

Database System Internals

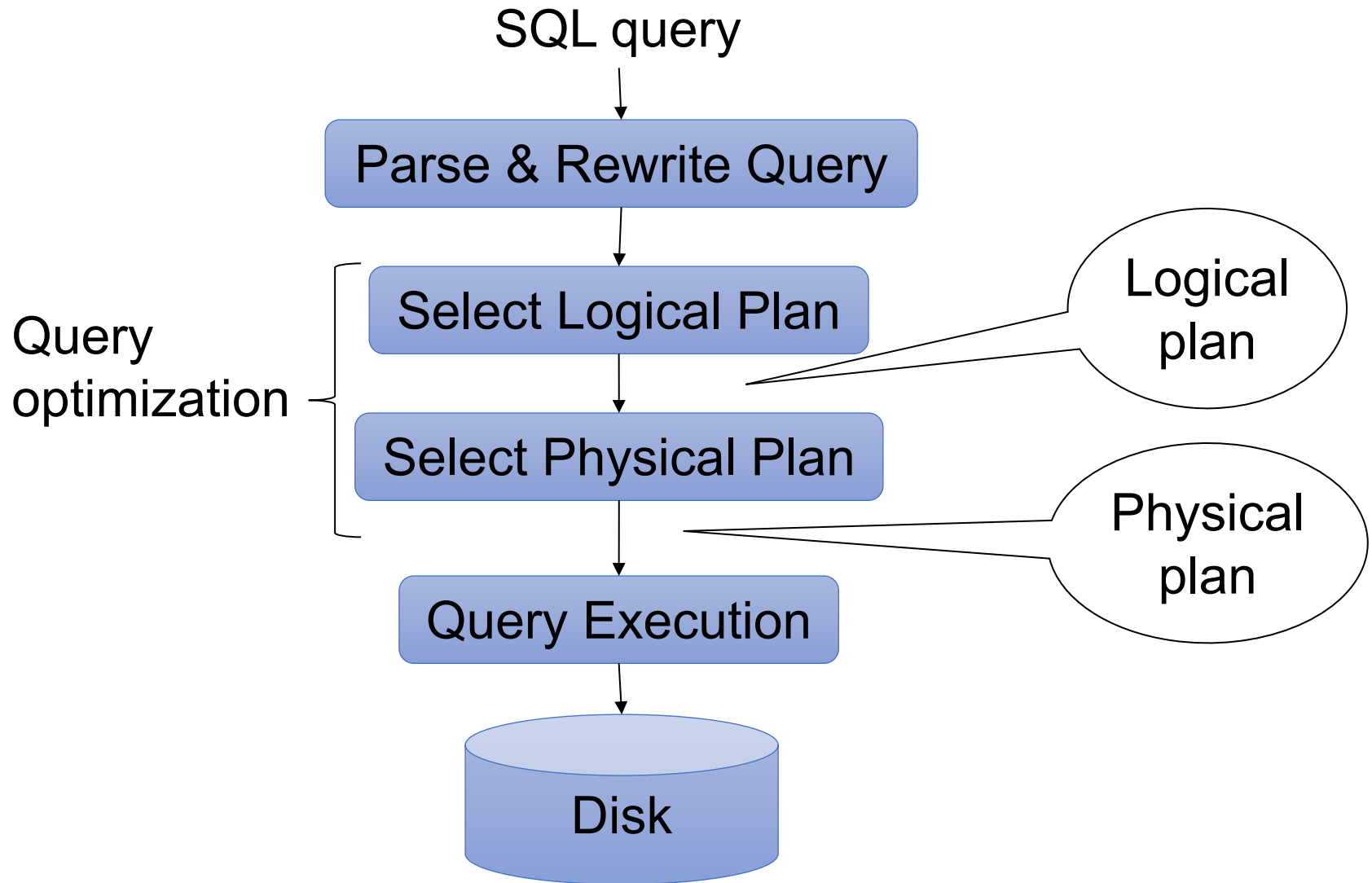
Relational Model Review

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Announcements

- Lab 1 part 1 is due on Monday, April 6
 - Lab 1 in full is due on April 15
 - “git pull upstream master” before building
 - Remember to git commit and git push often!
 - Thursday’s sections: SimpleDB repo and structure
- HW1 is due on April 10
 - Submit via gradescope
see Yin Yin’s guidelines in piazza
- 544M first paper review is due April 17
 - Submit via email to me.

Query Evaluation Steps Review



Database/Relation/Tuple

- A **Database** is collection of relations
- A **Relation** R is subset of $S_1 \times S_2 \times \dots \times S_n$
 - Where S_i is the domain of attribute i
 - n is number of attributes of the relation
 - A relation is a set of tuples
- A **Tuple** t is an element of $S_1 \times S_2 \times \dots \times S_n$

Other names: relation = **table**; tuple = **row**

Discussion

■ Rows in a relation:

Data independence!

- Ordering immaterial (a relation is a set)
- All rows are distinct – **set semantics**
- Query answers may have duplicates – **bag semantics**

■ Columns in a tuple:

- Ordering is significant (in theory, it shouldn't be)
- Applications refer to columns by their names

■ Domain of each column is a primitive type

Schema

- **Relation schema**: describes column heads
 - Relation name
 - Name of each field (or column, or attribute)
 - Domain of each field
- **Degree (or arity) of relation**: # attributes
- **Database schema**: set of all relation schemas

Instance

- **Relation instance**: concrete table content
 - Set of tuples (also called records) matching the schema
- **Cardinality of relation instance**: # tuples
- **Database instance**: set of all relation instances

What is the schema? What is the instance?

Supplier

sno	sname	scity	sstate
1	s1	city 1	WA
2	s2	city 1	WA
3	s3	city 2	MA
4	s4	city 2	MA

What is the schema? What is the instance?

Relation schema

Supplier(sno: integer, sname: string, scity: string, sstate: string)

Supplier

sno	sname	scity	sstate
1	s1	city 1	WA
2	s2	city 1	WA
3	s3	city 2	MA
4	s4	city 2	MA

instance

What is the schema? What is the instance?

Handled by SimpleDB
Catalog

Relation schema

Supplier(sno: integer, sname: string, scity: string, sstate: string)

Supplier

sno	sname	scity	sstate
1	s1	city 1	WA
2	s2	city 1	WA
3	s3	city 2	MA
4	s4	city 2	MA

SimpleDB **Storage
Manager**

instance

Integrity Constraints

- Condition specified on a database schema
- Restricts data that can be stored in db instance
- DBMS enforces integrity constraints
 - Ensures only legal database instances exist
- Simplest form of constraint is domain constraint
 - Attribute values must come from attribute domain

Key Constraints

- **Super Key:** “set of attributes that functionally determines all attributes”
- **Key:** Minimal super-key; a.k.a. “candidate key”
- **Primary key:** One minimal key can be selected as primary key

Foreign Key Constraints

- A relation can refer to a tuple in another relation
- **Foreign key**
 - Field that refers to tuples in another relation
 - This field refers to the primary key of other relation

Key Constraint SQL Examples

```
CREATE TABLE Part (  
    pno integer,  
    pname varchar(20),  
    psize integer,  
    pcolor varchar(20),  
    PRIMARY KEY (pno)  
);
```

Key Constraint SQL Examples

```
CREATE TABLE Supply(  
    sno integer,  
    pno integer,  
    qty integer,  
    price integer  
);
```

```
CREATE TABLE Part (  
    pno integer,  
    pname varchar(20),  
    psize integer,  
    pcolor varchar(20),  
    PRIMARY KEY (pno)  
);
```

Key Constraint SQL Examples

```
CREATE TABLE Supply(  
    sno integer,  
    pno integer,  
    qty integer,  
    price integer,  
    PRIMARY KEY (sno,pno)  
);
```

```
CREATE TABLE Part (  
    pno integer,  
    pname varchar(20),  
    psize integer,  
    pcolor varchar(20),  
    PRIMARY KEY (pno)  
);
```

Key Constraint SQL Examples

```
CREATE TABLE Supply(  
    sno integer,  
    pno integer,  
    qty integer,  
    price integer,  
    PRIMARY KEY (sno,pno) ,  
    FOREIGN KEY (sno) REFERENCES Supplier,  
    FOREIGN KEY (pno) REFERENCES Part  
);
```

```
CREATE TABLE Part (  
    pno integer,  
    pname varchar(20),  
    psize integer,  
    pcolor varchar(20),  
    PRIMARY KEY (pno)  
);
```

Key Constraint SQL Examples

```
CREATE TABLE Supply(  
    sno integer,  
    pno integer,  
    qty integer,  
    price integer,  
    PRIMARY KEY (sno,pno) ,  
    FOREIGN KEY (sno) REFERENCES Supplier  
        ON DELETE NO ACTION,  
    FOREIGN KEY (pno) REFERENCES Part  
        ON DELETE CASCADE  
);
```

```
CREATE TABLE Part (  
    pno integer,  
    pname varchar(20),  
    psize integer,  
    pcolor varchar(20),  
    PRIMARY KEY (pno)  
);
```

General Constraints

- **Table constraints serve to express complex constraints over a single table**

```
CREATE TABLE Part (  
    pno integer,  
    pname varchar(20),  
    psize integer,  
    pcolor varchar(20),  
    PRIMARY KEY (pno),  
    CHECK ( psize > 0 )  
);
```

Note: Also possible to create constraints over many tables
Alternative: use database triggers for that purpose

Relational Query Languages

Relational Query Language

- **Set-at-a-time:**
 - Query inputs and outputs are relations
- **Two variants of the query language:**
 - Relational algebra: specifies order of operations
 - Relational calculus / SQL: declarative

- We will go very quickly in class over the Relational Algebra and SQL
- Please review at home:
 - Read the slides that we skipped in class
 - Review material from 344 as needed

Relational Algebra

- **Queries specified in an operational manner**
 - A query gives a step-by-step procedure
- **Relational operators**
 - Take one or two relation instances as argument
 - Return one relation instance as result
 - Easy to compose into relational algebra expressions

Five Basic Relational Operators

- **Selection:** $\sigma_{\text{condition}}(S)$
 - Condition is Boolean combination (\wedge, \vee) of atomic predicates ($<, \leq, =, \neq, \geq, >$)
- **Projection:** $\pi_{\text{list-of-attributes}}(S)$
- **Union** (\cup)
- **Set difference** ($-$),
- **Cross-product/cartesian product** (\times),
Join: $R \bowtie_{\theta} S = \sigma_{\theta}(R \times S)$

Selection & Projection Examples

Patient

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

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

zip	disease
98125	flu
98125	heart
98120	lung
98120	heart

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

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

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

zip
98120
98125

Cross-Product Example

AnonPatient P

age	zip	disease
54	98125	heart
20	98120	flu

Voters V

name	age	zip
p1	54	98125
p2	20	98120

$P \times V$

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

Different Types of Join

- **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

Different Types of Join

Our focus in SimpleDB
We have a class for the
predicate θ

- **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

EqJoin Example

AnonPatient P

age	zip	disease
50	98125	heart
20	98120	flu

Voters V

name	age	zip
p1	54	98125
p2	20	98120

$$P \bowtie_{P.zip = V.zip \text{ and } P.age = V.age} V$$

P.age	P.zip	P.disease	V.name	V.age	V.zip
20	98120	flu	p2	20	98120

Theta-Join Example

AnonPatient P

age	zip	disease
50	98125	heart
19	98120	flu

Voters V

name	age	zip
p1	54	98125
p2	20	98120

$$P \bowtie_{P.zip = V.zip \text{ and } P.age \leq V.age + 1 \text{ and } P.age \geq V.age - 1} V$$

P.age	P.zip	P.disease	V.name	V.age	V.zip
19	98120	flu	p2	20	98120

Natural Join Example

AnonPatient P

age	zip	disease
54	98125	heart
20	98120	flu

Voters V

name	age	zip
p1	54	98125
p2	20	98120

$P \bowtie V$

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

Note:
age, zip
occur only
once

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

Voters V

name	age	zip
p1	54	98125
p2	20	98120

$P \bowtie V$

age	zip	disease	name
54	98125	heart	p1
20	98120	flu	p2
33	98120	lung	null

Logical Query Plans

Supplier(sno, sname, scity, sstate)

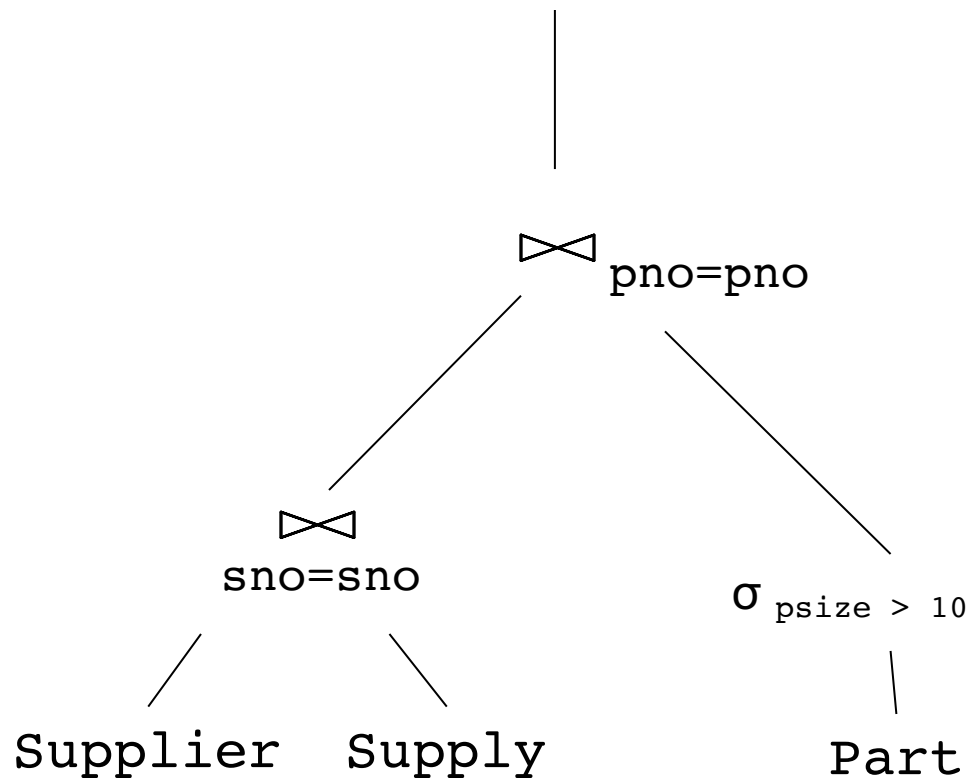
Supply(sno, pno, qty, price)

Part(pno, pname, psize, pcolor)

Logical Query Plans

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

$\Pi_{\text{sname, scity}}$



When we don't specify, we usually mean EqJoin

What does this query compute?

More Examples

Relations

Supplier(sno,sname,scity,sstate)

Part(pno,pname,psize,pcolor)

Supply(sno,pno,qty,price)

Name of supplier of parts with size greater than 10

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

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

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

(Many more examples in the book)

Extended Operators of RA

- **Duplicate elimination (δ)**
 - Since commercial DBMSs operate on multisets not sets
- **Aggregate operators (γ)**
 - Min, max, sum, average, count
- **Grouping operators (γ)**
 - Partitions tuples of a relation into “groups”
 - Aggregates can then be applied to groups
- **Sort operator (τ)**

Structured Query Language: SQL

- Declarative query language, based on the relational calculus (see 344)
- Data definition language
 - Statements to create, modify tables and views
- Data manipulation language
 - Statements to issue queries, insert, delete data

Basic form: (plus many many more bells and whistles)

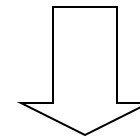
```
SELECT <attributes>  
FROM   <one or more relations>  
WHERE  <conditions>
```

Simple SQL Query

Product

PName	Price	Category	Manufacturer
Gizmo	\$19.99	Gadgets	GizmoWorks
Powergizmo	\$29.99	Gadgets	GizmoWorks
SingleTouch	\$149.99	Photography	Canon
MultiTouch	\$203.99	Household	Hitachi

```
SELECT *  
FROM Product  
WHERE category='Gadgets'
```



PName	Price	Category	Manufacturer
Gizmo	\$19.99	Gadgets	GizmoWorks
Powergizmo	\$29.99	Gadgets	GizmoWorks

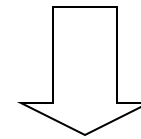
“selection”

Simple SQL Query

Product

PName	Price	Category	Manufacturer
Gizmo	\$19.99	Gadgets	GizmoWorks
Powergizmo	\$29.99	Gadgets	GizmoWorks
SingleTouch	\$149.99	Photography	Canon
MultiTouch	\$203.99	Household	Hitachi

```
SELECT PName, Price, Manufacturer
FROM   Product
WHERE  Price > 100
```



“selection” and
“projection”

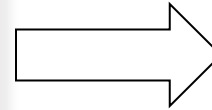
PName	Price	Manufacturer
SingleTouch	\$149.99	Canon
MultiTouch	\$203.99	Hitachi

Details

- Case insensitive:
 - Same: `SELECT` `Select` `select`
 - Same: `Product` `product`
 - Different: `'Seattle'` `'seattle'`
- Constants:
 - `'abc'` - yes
 - `"abc"` - no

Eliminating Duplicates

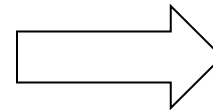
```
SELECT DISTINCT category  
FROM Product
```



Category
Gadgets
Photography
Household

Compare to:

```
SELECT category  
FROM Product
```



Category
Gadgets
Gadgets
Photography
Household

Ordering the Results

```
SELECT pname, price, manufacturer  
FROM Product  
WHERE category='gizmo' AND price > 50  
ORDER BY price, pname
```

Ties are broken by the second attribute on the ORDER BY list, etc.

Ordering is ascending, unless you specify the DESC keyword.

Joins

Product (pname, price, category, manufacturer)
Company (cname, stockPrice, country)

Find all products under \$200 manufactured in Japan;
return their names and prices.

```
SELECT PName, Price
FROM Product, Company
WHERE Manufacturer=CName AND Country='Japan'
      AND Price <= 200
```

Quick Review of SQL

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

```
SELECT DISTINCT z.pno, z.pname
FROM   Supplier x, Supply y, Part z
WHERE  x.sno = y.sno and y.pno = z.pno
       and x.scity = 'Seattle' and y.price < 100
```

What does
this query
compute?

Quick Review of SQL

Supplier(sno, sname, scity, sstate)

Supply(sno, pno, qty, price)

Part(pno, pname, psize, pcolor)

What about
this one?

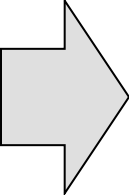
```
SELECT z.pname, count(*) as cnt, min(y.price)
FROM   Supplier x, Supply y, Part z
WHERE  x.sno = y.sno and y.pno = z.pno
GROUP BY z.pname
```

Tuple Variables

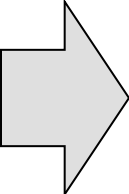
Person(pname, address, worksfor)
Company(cname, address)

Which
address ?

```
SELECT DISTINCT pname, address
FROM      Person, Company
WHERE     worksfor = cname
```



```
SELECT DISTINCT Person.pname, Company.address
FROM      Person, Company
WHERE     Person.worksfor = Company.cname
```



```
SELECT DISTINCT x.pname, y.address
FROM      Person AS x, Company AS y
WHERE     x.worksfor = y.cname
```

Nested Queries

- **Nested query**
 - Query that has another query embedded within it
 - The embedded query is called a **subquery**
- Why do we need them?
 - Enables to refer to a table that must itself be computed
- Subqueries can appear in
 - **WHERE** clause (common)
 - **FROM** clause (less common)
 - **HAVING** clause (less common)

Subqueries Returning Relations

Company(name, city)
Product(pname, maker)
Purchase(id, product, buyer)

Return cities where one can find companies that manufacture products bought by Joe Blow

```
SELECT DISTINCT Company.city
FROM    Company
WHERE   Company.name IN
        (SELECT Product.maker
         FROM    Purchase , Product
         WHERE   Product.pname=Purchase.product
         AND     Purchase .buyer = 'Joe Blow');
```

Subqueries Returning Relations

You can also use: $s > \text{ALL } R$
 $s > \text{ANY } R$
 $\text{EXISTS } R$

Product (pname, price, category, maker)

Find products that are more expensive than all those produced
By “Gizmo-Works”

```
SELECT pname
FROM   Product
WHERE  price > ALL (SELECT price
                    FROM   Purchase
                    WHERE  maker='Gizmo-Works')
```

Correlated Queries

Movie (title, year, director, length)

Find movies whose title appears in more than one year.

```
SELECT DISTINCT title
FROM Movie AS x
WHERE year <> ANY
      (SELECT year
       FROM Movie
       WHERE title = x.title);
```

correlation



Note (1) scope of variables (2) this can still be expressed as single SFW

Aggregation

```
SELECT avg(price)
FROM Product
WHERE maker="Toyota"
```

```
SELECT count(*)
FROM Product
WHERE year > 1995
```

SQL supports several aggregation operations:
sum, count, min, max, avg

Except count, all aggregations apply to a single attribute

Grouping and Aggregation

```
SELECT  S  
FROM    R1,...,Rn  
WHERE   C1  
GROUP BY a1,...,ak  
HAVING  C2
```

Conceptual evaluation steps:

1. Evaluate FROM-WHERE, apply condition C1
2. Group by the attributes a_1, \dots, a_k
3. Apply condition C2 to each group (may have aggregates)
4. Compute aggregates in S and return the result

Read more about it in the book...

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 = y.cid and
      x.price > 100 and z.city = 'Seattle'
```

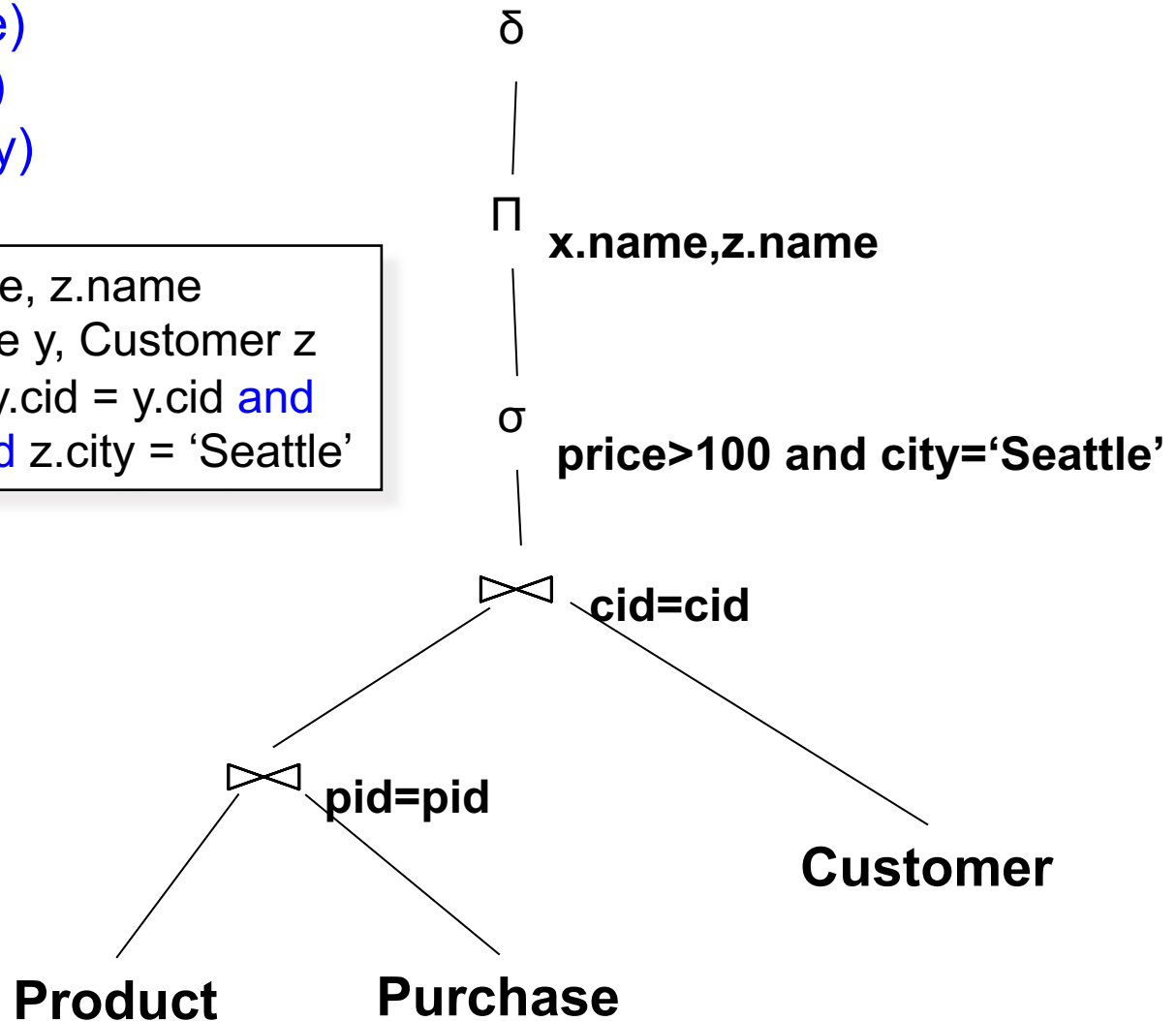
From SQL to RA

Product(pid, name, price)

Purchase(pid, cid, store)

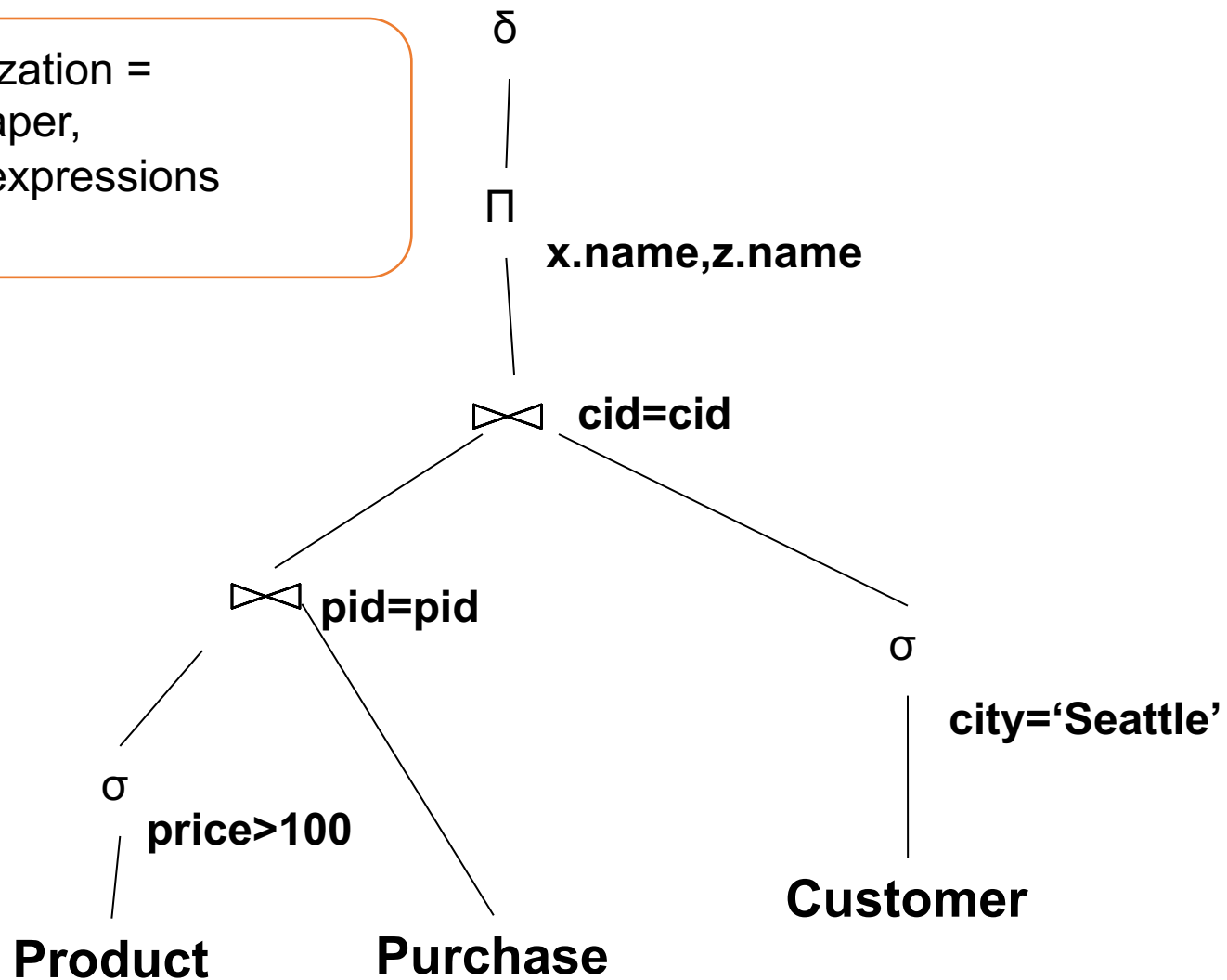
Customer(cid, name, city)

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



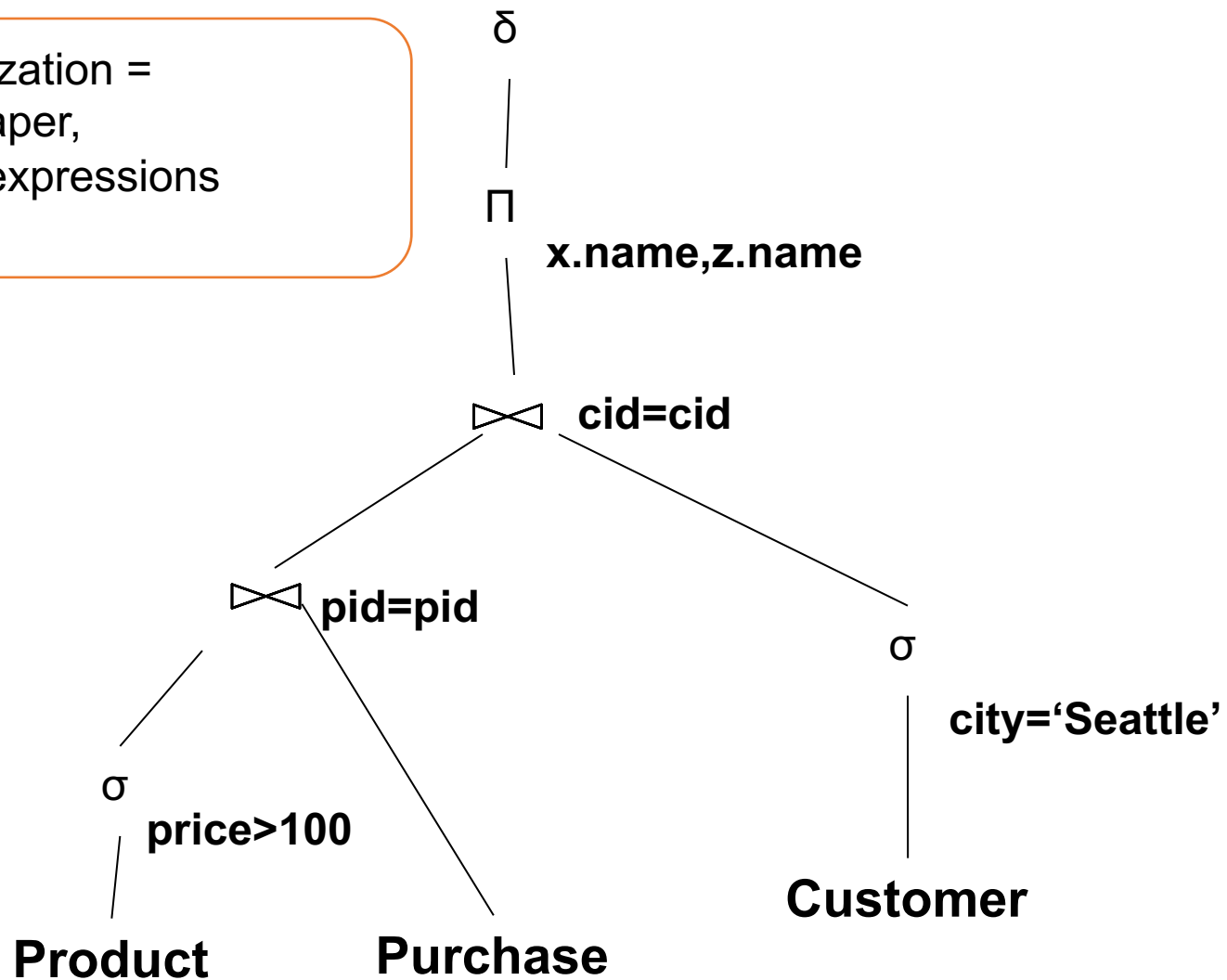
An Equivalent Expression

Query optimization =
finding cheaper,
equivalent expressions



An Equivalent Expression

Query optimization =
finding cheaper,
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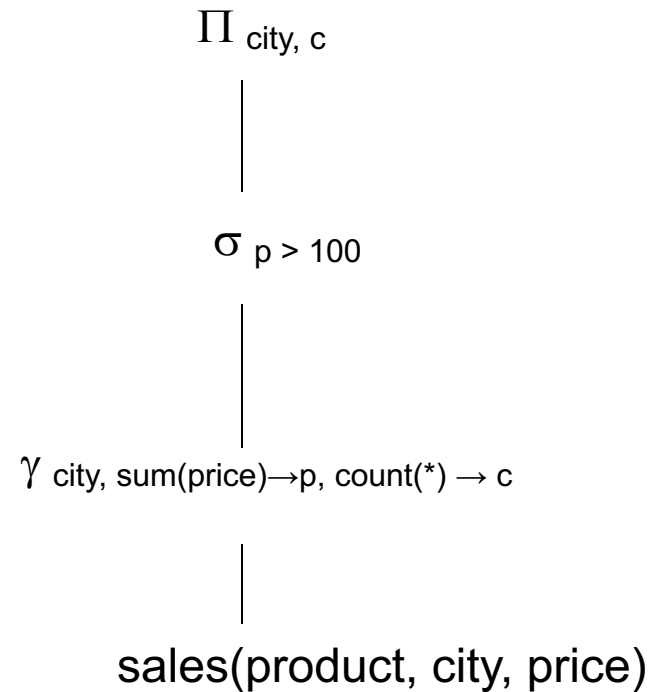


Extended RA: Operators on Bags

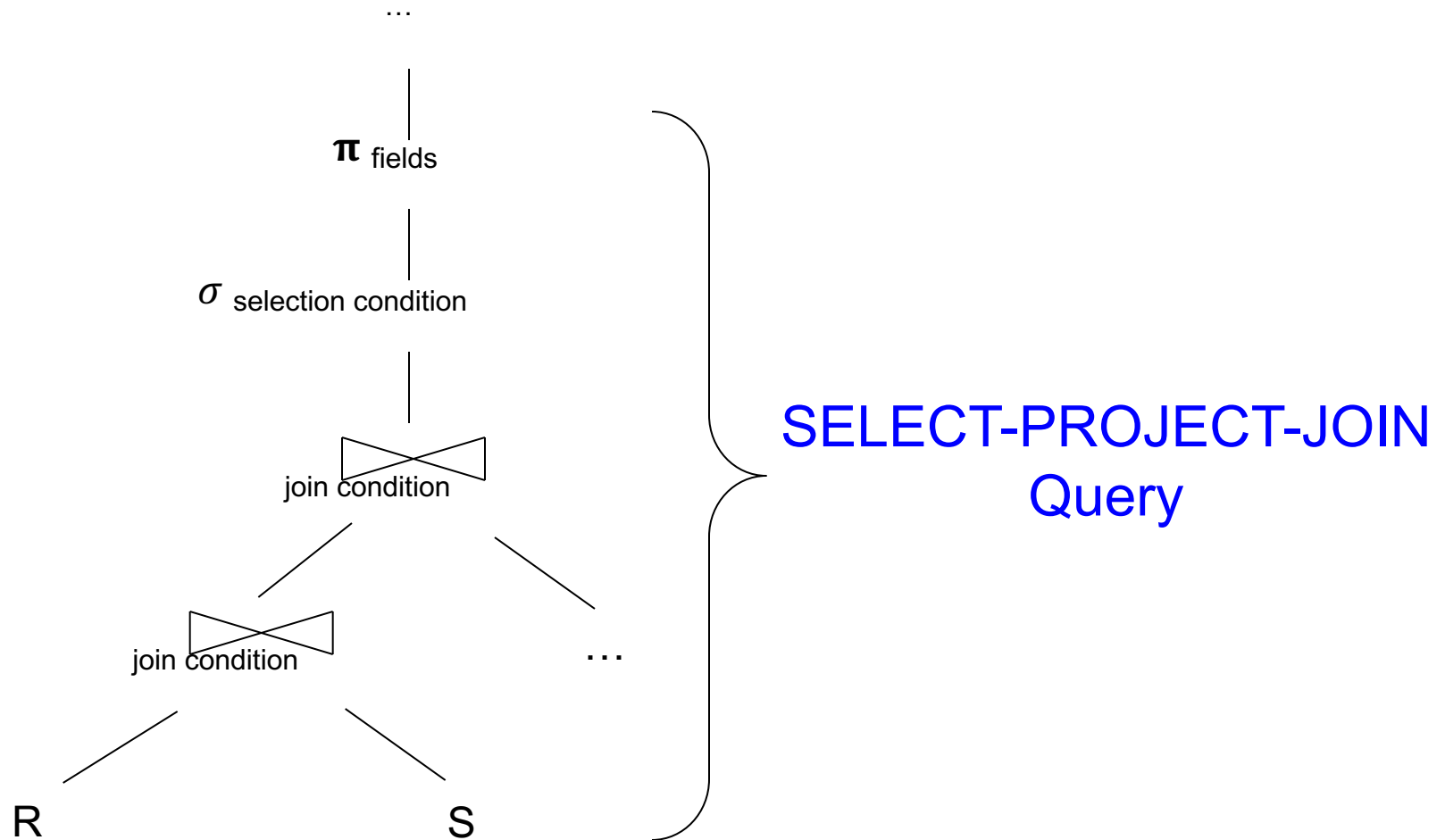
- Duplicate elimination δ
- Grouping γ
- Sorting τ

Logical Query Plan

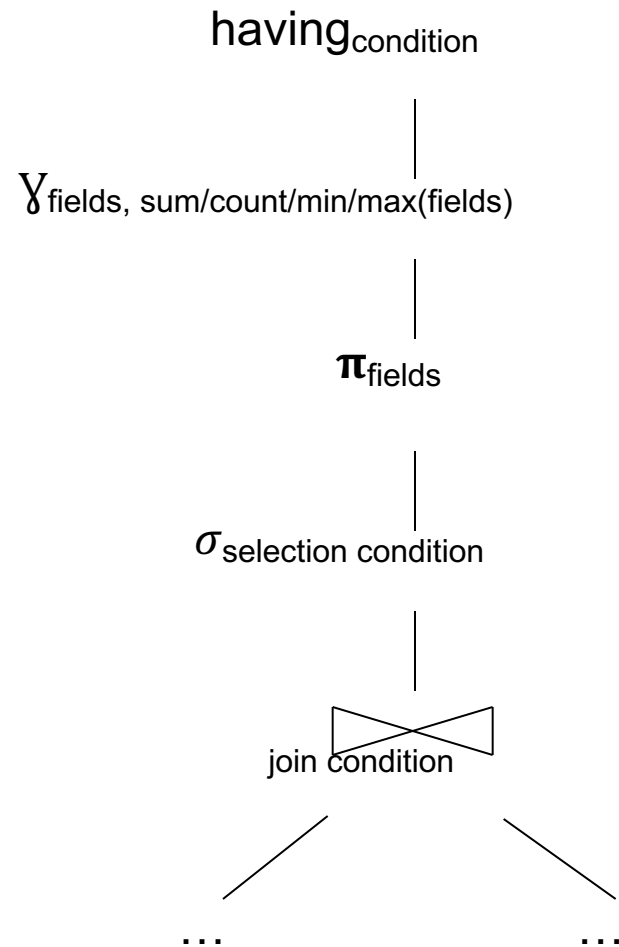
```
SELECT city, count(*)  
FROM sales  
GROUP BY city  
HAVING sum(price) > 100
```



Typical Plan for Complex Aggregates



Typical Plan for Complex Aggregates



Query Evaluation Steps Review

