Introduction to Database Systems CSE 414

Lectures 10-11: DB Systems Architecture and Relational Algebra

Announcements

- HW 3 due Wednesday night
- Next web quiz, due Friday (out now)
- HW 4 out Thur. (most likely), due following Wed.
  - Relational algebra and SQL<->RA translation
- Midterm exam: Monday, May 6 in class
  - Q&A session Sunday afternoon 5/5, 2pm.
- Today's lecture: 2.4 and 5.1-5.2 (relational algebra); 9.1 (database architecture)

Where We Are

- Motivation for using a DBMS for managing data
- SQL, SQL, SQL
  - Declaring the schema for our data (CREATE TABLE)
  - Inserting data one row at a time or in bulk (INSERT/.import)
  - Modifying the schema and updating the data (ALTER/UPDATE)
  - Querying the data (SELECT)
  - Tuning queries (CREATE INDEX)

- Next step: More knowledge of how DBMSs work
  - Client-server architecture
  - Relational algebra and query execution

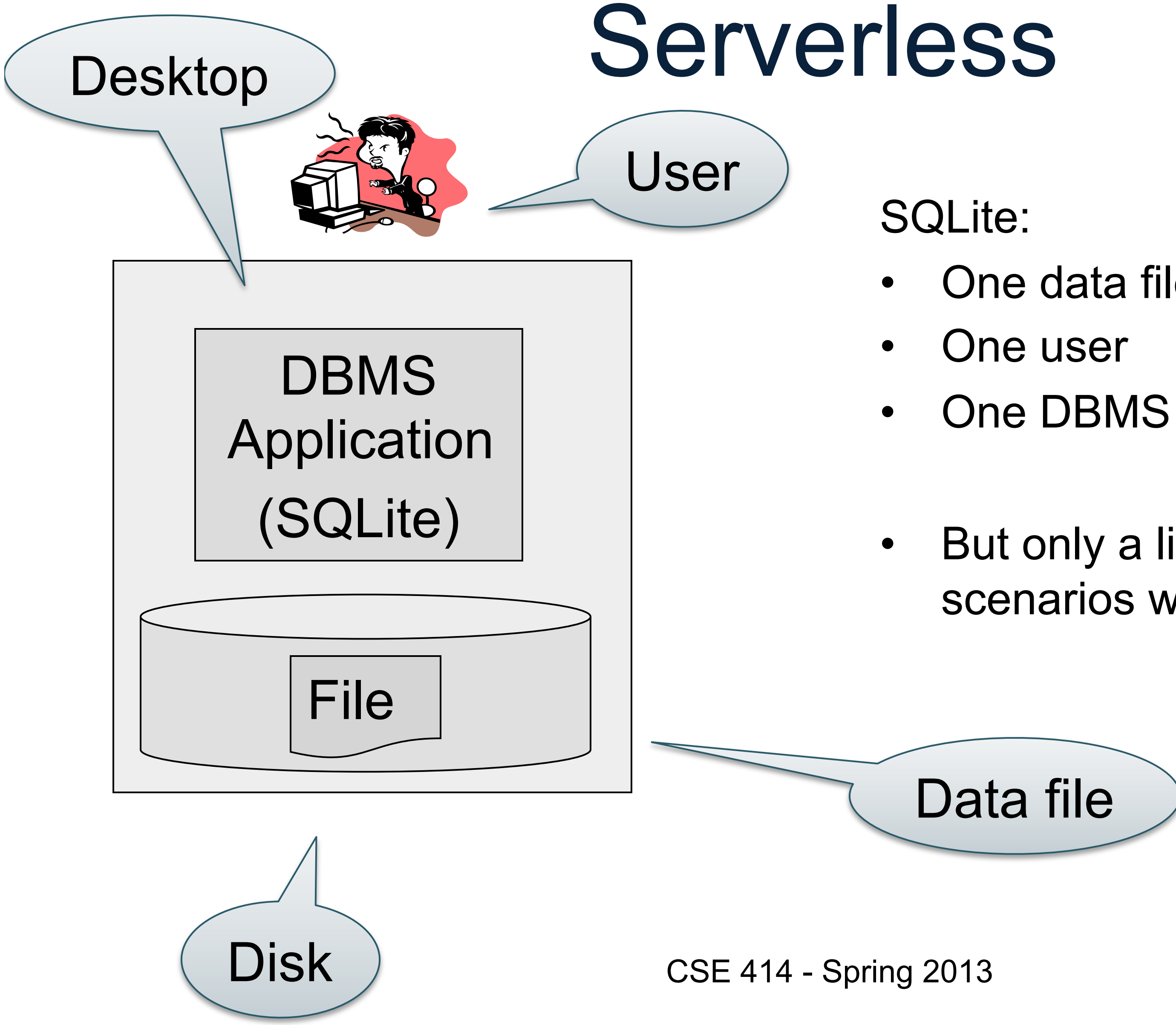
Architectures

1. Serverless

2. Two tier: client/server

3. Three tier: client/app-server/db-server

Serverless

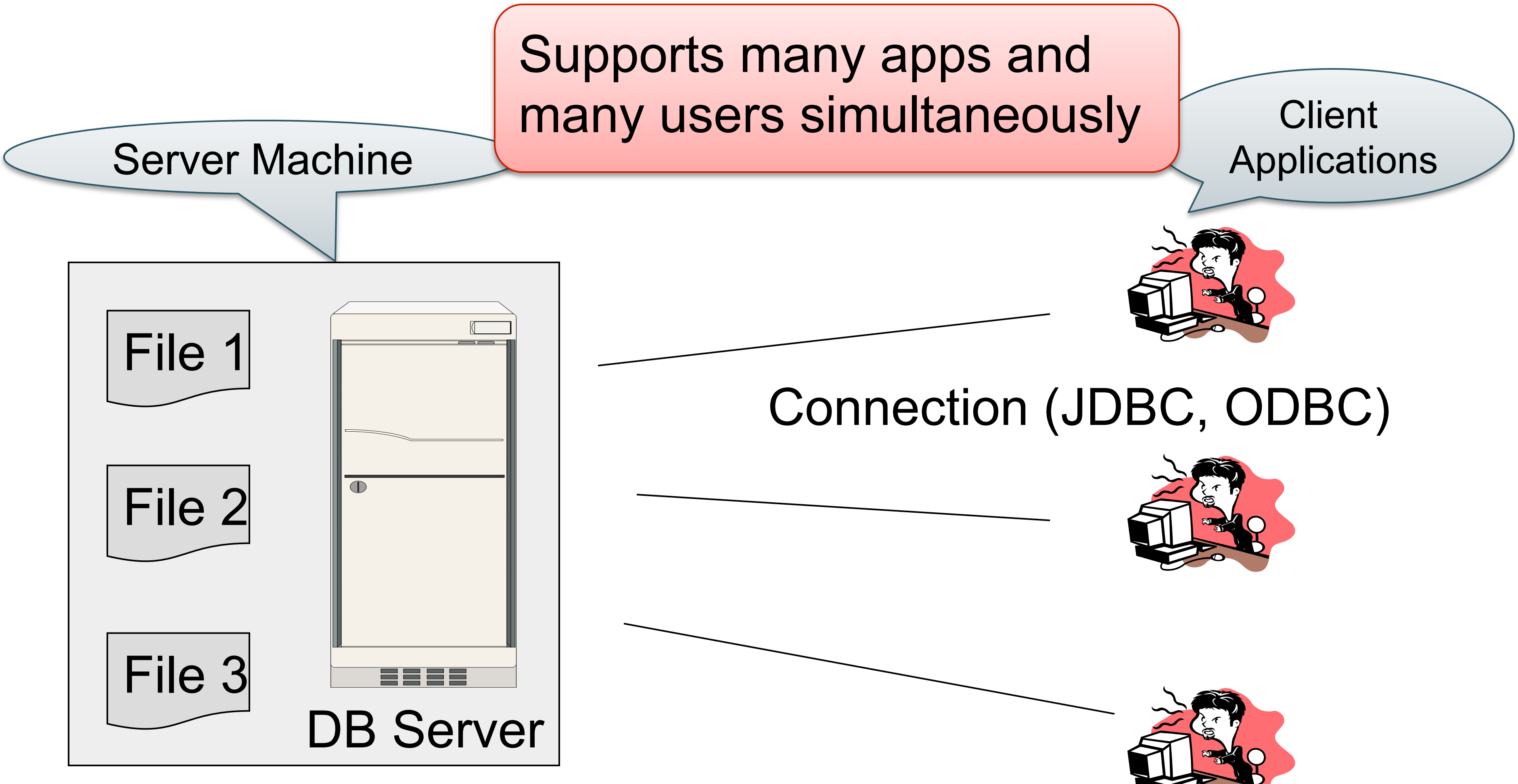


SQLite:

- One data file
- One user
- One DBMS application

- But only a limited number of scenarios work with such model

Client-Server

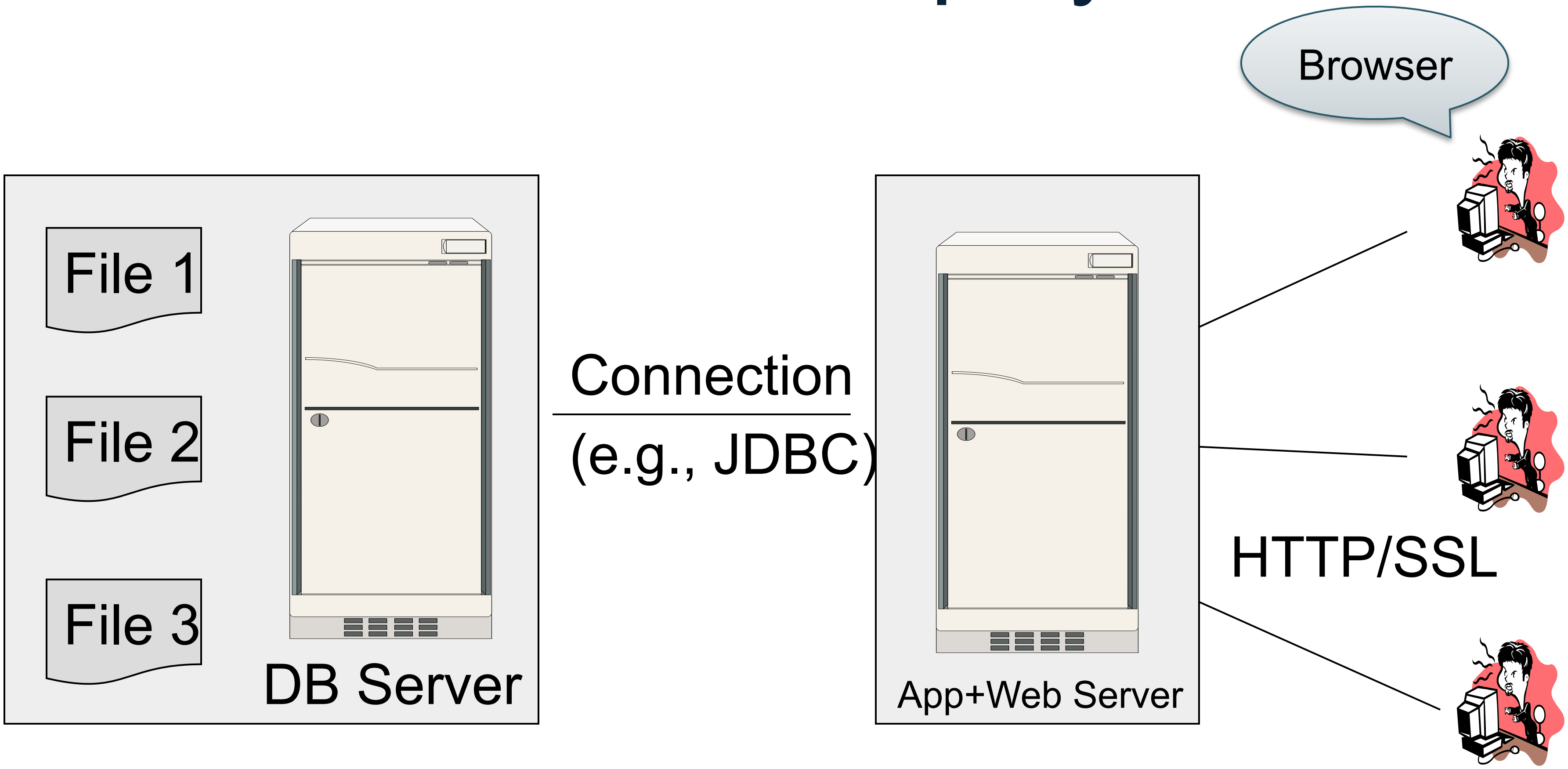


- One server running the database
- Many clients, connecting via the ODBC or JDBC (Java Database Connectivity) protocol

Client-Server

- One *server* that runs the DBMS (or RDBMS):
  - Your own desktop, or
  - Some beefy system, or
  - A cloud service (SQL Azure)
- Many *clients* run apps and connect to DBMS
  - Microsoft's Management Studio (for SQL Server), or
  - psql (for postgres)
  - A Java program (HW5) or a C++ program
- Clients "talk" to server using JDBC/ODBC protocol

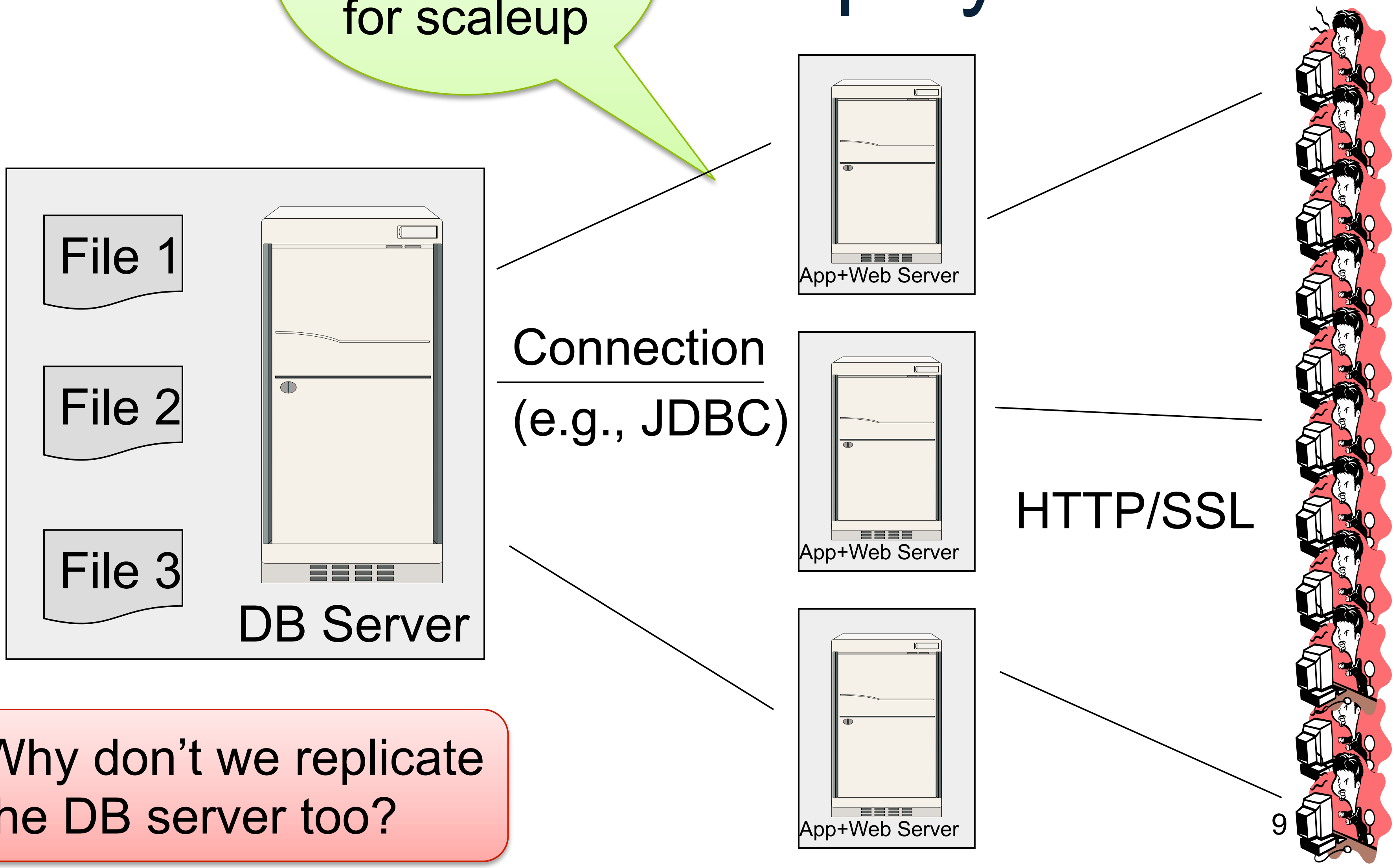
3-Tiers DBMS Deployment



Web-based applications

3-Ti S Deployment

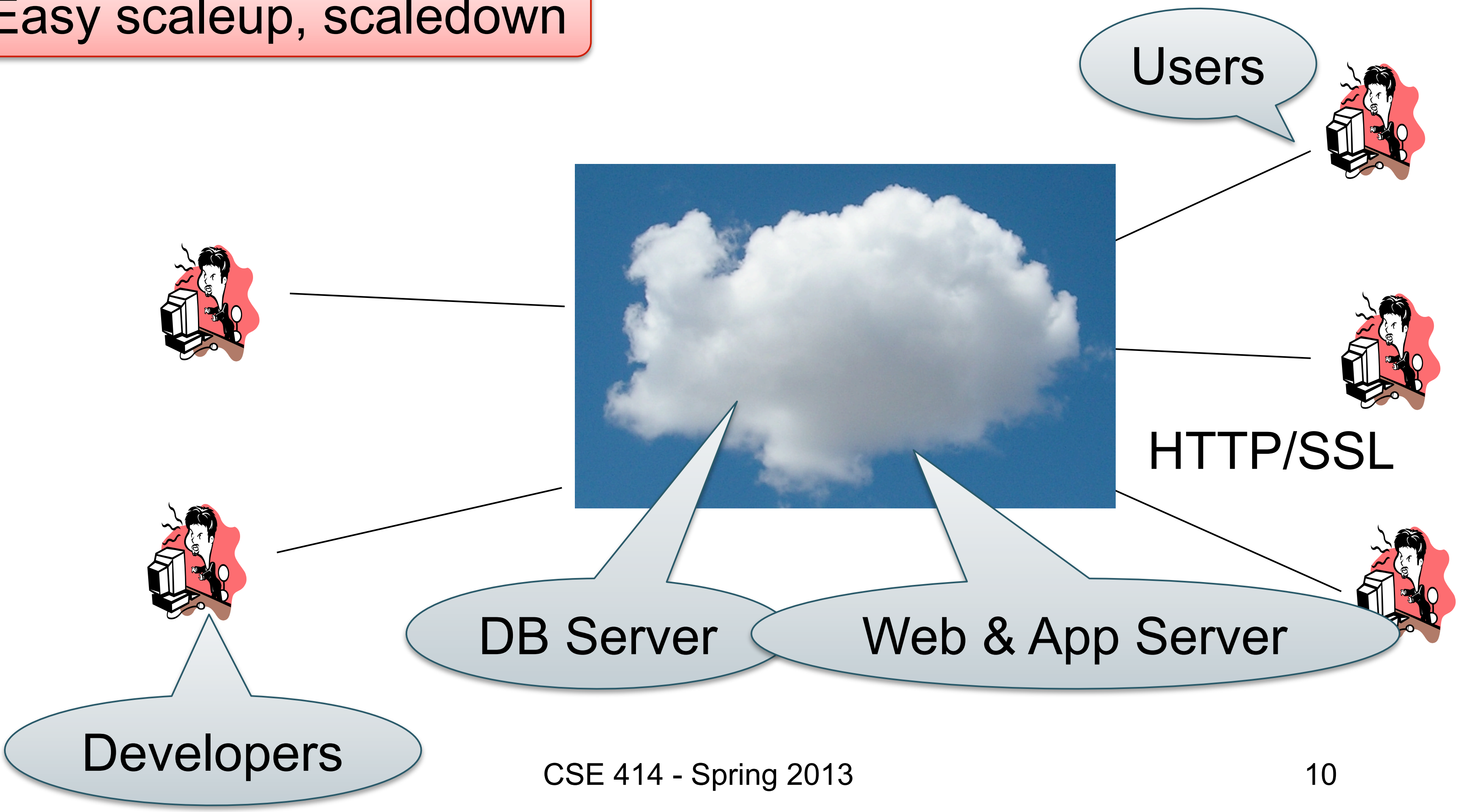
Replicate App server for scaleup



Why don't we replicate the DB server too?

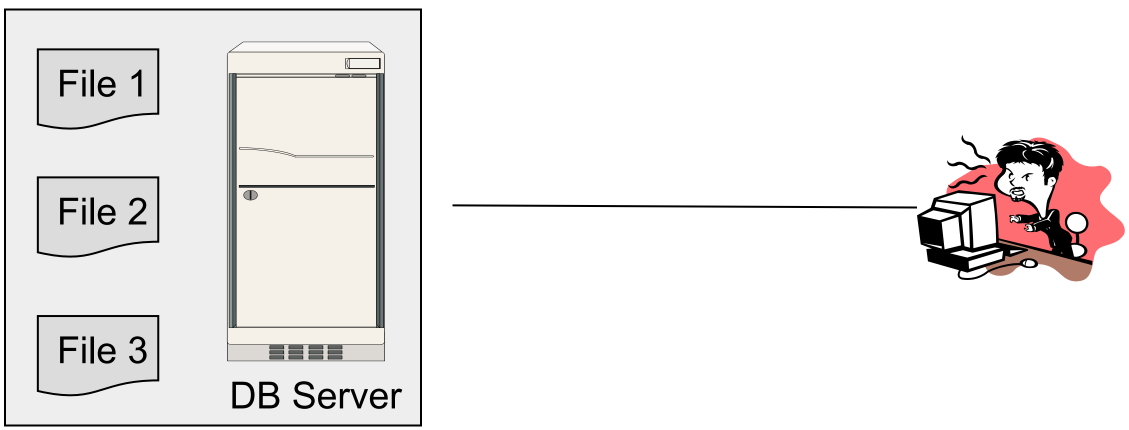
DBMS Deployment: Cloud

Easy scaleup, scaledown

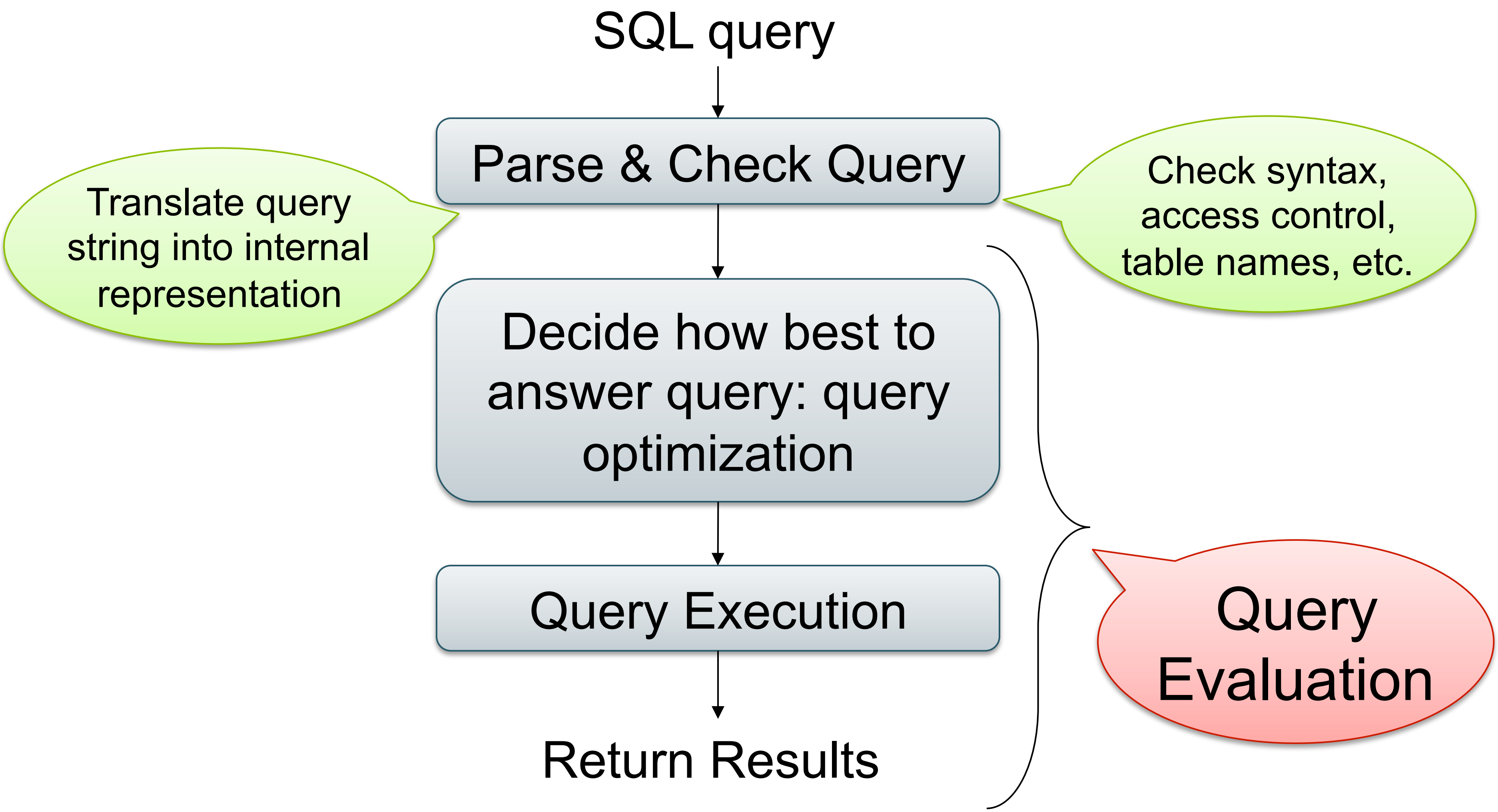


Using a DBMS Server

1. Client application establishes connection to server
2. Client must authenticate self
3. Client submits SQL commands to server
4. Server executes commands and returns results



Query Evaluation Steps



The WHAT and the HOW

- SQL = WHAT we want to get form the data
- Relational Algebra = HOW to get the data we want
- The passage from WHAT to HOW is called query optimization

Overview: SQL = WHAT

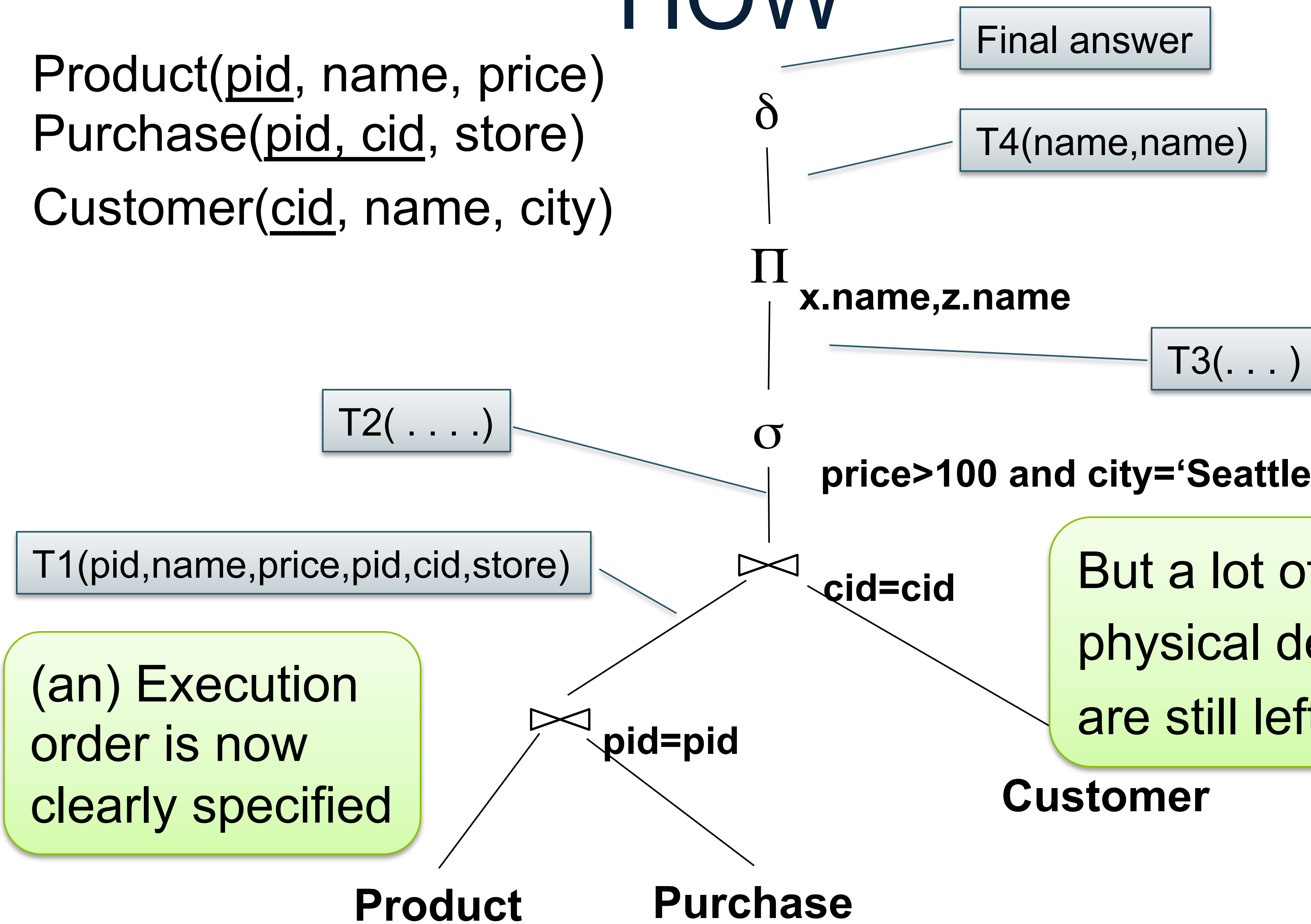
Product(pid, name, price)
Purchase(pid, cid, store)
Customer(cid, name, city)

```
SELECT DISTINCT x.name, z.name
FROM Product x, Purchase y, Customer z
WHERE x.pid = y.pid and y.cid = z.cid and
        x.price > 100 and z.city = 'Seattle'
```

It's clear WHAT we want, unclear HOW to get it

Overview: Relational Algebra = HOW

Product(pid, name, price)
Purchase(pid, cid, store)
Customer(cid, name, city)



(an) Execution order is now clearly specified

But a lot of physical details are still left open!

Relational Algebra

Sets v.s. Bags

- Sets: {a,b,c}, {a,d,e,f}, { }, . . .
- Bags: {a, a, b, c}, {b, b, b, b, b}, . . .

Relational Algebra has two semantics:

- Set semantics = standard Relational Algebra
- Bag semantics = extended Relational Algebra

Relational Algebra Operators

- Union ∪, intersection ∩, difference -
- Selection σ
- Projection Π
- Cartesian product ×, join ⋈
- Rename ρ
- Duplicate elimination δ
- Grouping and aggregation γ
- Sorting τ

RA

Extended RA

Vocabulary Alert

- Identical concepts have different names in SQL and relational algebra
  - RA Selection (σ) is SQL's WHERE
  - RA Projection (Π) is (part of) SQL's SELECT (another part is rename, ρ)

Union and Difference

$R1 \cup R2$

$R1 - R2$

What do they mean over bags ?

What about Intersection ?

- Derived operator using minus

$$R1 \cap R2 = R1 - (R1 - R2)$$

- Derived using join (will explain later)

$$R1 \cap R2 = R1 \bowtie R2$$

Selection

- Returns all tuples which satisfy a condition

$$\sigma_c(R)$$

- Examples
  - $\sigma_{\text{Salary > 40000}}$ (Employee)
  - $\sigma_{\text{name = “Smith”}}$ (Employee)
- The condition c can be =, <, ≤, >, ≥, <>
  - And the usual logical operators like and, or

Employee

SSN	Name	Salary
1234545	John	200000
5423341	Smith	600000
4352342	Fred	500000

$\sigma_{Salary > 40000}$ (Employee)

SSN	Name	Salary
5423341	Smith	600000
4352342	Fred	500000

Projection

- Eliminates columns

$$\Pi_{A1,\ldots,An}(R)$$

- Example: project social-security number and names:
  - $\Pi_{SSN,\ Name}$ (Employee)
  - Answer(SSN, Name)

Different semantics over sets or bags! Why?

Employee

SSN	Name	Salary
1234545	John	20000
5423341	John	60000
4352342	John	20000

$\Pi_{Name,Salary}$ (Employee)

Name	Salary
John	20000
John	60000
John	20000

Bag semantics

Name	Salary
John	20000
John	60000

Set semantics

Which is more efficient?

Composing RA Operators

Patient

no	name	zip	disease
1	p1	98125	flu
2	p2	98125	heart
3	p3	98120	lung
4	p4	98120	heart

$\pi_{zip,disease}$(Patient)

zip	disease
98125	flu
98125	heart
98120	lung
98120	heart

$\sigma_{disease='heart'}$(Patient)

no	name	zip	disease
2	p2	98125	heart
4	p4	98120	heart

π_{zip} ($\sigma_{disease='heart'}$(Patient))

zip
98120
98125

Cartesian Product

- Each tuple in R1 paired with with each tuple in R2

$$R1 \times R2$$

- Rare in practice; mainly used to express joins

Cross-Product Example

Employee

Name	SSN
John	999999999
Tony	777777777

Dependent

EmpSSN	DepName
999999999	Emily
777777777	Joe

Employee × Dependent

Name	SSN	EmpSSN	DepName
John	999999999	999999999	Emily
John	999999999	777777777	Joe
Tony	777777777	999999999	Emily
Tony	777777777	777777777	Joe

Renaming

- Changes the schema, not the instance

$$\rho_{B1,\ldots,Bn}(R)$$

- Example:
  - $\rho_{N,\ S}$(Employee) → Answer(N, S)

Not really used by systems, but needed on paper

Natural Join

$$R1 \bowtie R2$$

- Meaning: $R1 \bowtie R2 = \Pi_A(\sigma(R1 \times R2))$

- Where:
  - Selection σ checks equality of all common attributes
  - Projection eliminates duplicate common attributes

Natural Join Example

R

A	B
X	Y
X	Z
Y	Z
Z	V

S

B	C
Z	U
V	W
Z	V

R ⋈ S =

$\Pi_{ABC}(\sigma_{R.B=S.B}(R \times S))$

A	B	C
X	Z	U
X	Z	V
Y	Z	U
Y	Z	V
Z	V	W

Natural Join Example 2

AnonPatient P

age	zip	disease
54	98125	heart
20	98120	flu

Voters V

name	age	zip
p1	54	98125
p2	20	98120

P ⋈ V

age	zip	disease	name
54	98125	heart	p1
20	98120	flu	p2

Natural Join

- Given schemas R(A, B, C, D), S(A, C, E), what is the schema of R ⋈ S ?

- Given R(A, B, C), S(D, E), what is R ⋈ S ?

- Given R(A, B), S(A, B), what is R ⋈ S ?

Theta Join

- A join that involves a predicate

$$R1 \bowtie_{\theta} R2 \quad = \quad \sigma_{\theta}(R1 \times R2)$$

- Here θ can be any condition
- For our voters/disease example:

$$P \bowtie_{P.zip = V.zip \text{ and } P.age < V.age + 5 \text{ and } P.age > V.age - 5} V$$

Equijoin

- A theta join where θ is an equality

$$R1 \bowtie_{A=B} R2 \quad = \quad \sigma_{A=B} (R1 \times R2)$$

- This is by far the most used variant of join in practice

Equijoin Example

AnonPatient P

age	zip	disease
54	98125	heart
20	98120	flu

Voters V

name	age	zip
p1	54	98125
p2	20	98120

$P \bowtie_{P.age=V.age} V$

age	P.zip	disease	name	V.zip
54	98125	heart	p1	98125
20	98120	flu	p2	98120

Join Summary

- **Theta-join**: $R \bowtie_{\theta} S = \sigma_{\theta}(R \times S)$
  – Join of R and S with a join condition θ
  – Cross-product followed by selection θ
- **Equijoin**: $R \bowtie_{\theta} S = \pi_A (\sigma_{\theta}(R \times S))$
  – Join condition θ consists only of equalities
  – Projection π_A drops all redundant attributes
- **Natural join**: $R \bowtie S = \pi_A (\sigma_{\theta}(R \times S))$
  – Equijoin
  – Equality on **all** fields with same name in R and in S

So Which Join Is It ?

- When we write R ⋈ S we usually mean an equijoin, but we often omit the equality predicate when it is clear from the context

More Joins

- **Outer join**
  – Include tuples with no matches in the output
  – Use NULL values for missing attributes
- Variants
  – Left outer join
  – Right outer join
  – Full outer join

Outer Join Example

AnonPatient P

age	zip	disease
54	98125	heart
20	98120	flu
33	98120	lung

AnonJob J

job	age	zip
lawyer	54	98125
cashier	20	98120

P ⟕ J

age	zip	disease	job
54	98125	heart	lawyer
20	98120	flu	cashier
33	98120	lung	null

Some Examples

```
Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,qty,price)
```

Q2: Name of supplier of parts with size greater than 10

$\pi_{sname}(\text{Supplier} \bowtie \text{Supply} \bowtie (\sigma_{psize>10}\ (\text{Part}))$

Q3: Name of supplier of red parts or parts with size greater than 10

$\pi_{sname}(\text{Supplier} \bowtie \text{Supply} \bowtie (\sigma_{psize>10}\ (\text{Part}) \cup \sigma_{pcolor='red'}\ (\text{Part})\ )\ )$

From SQL to RA

From SQL to RA

Product(pid, name, price)
Purchase(pid, cid, store)
Customer(cid, name, city)

```
SELECT DISTINCT x.name, z.name
FROM Product x, Purchase y, Customer z
WHERE x.pid = y.pid and y.cid = z.cid and
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From SQL to RA

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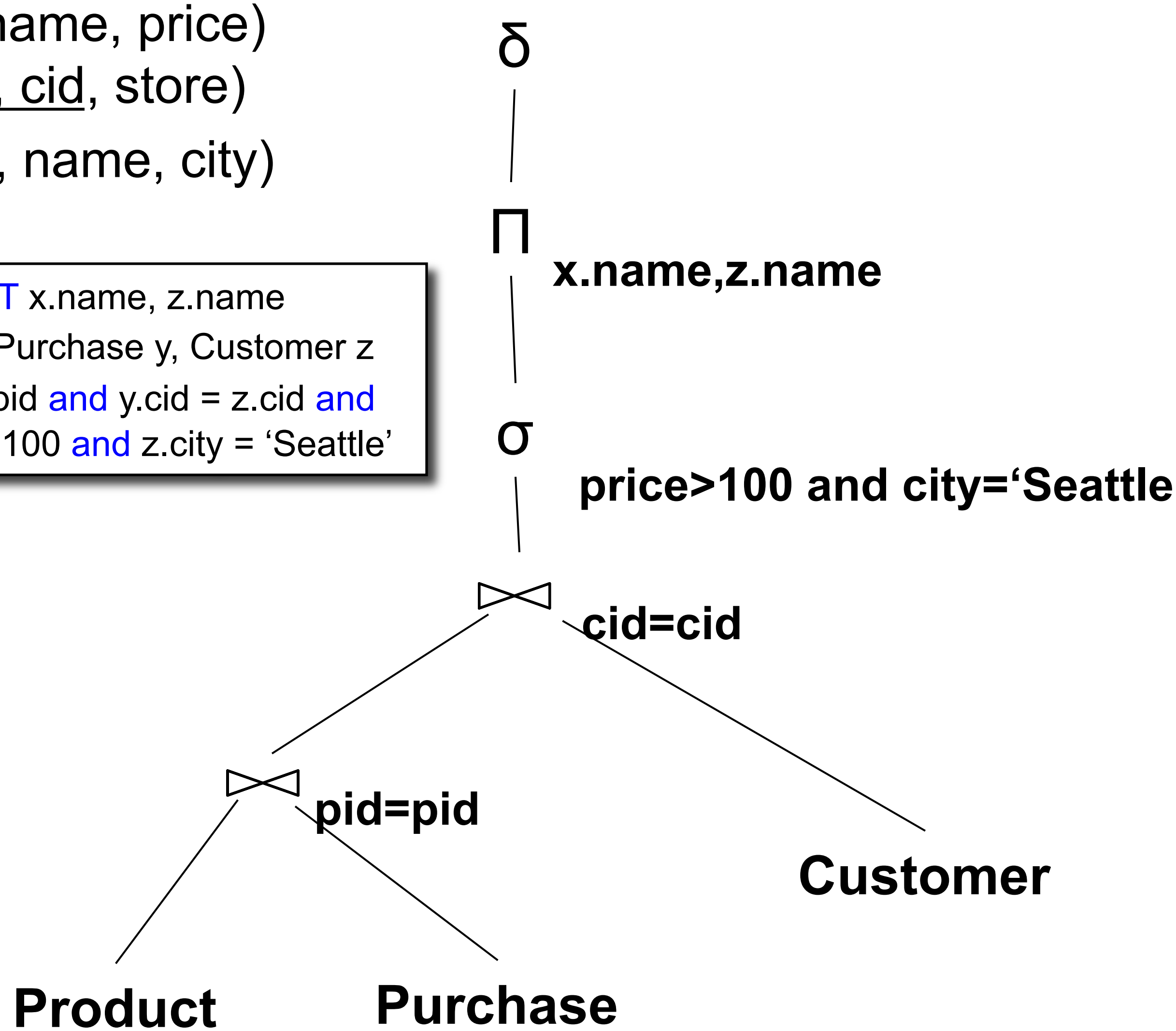
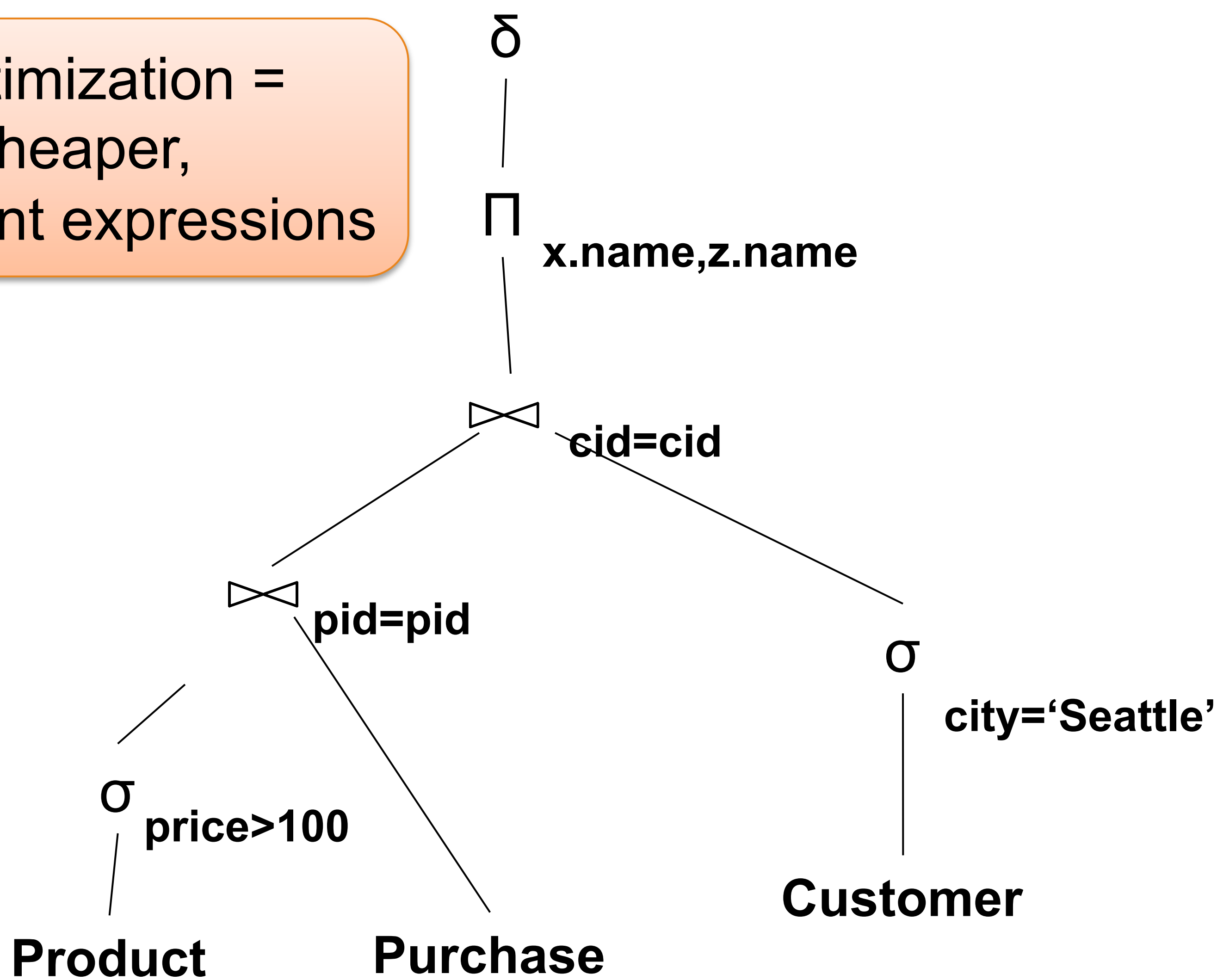


An Equivalent Expression

Query optimization =
finding cheaper,
equivalent expressions



Extended RA: Operators on Bags

- Duplicate elimination δ
- Grouping γ
- Sorting τ

Logical Query Plan

```
SELECT city, count(*)
FROM sales
GROUP BY city
HAVING sum(price) > 100
```

T3(city, c)

$\Pi_{\text{city, c}}$

T2(city,p,c)

$\sigma_{\text{p > 100}}$

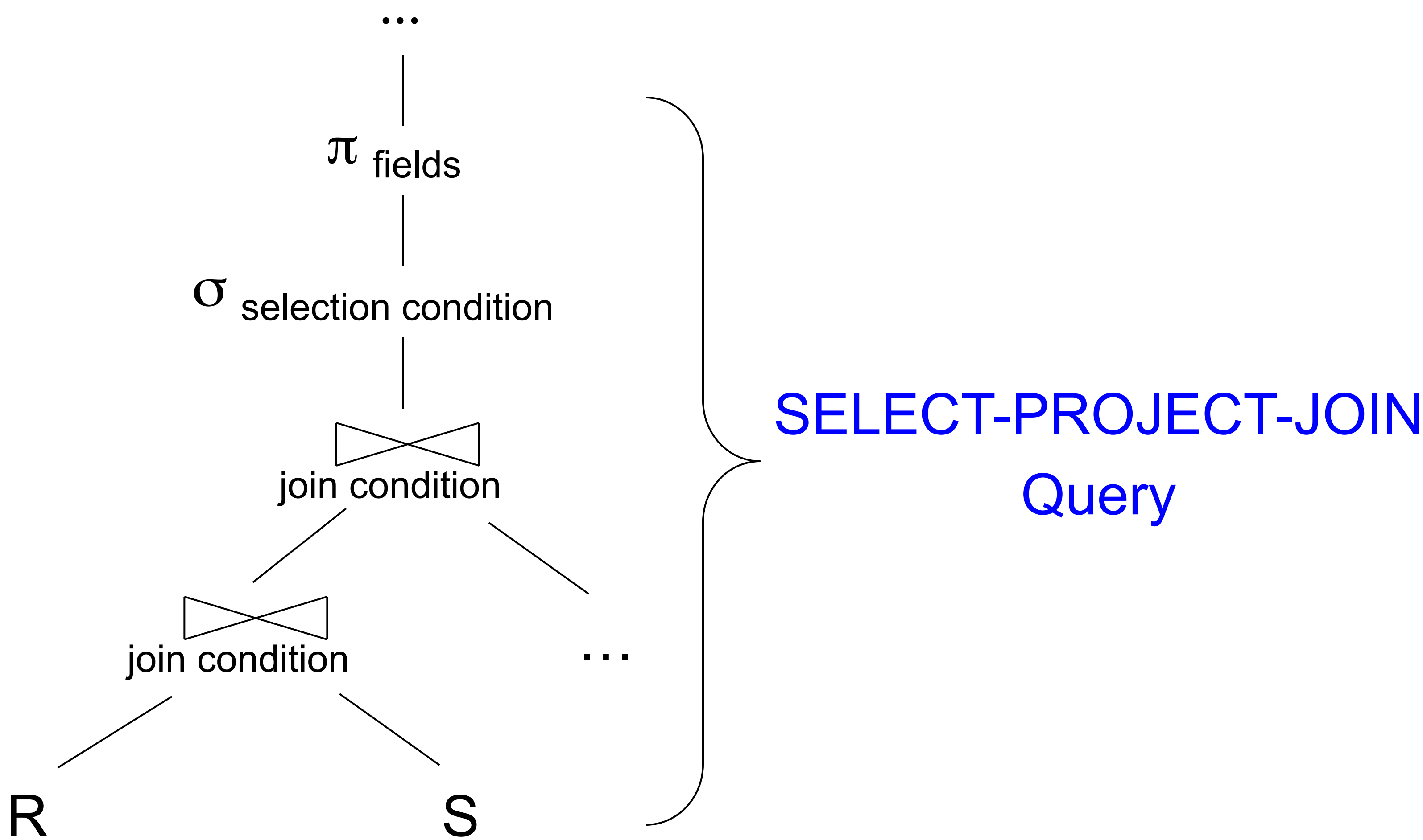
T1(city,p,c)

$\gamma_{\text{city, sum(price)} \rightarrow \text{p, count(*)} \rightarrow \text{c}}$

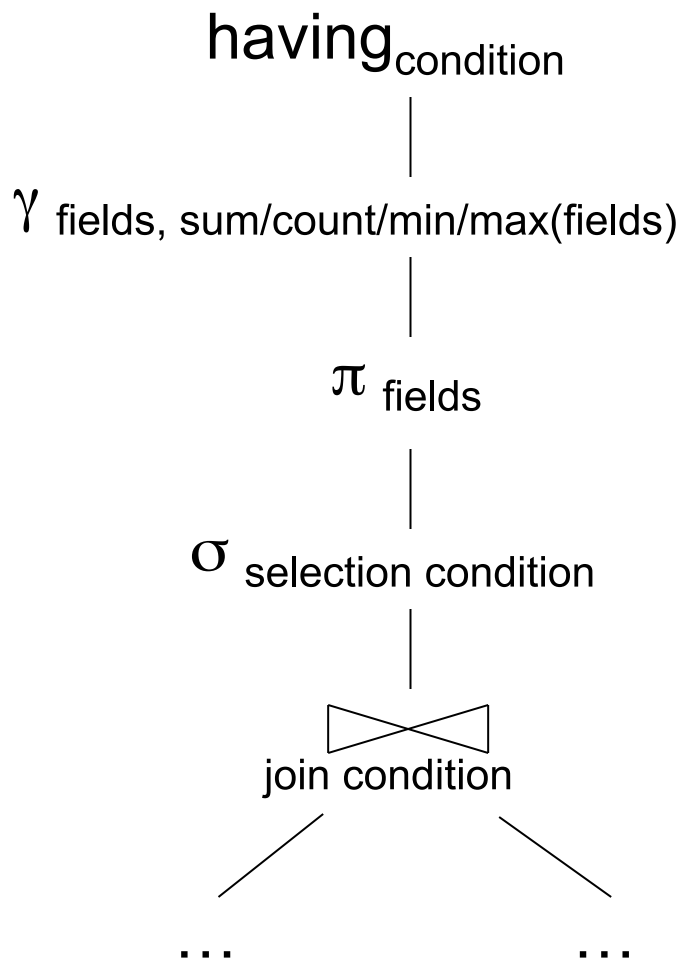
sales(product, city, price)

T1, T2, T3 = temporary tables

Typical Plan for Block (1/2)



Typical Plan For Block (2/2)



Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)

How about Subqueries?

```
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)
```

Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)

How about Subqueries?

```
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)
```

Correlation !

Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)

How about Subqueries?

```
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)
```

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)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)

How about Subqueries?

Un-nesting

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

```
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)
```

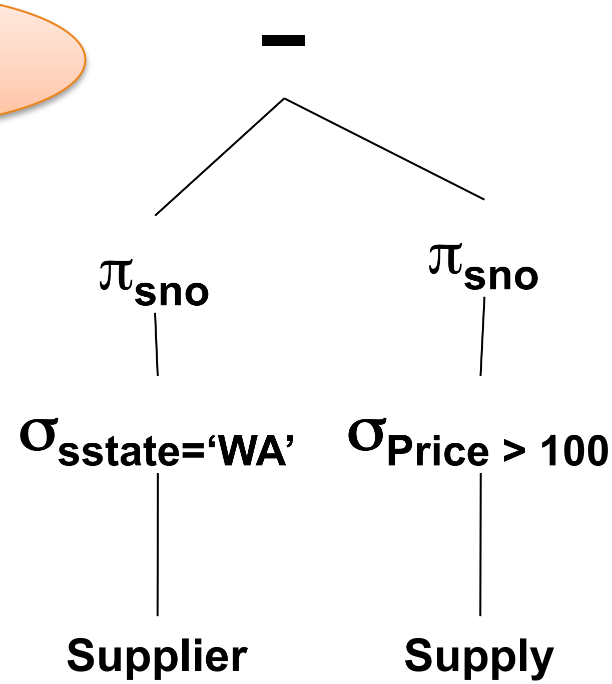
EXCEPT = set difference

Supplier(sno,sname,scity,sstate)
Part(pno,pname,psize,pcolor)
Supply(sno,pno,price)

How about Subqueries?

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

Finally…



From Logical Plans to Physical Plans

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Example

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

Give a relational algebra expression for this query

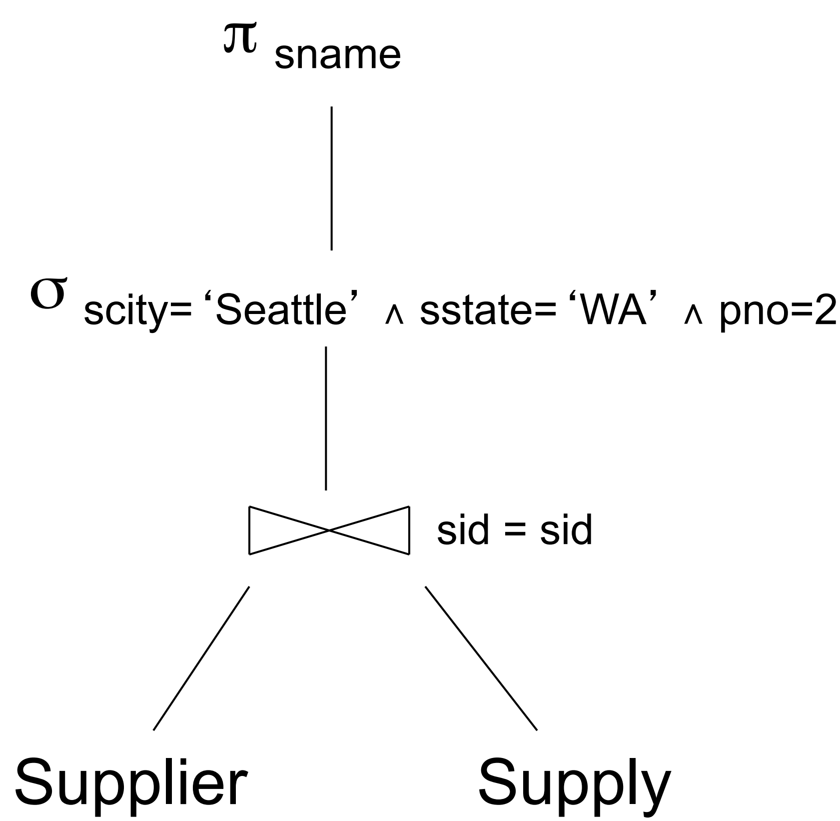
Supplier(sid, sname, scity, sstate)
Supply(sid, pno, quantity)

Relational Algebra

$$\pi_{\text{sname}}(\sigma_{\text{scity= 'Seattle'} \wedge \text{sstate= 'WA'} \wedge \text{pno=2}}(\text{Supplier} \bowtie_{\text{sid = sid}} \text{Supply}))$$

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

Relational Algebra

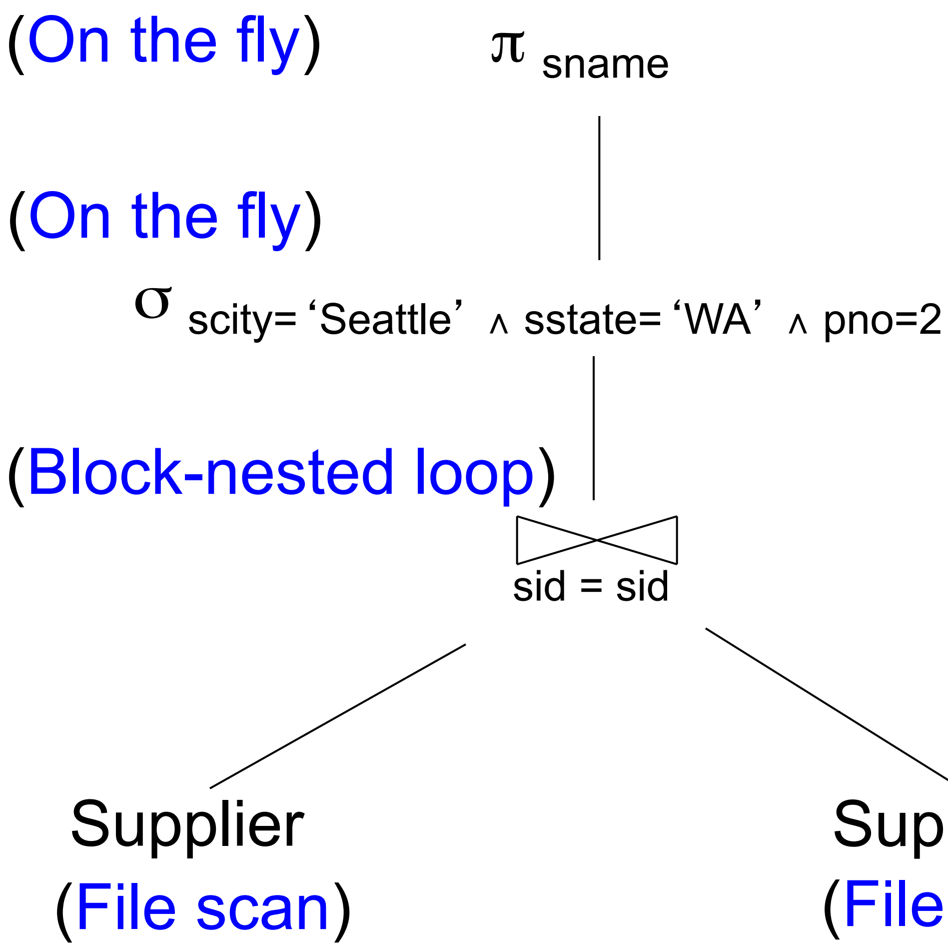


Relational algebra expression is also called the "logical query plan"

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Physical Query Plan 1

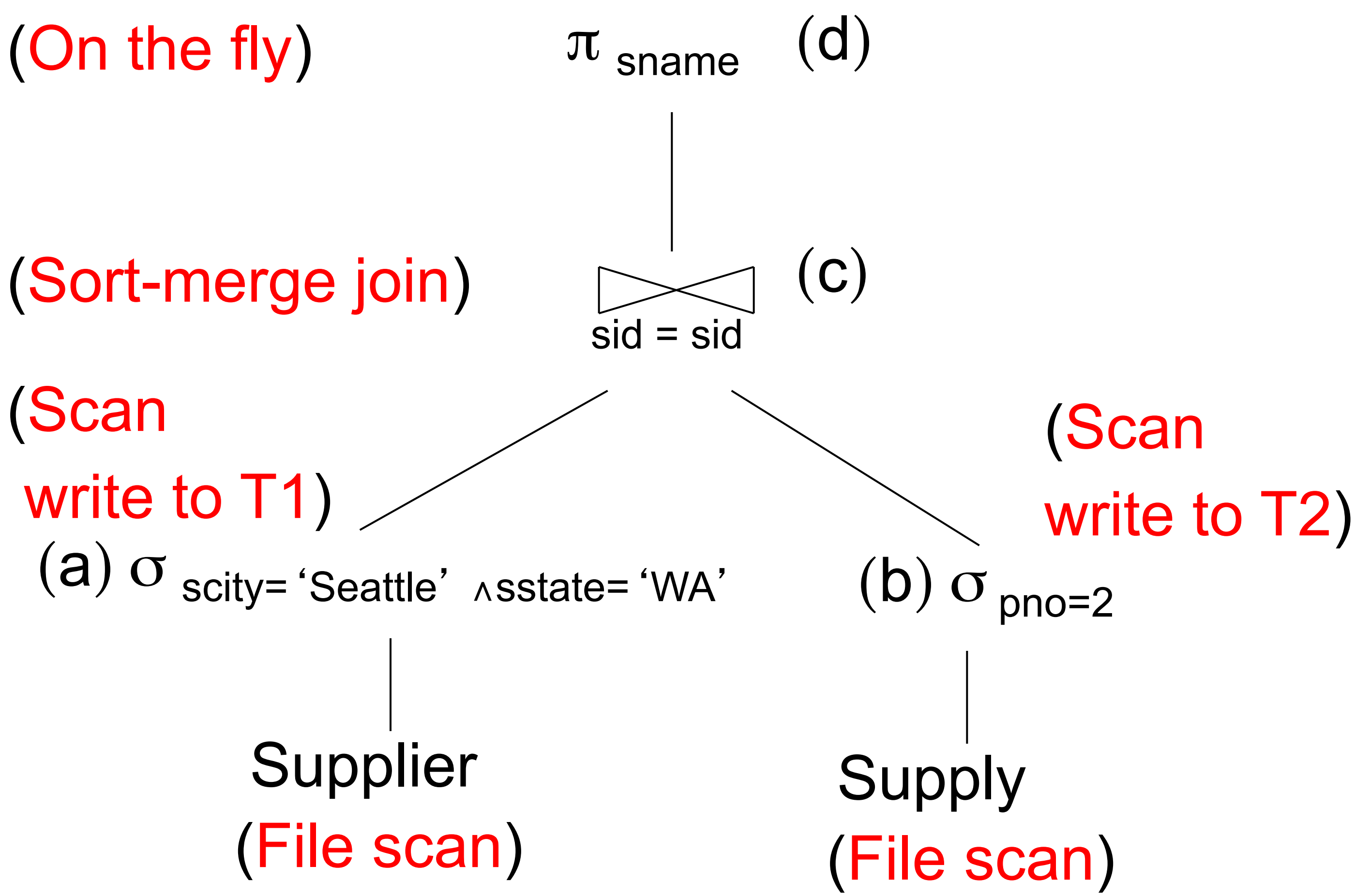


A physical query plan is a logical query plan annotated with physical implementation details

Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

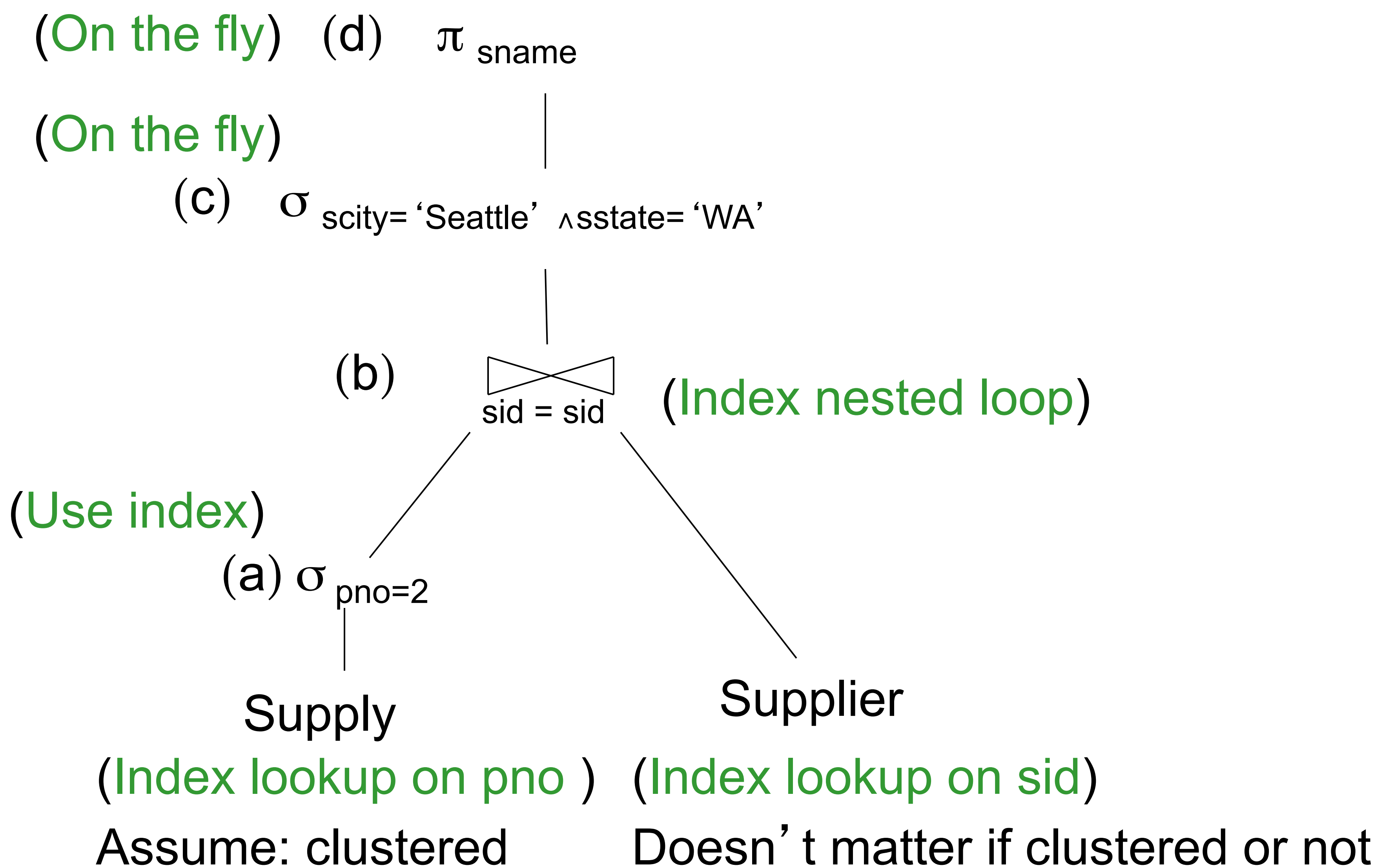
Physical Query Plan 2



Supplier(sid, sname, scity, sstate)

Supply(sid, pno, quantity)

Physical Query Plan 3



Physical Data Independence

- Means that applications are insulated from changes in physical storage details
  - E.g., can add/remove indexes without changing apps
  - Can do other physical tunings for performance

- SQL and relational algebra facilitate physical data independence because both languages are “set-at-a-time”: Relations as input and output