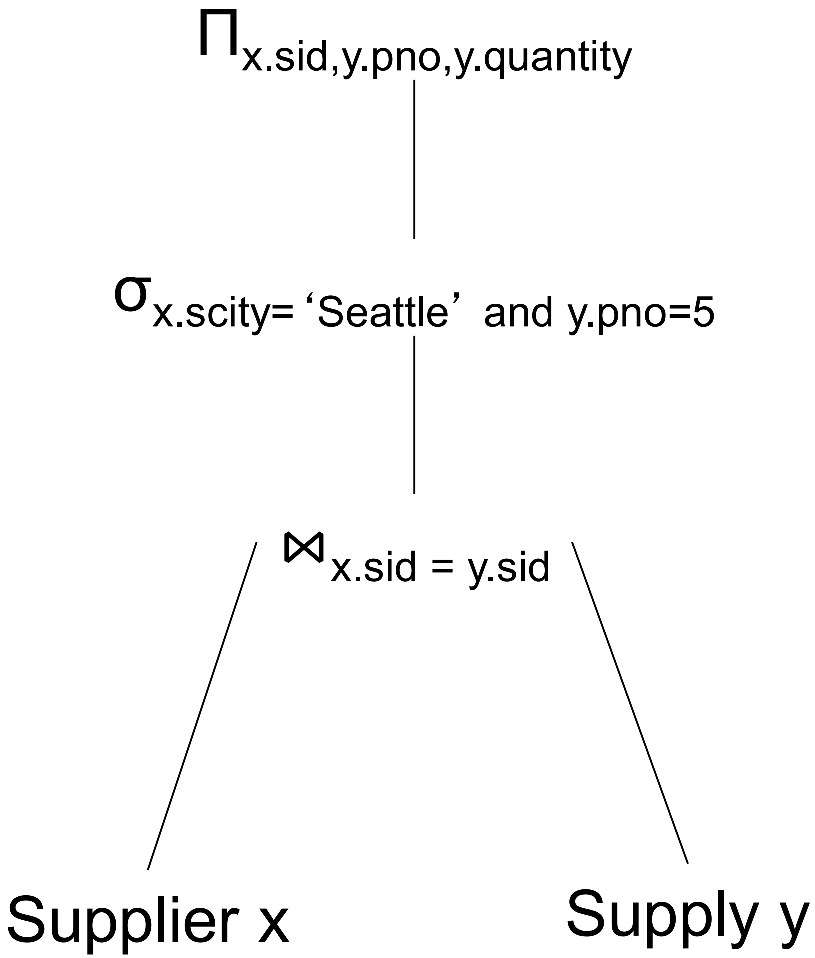


$\sigma_C(R \bowtie S) = \sigma_C(R) \bowtie S$ when C refers only to R

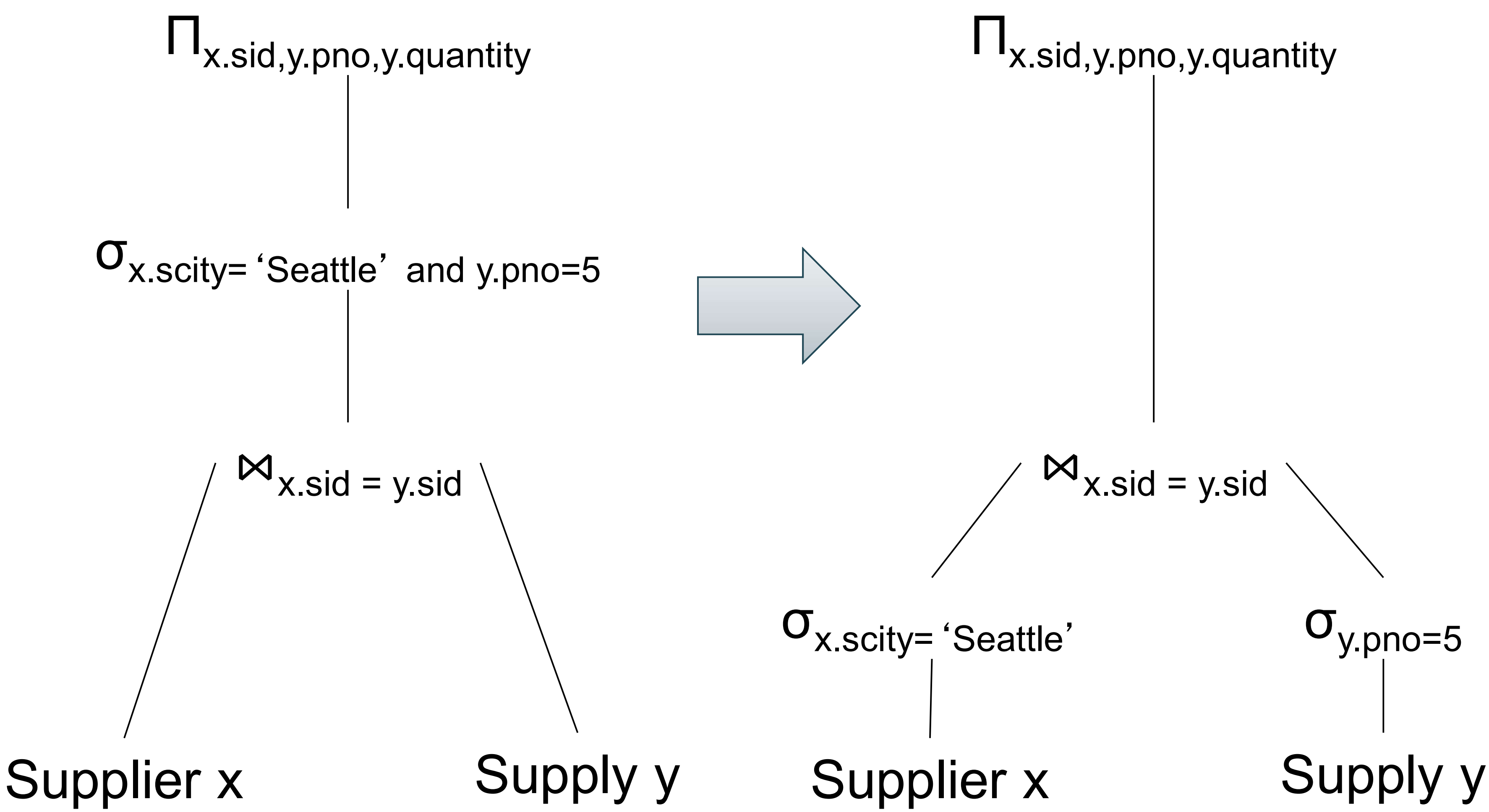
Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)

Push Selections Down



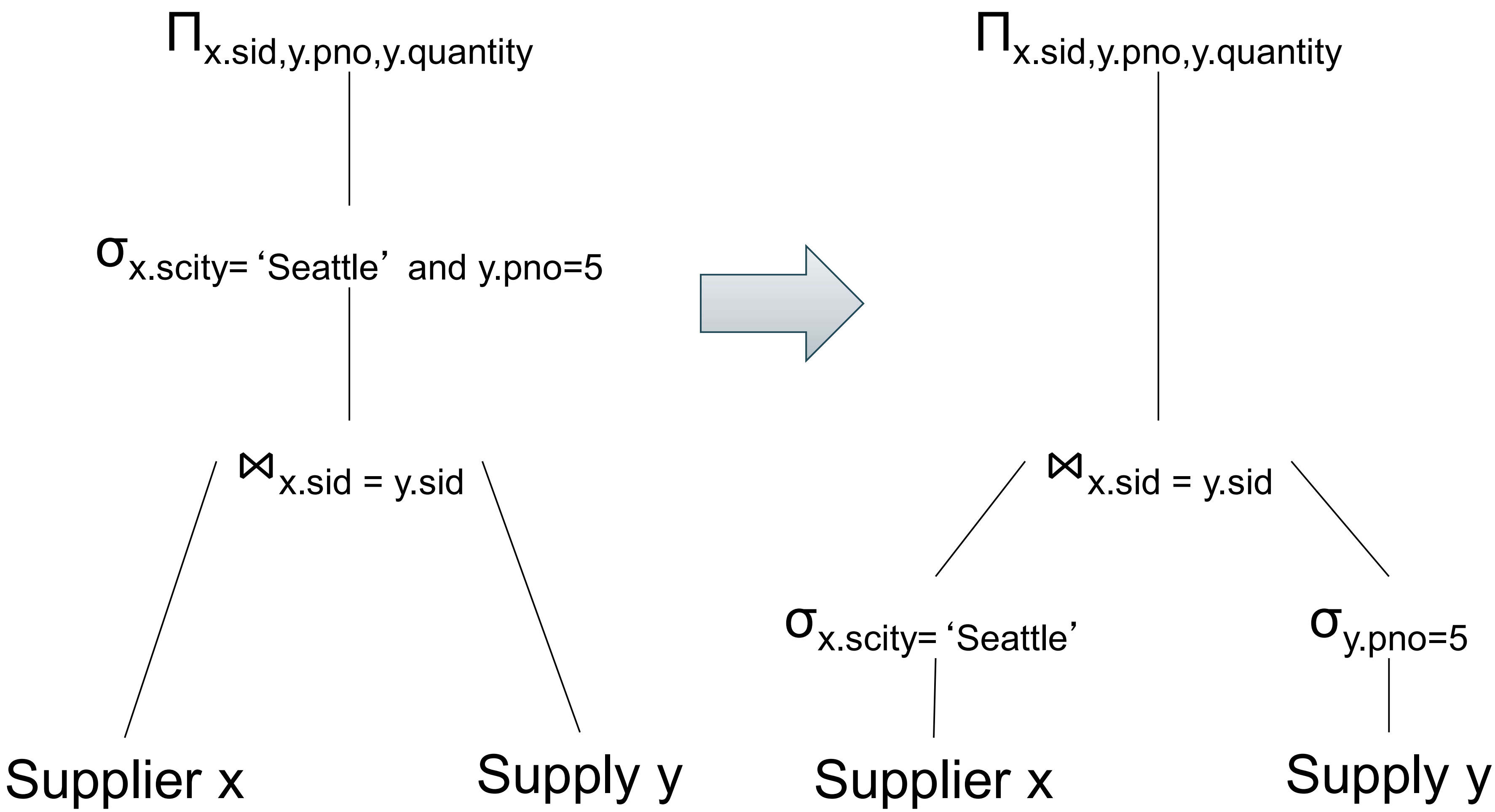
Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)

Push Selections Down



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

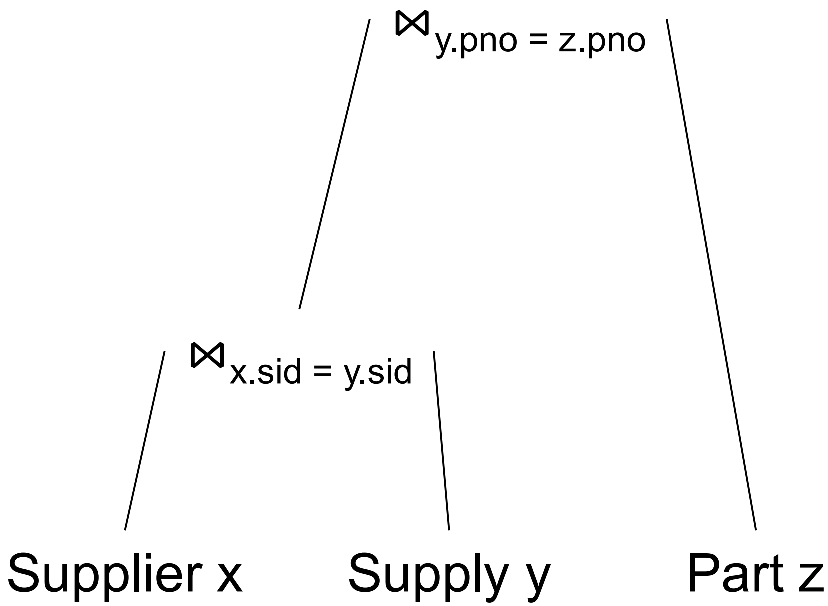
Push Selections Down



$\sigma_{C1 \text{ and } C2}(R \bowtie S) = \sigma_{C1}(\sigma_{C2}(R \bowtie S)) = \sigma_{C1}(R \bowtie \sigma_{C2}(S)) = \sigma_{C1}(R) \bowtie \sigma_{C2}(S)$

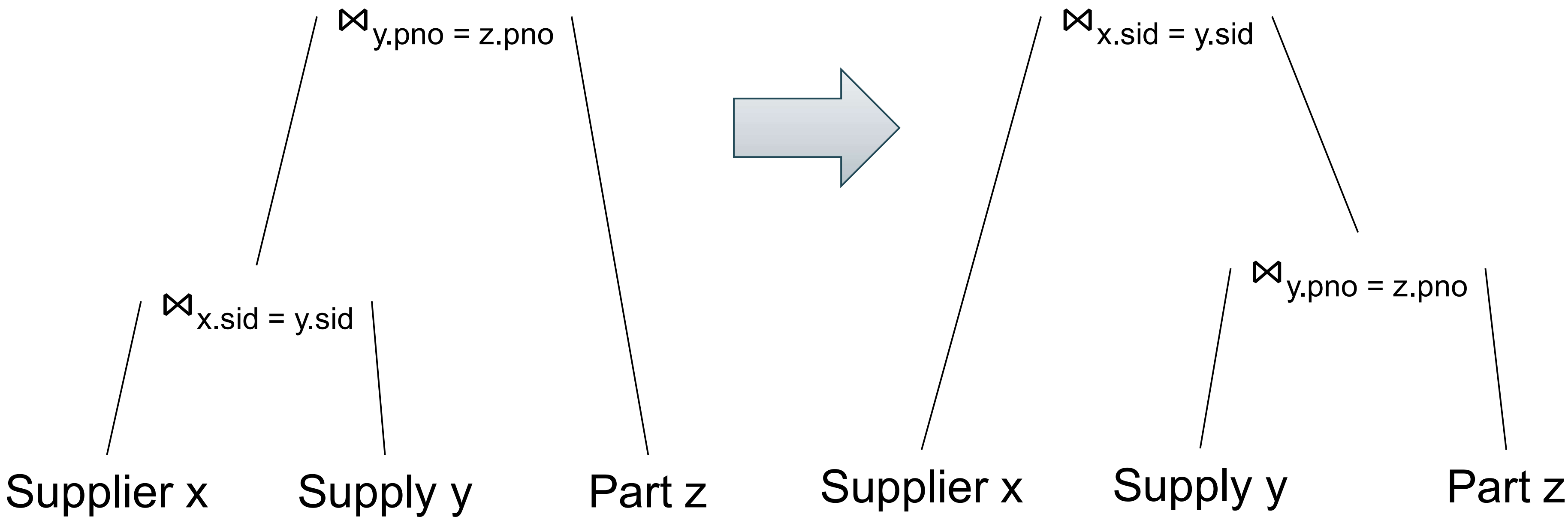
Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)
Part(pno, pname, pprice)

Join Reorder



Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)
Part(pno, pname, pprice)

Join Reorder

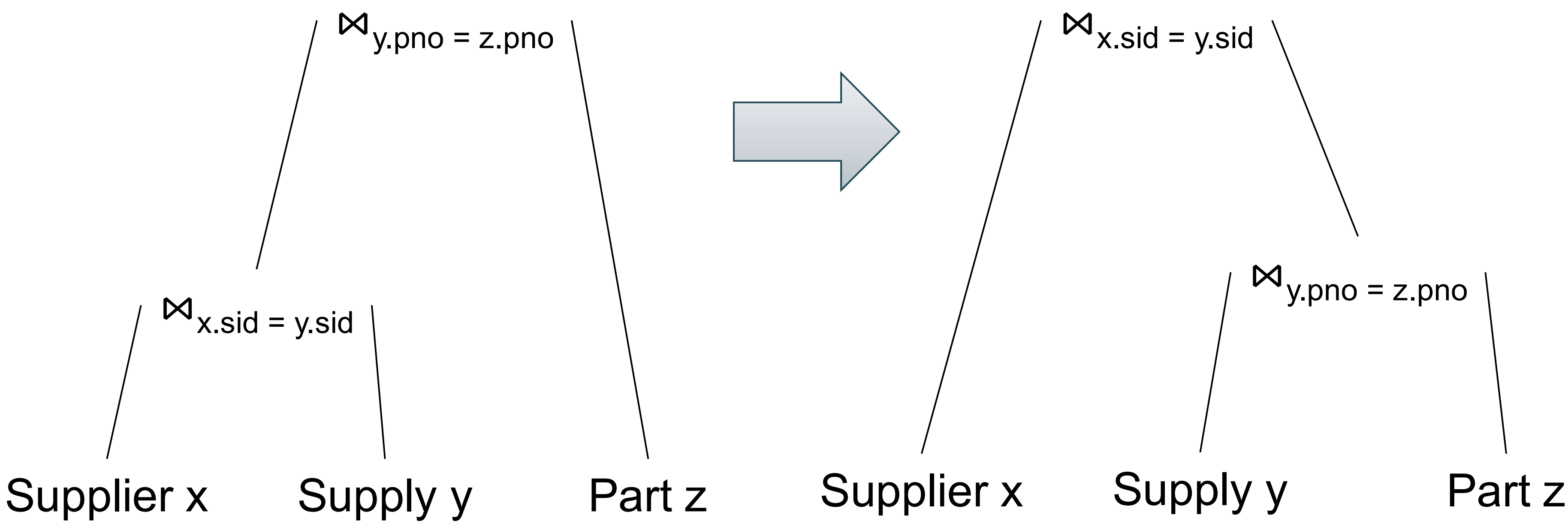


Supplier(<u>sid</u>, sname, scity, sstate)

Supply(<u>sid, pno</u>, quantity)

Part(<u>pno</u>, pname, pprice)

Join Reorder



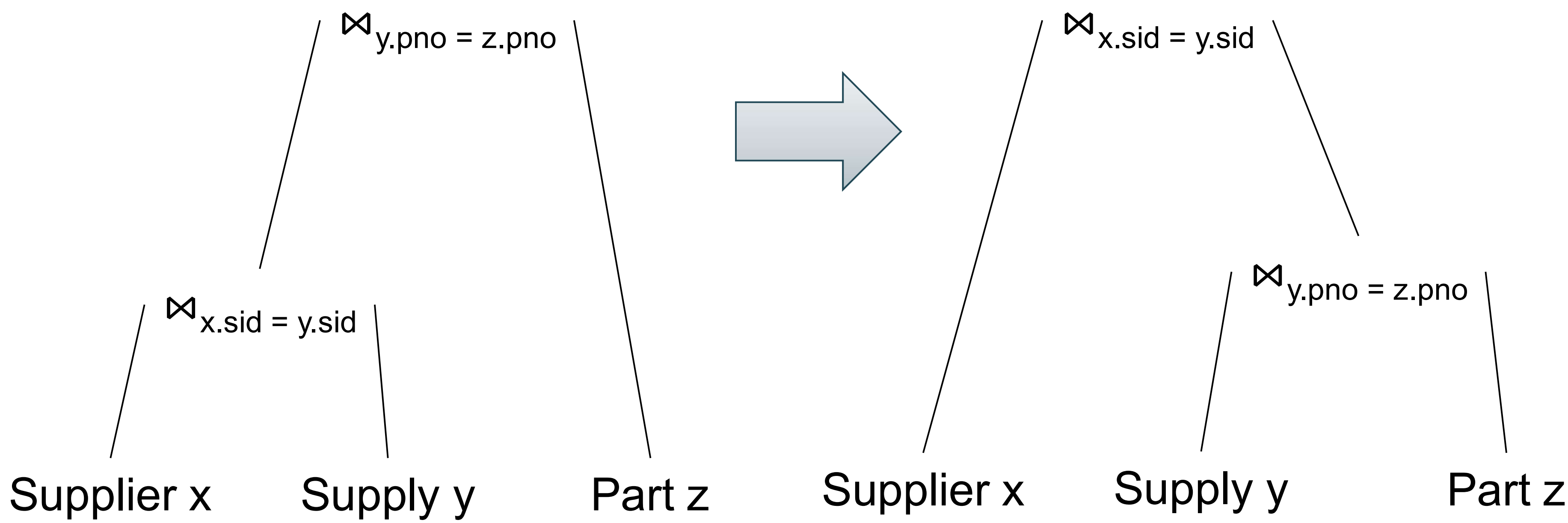
$(R \bowtie S) \bowtie T = R \bowtie (S \bowtie T)$

$R \bowtie S = S \bowtie R$

Supplier(<u>sid</u>, sname, scity, sstate)
Supply(<u>sid, pno</u>, quantity)
Part(<u>pno</u>, pname, pprice)

Join Reorder

When is one plan better than the other?



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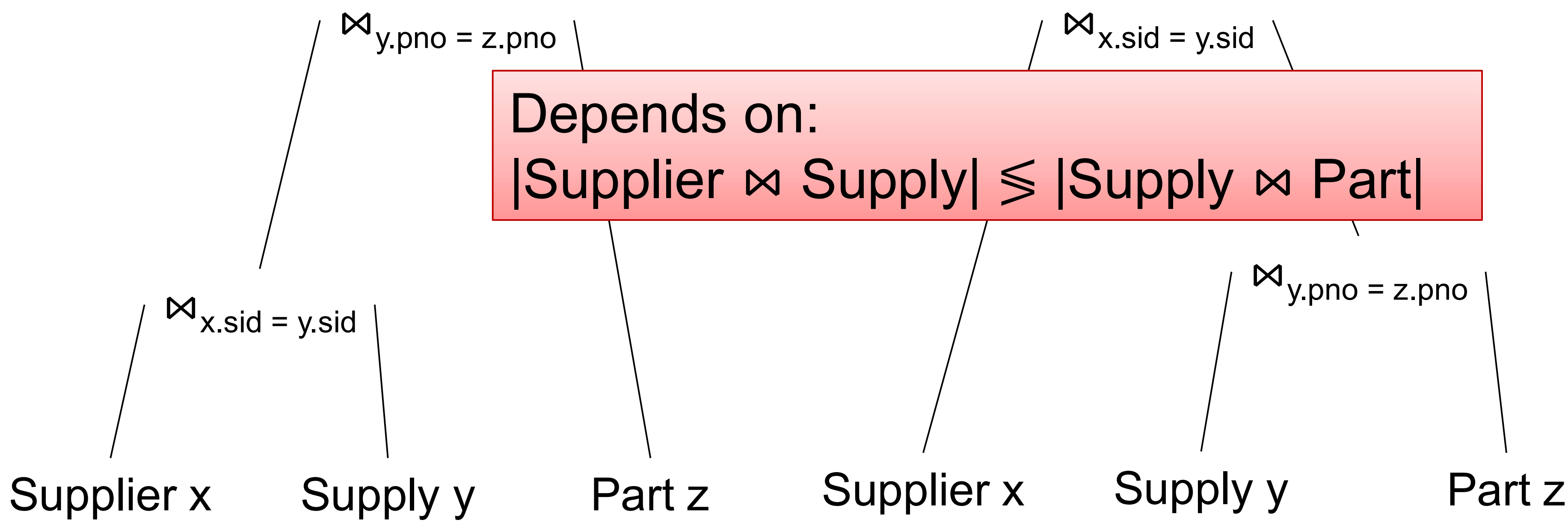
Join Reorder

When is one plan better than the other?



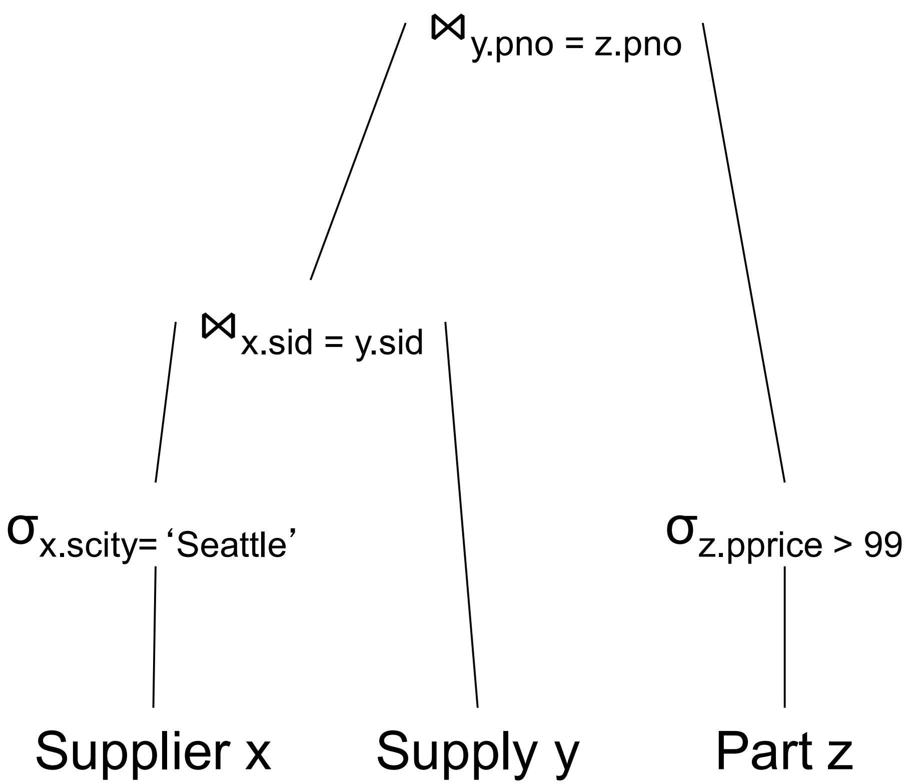
Depends on:
|Supplier ⋈ Supply| ⋚ |Supply ⋈ Part|

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

$R \bowtie S = S \bowtie R$

Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)
Part(pno, pname, pprice)

Join Reorder



Supplier(sid, sname, scity, sstate)
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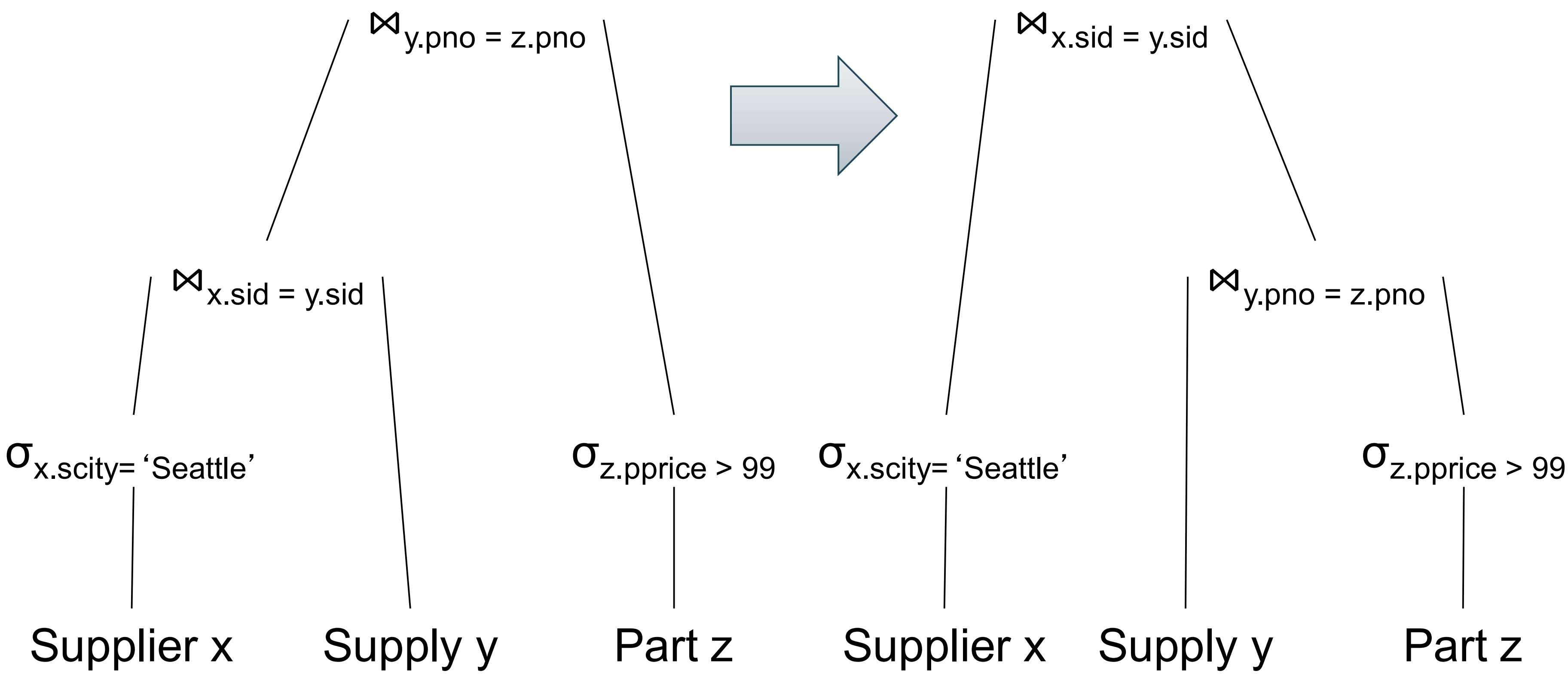

Supplier(sid, sname, scity, sstate)
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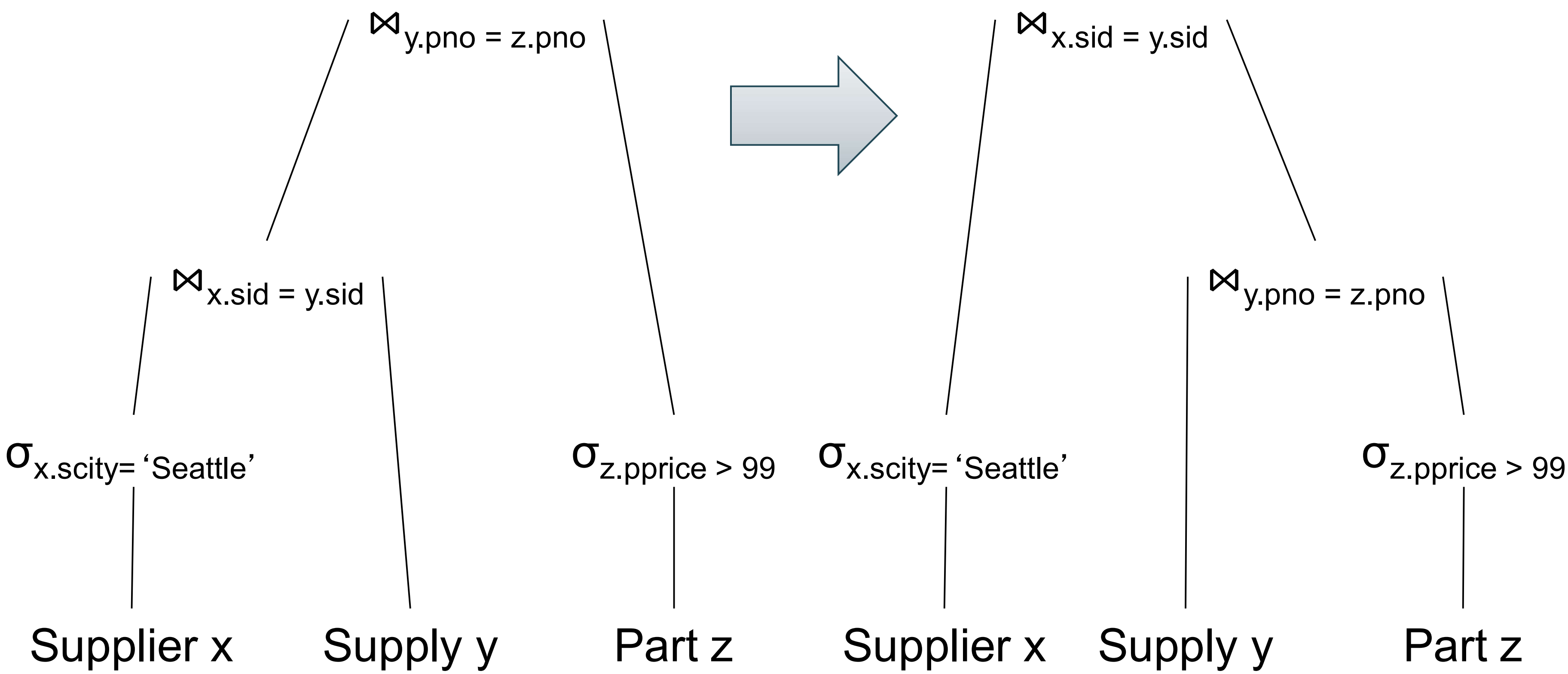
Join Reorder

When is one plan better than the other?



Lesson: need sizes of $\sigma_{x.scity=\text{'Seattle'}}$(Supplier), $\sigma_{z.pprice > 99}$(Part)

Search Space: Summary

- Large set of rewrite rules
- Generates many candidate plans
- Need to *estimate their cost*, choose best

Query Optimization

1. Search space
2. Cardinality and cost estimation
3. Plan enumeration algorithms (next time)

Cardinality Estimation

Problem: given statistics on base tables and a query, estimate size of the answer

Challenging, because:

- Need to do it very fast
- Need to use very little memory

Statistics on Base Data

- Number of tuples (cardinality) T(R)
- Number of physical pages B(R)
- Indexes, number of keys in the index V(R,a)

- Histograms: 1d or 2d (next lecture)

Computed periodically, often using sampling

Assumptions

- Uniformity
- Independence
- Containment of values
- Preservation of values

Size Estimation

Selection: size decreases by ***selectivity factor*** θ

$$T(\sigma_{pred}(R)) = \theta_{pred} * T(R)$$

Size Estimation

Selection: size decreases by *selectivity factor* θ

$T(\sigma_{pred}(R)) = \theta_{pred} * T(R)$

$T(R \bowtie_{A=B} S) = \theta_{A=B} * T(R) * T(S)$

$T(\sigma_{pred}(R)) = \theta_{pred} * T(R)$

Selectivity Factors

Uniformity assumption

Equality:

$\sigma_{A=c}(R)$

$T(\sigma_{pred}(R)) = \theta_{pred} * T(R)$

Selectivity Factors

Uniformity assumption

$\sigma_{A=c}(R)$

Equality:

- $\theta_{A=c} = 1/V(R,A)$

$T(\sigma_{pred}(R)) = \theta_{pred} * T(R)$

Selectivity Factors

Uniformity assumption

$\sigma_{A=c}(R)$

Equality:

- $\theta_{A=c} = 1/V(R,A)$

$\sigma_{c1<A<c2}(R)$

Range:

- $\theta_{c1<A<c2} = (c2 - c1)/(max(R,A) - min(R,A))$

$T(\sigma_{pred}(R)) = \theta_{pred} * T(R)$

Selectivity Factors

Uniformity assumption

$\sigma_{A=c}(R)$

Equality:

- $\theta_{A=c} = 1/V(R,A)$

$\sigma_{c1<A<c2}(R)$

Range:

- $\theta_{c1<A<c2} = (c2 - c1)/(max(R,A) - min(R,A))$

Conjunction

$\sigma_{A=c \text{ and } B=d}(R)$

$T(\sigma_{pred}(R)) = \theta_{pred} * T(R)$

Selectivity Factors

Uniformity assumption

$\sigma_{A=c}(R)$

Equality:

- $\theta_{A=c} = 1/V(R,A)$

$\sigma_{c1<A<c2}(R)$

Range:

- $\theta_{c1<A<c2} = (c2 - c1)/(max(R,A) - min(R,A))$

Conjunction

$\sigma_{A=c \text{ and } B=d}(R)$

Independence assumption

- $\theta_{pred1 \text{ and } pred2} = \theta_{pred1} * \theta_{pred2} = 1/V(R,A) * 1/V(R,B)$

$T(R \bowtie_{A=B} S) = \theta_{A=B} * T(R) * T(S)$

Selectivity Factors

$R \bowtie_{R.A=S.B} S$

Join

$T(R \bowtie_{A=B} S) = \theta_{A=B} * T(R) * T(S)$

Selectivity Factors

$R \bowtie_{R.A=S.B} S$

Join

- $\theta_{R.A=S.B} = 1/ (MAX(V(R,A), V(S,B))$

Why? Will explain next...

$T(R \bowtie_{A=B} S) = \theta_{A=B} * T(R) * T(S)$

Selectivity Factors

$R \bowtie_{R.A=S.B} S$

Containment of values: if $V(R,A) \leq V(S,B)$, then the set of A values of R is included in the set of B values of S

- Note: this indeed holds when A is a foreign key in R, and B is a key in S

$T(R \bowtie_{A=B} S) = \theta_{A=B} * T(R) * T(S)$

Selectivity Factors

$R \bowtie_{R.A=S.B} S$

Assume V(R,A) ≤ V(S,B)

- Tuple t in R joins with T(S)/V(S,B) tuples in S

$T(R \bowtie_{A=B} S) = \theta_{A=B} * T(R) * T(S)$

Selectivity Factors

$R \bowtie_{R.A=S.B} S$

Assume $V(R,A) \leq V(S,B)$

- Tuple t in R joins with $T(S)/V(S,B)$ tuples in S
- Hence $T(R \bowtie_{A=B} S) = T(R)\ T(S) / V(S,B)$

$T(R \bowtie_{A=B} S) = \theta_{A=B} * T(R) * T(S)$

Selectivity Factors

$R \bowtie_{R.A=S.B} S$

Assume $V(R,A) \leq V(S,B)$

- Tuple t in R joins with $T(S)/V(S,B)$ tuples in S
- Hence $T(R \bowtie_{A=B} S) = T(R)\ T(S) / V(S,B)$

In general:

- $T(R \bowtie_{A=B} S) = T(R)\ T(S) / \max(V(R,A),V(S,B))$
- $\theta_{R.A=S.B} = 1/ (\max(V(R,A), V(S,B))$

Final Assumption

Preservation of values:

For any other attribute C:

- $V(R \bowtie_{A=B} S, C) = V(R, C)$ or
- $V(R \bowtie_{A=B} S, C) = V(S, C)$

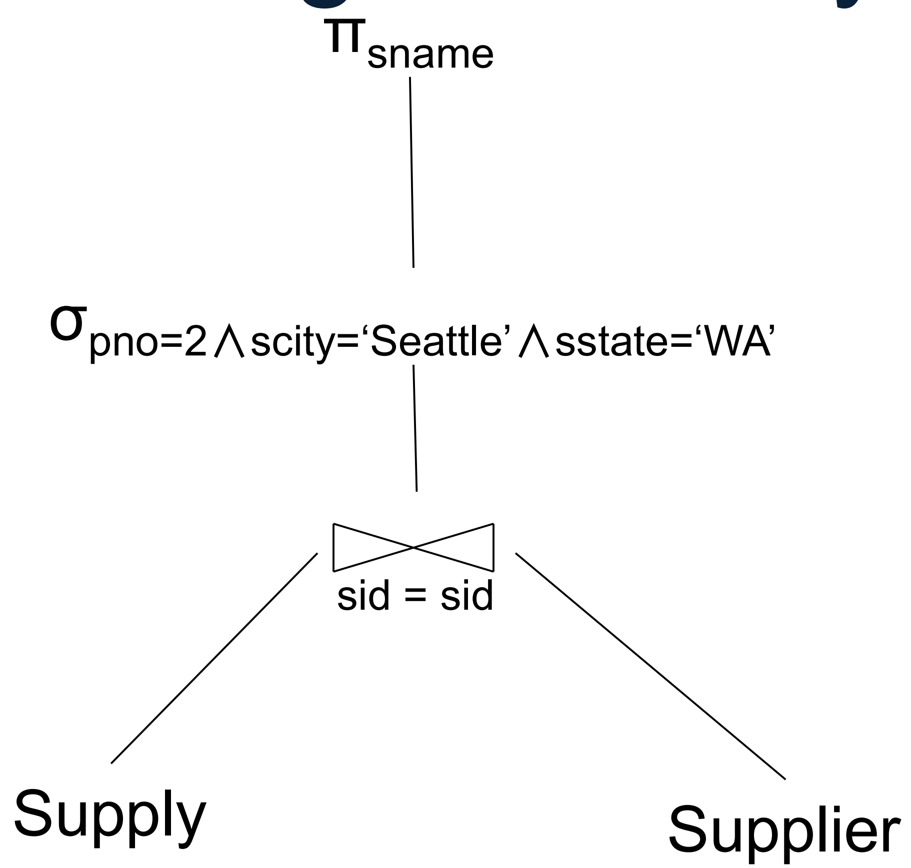
- This is needed higher up in the plan

Computing the Cost of a Plan

- Estimate cardinalities bottom-up
- Estimate cost by using estimated cardinalities
- Examples next...

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

Logical Query Plan 1




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

T(Supply) = 10000
V(Supply, pno) = 2500

T(Supplier) = 1000
V(Supplier, scity) = 20
V(Supplier, state) = 10

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

Logical Query Plan 1

```
SELECT sname
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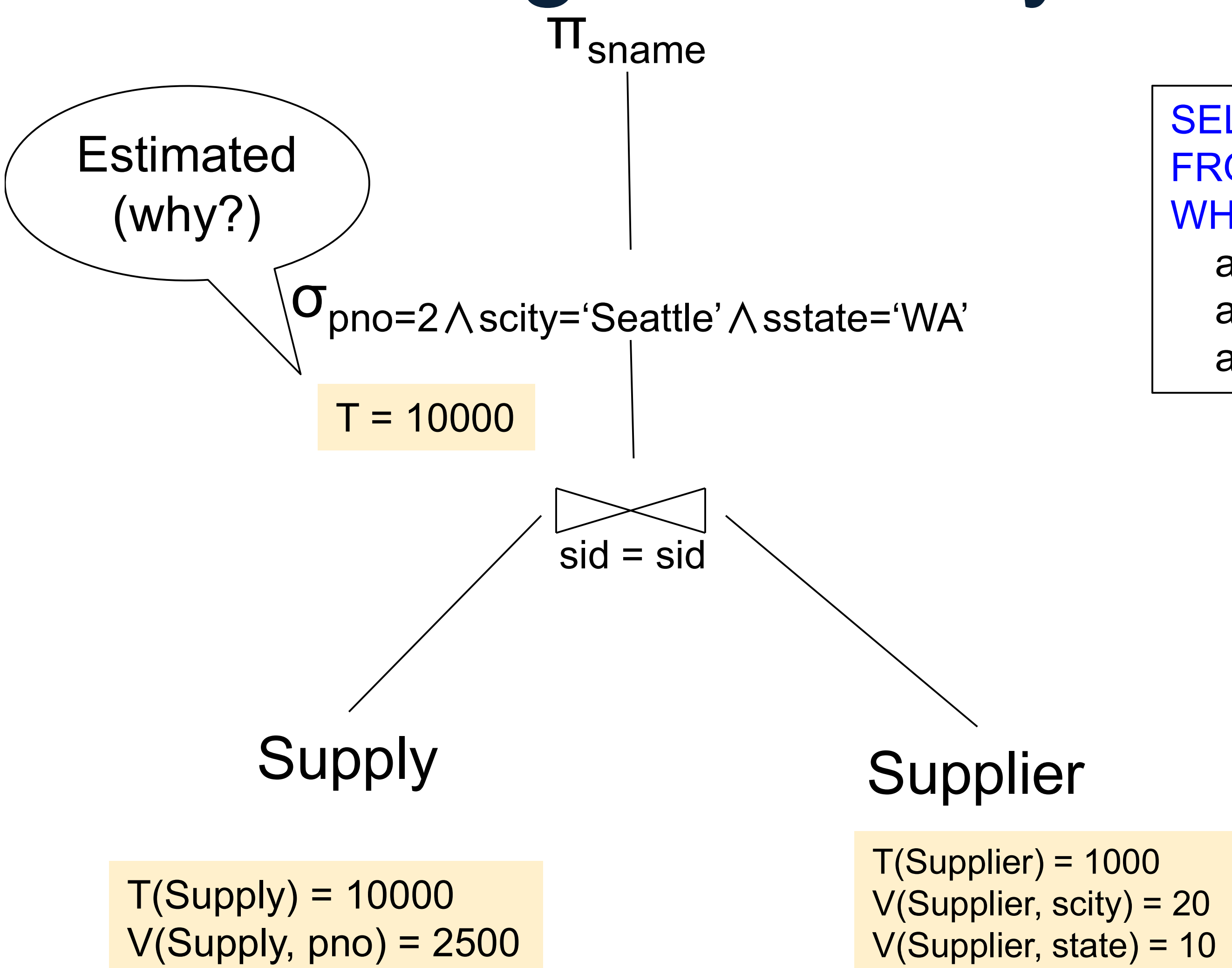
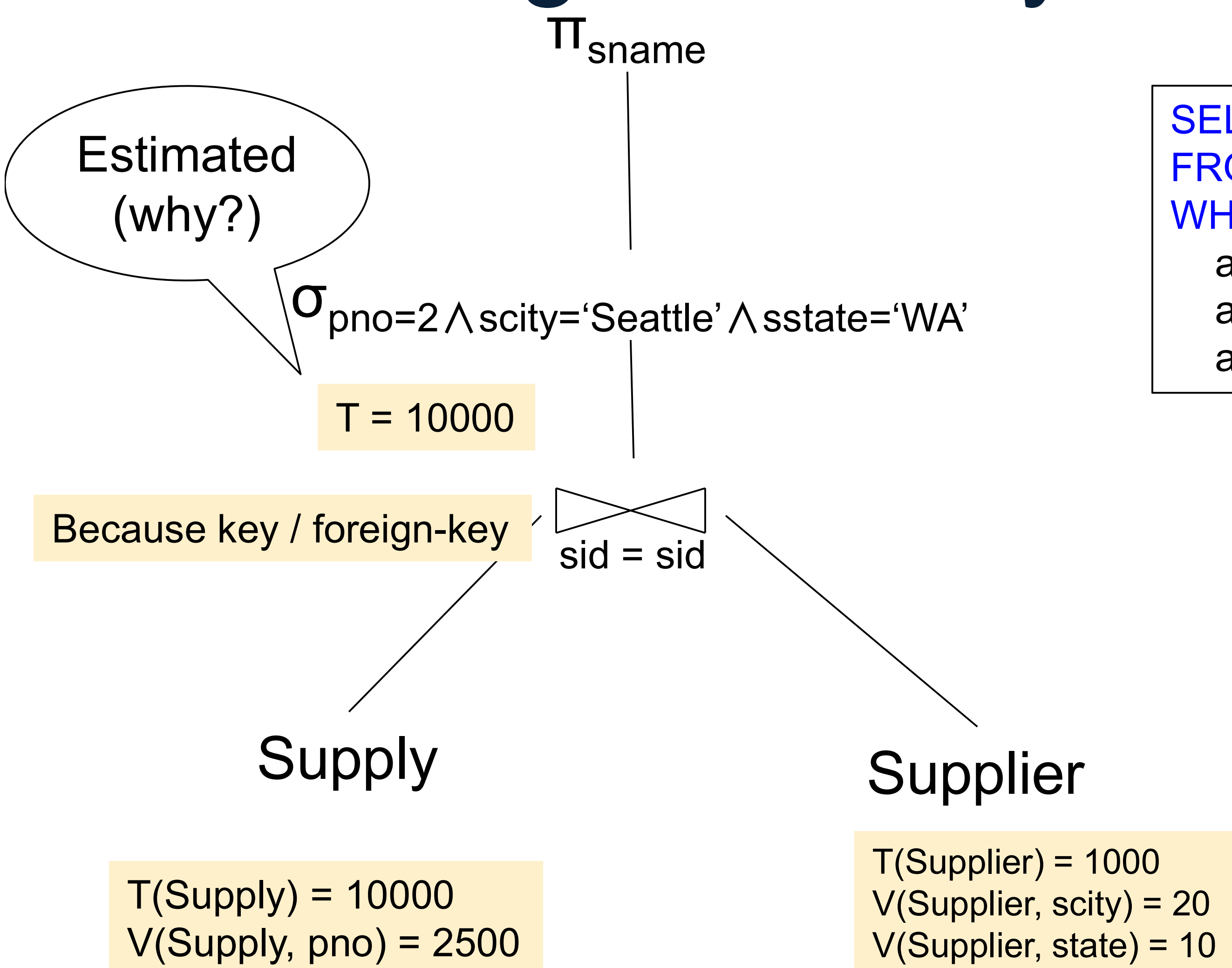


Supplier(<u>sid</u>, sname, scity, sstate)

Supply(<u>sid, pno</u>, quantity)

Logical Query Plan 1

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    and x.scity = 'Seattle'
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```

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

Logical Query Plan 1

π_{sname}

Estimated (why?)

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

T = 10000

$\bowtie_{sid = sid}$

Because key / foreign-key

Also: θ = 1/max(V(Supply,sid)*V(Supplier,sid) = 1/V(Supplier,sid)

Supply

T(Supply) = 10000
V(Supply, pno) = 2500

Supplier

T(Supplier) = 1000
V(Supplier, scity) = 20
V(Supplier, state) = 10

```
SELECT sname
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Supplier(sid, sname, scity, sstate)
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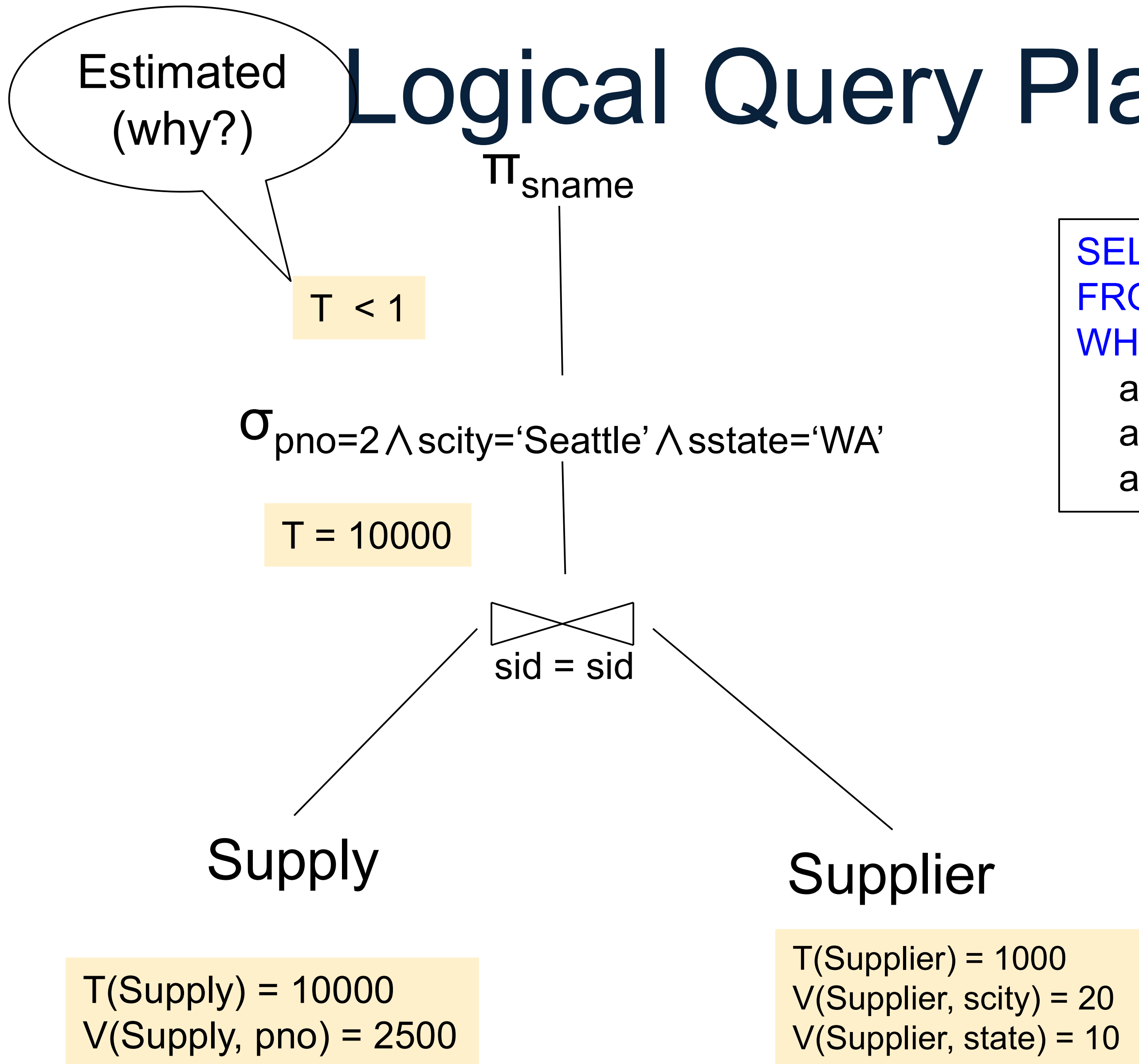
Logical Query Plan 1




```
SELECT sname
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WHERE x.sid = y.sid
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   and x.sstate = 'WA'
```
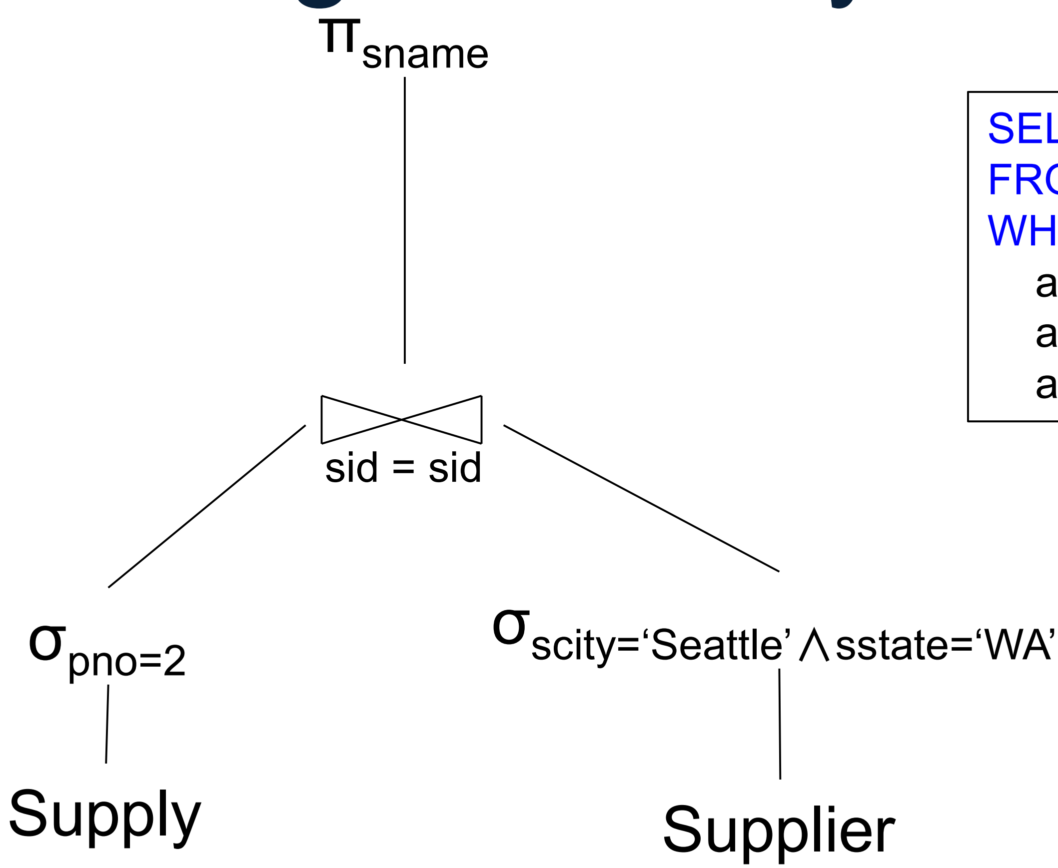

Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)

Logical Query Plan 2




```
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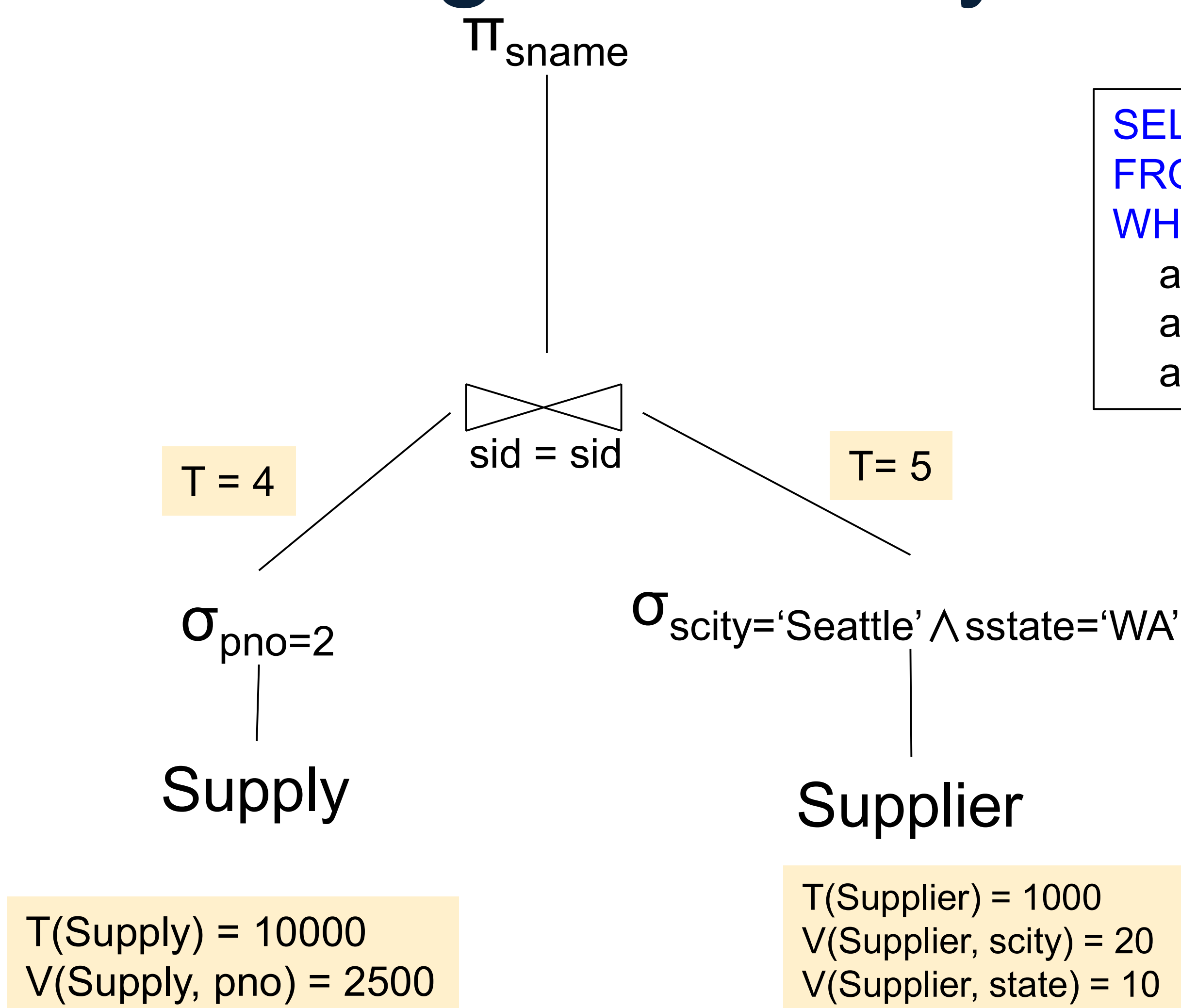
Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)

Logical Query Plan 2

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WHERE x.sid = y.sid
    and y.pno = 2
    and x.scity = 'Seattle'
    and x.sstate = 'WA'
```
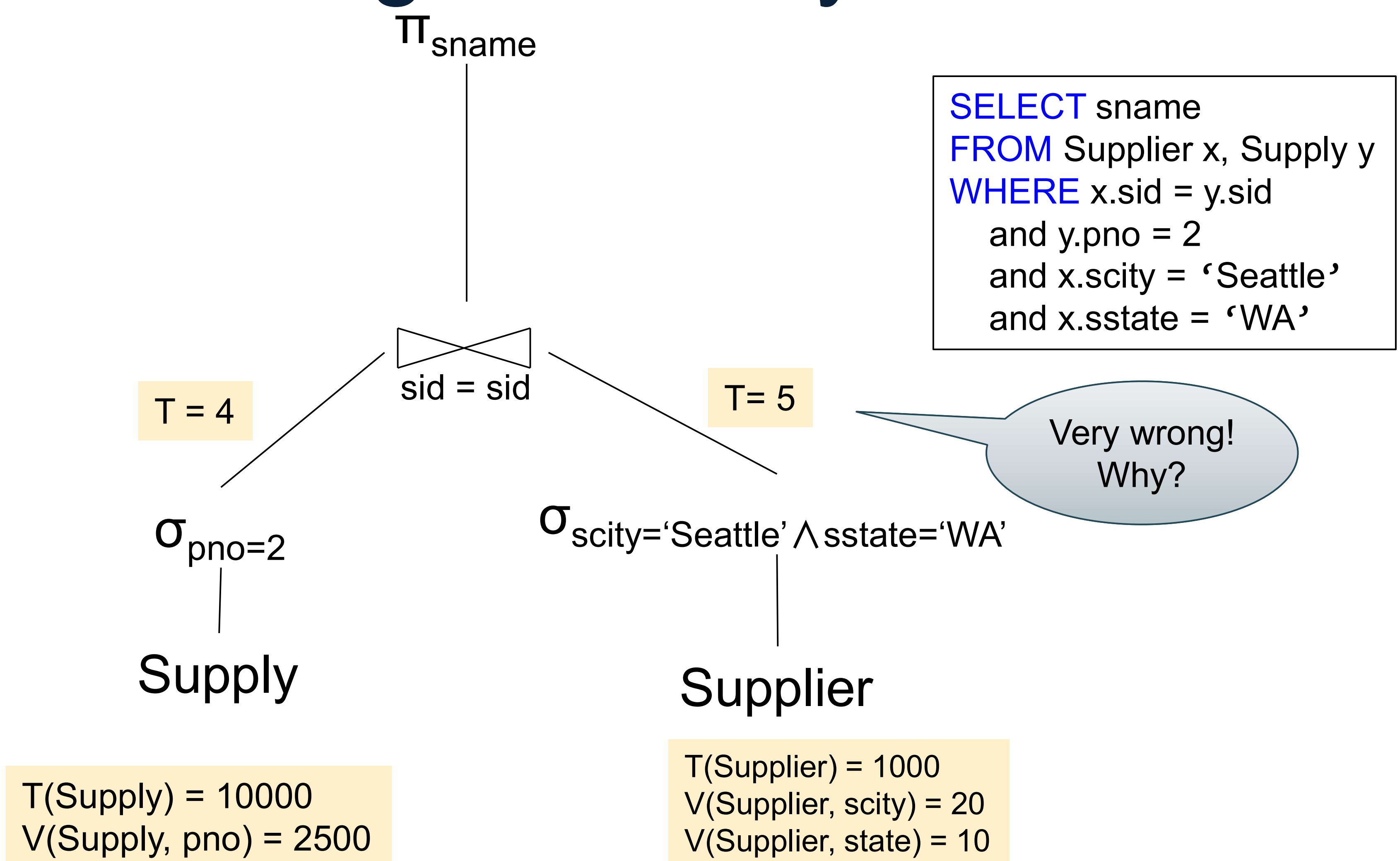

Supplier(sid, sname, scity, sstate)

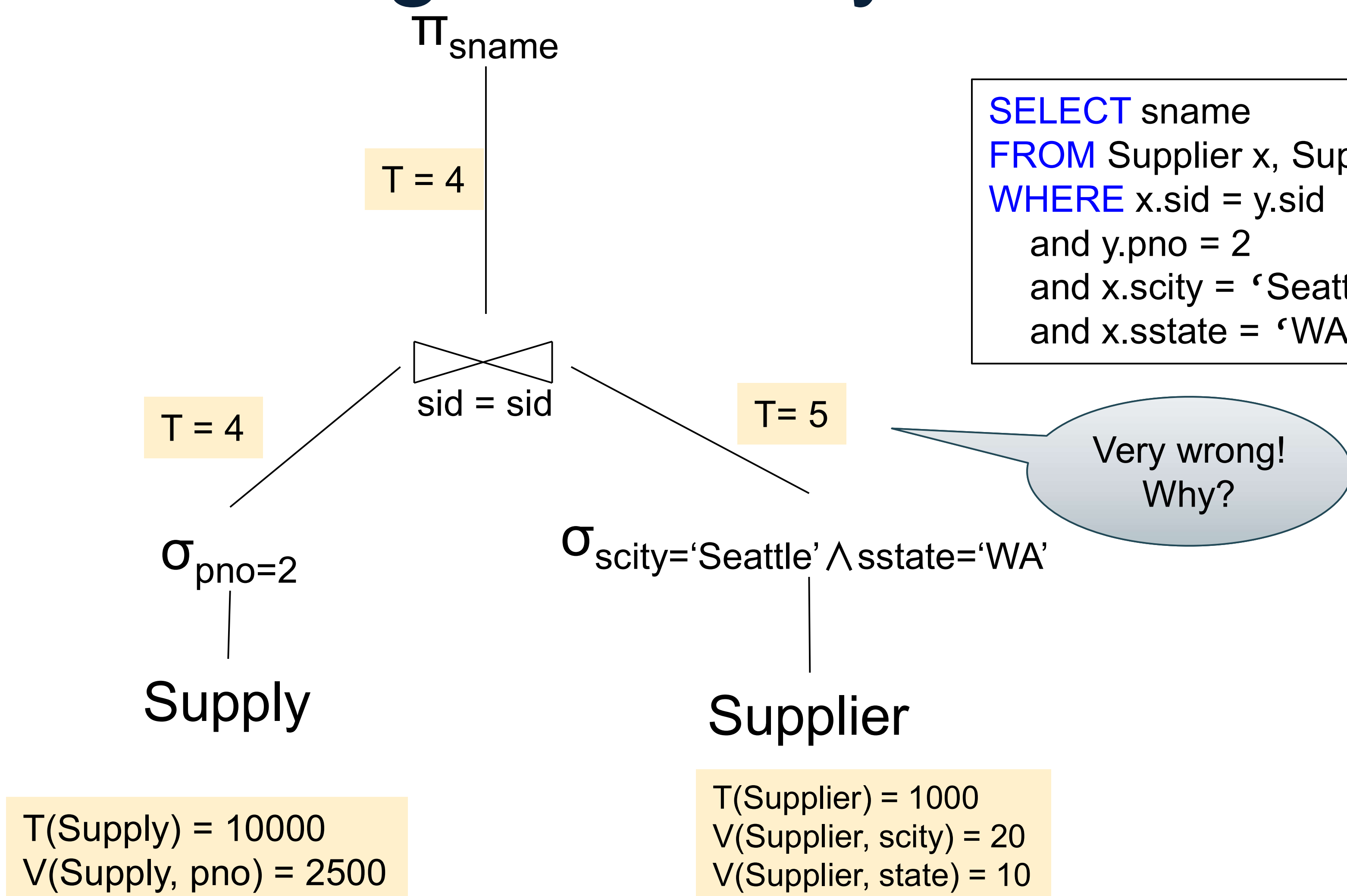
Supply(sid, pno, quantity)

Logical Query Plan 2



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

Logical Query Plan 2

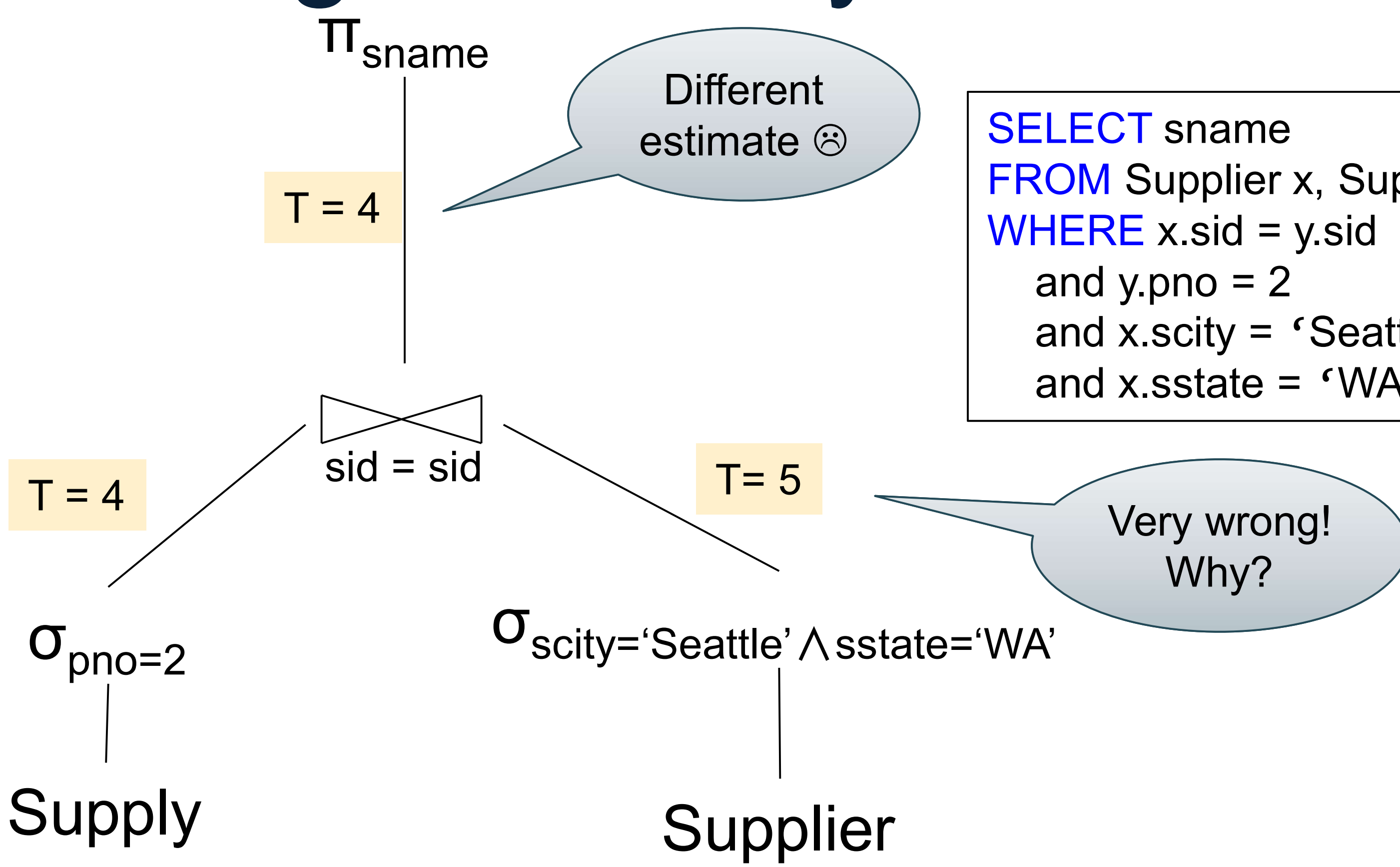



```
SELECT sname
FROM Supplier x, Supply y
WHERE x.sid = y.sid
   and y.pno = 2
   and x.scity = 'Seattle'
   and x.sstate = 'WA'
```

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Logical Query Plan 2

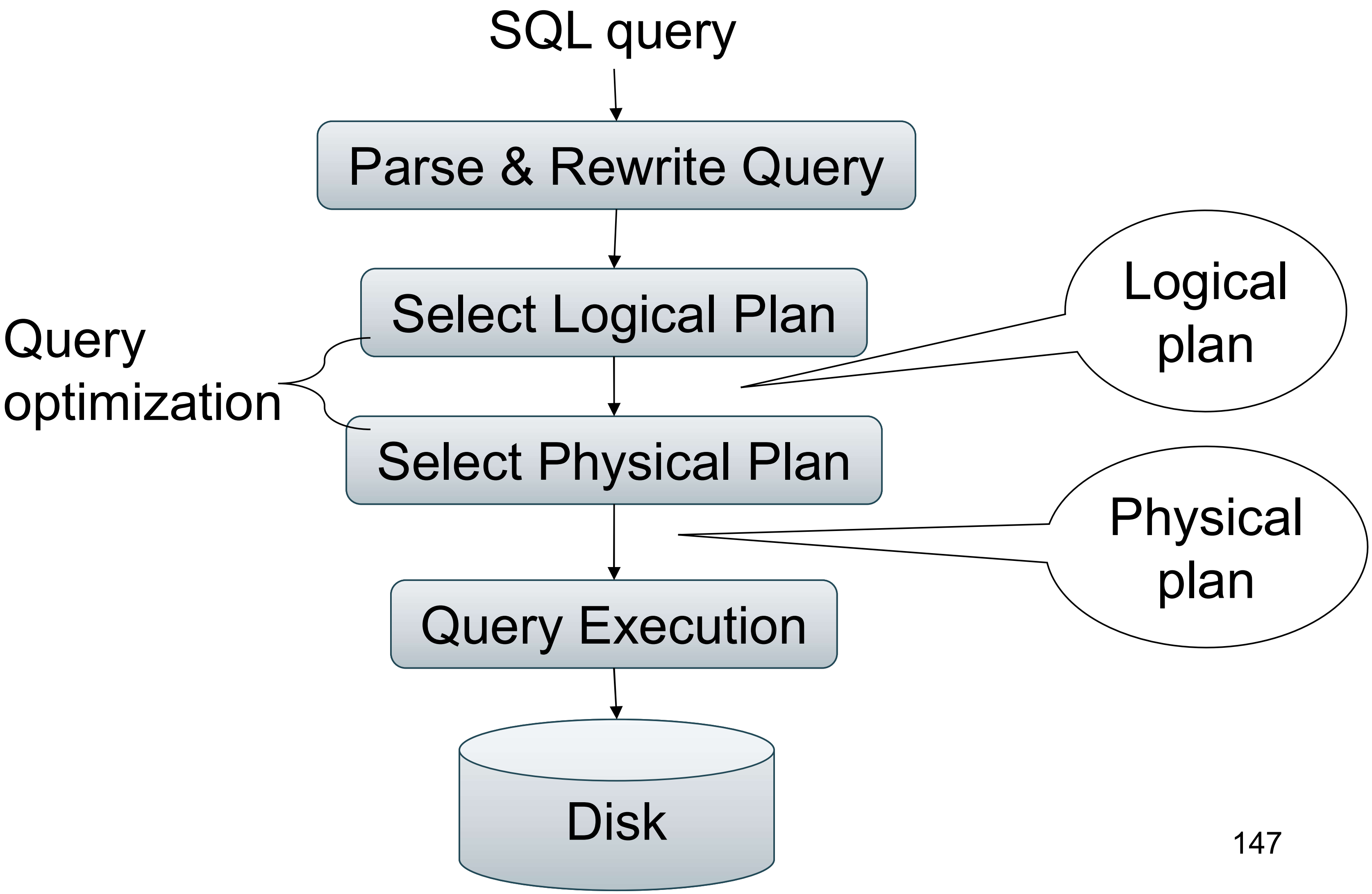



```
SELECT sname
FROM Supplier x, Supply y
WHERE x.sid = y.sid
   and y.pno = 2
   and x.scity = 'Seattle'
   and x.sstate = 'WA'
```

T(Supply) = 10000
V(Supply, pno) = 2500

T(Supplier) = 1000
V(Supplier, scity) = 20
V(Supplier, state) = 10

Lifecycle of a Query



Summary

- Optimizer has three components:
  - Search space
  - Cardinality and cost estimation
  - Plan enumeration algorithms (next time)
- Paper *How good are they* does a deep dive into modern optimizers
- Will continue optimizers next week