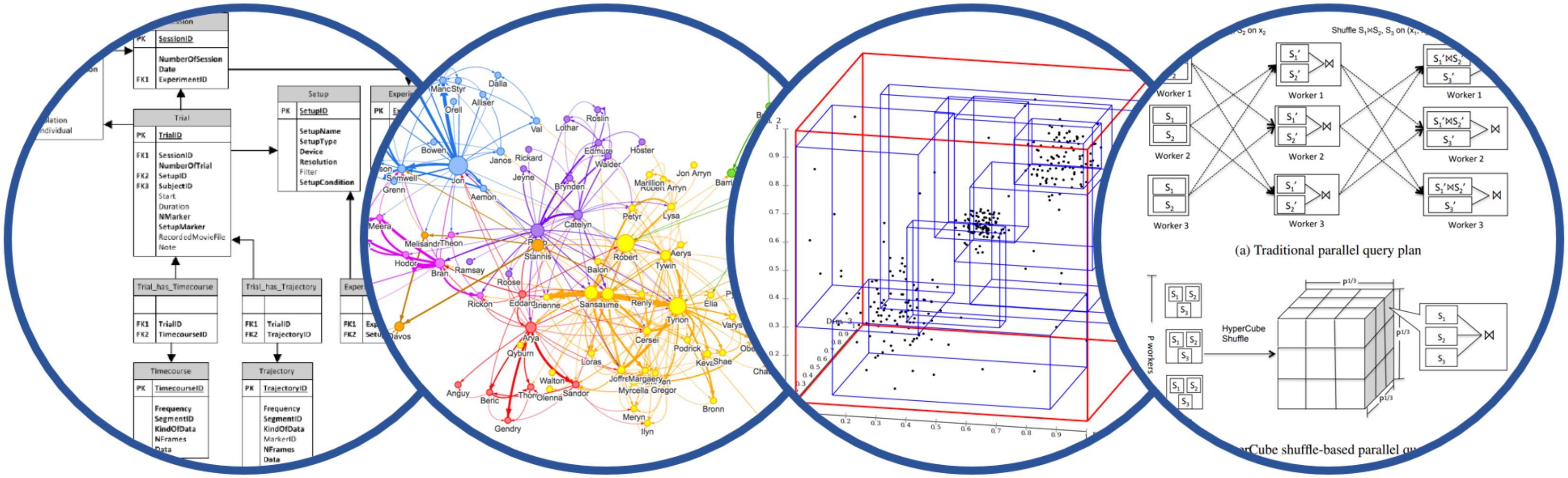


Database System Internals

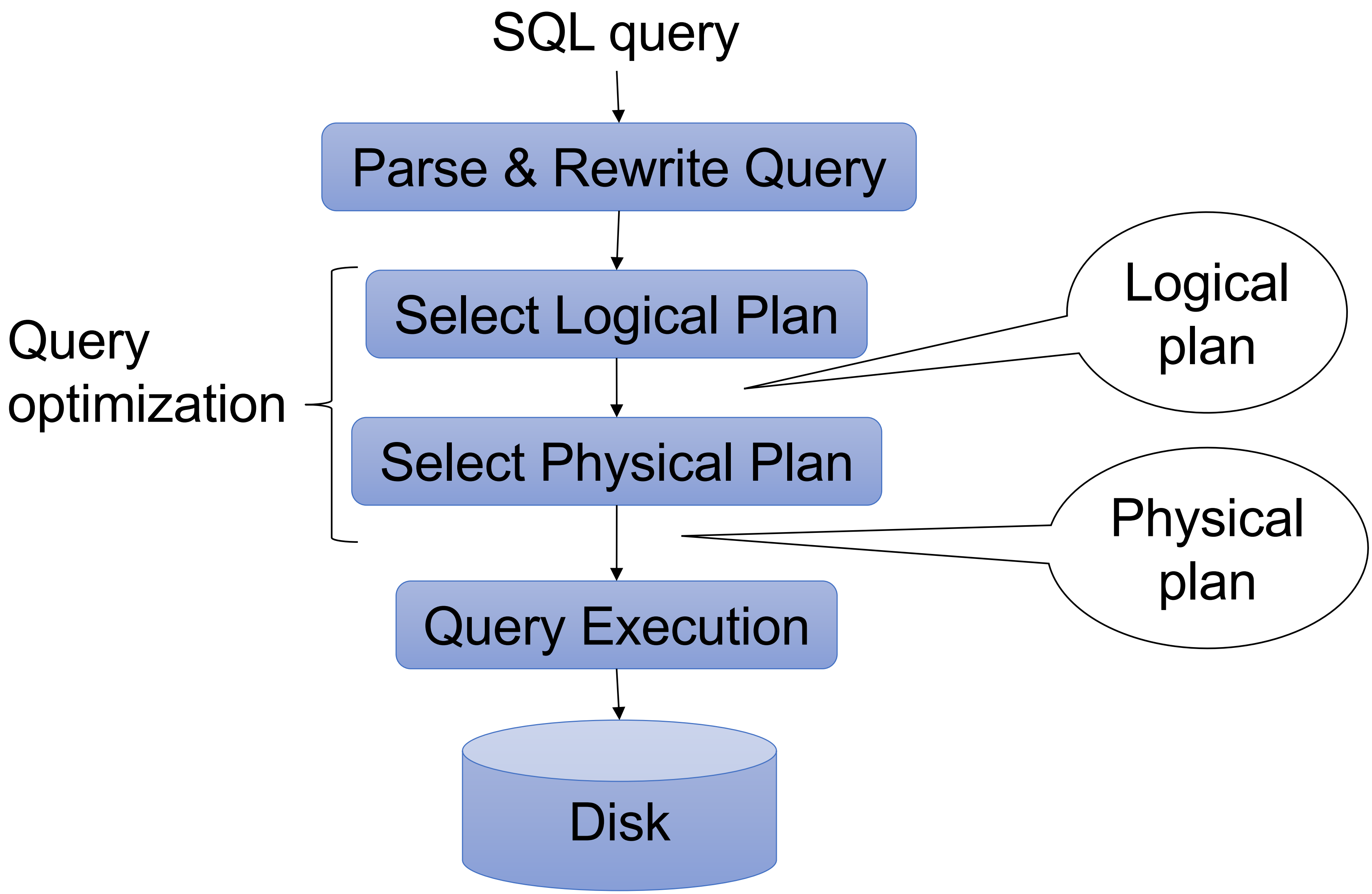
Relational Model Review

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

Announcements

- Lab 1 part 1 is due January 12th at 11pm
  - Lab 1 in full is due on January 19th
  - Remember to git commit and git push often!
  - In Thursday section we will introduce the SimpleDB repo and structure
  - Part 1 is due individually, we'll give instructions for groupwork next week
- HW1 is due next week January 14th
  - Upload to gradescope

Query Evaluation Steps Review



Database/Relation/Tuple

- A Database is collection of relations
- A Relation R is subset of $\mathbf{S_1 \times S_2 \times \ldots \times S_n}$
  - Where $\mathbf{S_i}$ 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 $\mathbf{S_1 \times S_2 \times \ldots \times S_n}$

Other names: relation = table; tuple = row

Discussion

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

Data independence!

- Columns in a tuple:
  - Ordering is significant
  - 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)

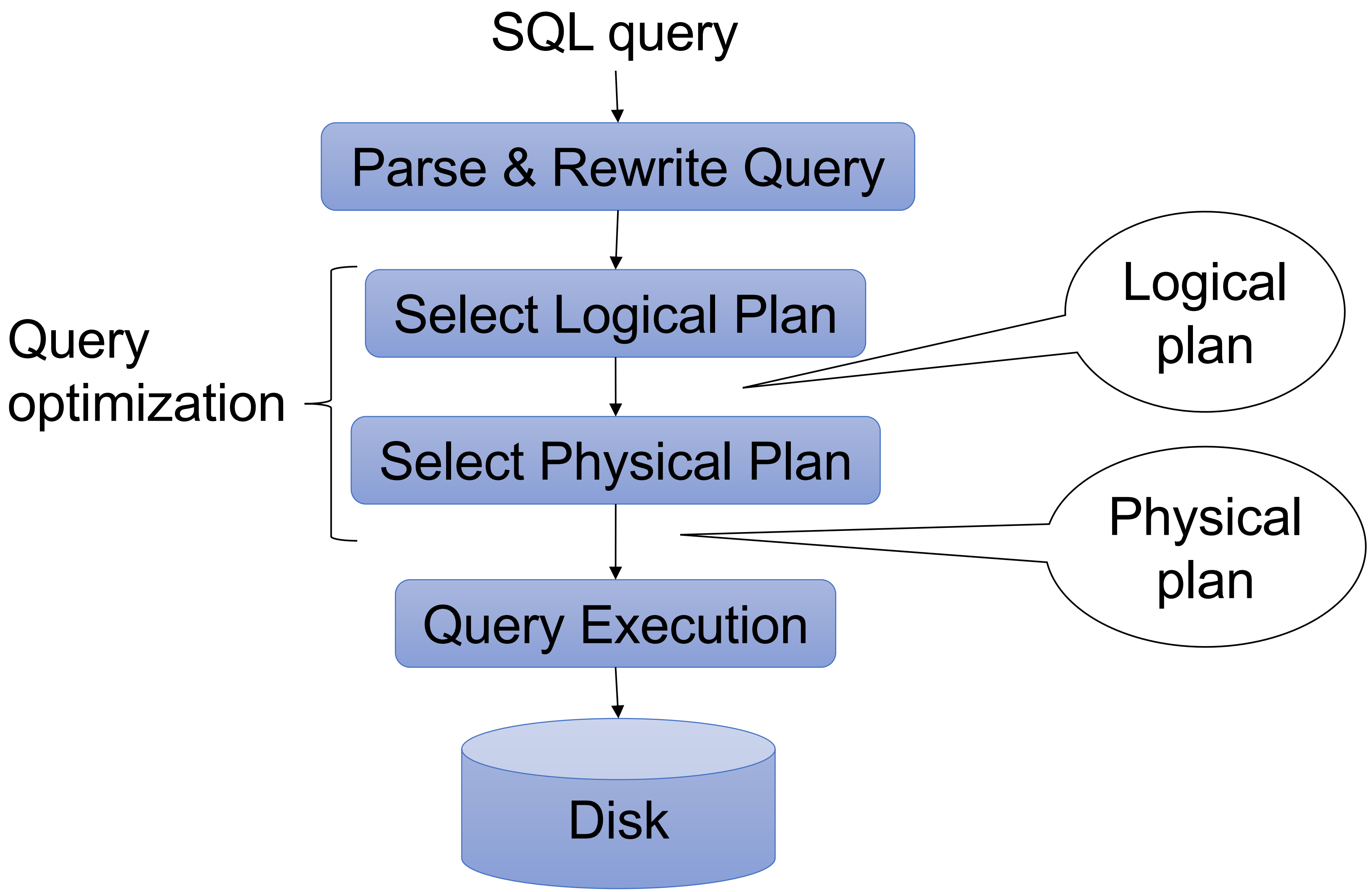
SimpleDB **Storage Manager**

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

Query Evaluation Steps Review



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
  - Typically, this field refers to the primary key of other relation
  - Can pick another field as well

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

Best to 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

Note

- 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

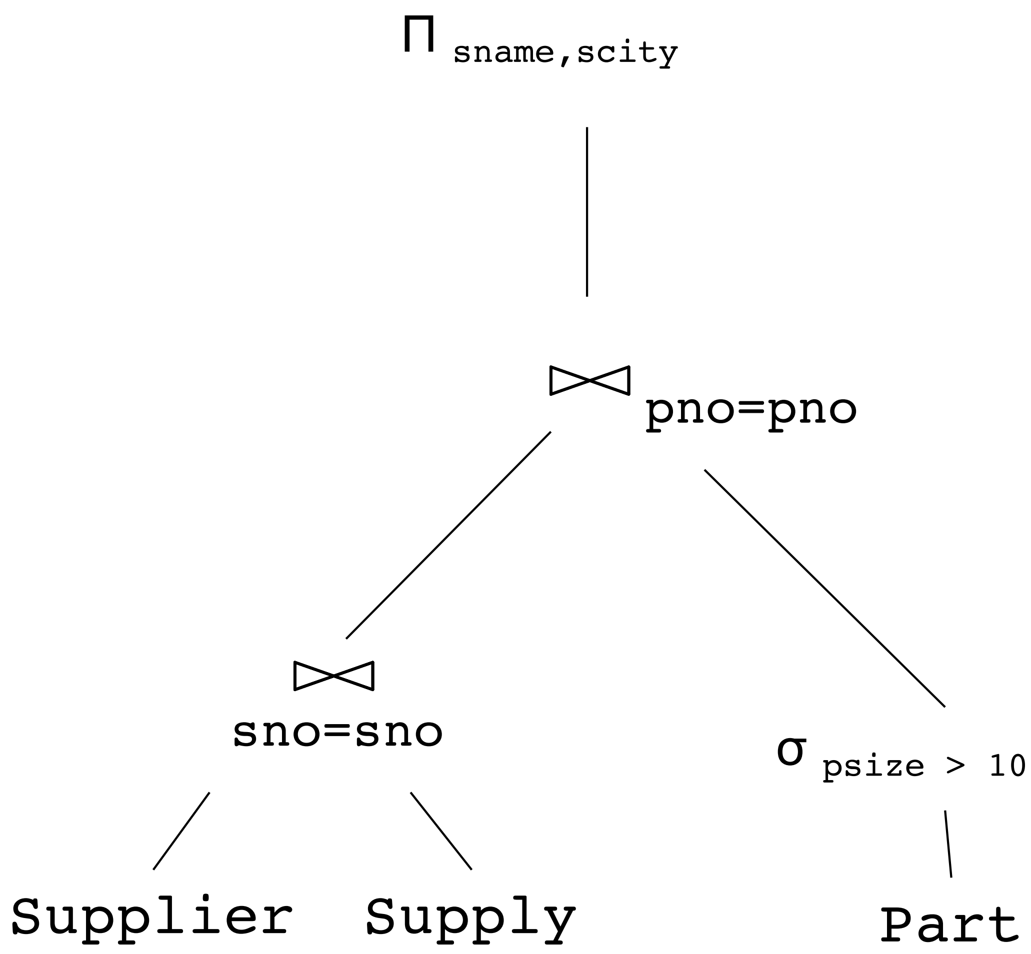
- Selection: $\sigma_{\text{condition}}(S)$
  - Condition is Boolean combination ($\wedge$,$\vee$) of atomic predicates (<, <=, =, ≠, >=, >)
- Projection: $\pi_{\text{list-of-attributes}}(S)$
- Union ($\cup$)
- Set difference (–),
- Cross-product/cartesian product ($\times$), Join: $R \bowtie_{\theta}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

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)
```



What does this query compute?

Selection & Projection Examples

Patient

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

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

zip	disease
98125	flu
98125	heart
98120	lung
98120	heart

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

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

π_{zip} ($\sigma_{disease=\text{'heart'}}$(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 × 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 $\boldsymbol{\theta}$

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

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

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

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

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

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

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

$P ⟕ V$

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

Example of Algebra Queries

Q1: Names of patients who have heart disease

$\boldsymbol{\pi}_{\text{name}}(\text{Voter} \bowtie (\sigma_{\text{disease='heart'}} (\text{AnonPatient})))$

More Examples

Relations

```
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

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

(Many more examples in the book)

Extended Operators of RA

- Duplicate elimination (δ)
  - Since commercial DBMSs operate on multisets not sets
- Aggregate operators (ɣ)
  - Min, max, sum, average, count
- Grouping operators (ɣ)
  - 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

SQL Query

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

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

Quick Review of SQL

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

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
```

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
```

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  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 > ALL R

s > ANY R

EXISTS R

Product (pname, price, category, maker)

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

```
SELECT   name
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 more than once.

```
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 $a_1,\ldots,a_k$
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

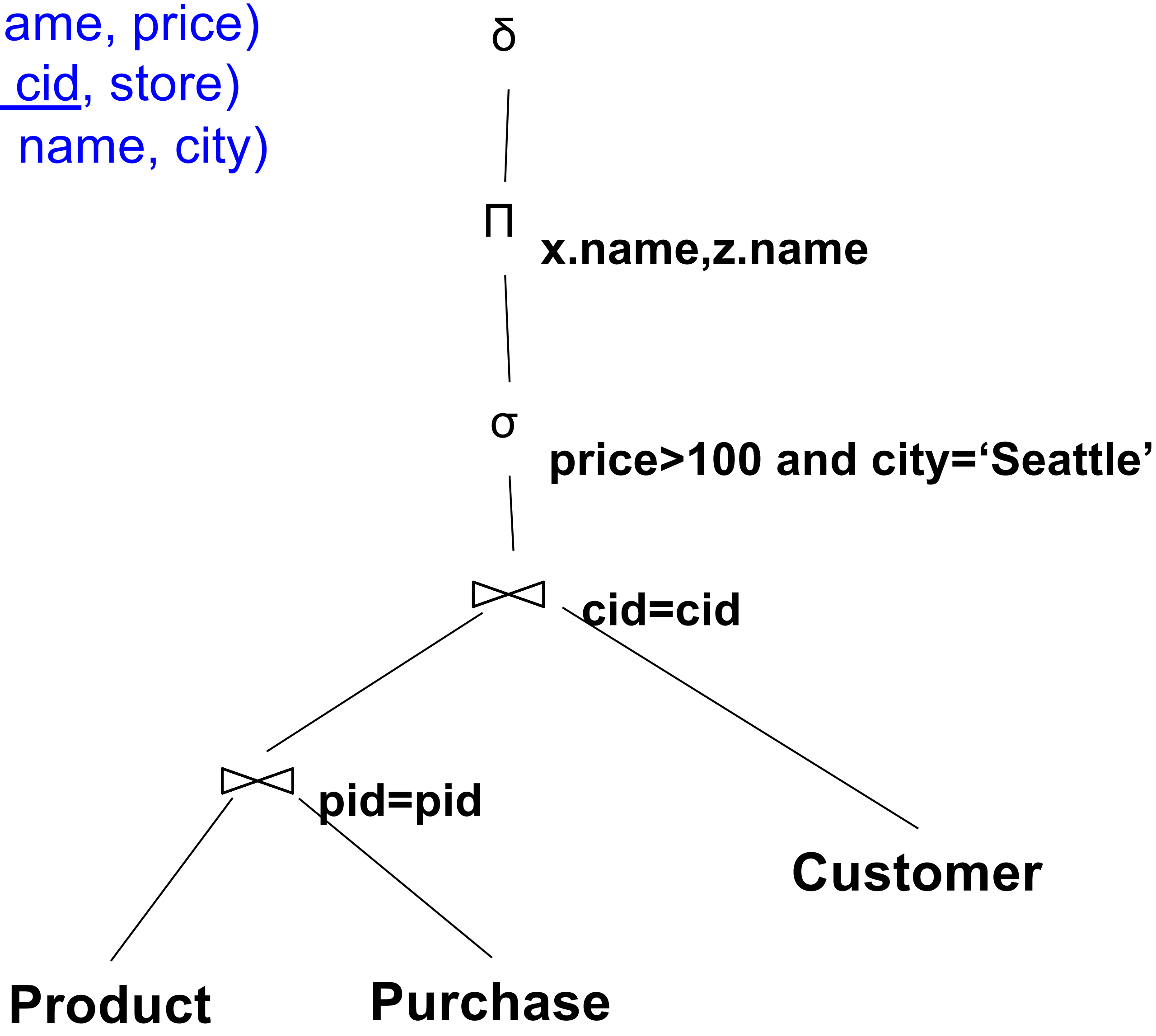
From SQL to RA

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'
```

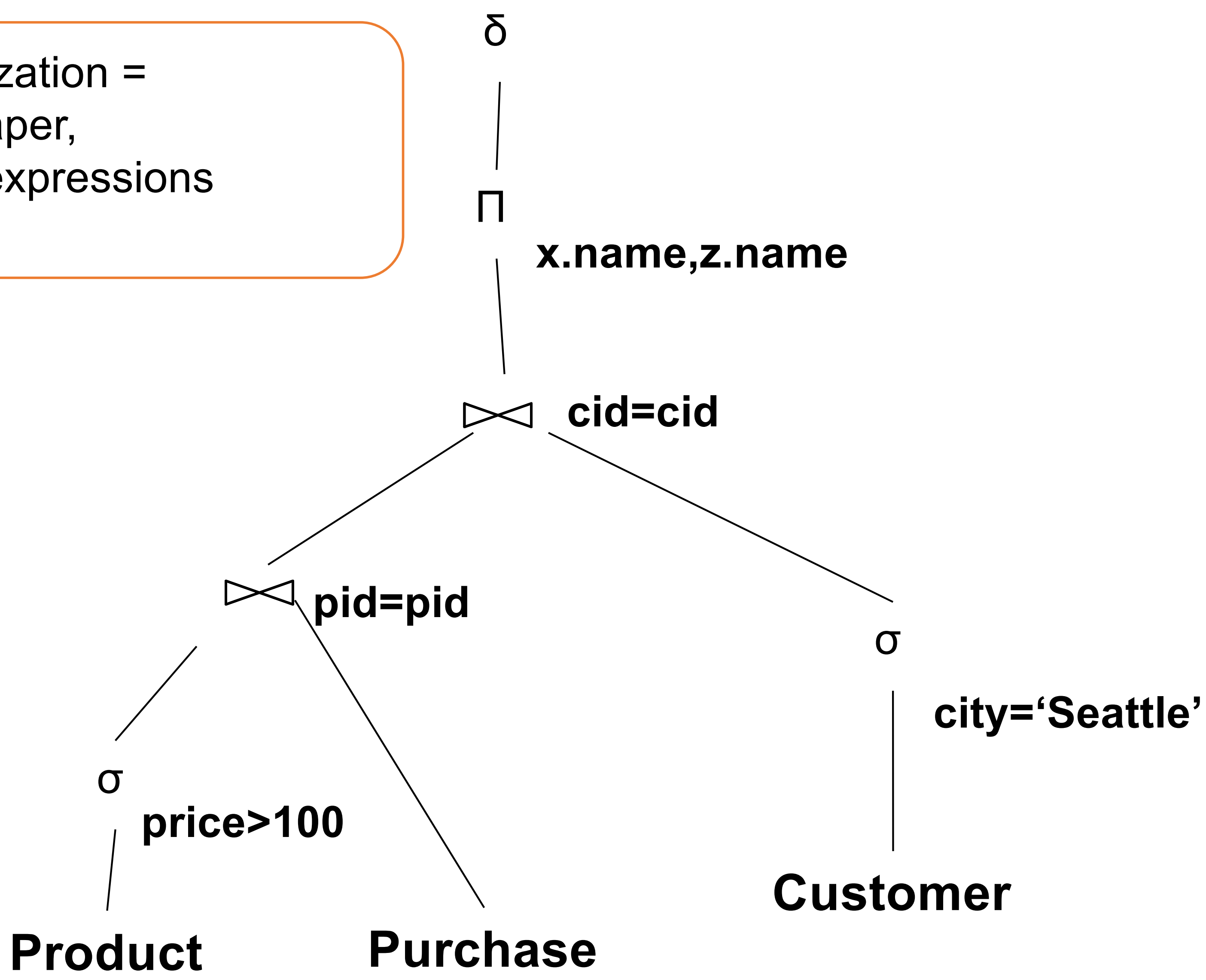
From SQL to RA

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



An Equivalent Expression

Query optimization =
finding cheaper,
equivalent expressions



An Equivalent Expression

Query optimization =
finding cheaper,
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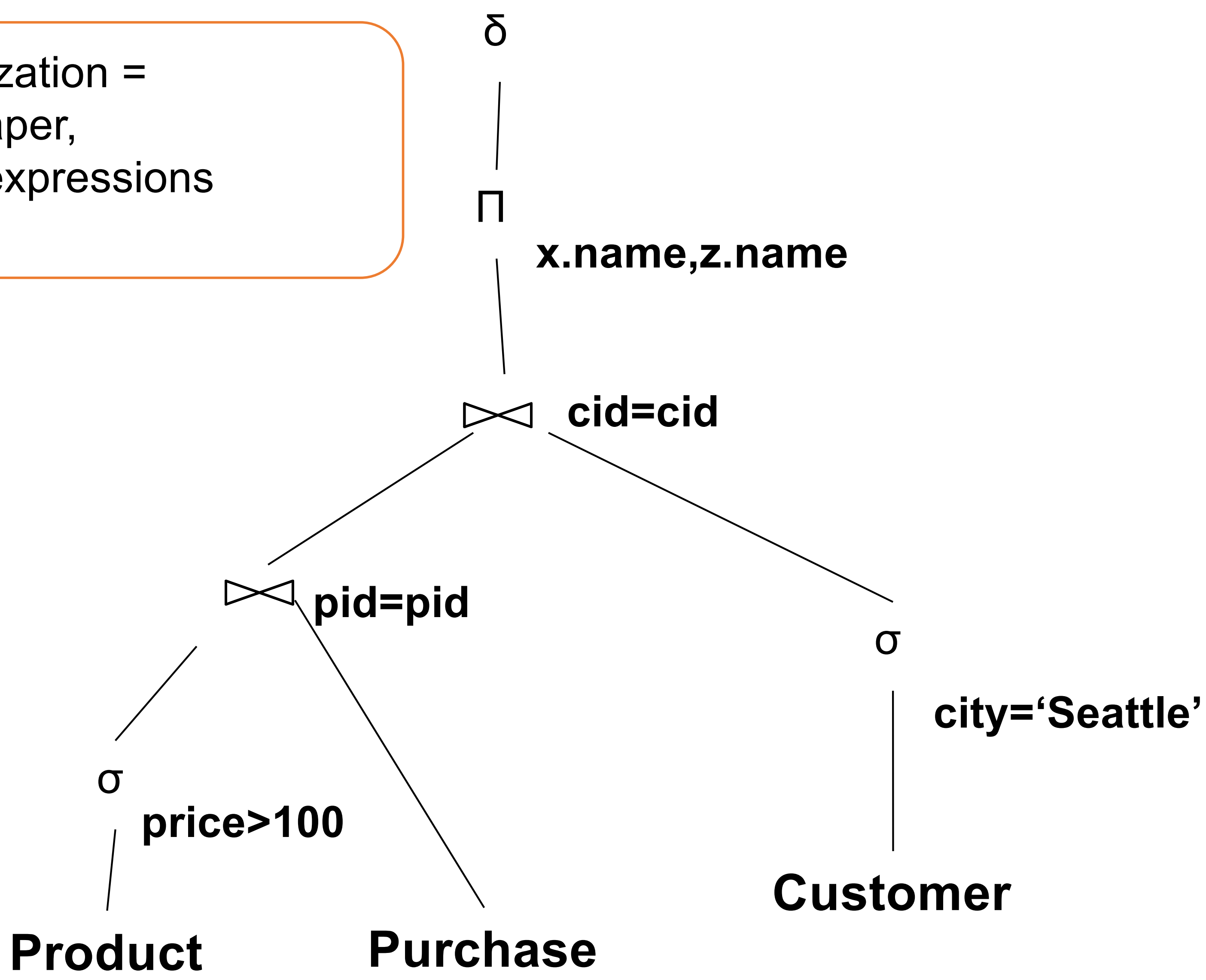


Extended RA: Operators on Bags

- Duplicate elimination δ
- Grouping γ
- Sorting τ

Logical Query Plan

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

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

|

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

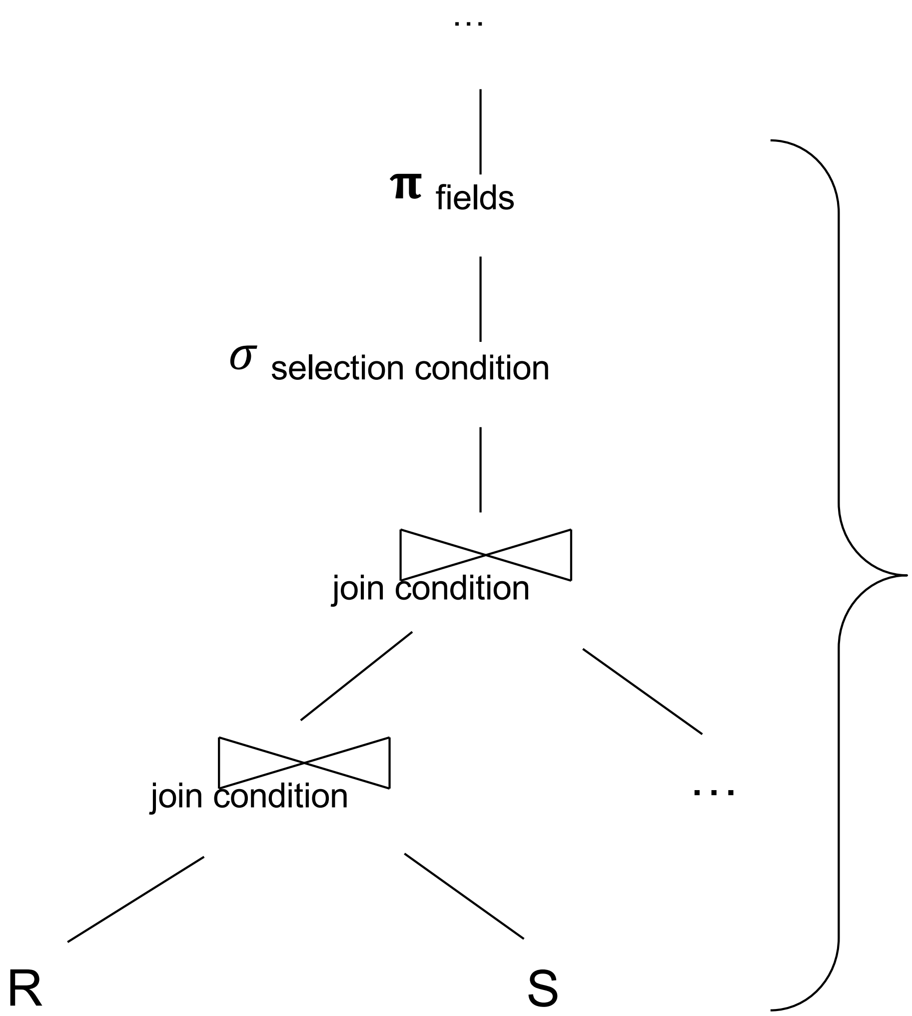
|

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

|

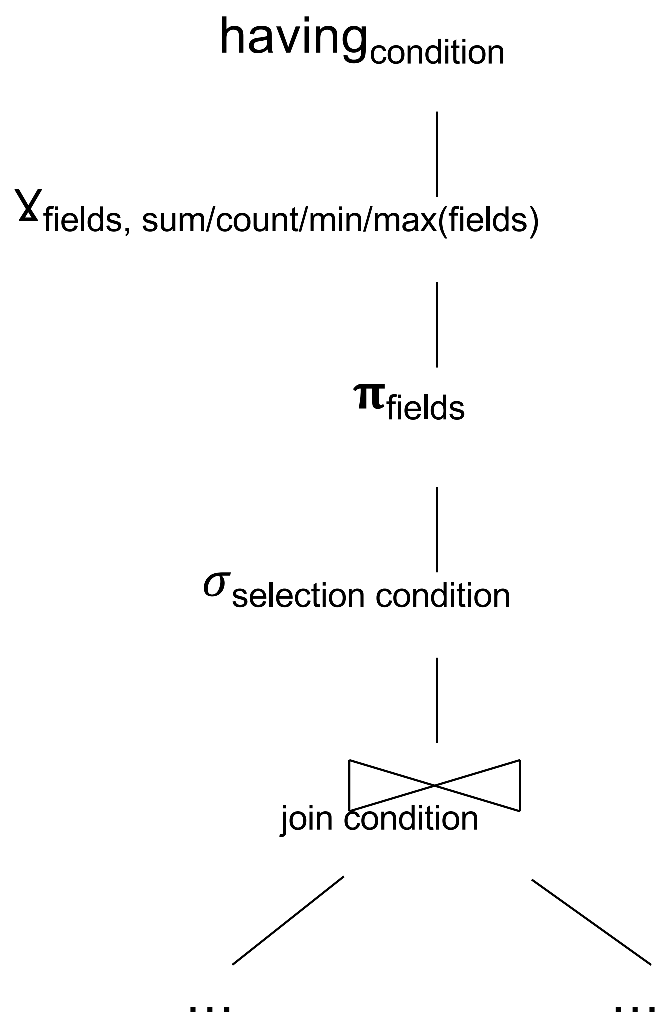
sales(product, city, price)

Typical Plan for Complex Aggregates

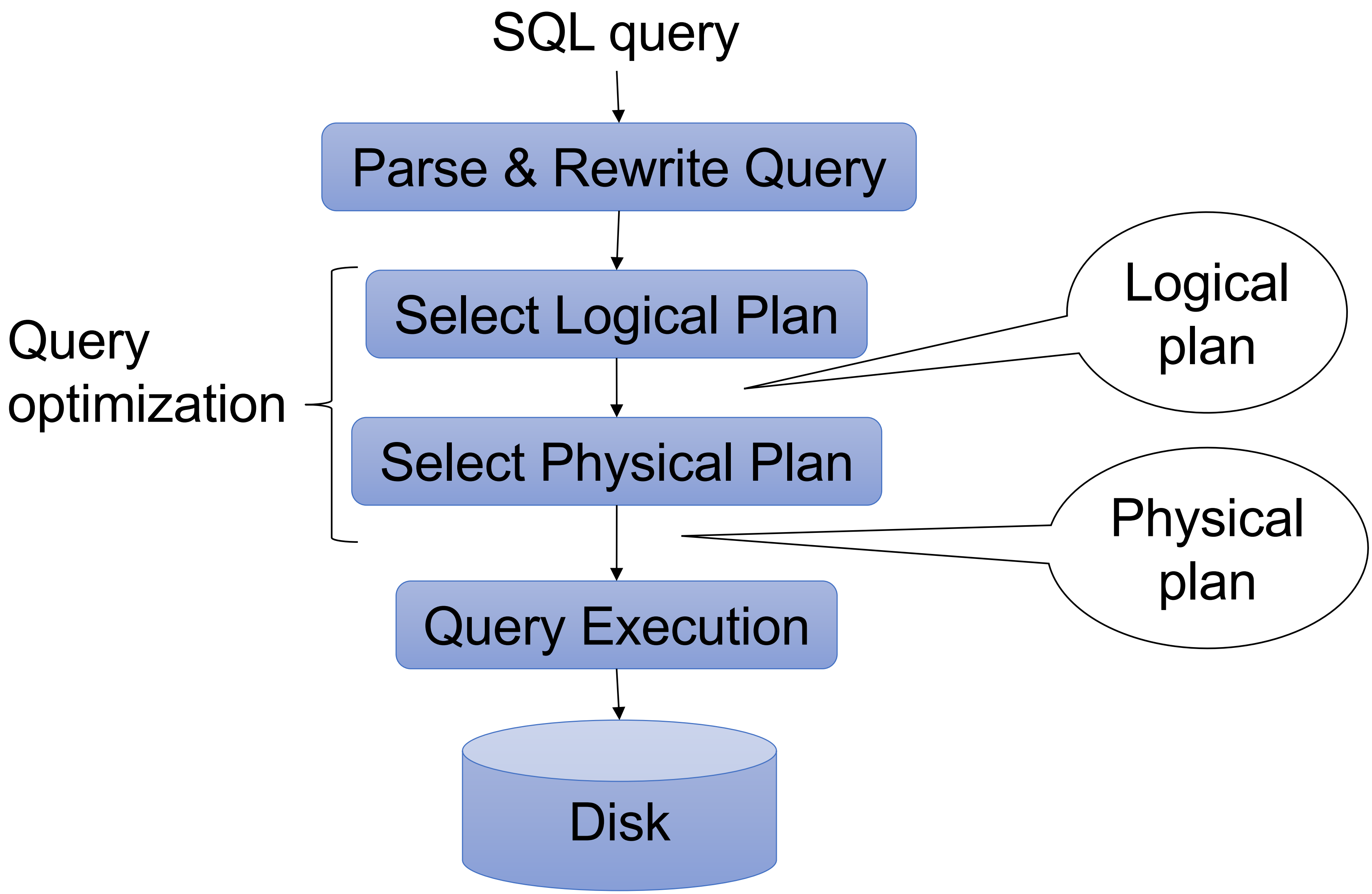


SELECT-PROJECT-JOIN Query

Typical Plan for Complex Aggregates

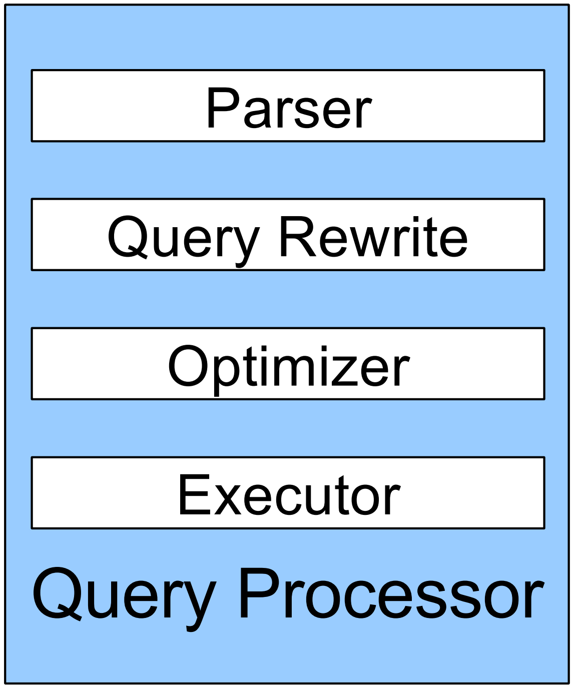


Query Evaluation Steps Review

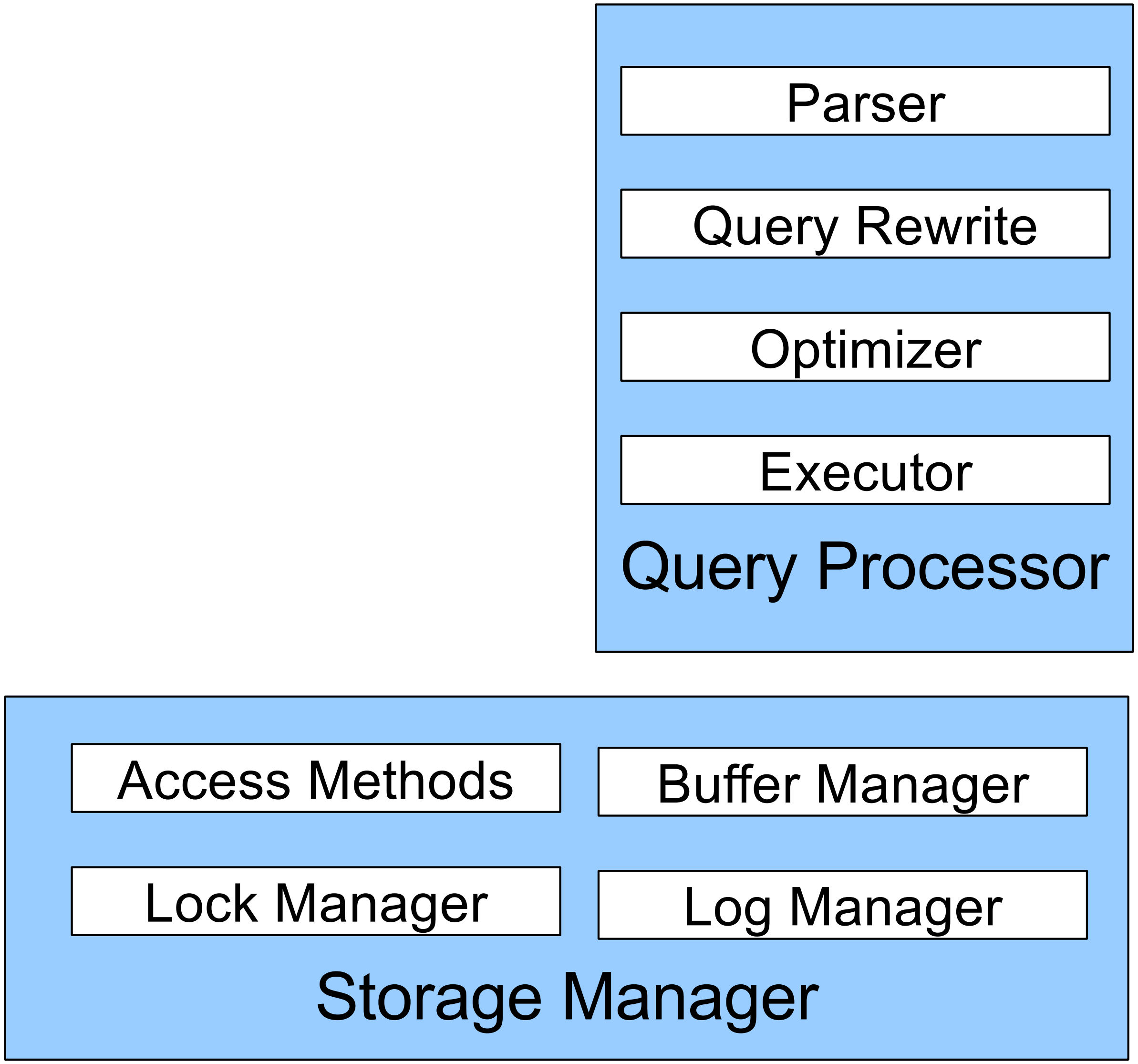


DBMS Architecture

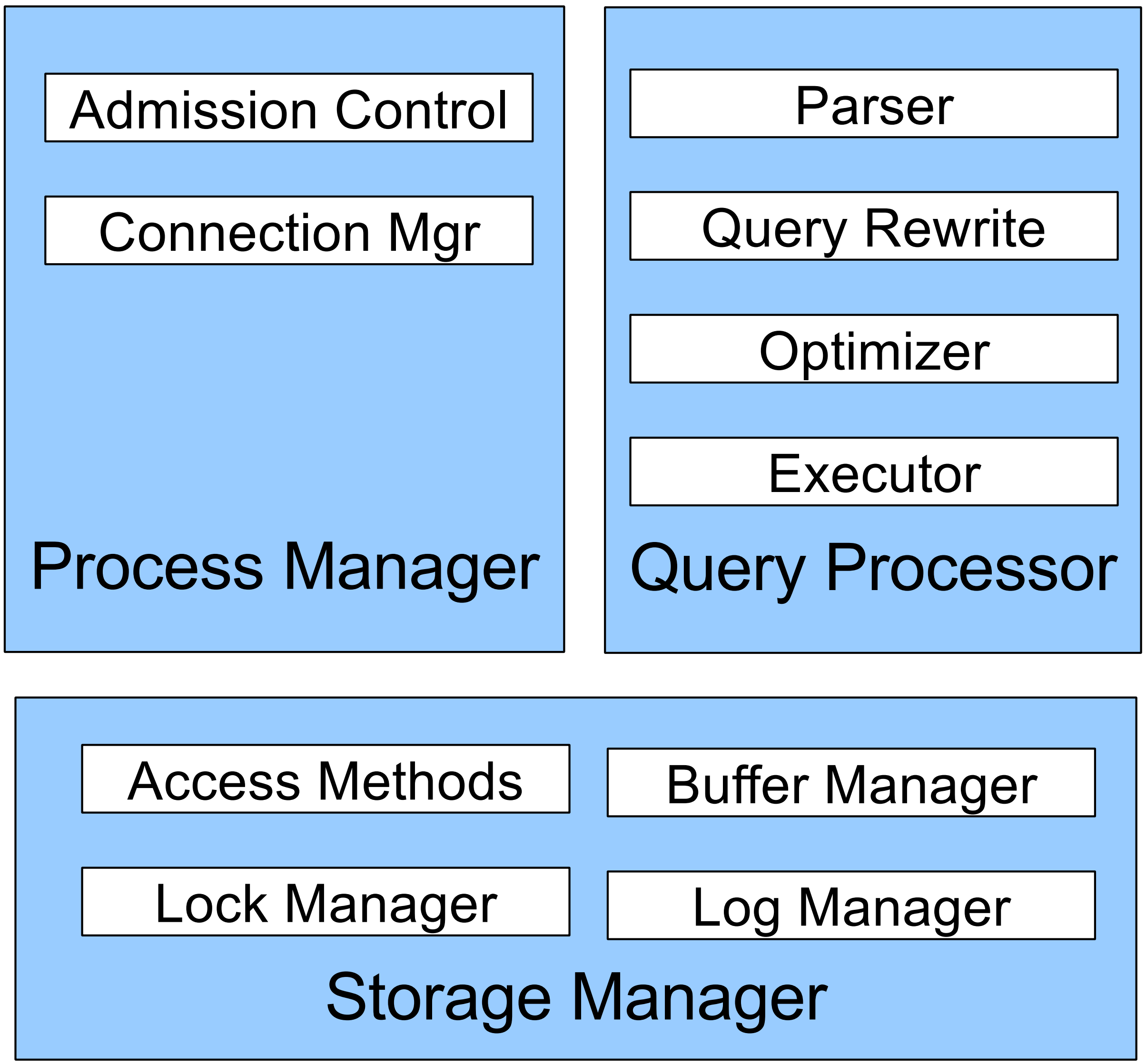
DBMS Architecture



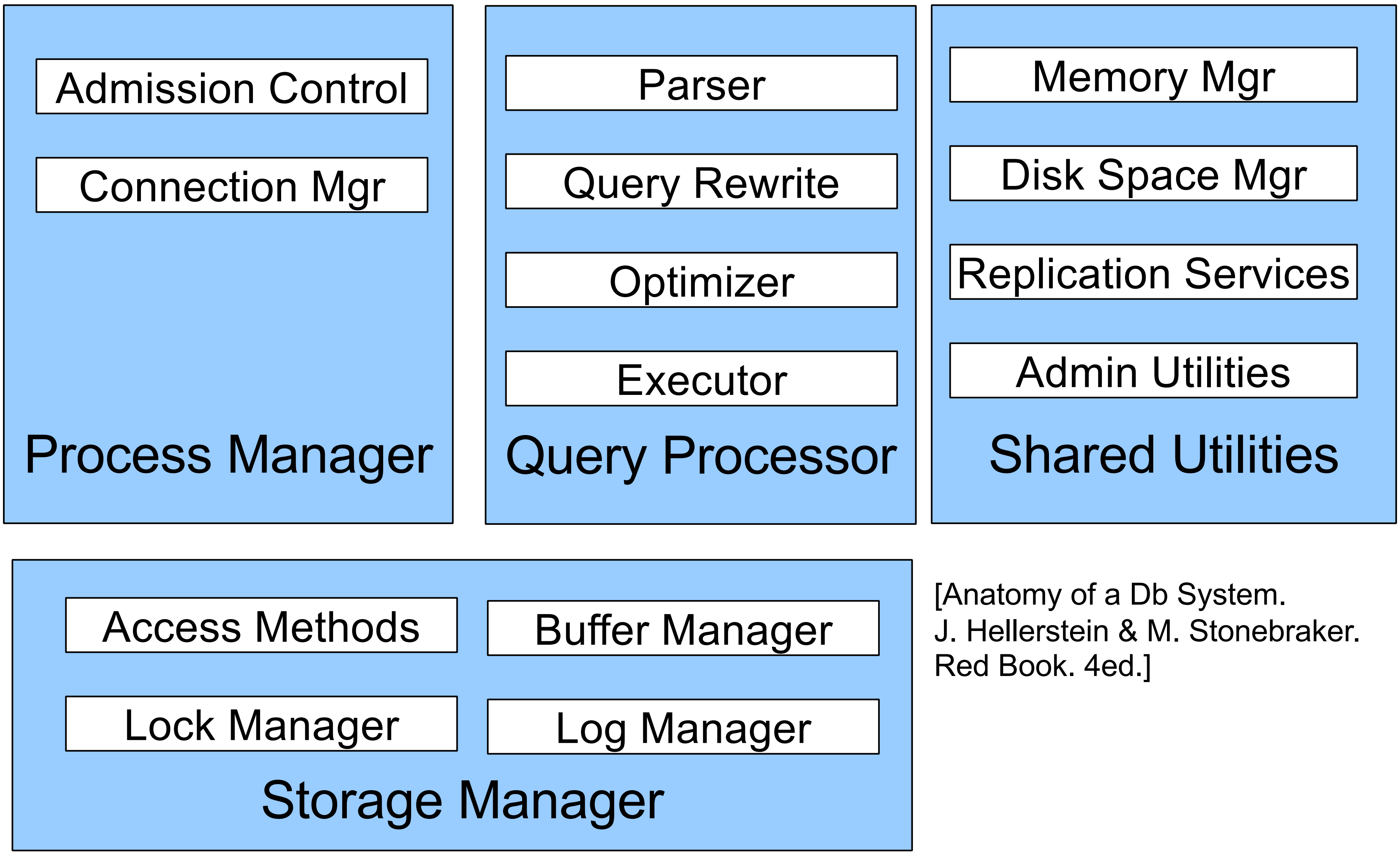
DBMS Architecture



DBMS Architecture



DBMS Architecture



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