Introduction to Data Management
CSE 414

Unit 2: The Relational Data Model

SQL

Relational Algebra

Datalog

(9 lectures*)

*Slides may change: refresh each lecture

Introduction to Data Management CSE 414

Lecture 2: Data Models

Class Overview

- Unit 1: Intro
- Unit 2: Relational Data Models and Query Languages
  - Data models, SQL RA, Datalog
- Unit 3: Non-relational data
- Unit 4: RDMBS internals and query optimization
- Unit 5: Parallel query processing
- Unit 6: DBMS usability, conceptual design
- Unit 7: Transactions
- Unit 8: Advanced topics (time permitting)

Reminders

- Sections tomorrow (bring your laptops)
- HW1 due on Friday
- Webquiz due on Saturday

Review

- What is a database?
  - A collection of files storing related data

- What is a DBMS?
  - An application program that allows us to manage efficiently the collection of data files

Data Models

- Recall our example: want to design a database of books:
  - author, title, publisher, pub date, price, etc
  - How should we describe this data?
- **Data model** = mathematical formalism (or conceptual way) for describing the data

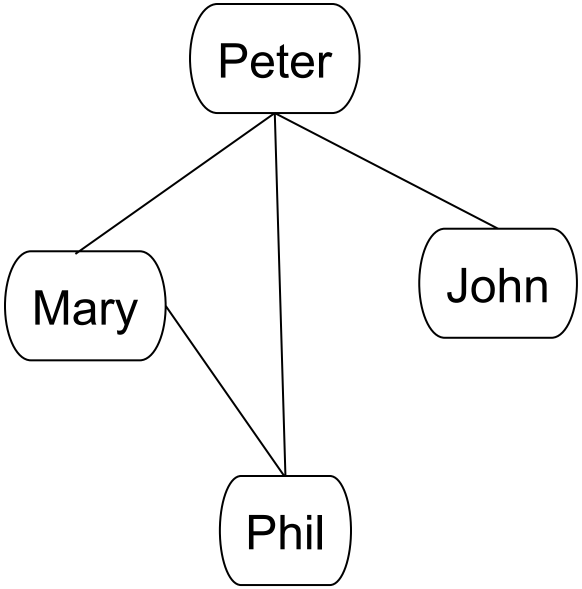
Data Models

- Relational
  - Data represented as relations
- Semi-structured (JSon)
  - Data represented as trees
- Key-value pairs
  - Used by NoSQL systems
- Graph
- Object-oriented

Unit 2

Unit 3

Example: storing FB friends



As a graph

OR

Person1	Person2	is_friend
Peter	John	1
John	Mary	0
Mary	Phil	1
Phil	Peter	1
…	…	…

As a relation

We will learn the tradeoffs of different data models later this quarter

3 Elements of Data Models

- Instance
  - The actual data
- Schema
  - Describe what data is being stored
- Query language
  - How to retrieve and manipulate data

Relational Model

columns /
attributes /
fields

- Data is a collection of relations / tables:

rows /
tuples /
records

cname	country	no_employees	for_profit
GizmoWorks	USA	20000	True
Canon	Japan	50000	True
Hitachi	Japan	30000	True
HappyCam	Canada	500	False

- mathematically, relation is a set of tuples
  - each tuple appears 0 or 1 times in the table
  - order of the rows is unspecified

The Relational Data Model

- Each attribute has a type. E.g.
  - Strings: CHAR(20), VARCHAR(50), TEXT
  - Numbers: INT, SMALLINT, FLOAT
  - MONEY, DATETIME, …
  - Few more that are vendor specific
- Types statically and strictly enforced
- #Attributes= “degree” (arity) of a relation

Keys

- Key = one (or multiple) attributes that uniquely identify a record

Keys

- Key = one (or multiple) attributes that uniquely identify a record

Key

cname	country	no_employees	for_profit
GizmoWorks	USA	20000	True
Canon	Japan	50000	True
Hitachi	Japan	30000	True
HappyCam	Canada	500	False

Keys

- Key = one (or multiple) attributes that uniquely identify a record

Key

Not a key

cname	country	no_employees	for_profit
GizmoWorks	USA	20000	True
Canon	Japan	50000	True
Hitachi	Japan	30000	True
HappyCam	Canada	500	False

Keys

- Key = one (or multiple) attributes that uniquely identify a record

Key

Not a key

Is this a key?

cname	country	no_employees	for_profit
GizmoWorks	USA	20000	True
Canon	Japan	50000	True
Hitachi	Japan	30000	True
HappyCam	Canada	500	False

Keys

- Key = one (or multiple) attributes that uniquely identify a record

No: future updates to the database may create duplicate no_employees

Key

Not a key

Is this a key?

<u>cname</u>	country	no_employees	for_profit
GizmoWorks	USA	20000	True
Canon	Japan	50000	True
Hitachi	Japan	30000	True
HappyCam	Canada	500	False

Multi-attribute Key

Key = fName,lName
(what does this mean?)

fName	lName	Income	Department
Alice	Smith	20000	Testing
Alice	Thompson	50000	Testing
Bob	Thompson	30000	SW
Carol	Smith	50000	Testing

Multiple Keys

Key

Another key

<u>SSN</u>	fName	lName	Income	Department
111-22-3333	Alice	Smith	20000	Testing
222-33-4444	Alice	Thompson	50000	Testing
333-44-5555	Bob	Thompson	30000	SW
444-55-6666	Carol	Smith	50000	Testing

We can choose one key and designate it as <u>*primary key*</u>

E.g.: primary key = SSN

Foreign Key

```
Company(cname, country, no_employees, for_profit)
Country(name, population)
```

Foreign key to Country.name

Company

cname	country	no_employees	for_profit
Canon	Japan	50000	Y
Hitachi	Japan	30000	Y

Country

name	population
USA	320M
Japan	127M

Keys: Summary

- Key = columns that uniquely identify tuple
  - Usually we underline
  - A relation can have many keys, but only one can be chosen as *primary key*
- Foreign key:
  - Attribute(s) whose value is a key of a record in some other relation
  - Foreign keys are sometimes called *semantic pointer*

Query Language

- SQL
  - **S**tructured **Q**uery **L**anguage
  - Developed by IBM in the 70s
  - Most widely used language to query relational data
- Other relational query languages
  - Datalog, relational algebra

Our First DBMS

- SQL Lite
- Will switch to SQL Server later in the quarter

Demo 1

Discussion

- Tables are NOT ordered
  - they are sets or multisets (bags)
- Tables are FLAT
  - No nested attributes
- Tables DO NOT prescribe how they are implemented / stored on disk
  - This is called **physical data independence**

Table Implementation

- How would you implement this?

cname	country	no_employees	for_profit
GizmoWorks	USA	20000	True
Canon	Japan	50000	True
Hitachi	Japan	30000	True
HappyCam	Canada	500	False

Table Implementation

- How would you implement this?

cname	country	no_employees	for_profit
GizmoWorks	USA	20000	True
Canon	Japan	50000	True
Hitachi	Japan	30000	True
HappyCam	Canada	500	False

Row major: as an array of objects

GizmoWorks USA 20000 True	Canon Japan 50000 True	Hitachi Japan 30000 True	HappyCam Canada 500 False

Table Implementation

- How would you implement this?

cname	country	no_employees	for_profit
GizmoWorks	USA	20000	True
Canon	Japan	50000	True
Hitachi	Japan	30000	True
HappyCam	Canada	500	False

Column major: as one array per attribute

GizmoWorks	Canon	Hitachi	HappyCam

USA	Japan	Japan	Canada

20000	50000	30000	500

True	True	True	False

Table Implementation

- How would you implement this?

cname	country	no_employees	for_profit
GizmoWorks	USA	20000	True
Canon	Japan	50000	True
Hitachi	Japan	30000	True
HappyCam	Canada	500	False

Physical data independence

The logical definition of the data remains unchanged, even when we make changes to the actual implementation

First Normal Form

cname	country	no_employees	for_profit
Canon	Japan	50000	Y
Hitachi	Japan	30000	Y

- All relations must be flat: we say that the relation is in *first normal form*

First Normal Form

cname	country	no_employees	for_profit
Canon	Japan	50000	Y
Hitachi	Japan	30000	Y

- All relations must be flat: we say that the relation is in *first normal form*
- E.g. we want to add products manufactured by each company:

First Normal Form

cname	country	no_employees	for_profit
Canon	Japan	50000	Y
Hitachi	Japan	30000	Y

- All relations must be flat: we say that the relation is in *first normal form*
- E.g. we want to add products manufactured by each company:

<table>
<tr><th>cname</th><th>country</th><th>no_employees</th><th>for_profit</th><th>products</th></tr>
<tr><td>Canon</td><td>Japan</td><td>50000</td><td>Y</td><td><table><tr><th>pname</th><th>price</th><th>category</th></tr><tr><td>SingleTouch</td><td>149.99</td><td>Photography</td></tr><tr><td>Gadget</td><td>200</td><td>Toy</td></tr></table></td></tr>
<tr><td>Hitachi</td><td>Japan</td><td>30000</td><td>Y</td><td><table><tr><th>pname</th><th>price</th><th>category</th></tr><tr><td>AC</td><td>300</td><td>Appliance</td></tr></table></td></tr>
</table>

First Normal Form

cname	country	no_employees	for_profit
Canon	Japan	50000	Y
Hitachi	Japan	30000	Y

- All relations must be flat: we say that the relation is in *first normal form*
- E.g. we want to add products manufactured by each company:

Non-1NF!

<table>
<tr><th>cname</th><th>country</th><th>no_employees</th><th>for_profit</th><th>products</th></tr>
<tr><td>Canon</td><td>Japan</td><td>50000</td><td>Y</td><td><table><tr><th>pname</th><th>price</th><th>category</th></tr><tr><td>SingleTouch</td><td>149.99</td><td>Photography</td></tr><tr><td>Gadget</td><td>200</td><td>Toy</td></tr></table></td></tr>
<tr><td>Hitachi</td><td>Japan</td><td>30000</td><td>Y</td><td><table><tr><th>pname</th><th>price</th><th>category</th></tr><tr><td>AC</td><td>300</td><td>Appliance</td></tr></table></td></tr>
</table>

First Normal Form

Now it's in 1NF

Company

cname	country	no_employees	for_profit
Canon	Japan	50000	Y
Hitachi	Japan	30000	Y

Products

pname	price	category	manufacturer
SingleTouch	149.99	Photography	Canon
AC	300	Appliance	Hitachi
Gadget	200	Toy	Canon

Data Models: Summary

- Schema + Instance + Query language
- Relational model:
  - Database = collection of tables
  - Each table is flat: “first normal form”
  - Key: may consists of multiple attributes
  - Foreign key: “semantic pointer”
  - Physical data independence

Introduction to Data Management
CSE 414

Lecture 3: SQL Basics

Review

- Relational data model
  - Schema+instance+query language
- Query language: SQL
  - Create tables
  - Retrieve records from tables
  - Declare keys and foreign keys

Review

- Tables are NOT ordered
  - they are sets or multisets (bags)
  - arity: # of attributes in a relation
  - cardinality: # of records in a relation
- Tables are FLAT
  - No nested attributes
- Tables DO NOT prescribe how they are implemented / stored on disk
  - This is called **physical data independence**

SQL

- **S**tructured **Q**uery **L**anguage
- Most widely used language to query relational data
- One of the many languages for querying relational data

- A **declarative** programming language

Selections in SQL

```
SELECT *
FROM   Product
WHERE  price > 100.0
```

Demo 2

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

Joins in SQL

pname	price	category	manufacturer
MultiTouch	199.99	gadget	Canon
SingleTouch	49.99	photography	Canon
Gizom	50	gadget	GizmoWorks
SuperGizmo	250.00	gadget	GizmoWorks

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

Retrieve all Japanese products that cost < $150

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

Joins in SQL

pname	price	category	manufacturer
MultiTouch	199.99	gadget	Canon
SingleTouch	49.99	photography	Canon
Gizom	50	gadget	GizmoWorks
SuperGizmo	250.00	gadget	GizmoWorks

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

Retrieve all Japanese products that cost < $150

```
SELECT pname, price
FROM   Product, Company
WHERE  ...
```

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

Joins in SQL

pname	price	category	manufacturer
MultiTouch	199.99	gadget	Canon
SingleTouch	49.99	photography	Canon
Gizom	50	gadget	GizmoWorks
SuperGizmo	250.00	gadget	GizmoWorks

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

Retrieve all Japanese products that cost < $150

```
SELECT pname, price
FROM   Product, Company
WHERE  manufacturer=cname AND
       country='Japan' AND price < 150
```

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

Joins in SQL

pname	price	category	manufacturer
MultiTouch	199.99	gadget	Canon
SingleTouch	49.99	photography	Canon
Gizom	50	gadget	GizmoWorks
SuperGizmo	250.00	gadget	GizmoWorks

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

Retrieve all USA companies that manufacture “gadget” products

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

Joins in SQL

pname	price	category	manufacturer
MultiTouch	199.99	gadget	Canon
SingleTouch	49.99	photography	Canon
Gizom	50	gadget	GizmoWorks
SuperGizmo	250.00	gadget	GizmoWorks

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

Retrieve all USA companies that manufacture "gadget" products

```
SELECT DISTINCT cname
FROM    Product, Company
WHERE   country='USA' AND category = 'gadget'
        AND manufacturer = cname
```

Why DISTINCT?

Joins in SQL

- The standard join in SQL is sometimes called an inner join
  - Each row in the result **must come from both tables in the join**
- Sometimes we want to include rows from only one of the two table: outer join

```
Employee(id, name)
Sales(employeeID, productID)
```

Inner Join

Employee

id	name
1	Joe
2	Jack
3	Jill

Sales

employeeID	productID
1	344
1	355
2	544

Retrieve employees and their sales

```
Employee(id, name)
Sales(employeeID, productID)
```

Inner Join

Employee

id	name
1	Joe
2	Jack
3	Jill

Sales

employeeID	productID
1	344
1	355
2	544

Retrieve employees and their sales

```
SELECT *
FROM   Employee E, Sales S
WHERE  E.id = S.employeeID
```

```
Employee(id, name)
Sales(employeeID, productID)
```

Inner Join

Employee

id	name
1	Joe
2	Jack
3	Jill

Sales

employeeID	productID
1	344
1	355
2	544

Retrieve employees and their sales

```
SELECT *
FROM   Employee E, Sales S
WHERE  E.id = S.employeeID
```

id	name	empolyeeID	productID
1	Joe	1	344
1	Joe	1	355
2	Jack	2	544

```
Employee(id, name)
Sales(employeeID, productID)
```

Inner Join

Employee

id	name
1	Joe
2	Jack
3	Jill

Sales

employeeID	productID
1	344
1	355
2	544

Retrieve employees and their sales

Jill is missing

```
SELECT *
FROM   Employee E, Sales S
WHERE  E.id = S.employeeID
```

id	name	empolyeeID	productID
1	Joe	1	344
1	Joe	1	355
2	Jack	2	544

```
Employee(id, name)
Sales(employeeID, productID)
```

Inner Join

Employee

id	name
1	Joe
2	Jack
3	Jill

Sales

employeeID	productID
1	344
1	355
2	544

Retrieve employees and their sales

Jill is missing

Alternative syntax

```
SELECT *
FROM   Employee E
       INNER JOIN
       Sales S
    ON E.id = S.employeeID
```

id	name	empolyeeID	productID
1	Joe	1	344
1	Joe	1	355
2	Jack	2	544

Employee(<u>id</u>, name)
Sales(<u>employeeID</u>, productID)

Outer Join

Employee

<u>id</u>	name
1	Joe
2	Jack
3	Jill

Sales

employeeID	productID
1	344
1	355
2	544

Retrieve employees and their sales

```
SELECT *
FROM   Employee E
       LEFT OUTER JOIN
       Sales S
    ON E.id = S.employeeID
```

Jill is present

id	name	empolyeeID	productID
1	Joe	1	344
1	Joe	1	355
2	Jack	2	544
3	Jill	NULL	NULL

Introduction to Data Management
CSE 414

Lecture 4: Joins and Aggregates

Review: Our SQL Toolchest

- Selection
- Projection
- Ordering and distinct

- Inner Join
- Outer Join

(Inner) joins

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

```
manufacturer = foreign key to Company.cname
```

Return all companies in the ‘USA’ that manufacture some product in the ‘gadget’ category.

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

(Inner) joins

```
SELECT DISTINCT cname
FROM   Product, Company
WHERE  country='USA' AND category = 'gadget'
       AND manufacturer = cname
```

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

(Inner) joins

```
SELECT DISTINCT cname
FROM   Product, Company
WHERE  country='USA' AND category = 'gadget'
       AND manufacturer = cname
```

Product

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
Camera	Photo	Hitachi
OneClick	Photo	Hitachi

Company

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

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

(Inner) joins

```
SELECT DISTINCT cname
FROM   Product, Company
WHERE  country='USA' AND category = 'gadget'
       AND manufacturer = cname
```

Product

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
Camera	Photo	Hitachi
OneClick	Photo	Hitachi

Company

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

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

(Inner) joins

```
SELECT DISTINCT cname
FROM   Product, Company
WHERE  country='USA' AND category = 'gadget'
       AND manufacturer = cname
```

Product

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
Camera	Photo	Hitachi
OneClick	Photo	Hitachi

Company

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

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

(Inner) joins

```
SELECT DISTINCT cname
FROM    Product, Company
WHERE   country='USA' AND category = 'gadget'
        AND manufacturer = cname
```

Product

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
Camera	Photo	Hitachi
OneClick	Photo	Hitachi

Company

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

pname	category	manufacturer	cname	country
Gizmo	gadget	GizmoWorks	GizmoWorks	USA

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

(Inner) joins

```
SELECT DISTINCT cname
FROM   Product, Company
WHERE  country='USA' AND category = 'gadget'
       AND manufacturer = cname
```

Product

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
Camera	Photo	Hitachi
OneClick	Photo	Hitachi

Company

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

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

(Inner) joins

```
SELECT DISTINCT cname
FROM   Product, Company
WHERE  country='USA' AND category = 'gadget'
       AND manufacturer = cname
```

Product

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
Camera	Photo	Hitachi
OneClick	Photo	Hitachi

Company

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

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

(Inner) joins

```
SELECT DISTINCT cname
FROM   Product, Company
WHERE  country='USA' AND category = 'gadget'
       AND manufacturer = cname
```

Product

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
Camera	Photo	Hitachi
OneClick	Photo	Hitachi

Company

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

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

(Inner) joins

```
SELECT DISTINCT cname
FROM    Product, Company
WHERE   country='USA' AND category = 'gadget'
        AND manufacturer = cname
```

Product

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
Camera	Photo	Hitachi
OneClick	Photo	Hitachi

Company

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

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

(Inner) joins

```
SELECT DISTINCT cname
FROM   Product, Company
WHERE  country='USA' AND category = 'gadget'
       AND manufacturer = cname
```

Product

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
Camera	Photo	Hitachi
OneClick	Photo	Hitachi

Company

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

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

(Inner) joins

```
SELECT DISTINCT cname
FROM    Product, Company
WHERE   country='USA' AND category = 'gadget'
        AND manufacturer = cname
```

Product

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
Camera	Photo	Hitachi
OneClick	Photo	Hitachi

Company

cname	country
GizmoWorks	USA
Canon	Japan
Hitachi	Japan

And son on…

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

(Inner) joins

```
SELECT DISTINCT cname
FROM   Product, Company
WHERE  country='USA' AND category = 'gadget'
       AND manufacturer = cname
```

```
SELECT DISTINCT cname
FROM   Product JOIN Company ON
       country = 'USA' AND category = 'gadget'
       AND manufacturer = cname
```

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

(Inner) joins

```
SELECT DISTINCT cname
FROM    Product, Company
WHERE   country='USA' AND category = 'gadget'
        AND manufacturer = cname
```

```
SELECT DISTINCT cname
FROM    Product JOIN Company ON
        country = 'USA' AND category = 'gadget'
        AND manufacturer = cname
```

Same thing, different syntax

(Inner) Joins

```
SELECT   x1.a1, x2.a2, … xm.am
FROM     R1 as x1, R2 as x2, … Rm as xm
WHERE    Cond
```

```
for x1 in R1:
   for x2 in R2:

      ...
         for xm in Rm:
            if Cond(x1, x2…):
               output(x1.a1, x2.a2, … xm.am)
```

This is called nested loop semantics since we are interpreting what a join means using a nested loop

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

Another example

Retrieve all USA companies that manufacture products in both ‘gadget’ and ‘photography’ categories

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

Another example

Retrieve all USA companies that manufacture products in both 'gadget' and 'photography' categories

```
SELECT DISTINCT z.cname
FROM Product x, Company z
WHERE z.country = 'USA'
  AND x.manufacturer = z.cname
  AND x.category = 'gadget'
  AND x.category = 'photography;
```

Does this work?

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

Another example

Retrieve all USA companies that manufacture products in both ‘gadget’ and ‘photography’ categories

```
SELECT DISTINCT z.cname
FROM Product x, Company z
WHERE z.country = ’USA’
  AND x.manufacturer = z.cname
  AND x.category = 'gadget’
  AND x.category = 'photography;
```

Does this work?

Returns the empty set

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

Another example

Retrieve all USA companies that manufacture products in both 'gadget' and 'photography' categories

What about this?

```
SELECT DISTINCT z.cname
FROM Product x, Company z
WHERE z.country = 'USA'
  AND x.manufacturer = z.cname
  AND (x.category = 'gadget'
       OR x.category = 'photography);
```

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

Another example

Retrieve all USA companies that manufacture products in both 'gadget' and 'photography' categories

What about this?

```
SELECT DISTINCT z.cname
FROM Product x, Company z
WHERE z.country = 'USA'
  AND x.manufacturer = z.cname
  AND (x.category = 'gadget'
       OR x.category = 'photography');
```

Returns too much

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

Another example

Retrieve all USA companies that manufacture products in both ‘gadget’ and ‘photography’ categories

```
SELECT DISTINCT z.cname
FROM Product x, Product y, Company z
WHERE z.country = ’USA’
  AND x.manufacturer = z.cname
  AND y.manufacturer = z.cname
  AND x.category = 'gadget’
  AND y.category = 'photography;
```

Need to include Product twice!

Self-Joins and Tuple Variables

- Find USA companies that manufacture both products in the ‘gadgets’ and ‘photo’ category

- Joining Product with Company is insufficient: need to join Product, with Product, and with Company

- When a relation occurs twice in the FROM clause we call it a self-join; in that case we must use tuple variables (why?)

Self-joins

```
SELECT DISTINCT z.cname
FROM   Product x, Product y, Company z
WHERE  z.country = 'USA'
       AND x.category = 'gadget'
       AND y.category = 'photo'
       AND x.manufacturer = z.cname
       AND y.manufacturer = z.cname;
```

Product

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
SingleTouch	photo	Hitachi
MultiTouch	Photo	GizmoWorks

Company

cname	country
GizmoWorks	USA
Hitachi	Japan

Self-joins

```
SELECT DISTINCT z.cname
FROM   Product x, Product y, Company z
WHERE  z.country = 'USA'
       AND x.category = 'gadget'
       AND y.category = 'photo'
       AND x.manufacturer = z.cname
       AND y.manufacturer = z.cname;
```

Product

x

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
SingleTouch	photo	Hitachi
MultiTouch	Photo	GizmoWorks

Company

cname	country
GizmoWorks	USA
Hitachi	Japan

Self-joins

```
SELECT DISTINCT z.cname
FROM   Product x, Product y, Company z
WHERE  z.country = 'USA'
       AND x.category = 'gadget'
       AND y.category = 'photo'
       AND x.manufacturer = z.cname
       AND y.manufacturer = z.cname;
```

Product

x

y

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
SingleTouch	photo	Hitachi
MultiTouch	Photo	GizmoWorks

Company

cname	country
GizmoWorks	USA
Hitachi	Japan

Self-joins

```
SELECT DISTINCT z.cname
FROM   Product x, Product y, Company z
WHERE  z.country = 'USA'
       AND x.category = 'gadget'
       AND y.category = 'photo'
       AND x.manufacturer = z.cname
       AND y.manufacturer = z.cname;
```

Product

x

y

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
SingleTouch	photo	Hitachi
MultiTouch	Photo	GizmoWorks

Company

z

cname	country
GizmoWorks	USA
Hitachi	Japan

Self-joins

```
SELECT DISTINCT z.cname
FROM   Product x, Product y, Company z
WHERE  z.country = 'USA'
       AND x.category = 'gadget'
       AND y.category = 'photo'
       AND x.manufacturer = z.cname
       AND y.manufacturer = z.cname;
```

Product

x

y

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
SingleTouch	photo	Hitachi
MultiTouch	Photo	GizmoWorks

Company

z

cname	country
GizmoWorks	USA
Hitachi	Japan

Self-joins

```
SELECT DISTINCT z.cname
FROM   Product x, Product y, Company z
WHERE  z.country = 'USA'
       AND x.category = 'gadget'
       AND y.category = 'photo'
       AND x.manufacturer = z.cname
       AND y.manufacturer = z.cname;
```

Product

	pname	category	manufacturer
x	Gizmo	gadget	GizmoWorks
y	SingleTouch	photo	Hitachi
	MultiTouch	Photo	GizmoWorks

Company

cname	country	
GizmoWorks	USA	z
Hitachi	Japan	

Self-joins

```
SELECT DISTINCT z.cname
FROM   Product x, Product y, Company z
WHERE  z.country = 'USA'
       AND x.category = 'gadget'
       AND y.category = 'photo'
       AND x.manufacturer = z.cname
       AND y.manufacturer = z.cname;
```

Product

x

y

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
SingleTouch	photo	Hitachi
MultiTouch	Photo	GizmoWorks

Company

z

cname	country
GizmoWorks	USA
Hitachi	Japan

Self-joins

```
SELECT DISTINCT z.cname
FROM   Product x, Product y, Company z
WHERE  z.country = 'USA'
       AND x.category = 'gadget'
       AND y.category = 'photo'
       AND x.manufacturer = z.cname
       AND y.manufacturer = z.cname;
```

Product

x

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
SingleTouch	photo	Hitachi
MultiTouch	Photo	GizmoWorks

y

Company

z

cname	country
GizmoWorks	USA
Hitachi	Japan

Self-joins

```
SELECT DISTINCT z.cname
FROM   Product x, Product y, Company z
WHERE  z.country = 'USA'
       AND x.category = 'gadget'
       AND y.category = 'photo'
       AND x.manufacturer = z.cname
       AND y.manufacturer = z.cname;
```

Product

	pname	category	manufacturer
x	Gizmo	gadget	GizmoWorks
	SingleTouch	photo	Hitachi
y	MultiTouch	Photo	GizmoWorks

Company

	cname	country
z	GizmoWorks	USA
	Hitachi	Japan

x.pname	x.category	x.manufacturer	y.pname	y.category	y.manufacturer	z.cname	z.country
Gizmo	gadget	GizmoWorks	MultiTouch	Photo	GizmoWorks	GizmoWorks	USA

Self-joins

```
SELECT DISTINCT z.cname
FROM   Product x, Product y, Company z
WHERE  z.country = 'USA'
       AND x.category = 'gadget'
       AND y.category = 'photo'
       AND x.manufacturer = z.cname
       AND y.manufacturer = z.cname;
```

Product

x

pname	category	manufacturer
Gizmo	gadget	GizmoWorks
SingleTouch	photo	Hitachi
MultiTouch	Photo	GizmoWorks

y

Company

z

cname	country
GizmoWorks	USA
Hitachi	Japan

x.pname	x.category	x.manufacturer	y.pname	y.category	y.manufacturer	z.cname	z.country
Gizmo	gadget	GizmoWorks	MultiTouch	Photo	GizmoWorks	GizmoWorks	USA

Outer joins

```
Product(name, category)
Purchase(prodName, store)

-- prodName is foreign key
```

Retrieve all product names and the stores where they were purchased.
Include products that never sold

Outer joins

Retrieve all product names and the stores where they were purchased.
Include products that never sold

```
Product(name, category)
Purchase(prodName, store)

-- prodName is foreign key
```

```
SELECT Product.name, Purchase.store
FROM   Product, Purchase
WHERE  Product.name = Purchase.prodName
```

Outer joins

Retrieve all product names and the stores where they were purchased.
Include products that never sold

```
Product(name, category)
Purchase(prodName, store)

-- prodName is foreign key
```

```
SELECT Product.name, Purchase.store
FROM   Product, Purchase
WHERE  Product.name = Purchase.prodName
```

Does not include products
that never sold! (why?)

Outer joins

Retrieve all product names and the stores where they were purchased.
Include products that never sold

```
Product(name, category)
Purchase(prodName, store)

-- prodName is foreign key
```

```
SELECT Product.name, Purchase.store
FROM   Product LEFT OUTER JOIN Purchase ON
       Product.name = Purchase.prodName
```

Outer joins

Retrieve all product names and the stores where they were purchased.
Include products that never sold

```
Product(name, category)
Purchase(prodName, store)

-- prodName is foreign key
```

```
SELECT Product.name, Purchase.store
FROM   Product LEFT OUTER JOIN Purchase ON
       Product.name = Purchase.prodName
```

Now they show up!

```sql
SELECT Product.name, Purchase.store
FROM   Product JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

```sql
SELECT Product.name, Purchase.store
FROM   Product JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

```sql
SELECT Product.name, Purchase.store
FROM   Product JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

Output

Name	Store
Gizmo	Wiz

```sql
SELECT Product.name, Purchase.store
FROM   Product JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

Output

Name	Store
Gizmo	Wiz

```sql
SELECT Product.name, Purchase.store
FROM   Product JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

Output

Name	Store
Gizmo	Wiz

```sql
SELECT Product.name, Purchase.store
FROM   Product JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

Output

Name	Store
Gizmo	Wiz

```
SELECT Product.name, Purchase.store
FROM   Product JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

Output

Name	Store
Gizmo	Wiz
Camera	Ritz

```sql
SELECT Product.name, Purchase.store
FROM   Product JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

Output

Name	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

```sql
SELECT Product.name, Purchase.store
FROM   Product JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

Output

Name	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

```
SELECT Product.name, Purchase.store
FROM   Product LEFT OUTER JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

Output

Name	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

```sql
SELECT Product.name, Purchase.store
FROM   Product LEFT OUTER JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz

Output

Name	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz
OneClick	NULL

```sql
SELECT Product.name, Purchase.store
FROM   Product FULL OUTER JOIN Purchase ON
       Product.name = Purchase.prodName
```

Product

Name	Category
Gizmo	gadget
Camera	Photo
OneClick	Photo

Purchase

ProdName	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz
Phone	Foo

Output

Name	Store
Gizmo	Wiz
Camera	Ritz
Camera	Wiz
OneClick	NULL
NULL	Foo

Outer Joins

```
tableA (LEFT/RIGHT/FULL) OUTER JOIN tableB ON p
```

- Left outer join:
  - Include tuples from `tableA` even if no match
- Right outer join:
  - Include tuples from `tableB` even if no match
- Full outer join:
  - Include tuples from both even if no match

- In all cases:
  - Patch tuples without matches using `NULL`

Loading Data into SQLite

```
>sqlite3 lecture04

sqlite> create table Purchase
       (pid int primary key,
        product text,
        price float,
        quantity int,
        month varchar(15));

sqlite> -- download data.txt
sqlite> .import lec04-data.txt Purchase
```

Specify a filename where the database will be stored

Other DBMSs have other ways of importing data

Comment about SQLite

- Cannot load NULL values such that they are actually loaded as null values

- So we need to use two steps:
  – Load null values using some type of special value
  – Update the special values to actual null values

```
update Purchase
  set price = null
  where price = ‘null’
```

Simple Aggregations

Five basic aggregate operations in SQL

```
select count(*) from Purchase
select sum(quantity) from Purchase
select avg(price) from Purchase
select max(quantity) from Purchase
select min(quantity) from Purchase
```

count of an empty table is 0

Except count, all aggregations apply to a single attribute

Aggregates and NULL Values

Null values are not used in aggregates

```
insert into Purchase
values(12, 'gadget', NULL, NULL, 'april')
```

Let's try the following

```
select count(*) from Purchase
select count(quantity) from Purchase

select sum(quantity) from Purchase

select count(*)
from Purchase
where quantity is not null;
```

Counting Duplicates

`COUNT` applies to duplicates, unless otherwise stated:

```
SELECT count(product)
FROM   Purchase
WHERE  price > 4.99
```

same as `count(*)` if no nulls

We probably want:

```
SELECT count(DISTINCT product)
FROM   Purchase
WHERE  price > 4.99
```

More Examples

```
SELECT  Sum(price * quantity)
FROM    Purchase
```

```
SELECT  Sum(price * quantity)
FROM    Purchase
WHERE   product = 'bagel'
```

What do they mean ?

Introduction to Data Management CSE 414

Lecture 5: Grouping and Query Evaluation

Announcements

- Welcome new TA: Esteban Posada!
- New section AG, starting next week
- Webquiz due tonight
- Homework 2 due on Monday
- No lecture on Monday!
  Makeup lecture Thursday, 4/18, 5:30pm

Grouping and Aggregation

```
Purchase(product, price, quantity)
```

Find total quantities for all sales over $1, by product.

Grouping and Aggregation

Product	Price	Quantity
Bagel	3	20
Bagel	1.50	20
Banana	0.5	50
Banana	2	10
Banana	4	10

```
SELECT   product, Sum(quantity) AS TotalSales
FROM     Purchase
WHERE    price > 1
GROUP BY product
```

Grouping and Aggregation

Product	Price	Quantity
Bagel	3	20
Bagel	1.50	20
Banana	~~0.5~~	~~50~~
Banana	2	10
Banana	4	10

```sql
SELECT   product, Sum(quantity) AS TotalSales
FROM     Purchase
WHERE    price > 1
GROUP BY product
```

Grouping and Aggregation

Product	Price	Quantity
Bagel	3	20
Bagel	1.50	20
Banana	~~0.5~~	~~50~~
Banana	2	10
Banana	4	10

Product	TotalSales
Bagel	40
Banana	20

```sql
SELECT    product, Sum(quantity) AS TotalSales
FROM      Purchase
WHERE     price > 1
GROUP BY  product
```

Other Examples

Compare these two queries:

```
SELECT   product, count(*)
FROM     Purchase
GROUP BY product
```

```
SELECT   month, count(*)
FROM     Purchase
GROUP BY month
```

Other Examples

Compare these two queries:

```
SELECT   product, count(*)
FROM     Purchase
GROUP BY product
```

```
SELECT   month, count(*)
FROM     Purchase
GROUP BY month
```

One answer for each product.

One answer for each month.

Other Examples

Mutliple aggregates OK

```
SELECT   product,
         sum(quantity) AS SumQuantity,
         max(price) AS MaxPrice
FROM     Purchase
GROUP BY product
```

Need to be Careful…

```
SELECT product,
       max(quantity)
FROM   Purchase
GROUP BY product
```

Product	Price	Quantity
Bagel	3	20
Bagel	1.50	20
Banana	0.5	50
Banana	2	10
Banana	4	10

Need to be Careful…

```
SELECT product,
       max(quantity)
FROM   Purchase
GROUP BY product
```

Product	Price	Quantity
Bagel	3	20
Bagel	1.50	20
Banana	0.5	50
Banana	2	10
Banana	4	10

Product	Max(quantity)
Bagel	20
Banana	50

Need to be Careful…

```
SELECT product,
       max(quantity)
FROM   Purchase
GROUP BY product
```

```
SELECT   product, quantity
FROM     Purchase
GROUP BY product
-- what does this mean?
```

Product	Price	Quantity
Bagel	3	20
Bagel	1.50	20
Banana	0.5	50
Banana	2	10
Banana	4	10

Product	Max(quantity)
Bagel	20
Banana	50

Need to be Careful…

```
SELECT product,
       max(quantity)
FROM   Purchase
GROUP BY product
```

```
SELECT   product, quantity
FROM     Purchase
GROUP BY product
-- what does this mean?
```

Product	Price	Quantity
Bagel	3	20
Bagel	1.50	20
Banana	0.5	50
Banana	2	10
Banana	4	10

Product	Max(quantity)
Bagel	20
Banana	50

Product	Quantity
Bagel	20
Banana	??

Need to be Careful…

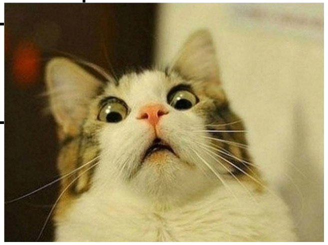
```
SELECT product,
       max(quantity)
FROM   Purchase
GROUP BY product
```

```
SELECT   product, quantity
FROM     Purchase
GROUP BY product
-- what does this mean?
```

Product	Price	Quantity
Bagel	3	20
Bagel	1.50	20
Banana	0.5	50
Banana	2	10
Banana	4	10

Product	Max(quantity)
Bagel	20
Banana	50

Product	Quantity
Bagel	20
Banana	??



Everything in SELECT must be either a GROUP-BY attribute, or an aggregate

Need to be Careful…

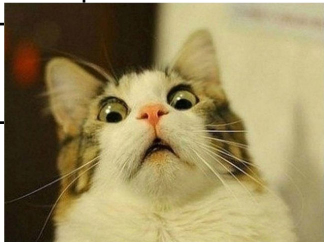
```
SELECT product,
       max(quantity)
FROM   Purchase
GROUP BY product
```

```
SELECT   product, quantity
FROM     Purchase
GROUP BY product
-- what does this mean?
```

Product	Price	Quantity
Bagel	3	20
Bagel	1.50	20
Banana	0.5	50
Banana	2	10
Banana	4	10

Product	Max(quantity)
Bagel	20
Banana	50

Product	Quantity
Bagel	20
Banana	??



Number of Groups

`Purchase(product, price, quantity)`

Find total quantities for all sales over $1, by product.

```
SELECT   product, Sum(quantity) AS TotalSales
FROM     Purchase
WHERE    price > 1
GROUP BY product
```

Number of Groups

```
Purchase(product, price, quantity)
```

Find total quantities for all sales over $1, by product.

```sql
SELECT   product, Sum(quantity) AS TotalSales
FROM     Purchase
WHERE    price > 1
GROUP BY product
```

Cleary, queries return different answers. What about # groups?

```sql
SELECT   product, Sum(quantity) AS TotalSales
FROM     Purchase
GROUP BY product
```

Number of Groups

`Purchase(product, price, quantity)`

Find total quantities for all sales over $1, by product.

```
SELECT   product, Sum(quantity) AS TotalSales
FROM     Purchase
WHERE    price > 1
GROUP BY product
```

Cleary, queries return different answers. What about # groups?

```
SELECT   product, Sum(quantity) AS TotalSales
FROM     Purchase
GROUP BY product
```

Empty groups are removed, hence first query may return fewer groups

Grouping and Aggregation

1. Compute the FROM and WHERE clauses.

2. Group by the attributes in the GROUPBY

3. Compute the SELECT clause:
   grouped attributes and aggregates.

$\boxed{\text{FWGS}}$ TM

1,2: From, Where

FWGS

Product	Price	Quantity
Bagel	3	20
Bagel	1.50	20
Banana	~~0.5~~	~~50~~
Banana	2	10
Banana	4	10

WHERE price > 1

```
SELECT   product, Sum(quantity) AS TotalSales
FROM     Purchase
WHERE    price > 1
GROUP BY product
```

3,4. Grouping, Select

FWGS

Product	Price	Quantity
Bagel	3	20
Bagel	1.50	20
Banana	~~0.5~~	~~50~~
Banana	2	10
Banana	4	10

Product	TotalSales
Bagel	40
Banana	20

```
SELECT   product, Sum(quantity) AS TotalSales
FROM     Purchase
WHERE    price > 1
GROUP BY product
```

Ordering Results

```
SELECT product, sum(price*quantity) as rev
FROM     Purchase
GROUP BY product
ORDER BY rev DESC
```

FWGOS TM

Note: some SQL engines want you to say

```
ORDER BY sum(price*quantity) DESC
```

HAVING Clause

Same query as before, except that we consider only products that had at least 30 sales.

```
SELECT   product, sum(price*quantity)
FROM     Purchase
WHERE    price > 1
GROUP BY product
HAVING   sum(quantity) > 30
```

HAVING clause contains conditions on aggregates.

General form of Grouping and Aggregation

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

Why ?

S = may contain attributes $a_1,\ldots,a_k$ and/or any aggregates but NO OTHER ATTRIBUTES

C1 = is any condition on the attributes in $R_1,\ldots,R_n$

C2 = is any condition on aggregate expressions and on attributes $a_1,\ldots,a_k$

Semantics of SQL With Group-By

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

FWGHOS

Evaluation steps:

1. Evaluate FROM-WHERE using Nested Loop Semantics
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

`Purchase(pid, product, price, quantity, month)`

Exercise

Compute the total income per month
Show only months with less than 10 items sold
Order by quantity sold and display as “TotalSold”

Exercise

Compute the total income per month
Show only months with less than 10 items sold
Order by quantity sold and display as "TotalSold"

```
FROM       Purchase
```

Exercise

Compute the total income per month
Show only months with less than 10 items sold
Order by quantity sold and display as “TotalSold”

```
FROM      Purchase
GROUP BY  month
```

```
Purchase(pid, product, price, quantity, month)
```

Exercise

Compute the total income per month
Show only months with less than 10 items sold
Order by quantity sold and display as “TotalSold”

```
FROM      Purchase
GROUP BY  month
HAVING    sum(quantity) < 10
```

Exercise

Compute the total income per month
Show only months with less than 10 items sold
Order by quantity sold and display as "TotalSold"

```
SELECT   month, sum(price*quantity),
         sum(quantity) as TotalSold
FROM     Purchase
GROUP BY month
HAVING   sum(quantity) < 10
```

`Purchase(pid, product, price, quantity, month)`

Exercise

Compute the total income per month
Show only months with less than 10 items sold
Order by quantity sold and display as "TotalSold"

```
SELECT    month, sum(price*quantity),
          sum(quantity) as TotalSold
FROM      Purchase
GROUP BY  month
HAVING    sum(quantity) < 10
ORDER BY  sum(quantity)
```

WHERE vs HAVING

- WHERE condition is applied to individual rows
  - The rows may or may not contribute to the aggregate
  - No aggregates allowed here
  - Occasionally, some groups become empty and are removed

- HAVING condition is applied to the entire group
  - Entire group is returned, or removed
  - May use aggregate functions on the group

Purchase(pid, product, price, quantity, month)

Mystery Query

What do they compute?

```
SELECT      month, sum(quantity), max(price)
FROM        Purchase
GROUP BY    month
```

```
SELECT      month, sum(quantity)
FROM        Purchase
GROUP BY    month
```

```
SELECT      month
FROM        Purchase
GROUP BY    month
```

Mystery Query

What do they compute?

```
SELECT      month, sum(quantity), max(price)
FROM        Purchase
GROUP BY    month
```

```
SELECT      month, sum(quantity)
FROM        Purchase
GROUP BY    month
```

```
SELECT      month
FROM        Purchase
GROUP BY    month
```

Lesson: DISTINCT is a special case of GROUP BY

```
Product(product_id,pname,manufacturer)
Purchase(pid,product_id,price,month)
```

Aggregate + Join

For each manufacturer, compute how many products with price > $100 they sold

```
Product(product_id,pname,manufacturer)
Purchase(pid,product_id,price,month)
```

Aggregate + Join

For each manufacturer, compute how many products with price > $100 they sold

Problem: manufacturer is in Product, price is in Purchase...

```
Product(product_id,pname,manufacturer)
Purchase(pid,product_id,price,month)
```

Aggregate + Join

For each manufacturer, compute how many products with price > $100 they sold

Problem: manufacturer is in Product, price is in Purchase...

```
-- step 1: think about their join
SELECT ...
FROM Product x, Purchase y
WHERE x.product_id = y.product_id
  and y.price > 100
```

manu facturer	...	price	...
Hitachi		150	
Canon		300	
Hitachi		180	

```
Product(product_id,pname,manufacturer)
Purchase(pid,product_id,price,month)
```

Aggregate + Join

For each manufacturer, compute how many products with price > $100 they sold

Problem: manufacturer is in Product, price is in Purchase...

```
-- step 1: think about their join
SELECT ...
FROM Product x, Purchase y
WHERE x.product_id = y.product_id
  and y.price > 100
```

manu facturer	...	price	...
Hitachi		150	
Canon		300	
Hitachi		180	

```
-- step 2: do the group-by on the join
SELECT x.manufacturer, count(*)
FROM Product x, Purchase y
WHERE x.product_id = y.product_id
  and y.price > 100
GROUP BY  x.manufacturer
```

manu facturer	count(*)
Hitachi	2
Canon	1
...	

```
Product(product_id,pname,manufacturer)
Purchase(pid,product_id,price,month)
```

Aggregate + Join

Variant:
For each manufacturer, compute how many products with price > $100 they sold in each month

```
SELECT x.manufacturer, y.month, count(*)
FROM Product x, Purchase y
WHERE x.product_id = y.product_id
  and y.price > 100
GROUP BY  x.manufacturer, y.month
```

manu facturer	month	count(*)
Hitachi	Jan	2
Hitachi	Feb	1
Canon	Jan	3
...		

```
Product(product_id,pname,manufacturer)
Purchase(pid,product_id,price,month)
```

FWGHOS

Including Empty Groups

- In the result of a group by query, there is one row per group in the result

Count(*) is never 0

```
SELECT x.manufacturer, count(*)
FROM Product x, Purchase y
WHERE x.product_id= y.product_id
GROUP BY x.manufacturer
```

Including Empty Groups

```sql
SELECT x.manufacturer, count(*)
FROM Product x, Purchase y
WHERE x.product_id= y.product_id
GROUP BY x.manufacturer
```

Product

pname	manufacturer	…
Gizmo	GizmoWorks	
Camera	Canon	
OneClick	Hitachi	

Purchase

product	price	...
Camera	150	
Camera	300	
OneClick	180	

Join(Product, Purchase)

pname	manu facturer	…	manu facturer	price	…
Camera	Canon		Canon	150	
Camera	Canon		Canon	300	
OneClick	Hitachi		Hitachi	180	

No GizmoWorks!

Final results

manufacturer	Count(*)
Canon	2
Hitachi	1

Including Empty Groups

```
SELECT x.manufacturer, count(y.pid)
FROM Product x LEFT OUTER JOIN Purchase y
ON x.product_id = y.product_id
GROUP BY x.manufacturer
```

Count(pid) is 0
when all pid's in
the group are
NULL

Including Empty Groups

```
SELECT x.manufacturer, count(y.pid)
FROM Product x LEFT OUTER JOIN Purchase y
ON x.product_id = y.product_id
GROUP BY x.manufacturer
```

Product

prod_id	manufacturer	…
Gizmo	GizmoWorks	
Camera	Canon	
OneClick	Hitachi	

Purchase

prod_id	price	...
Camera	150	
Camera	300	
OneClick	180	

Why 0 for GizmoWorks?

Final results

manufacturer	Count(y.pid)
Canon	2
Hitachi	1
GizmoWorks	0

Left Outer Join(Product, Purchase)

prod_id	manufacturer	…	prod_id	price	…
Camera	Canon		Camera	150	
Camera	Canon		Camera	300	
OneClick	Hitachi		OneClick	180	
Gizmo	GizmoWorks	…	NULL	NULL	NULL

GizmoWorks is paired with NULLs

Including Empty Groups

```
SELECT x.manufacturer, count(*)
FROM Product x LEFT OUTER JOIN Purchase y
ON x.product_id = y.product_id
GROUP BY x.manufacturer
```

Product

prod_id	manufacturer	…
Gizmo	GizmoWorks	
Camera	Canon	
OneClick	Hitachi	

Purchase

product	price	...
Camera	150	
Camera	300	
OneClick	180	

Final results

manufacturer	Count(*)
Canon	2
Hitachi	1
GizmoWorks	1

Left Outer Join(Product, Purchase)

prod_id	manufacturer	…	product	price	…
Camera	Canon		Camera	150	
Camera	Canon		Camera	300	
OneClick	Hitachi		OneClick	180	
Gizmo	GizmoWorks	…	NULL	NULL	NULL

Probably not what we want!

Introduction to Data Management
CSE 414

Lecture 6: Nested Queries in SQL

Announcements

- No lecture on Monday, 4/15
- Makeup lecture on Thursday, 4/18, 5:30-6:20, in G20
- Webquiz tomorrow
- Homework 2 due on Monday

What have we learned so far

- Data models
- Relational data model
  - Instance: relations
  - Schema: table with attribute names
  - Language: SQL

What have we learned so far

SQL features

- Projections
- Selections
- Joins (inner and outer)
- Aggregates
- Group by
- Inserts, updates, and deletes

Make sure you read the textbook!

Lecture Goals

- Today we will learn how to write (even) more powerful SQL queries

- Reading: Ch. 6.3

Subqueries

- A subquery is a SQL query nested inside a larger query
- Such inner-outer queries are called nested queries
- A subquery may occur in:
  - A `SELECT` clause
  - A `FROM` clause
  - A `WHERE` clause

- Rule of thumb: avoid nested queries when possible
  - But sometimes it's impossible, as we will see

Subqueries…

- Can return a single value to be included in a `SELECT` clause
- Can return a relation to be included in the `FROM` clause, aliased using a tuple variable
- Can return a single value to be compared with another value in a `WHERE` clause
- Can return a relation to be used in the `WHERE or` `HAVING` clause under an existential quantifier

1. Subqueries in SELECT

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

For each product return the city where it is manufactured

```
SELECT X.pname, (SELECT Y.city
                 FROM Company Y
                 WHERE Y.cid=X.cid) as City
FROM  Product X
```

"correlated subquery"

What happens if the subquery returns more than one city?

We get a runtime error

(and SQLite simply ignores the extra values…)

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

1. Subqueries in SELECT

Whenever possible, don't use a nested queries:

```
SELECT X.pname, (SELECT Y.city
                 FROM Company Y
                 WHERE Y.cid=X.cid) as City
FROM   Product X
```

=

```
SELECT X.pname, Y.city
FROM   Product X, Company Y
WHERE  X.cid=Y.cid
```

We have "unnested" the query

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

1. Subqueries in SELECT

Compute the number of products made by each company

Product (pname, price, cid)
Company (cid, cname, city)

1. Subqueries in SELECT

Compute the number of products made by each company

```
SELECT C.cid, C.cname, (SELECT count(*)
                                FROM Product P
                                WHERE P.cid=C.cid)
FROM  Company C
```

```
Product (pname, price, cid)
Company (cid, cname, city)
```

1. Subqueries in SELECT

Compute the number of products made by each company

```
SELECT C.cid, C.cname, (SELECT count(*)
                        FROM Product P
                        WHERE P.cid=C.cid)
FROM  Company C
```

Better: we can unnest using a GROUP BY

```
SELECT C.cid, C.cname, count(*)
FROM   Company C, Product P
WHERE  C.cid=P.cid
GROUP BY C.cid, C.cname
```

Product (<u>pname</u>, price, cid)
Company (<u>cid</u>, cname, city)

1. Subqueries in SELECT

But are these really equivalent?

```
SELECT C.cid, C.cname, (SELECT count(*)
                        FROM Product P
                        WHERE P.cid=C.cid)
FROM  Company C
```

```
SELECT C.cid, C.cname, count(*)
FROM   Company C, Product P
WHERE  C.cid=P.cid
GROUP BY C.cid, C.cname
```

Product (pname, price, cid)
Company (cid, cname, city)

1. Subqueries in SELECT

Recall: count of an empty table is 0

But are these really equivalent?

```
SELECT C.cid, C.cname, (SELECT count(*)
                        FROM Product P
                        WHERE P.cid=C.cid)
FROM  Company C
```

```
SELECT C.cid, C.cname, count(*)
FROM   Company C, Product P
WHERE  C.cid=P.cid
GROUP BY C.cid, C.cname
```

No! Different results if a company has no products

```
SELECT C.cid, C.cname, count(pname)
FROM Company C LEFT OUTER JOIN Product P
ON   C.cid=P.cid
GROUP BY C.cid, C.cname
```

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

2. Subqueries in FROM

Find all products whose prices is > 20 and < 500

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

2. Subqueries in FROM

Find all products whose prices is > 20 and < 500

```
SELECT X.pname
FROM (SELECT *
      FROM Product AS Y
      WHERE price > 20) as X
WHERE X.price < 500
```

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

2. Subqueries in FROM

Find all products whose prices is > 20 and < 500

```
SELECT X.pname
FROM (SELECT *
      FROM Product AS Y
      WHERE price > 20) as X
WHERE X.price < 500
```

Try unnest this query !

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

2. Subqueries in FROM

Find all products whose prices is > 20 and < 500

```
SELECT X.pname
FROM (SELECT *
      FROM Product AS Y
      WHERE price > 20) as X
WHERE X.price < 500
```

Side note: This is not a correlated subquery. (why?)

Try unnest this query !

2. Subqueries in FROM

Sometimes we need to compute an intermediate table only to use it later in a SELECT-FROM-WHERE

- Option 1: use a subquery in the FROM clause
- Option 2: use the WITH clause

Product (pname, price, cid)
Company (cid, cname, city)

2. Subqueries in FROM

```
SELECT X.pname
FROM (SELECT *
      FROM Product AS Y
      WHERE price > 20) as X
WHERE X.price < 500
```

=

A subquery whose result we called myTable

```
WITH myTable AS (SELECT * FROM Product AS Y WHERE price > 20)
  SELECT X.pname
  FROM myTable as X
  WHERE X.price < 500
```

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies that make some products with price < 200

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies that make some products with price < 200

Existential quantifiers

Product (pname, price, cid)
Company (cid, cname, city)

3. Subqueries in WHERE

Find all companies that make some products with price < 200

Existential quantifiers

Using EXISTS:

```
SELECT C.cid, C.cname
FROM   Company C
WHERE  EXISTS (SELECT *
               FROM Product P
               WHERE C.cid = P.cid and P.price < 200)
```

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies that make some products with price < 200

Existential quantifiers

Using IN

```
SELECT C.cid, C.cname
FROM  Company C
WHERE C.cid IN (SELECT P.cid
                FROM Product P
                WHERE P.price < 200)
```

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies that make some products with price < 200

Existential quantifiers

Using ANY:

```
SELECT C.cid, C.cname
FROM   Company C
WHERE 200 > ANY (SELECT price
                 FROM Product P
                 WHERE P.cid = C.cid)
```

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies that make some products with price < 200

Existential quantifiers

Using ANY:

```
SELECT C.cid, C.cname
FROM   Company C
WHERE 200 > ANY (SELECT price
                 FROM Product P
                 WHERE P.cid = C.cid)
```

Not supported in sqlite

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies that make some products with price < 200

Existential quantifiers

Now let's unnest it:

```
SELECT DISTINCT C.cid, C.cname
FROM   Company C, Product P
WHERE  C.cid = P.cid and P.price < 200
```

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies that make some products with price < 200

Existential quantifiers

Now let's unnest it:

```
SELECT DISTINCT C.cid, C.cname
FROM   Company C, Product P
WHERE  C.cid = P.cid and P.price < 200
```

Existential quantifiers are easy! ☺

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies s.t. all their products have price < 200

same as:

Find all companies that make only products with price < 200

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies s.t. all their products have price < 200

same as:

Find all companies that make only products with price < 200

Universal quantifiers

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies s.t. all their products have price < 200

same as:

Find all companies that make only products with price < 200

Universal quantifiers

Universal quantifiers are hard! ☹

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies s.t. all their products have price < 200

1. Find *the other* companies … …which ones?

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies s.t. all their products have price < 200

1. Find *the other* companies that make some product ≥ 200

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies s.t. all their products have price < 200

1. Find *the other* companies that make some product ≥ 200

```
SELECT C.cid, C.cname
FROM   Company C
WHERE  C.cid IN (SELECT P.cid
                 FROM Product P
                 WHERE P.price >= 200)
```

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies s.t. all their products have price < 200

1. Find *the other* companies that make some product ≥ 200

```sql
SELECT C.cid, C.cname
FROM   Company C
WHERE  C.cid IN (SELECT P.cid
                 FROM Product P
                 WHERE P.price >= 200)
```

2. Find all companies s.t. all their products have price < 200

```sql
SELECT C.cid, C.cname
FROM   Company C
WHERE  C.cid NOT IN (SELECT P.cid
                     FROM Product P
                     WHERE P.price >= 200)
```

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies s.t. all their products have price < 200

Universal quantifiers

Using EXISTS:

```
SELECT C.cid, C.cname
FROM   Company C
WHERE NOT EXISTS (SELECT *
                  FROM Product P
                  WHERE P.cid = C.cid and P.price >= 200)
```

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

3. Subqueries in WHERE

Find all companies s.t. all their products have price < 200

Universal quantifiers

Using ALL:

```
SELECT C.cid, C.cname
FROM   Company C
WHERE 200 >= ALL (SELECT price
                  FROM Product P
                  WHERE P.cid = C.cid)
```

Product (pname, price, cid)
Company (cid, cname, city)

3. Subqueries in WHERE

Find all companies s.t. all their products have price < 200

Universal quantifiers

Using ALL:

```
SELECT C.cid, C.cname
FROM   Company C
WHERE 200 >= ALL (SELECT price
                  FROM Product P
                  WHERE P.cid = C.cid)
```

Not supported in sqlite

Question for Database Theory Fans and their Friends

- Can we unnest the *universal quantifier* query?

- We need to first discuss the concept of *monotonicity*

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

Monotone Queries

- Definition A query Q is monotone if:
  - Whenever we add tuples to one or more input tables, the answer to the query will not lose any output tuple

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

Monotone Queries

- Definition A query Q is monotone if:
  - Whenever we add tuples to one or more input tables, the answer to the query will not lose any output tuple

Product

pname	price	cid
Gizmo	19.99	c001
Gadget	999.99	c004
Camera	149.99	c003

Company

cid	cname	city
c002	Sunworks	Bonn
c001	DB Inc.	Lyon
c003	Builder	Lodtz

Q

pname	city
Gizmo	Lyon
Camera	Lodtz

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

Monotone Queries

- Definition A query Q is monotone if:
  - Whenever we add tuples to one or more input tables, the answer to the query will not lose any output tuple

Product

pname	price	cid
Gizmo	19.99	c001
Gadget	999.99	c004
Camera	149.99	c003

Company

cid	cname	city
c002	Sunworks	Bonn
c001	DB Inc.	Lyon
c003	Builder	Lodtz

Q

pname	city
Gizmo	Lyon
Camera	Lodtz

Product

pname	price	cid
Gizmo	19.99	c001
Gadget	999.99	c004
Camera	149.99	c003
iPad	499.99	c001

Company

cid	cname	city
c002	Sunworks	Bonn
c001	DB Inc.	Lyon
c003	Builder	Lodtz

Q

pname	city
Gizmo	Lyon
Camera	Lodtz
iPad	Lyon

So far it looks monotone...

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

Monotone Queries

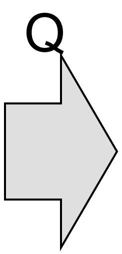
- Definition A query Q is monotone if:
  - Whenever we add tuples to one or more input tables, the answer to the query will not lose any output tuple

Product

pname	price	cid
Gizmo	19.99	c001
Gadget	999.99	c004
Camera	149.99	c003

Company

cid	cname	city
c002	Sunworks	Bonn
c001	DB Inc.	Lyon
c003	Builder	Lodtz



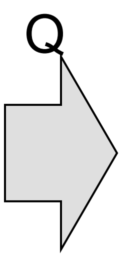
pname	city
Gizmo	Lyon
Camera	Lodtz

Product

pname	price	cid
Gizmo	19.99	c001
Gadget	999.99	c004
Camera	149.99	c003
iPad	499.99	c001

Company

cid	cname	city
c002	Sunworks	Bonn
c001	DB Inc.	Lyon
c003	Builder	Lodtz
c004	Crafter	Lodtz



Q is not monotone!

pname	city
Gizmo	Lodtz
Camera	Lodtz
iPad	Lyon

Monotone Queries

- Theorem: If Q is a SELECT-FROM-WHERE query that does not have subqueries, and no aggregates, then it is monotone.

Monotone Queries

- Theorem: If Q is a SELECT-FROM-WHERE query that does not have subqueries, and no aggregates, then it is monotone.

- Proof. We use the nested loop semantics: if we insert a tuple in a relation R_i, this will not remove any tuples from the answer

```
SELECT a1, a2, …, ak
FROM   R1 AS x1, R2 AS x2, …, Rn AS xn
WHERE  Conditions
```

```
for x1 in R1 do
  for x2 in R2 do
    …
      for xn in Rn do
        if Conditions
          output (a1,…,ak)
```

Monotone Queries

- Theorem: If Q is a SELECT-FROM-WHERE query that does not have subqueries, and no aggregates, then it is monotone.

- Proof. We use the nested loop semantics: if we insert a tuple in a relation R_i, this will not remove any tuples from the answer

Add a tuple to R_2…

```
SELECT a₁, a₂, …, aₖ
FROM   R₁ AS x₁, R₂ AS x₂, …, Rₙ AS xₙ
WHERE  Conditions
```

```
for x₁ in R₁ do
  for x₂ in R₂ do
    …
      for xₙ in Rₙ do
        if Conditions
          output (a₁,…,aₖ)
```

Monotone Queries

- Theorem: If Q is a SELECT-FROM-WHERE query that does not have subqueries, and no aggregates, then it is monotone.

- Proof. We use the nested loop semantics: if we insert a tuple in a relation R_i, this will not remove any tuples from the answer

Add a tuple to R_2…

```
SELECT a1, a2, …, ak
FROM   R1 AS x1, R2 AS x2, …, Rn AS xn
WHERE  Conditions
```

```
for x1 in R1 do
  for x2 in R2 do
    …
      for xn in Rn do
        if Conditions
          output (a1,…,ak)
```

…can't lose anything here.

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

Monotone Queries

- The query:

Find all companies s.t. all their products have price < 200 is not monotone

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

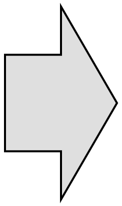
Monotone Queries

- The query:

Find all companies s.t. all their products have price < 200 is not monotone

pname	price	cid
Gizmo	19.99	c001

cid	cname	city
c001	Sunworks	Bonn



cname
Sunworks

`Product (pname,  price, cid)`
`Company (cid, cname, city)`

Monotone Queries

- The query:

Find all companies s.t. all their products have price < 200
is not monotone

pname	price	cid
Gizmo	19.99	c001

cid	cname	city
c001	Sunworks	Bonn

cname
Sunworks

pname	price	cid
Gizmo	19.99	c001
Gadget	999.99	c001

cid	cname	city
c001	Sunworks	Bonn

cname

- Consequence: If a query is not monotone, then we cannot write it as a SELECT-FROM-WHERE query without nested subqueries

Queries that must be nested

- Queries with universal quantifiers or with negation

Queries that must be nested

- Queries with universal quantifiers or with negation
- Queries with aggregates are usually not monotone
  - `sum(..)` and `count(*)` are NOT monotone, because they do not satisfy set containment
  - `select count(*) from R` is not monotone!

Introduction to Data Management CSE 414

Lecture 7-8: SQL Wrap-up

Relational Algebra

Announcements

- Webquiz tonight
- Makeup lecture tomorrow, 5:30pm, this room

Purchase(pid, product, quantity, price)

GROUP BY v.s. Nested Queries

```
SELECT   product, Sum(quantity) AS TotalSales
FROM     Purchase
WHERE    price > 1
GROUP BY product
```

```
SELECT DISTINCT x.product, (SELECT Sum(y.quantity)
                            FROM    Purchase y
                            WHERE x.product = y.product
                              AND y.price > 1)
                            AS TotalSales
FROM  Purchase x
WHERE x.price > 1
```

Why twice ?

`Author(login,name)`

`Wrote(login,url)`

More Unnesting

Find authors who wrote ≥ 10 documents:

Author(<u>login</u>,name)

Wrote(login,url)

More Unnesting

Find authors who wrote ≥ 10 documents:

Attempt 1: with nested queries

This is SQL by a novice

```
SELECT DISTINCT Author.name
FROM        Author
WHERE        (SELECT count(Wrote.url)
              FROM Wrote
              WHERE Author.login=Wrote.login)
                 >= 10
```

Author(login,name)
Wrote(login,url)

More Unnesting

Find authors who wrote ≥ 10 documents:

Attempt 1: with nested queries

Attempt 2: using GROUP BY and HAVING

```
SELECT    Author.name
FROM      Author, Wrote
WHERE     Author.login=Wrote.login
GROUP BY  Author.name
HAVING    count(wrote.url) >= 10
```

This is SQL by an expert

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

Finding Witnesses

For each city, find the most expensive product made in that city

Product (pname, price, cid)
Company (cid, cname, city)

Finding Witnesses

For each city, find the most expensive product made in that city

Finding the maximum price is easy…

```
SELECT x.city, max(y.price)
FROM   Company x, Product y
WHERE  x.cid = y.cid
GROUP BY x.city;
```

But we need the *witnesses*, i.e., the products with max price

Product (<u>pname</u>, price, cid)
Company (<u>cid</u>, cname, city)

Finding Witnesses

To find the witnesses, compute the maximum price in a subquery (in FROM or in WITH)

```
WITH CityMax AS
  (SELECT x.city, max(y.price) as maxprice
   FROM Company x, Product y
   WHERE x.cid = y.cid
   GROUP BY x.city)
```

Product (pname, price, cid)
Company (cid, cname, city)

Finding Witnesses

To find the witnesses, compute the maximum price in a subquery (in FROM or in WITH)

```
WITH CityMax AS
  (SELECT x.city, max(y.price) as maxprice
   FROM Company x, Product y
   WHERE x.cid = y.cid
   GROUP BY x.city)
SELECT DISTINCT u.city, v.pname, v.price
FROM Company u, Product v, CityMax w
WHERE u.cid = v.cid
      and u.city = w.city
      and v.price = w.maxprice;
```

Product (<u>pname</u>, price, cid)
Company (<u>cid</u>, cname, city)

Finding Witnesses

To find the witnesses, compute the maximum price in a subquery (in FROM or in WITH)

```
SELECT DISTINCT u.city, v.pname, v.price
FROM Company u, Product v,
     (SELECT x.city, max(y.price) as maxprice
      FROM Company x, Product y
      WHERE x.cid = y.cid
      GROUP BY x.city) w
WHERE u.cid = v.cid
      and u.city = w.city
      and v.price = w.maxprice;
```

```
Product (pname,  price, cid)
Company (cid, cname, city)
```

Finding Witnesses

Or we can use a subquery in where clause

```
SELECT u.city, v.pname, v.price
FROM Company u, Product v
WHERE u.cid = v.cid
  and v.price >= ALL (SELECT y.price
                      FROM Company x, Product y
                      WHERE u.city=x.city
                      and x.cid=y.cid);
```

Product (<u>pname</u>, price, cid)
Company (<u>cid</u>, cname, city)

Finding Witnesses

There is a more concise solution here:

```
SELECT u.city, v.pname, v.price
FROM Company u, Product v, Company x, Product y
WHERE u.cid = v.cid
      and u.city = x.city
      and x.cid = y.cid
GROUP BY u.city, v.pname, v.price
HAVING v.price = max(y.price)
```

SQL: Our first language for the relational model

- Projections
- Selections
- Joins (inner and outer)
- Inserts, updates, and deletes
- Aggregates
- Grouping
- Ordering
- Nested queries

Relational Algebra

Relational Algebra

- In SQL we say *what* we want
- In RA we can express *how* to get it
- RA = set-at-a-time algebra for relations

- Every DBMS implementations converts a SQL query to RA in order to execute it
- An RA expression is called a *query plan*

Basics

- Inputs: Relations (with attributes)
- RA: defines a function on relations
  - Returns a relation
  - Can be composed together
  - Often displayed using a tree rather than linearly
  - Use Greek symbols: σ, π, δ, etc

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 flavors:

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

DB systems implement bag semantics (Why?)

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

All operators take in 1 or 2 relations as inputs and return another relation

Union and Difference

$R1 \cup R2$

$R1 - R2$

Only make sense if R1, R2 have the same schema

What do they mean over bags ?

What about Intersection ?

- Derived operator using minus

$$\boxed{R1 \cap R2 = R1 - (R1 - R2)}$$

- Derived using join

$$\boxed{R1 \cap R2 = R1 \bowtie R2}$$

Selection

- Returns all tuples which satisfy a condition

$$\boxed{\sigma_c(R)}$$

- Examples
  - $\sigma_{Salary > 40000}$ (Employee)
  - $\sigma_{name = \text{“Smith”}}$ (Employee)
- The condition c can be =, <, <=, >, >=, <> combined with AND, OR, NOT

Employee

SSN	Name	Salary
1234545	John	20000
5423341	Smith	60000
4352342	Fred	50000

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

SSN	Name	Salary
5423341	Smith	60000
4352342	Fred	50000

Projection

- Eliminates columns

$$\boxed{\pi_{A1,\ldots,An}(R)}$$

- 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

$\pi_{\text{Name,Salary}}$ (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

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

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

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

zip	disease
98125	heart
98120	heart

Cartesian Product

- Each tuple in R1 with each tuple in R2

$$\boxed{R1 \times R2}$$

- 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

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

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

Natural Join

$$\boxed{R1 \bowtie R2}$$

- Meaning: $R1 \bowtie R2 = \Pi_A(\sigma_\theta(R1 \times R2))$
- Where:
  - Selection σ_θ checks equality of all common attributes (i.e., attributes with same names)
  - Projection Π_A 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 $\bowtie$ **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
Alice	54	98125
Bob	20	98120

$P \bowtie V$

age	zip	disease	name
54	98125	heart	Alice
20	98120	flu	Bob

Natural Join

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

AnonPatient (age, zip, disease)
Voters (name, age, zip)

Theta Join

- A join that involves a predicate

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

- Here θ can be any condition
- No projection in this case!
- For our voters/patients example:

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

Equijoin

- A theta join where θ is an equality predicate

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

- By far the most used variant of join in practice
- What is the relationship with natural join?

Equijoin Example

AnonPatient P

age	zip	disease
54	98125	heart
20	98120	flu

Voters V

name	age	zip
p1	54	98125
p2	20	98120

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

P.age	P.zip	P.disease	V.name	V.age	V.zip
54	98125	heart	p1	54	98125
20	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	~~V.age~~	~~V.zip~~
54	98125	heart	p1	~~54~~	~~98125~~
20	98120	flu	p2	~~20~~	~~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
  - No projection
- **Equijoin**: $R \bowtie_\theta S = \sigma_\theta (R \times S)$
  - Join condition θ consists only of equalities
  - No projection
- **Natural join**: $R \bowtie S = \pi_A (\sigma_\theta (R \times S))$
  - Equality on **all** fields with same name in R and in S
  - Projection π_A drops all redundant attributes

So Which Join Is It ?

When we write R $\bowtie$ 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
  - Does not eliminate duplicate columns
- 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

AnnonJob J

job	age	zip
lawyer	54	98125
cashier	20	98120

$P ⟕ J$

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

Some Examples

```
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

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

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

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

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

Can be represented as trees as well

Some Examples

```
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

```
Project[sname](Supplier Join[sno=sno]
              (Supply Join[pno=pno] (Select[psize>10](Part))))
```

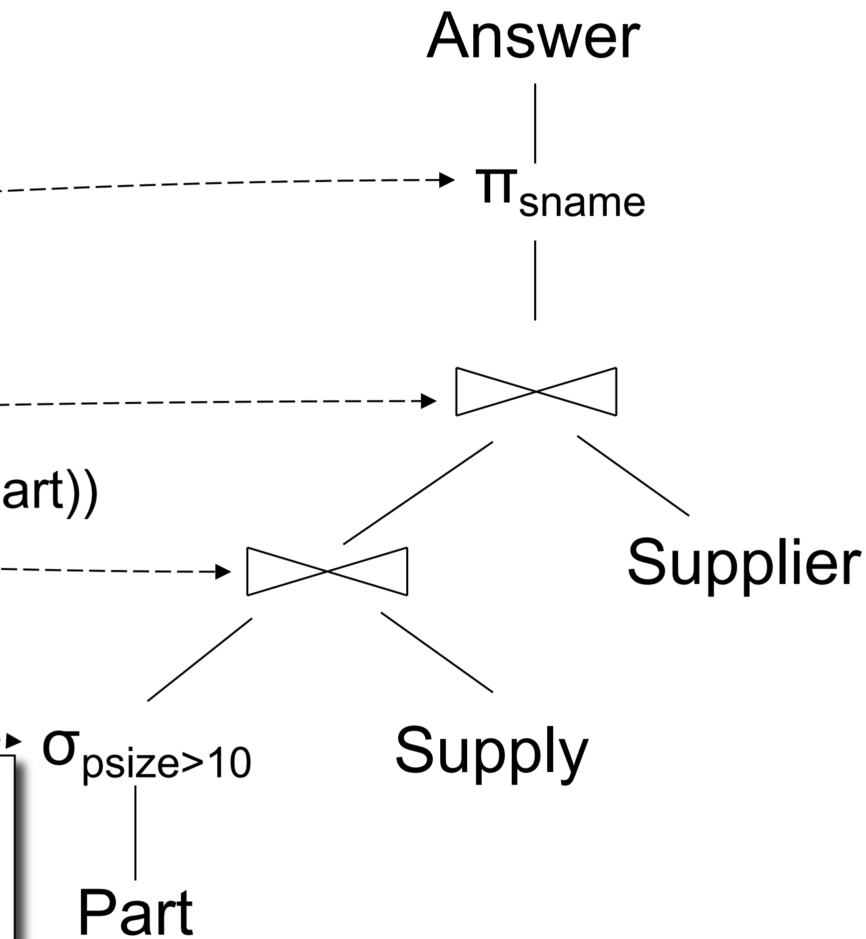
Name of supplier of red parts or parts with size greater than 10

```
Project[sname](Supplier Join[sno=sno]
              (Supply Join[pno=pno]
              ((Select[psize>10](Part)) Union
                                         (Select[pcolor='red'](Part)))

Project[sname](Supplier Join[sno=sno] (Supply Join[pno=pno]
                              (Select[psize>10 OR pcolor='red'](Part))))
```

Can be represented as trees as well

Representing RA Queries as Trees

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



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

```
SELECT z.sname
FROM Part x, Supply y, Supplier z
WHERE x.psize > 10
  and x.pno = y.pno
  and y.sno = z.sno
```

Relational Algebra Operators

- Union $\cup$, ~~intersection $\cap$,~~ difference -
- Selection σ
- Projection π
- Cartesian product X, join $\bowtie$
- (Rename ρ)
- Duplicate elimination δ
- Grouping and aggregation γ
- Sorting τ

RA

Extended RA

All operators take in 1 or 2 relations as inputs and return another relation

Extended RA: Operators on Bags

- Duplicate elimination δ
- Grouping γ
  - Takes in relation and a list of grouping operations (e.g., aggregates). Returns a new relation.
- Sorting τ
  - Takes in a relation, a list of attributes to sort on, and an order. Returns a new relation.

Using Extended RA Operators

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

Answer

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

T2(city,q,c)

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

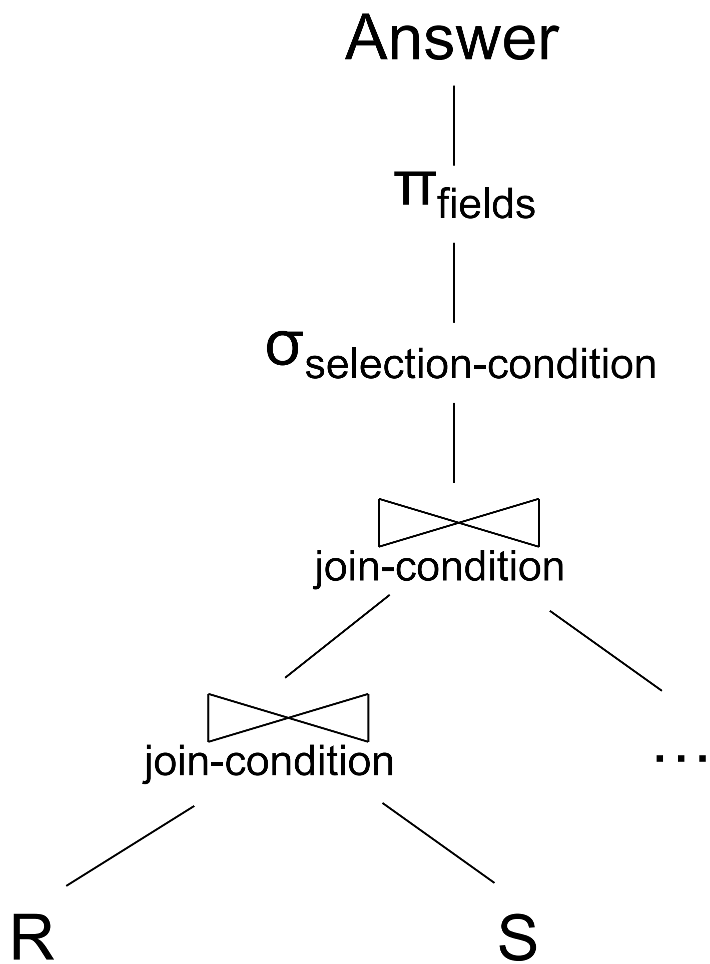
T1(city,q,c)

$\gamma_{\text{city, sum(quantity)} \to \text{q, count(*)} \to \text{c}}$

sales(product, city, quantity)

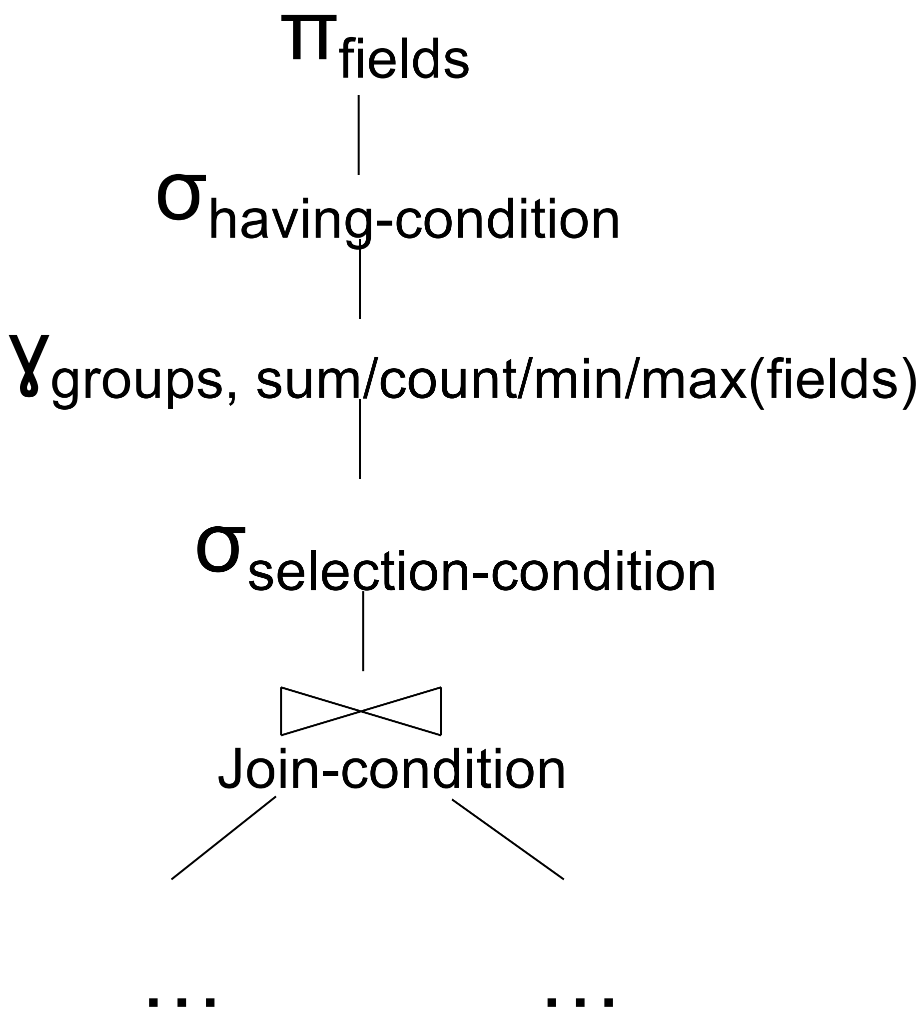
T1, T2 = temporary tables

Typical Plan for a Query (1/2)




```
SELECT fields
FROM R, S, …
WHERE condition
```

Typical Plan for a Query (1/2)




```
SELECT fields
FROM R, S, …
WHERE condition
GROUP BY groups
HAVING condition
```

```
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)
```

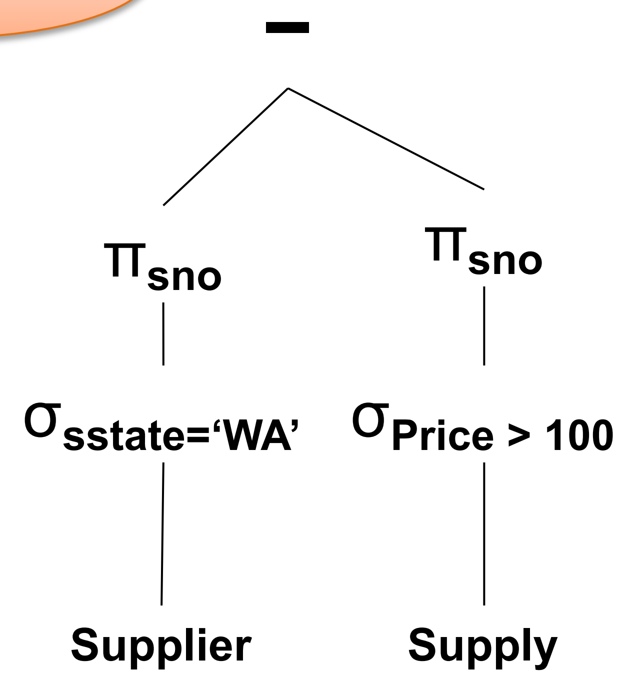
EXCEPT = set difference

```
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…



Summary of RA and SQL

- SQL = a declarative language where we say *what* data we want to retrieve
- RA = an algebra where we say *how* we want to retrieve the data
- **Theorem**: SQL and RA can express exactly the same class of queries

RDBMS translate SQL → RA, then optimize RA

Introduction to Data Management CSE 414

Lectures 9-10: Datalog

Class Overview

- Unit 1: Intro
- Unit 2: Relational Data Models and Query Languages
  - Data models, SQL, Datalog, Relational Algebra
- Unit 3: Non-relational data
- Unit 4: RDMBS internals and query optimization
- Unit 5: Parallel query processing
- Unit 6: DBMS usability, conceptual design
- Unit 7: Transactions

What is Datalog?

- Another query language for relational model
  - Designed in the 80's
  - Simple, concise, elegant
  - Extends relational queries with *recursion*
- Today is a hot topic:
  - Souffle (we will use in HW4)
  - Beyond databases in many research projects: network protocols, static program analysis

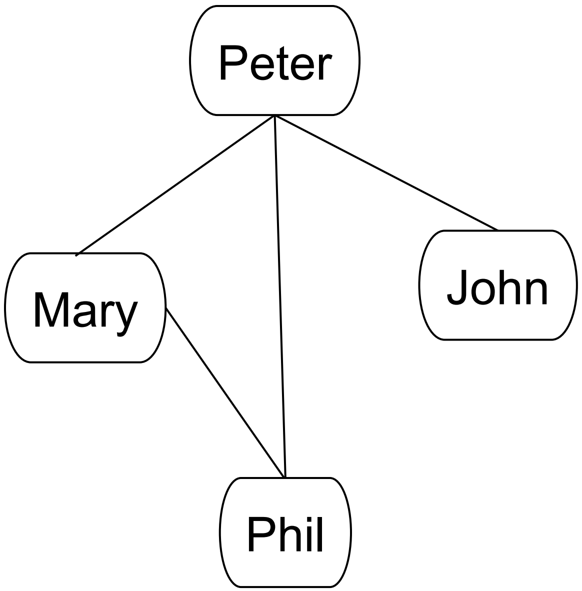
Soufflé

- Open-source implementation of Datalog DBMS
- Under active development
- Commercial implementations are available
  - More difficult to set up and use
- “sqlite” of Datalog
  - Set-based rather than bag-based

- Install in your VM
  - Run `sudo yum install souffle` in terminal
  - More details in upcoming HW4

Why bother with *yet* another relational query language?

Example: storing FB friends



As a graph

Or

Person1	Person2	is_friend
Peter	John	1
John	Mary	0
Mary	Phil	1
Phil	Peter	1
…	…	…

As a relation

We will learn the tradeoffs of different data models later this quarter

Compute your friends graph

p1	p2	isFriend
Peter	John	1
John	Mary	0
Mary	Phil	1
Phil	Peter	1
…	…	…

`Friends(p1, p2, isFriend)`

```
SELECT f.p2
FROM Friends as f
WHERE f.p1 = ‘me’ AND f.isFriend = 1
```

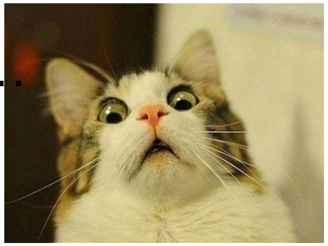
My own friends

```
SELECT f1.p2
FROM Friends as f1,
     (SELECT f.p2
      FROM Friends as f
      WHERE f.p1 = ‘me’ AND
      f.isFriend = 1) as f2
WHERE f1.p1 = f2.p2 AND
      f1.isFriend = 1
```

My FoF

My FoFoF… My FoFoFoF…

When does it end???



Datalog allows us to write *recursive queries* easily

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Schema

Datalog: Facts and Rules

Facts = tuples in the database

Rules = queries

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

Rules = queries

```
.decl Actor(id:number, fname:symbol, lname:symbol)
.decl Casts(id:number, mid:number)
.decl Movie(id:number, name:symbol, year:number)

Actor(344759,‘Douglas’, ‘Fowley’).
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, ‘A Night in Armour’, 1910).
Movie(29000, ‘Arizona’, 1940).
Movie(29445, ‘Ave Maria’, 1940).
```

Table declaration

Types in Souffle:
number
symbol (aka varchar)

Insert data

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

Rules = queries

```
Q1(y) :- Movie(x,y,z), z=1940.
```

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

Rules = queries

```
Q1(y) :- Movie(x,y,z), z=1940.
```

Find Movies made in 1940

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

Rules = queries

```
Q1(y) :- Movie(x,y,z), z=1940.
```

SQL

```
SELECT name
FROM Movie
WHERE year = 1940
```

Find Movies made in 1940

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

Rules = queries

id name year

```
Q1(y) :- Movie(x,y,z), z=1940.
```

Order of variable matters!

Find Movies made in 1940

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

Rules = queries

```
Q1(y) :- Movie(iDontCare,y,z),
         z=1940.
```

Find Movies made in 1940

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

Rules = queries

```
Q1(y) :- Movie(_,y,z), z=1940.
```

_ = "don't care" variables

Find Movies made in 1940

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

Rules = queries

```
Q1(y) :- Movie(x,y,z), z=1940.
```

```
Q2(f,l) :- Actor(z,f,l), Casts(z,x),
           Movie(x,y,1940).
```

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

Rules = queries

```
Q1(y) :- Movie(x,y,z), z=1940.
```

```
Q2(f,l) :- Actor(z,f,l), Casts(z,x),
           Movie(x,y,1940).
```

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

Rules = queries

```
Q1(y) :- Movie(x,y,z), z=1940.
```

```
Q2(f,l) :- Actor(z,f,l), Casts(z,x),
           Movie(x,y,1940).
```

Find Actors who acted in Movies made in 1940

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

Rules = queries

```
Q1(y) :- Movie(x,y,z), z=1940.
```

```
Q2(f,l) :- Actor(z,f,l), Casts(z,x),
           Movie(x,y,1940).
```

```
Q3(f,l) :- Actor(z,f,l), Casts(z,x1), Movie(x1,y1,1910),
                         Casts(z,x2), Movie(x2,y2,1940).
```

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

Rules = queries

```
Q1(y) :- Movie(x,y,z), z=1940.
```

```
Q2(f,l) :- Actor(z,f,l), Casts(z,x),
           Movie(x,y,1940).
```

```
Q3(f,l) :- Actor(z,f,l), Casts(z,x1), Movie(x1,y1,1910),
                         Casts(z,x2), Movie(x2,y2,1940).
```

Find Actors who acted in a Movie in 1940 and in one in 1910

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Datalog: Facts and Rules

Facts = tuples in the database

Rules = queries

```
Actor(344759,'Douglas', 'Fowley').
Casts(344759, 29851).
Casts(355713, 29000).
Movie(7909, 'A Night in Armour', 1910).
Movie(29000, 'Arizona', 1940).
Movie(29445, 'Ave Maria', 1940).
```

```
Q1(y) :- Movie(x,y,z), z=1940.
```

```
Q2(f,l) :- Actor(z,f,l), Casts(z,x),
           Movie(x,y,1940).
```

```
Q3(f,l) :- Actor(z,f,l), Casts(z,x1), Movie(x1,y1,1910),
                         Casts(z,x2), Movie(x2,y2,1940).
```

Extensional Database Predicates = EDB = Actor, Casts, Movie

Intensional Database Predicates = IDB = Q1, Q2, Q3

Datalog: Terminology

head body

atom atom atom (aka subgoal)

```
Q2(f, l) :-  Actor(z,f,l), Casts(z,x), Movie(x,y,1940).
```

f, l = head variables

x,y,z = existential variables

More Datalog Terminology

```
Q(args) :- R1(args), R2(args), ...
```

- $R_i(args_i)$ called an *atom*, or a *relational predicate*
- $R_i(args_i)$ evaluates to true when relation R_i contains the tuple described by $args_i$.
  - Example: `Actor(344759, ‘Douglas’, ‘Fowley’)` is true
- In addition we can also have arithmetic predicates
  - Example: `z > 1940`.
- Book uses AND instead of ,

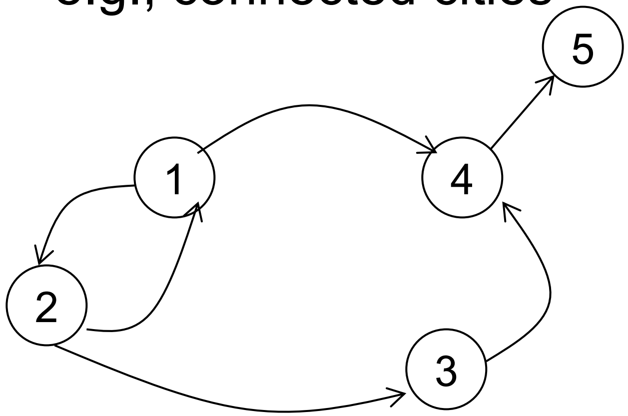
```
Q(args) :- R1(args) AND R2(args) ...
```

Datalog program

- A Datalog program consists of several rules
- Importantly, rules may be recursive!
  - Recall CSE 143!
- Usually there is one distinguished predicate that's the output
- We will show an example first, then give the general semantics.

Example

R encodes a graph
e.g., connected cities

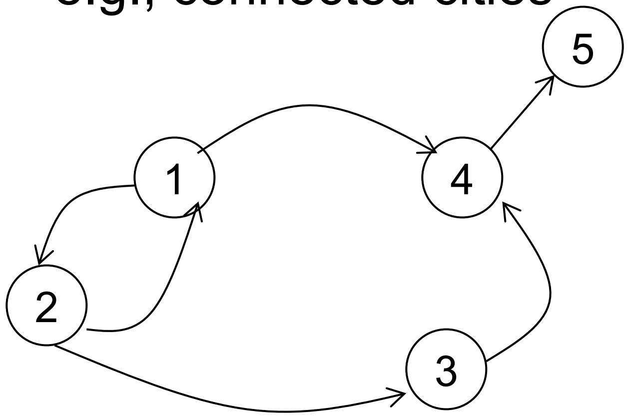


R=

1	2
2	1
2	3
1	4
3	4
4	5

Example

R encodes a graph
e.g., connected cities



R=

1	2
2	1
2	3
1	4
3	4
4	5

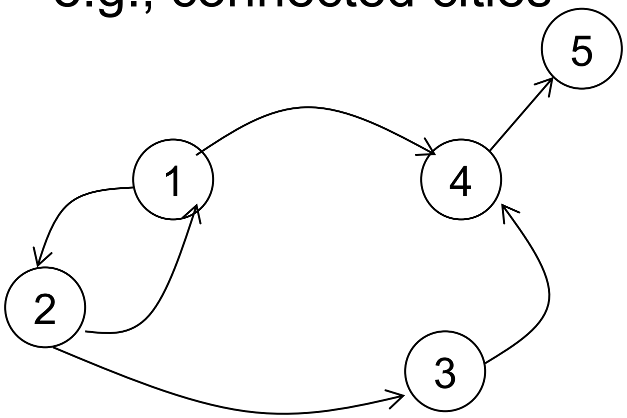
```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

Multiple rules for the same IDB means OR

What does it compute?

Example

R encodes a graph
e.g., connected cities



$T(x,y) \text{ :- } R(x,y).$

$T(x,y) \text{ :- } R(x,z),\ T(z,y).$

What does it compute?

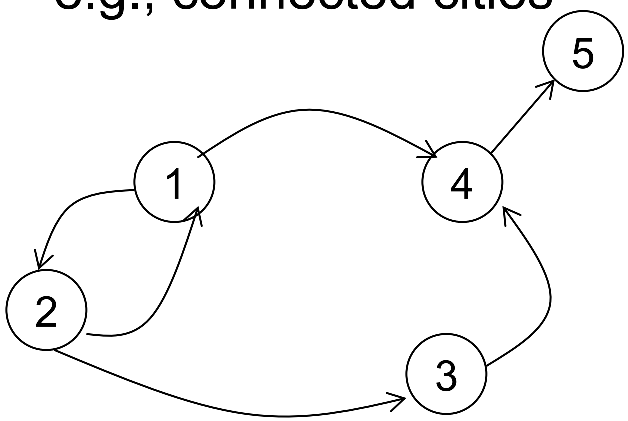
R=

1	2
2	1
2	3
1	4
3	4
4	5

Initially:
T is empty.

Example

R encodes a graph
e.g., connected cities




```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

What does it compute?

R=

1	2
2	1
2	3
1	4
3	4
4	5

Initially:
T is empty.

First iteration:
T =

1	2
2	1
2	3
1	4
3	4
4	5

First rule generates this

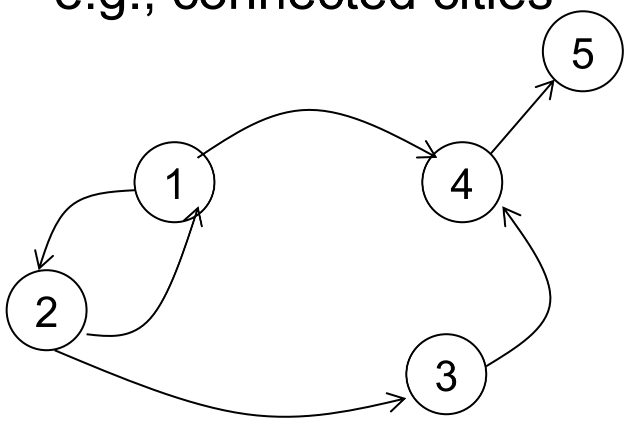
Second rule
generates nothing
(because T is empty)

Example

T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).

What does it compute?

R encodes a graph
e.g., connected cities



R=

1	2
2	1
2	3
1	4
3	4
4	5

Initially:
T is empty.

First iteration:
T =

1	2
2	1
2	3
1	4
3	4
4	5

Second iteration:
T =

1	2
2	1
2	3
1	4
3	4
4	5
1	1
2	2
1	3
2	4
1	5
3	5

First rule generates this

Second rule generates this

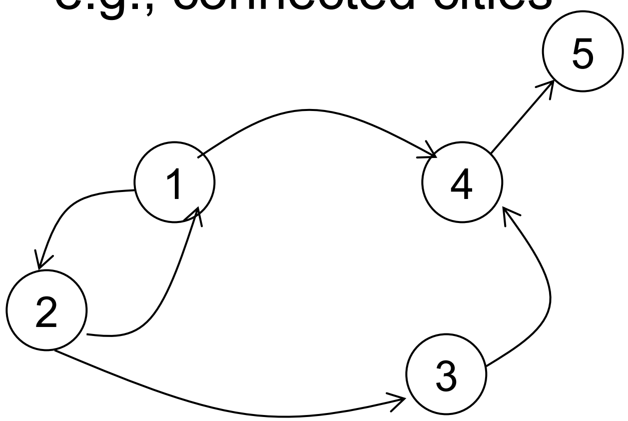
New facts

R encodes a graph
e.g., connected cities

Example

$T(x,y)$:- $R(x,y)$.
$T(x,y)$:- $R(x,z)$, $T(z,y)$.

What does it compute?



R=

1	2
2	1
2	3
1	4
3	4
4	5

Initially:
T is empty.

First iteration:
T =

1	2
2	1
2	3
1	4
3	4
4	5

Second iteration:
T =

1	2
2	1
2	3
1	4
3	4
4	5
1	1
2	2
1	3
2	4
1	5
3	5

Third iteration:
T =

1	2
2	1
2	3
1	4
3	4
4	5
1	1
2	2
1	3
2	4
1	5
3	5
2	5

Both rules

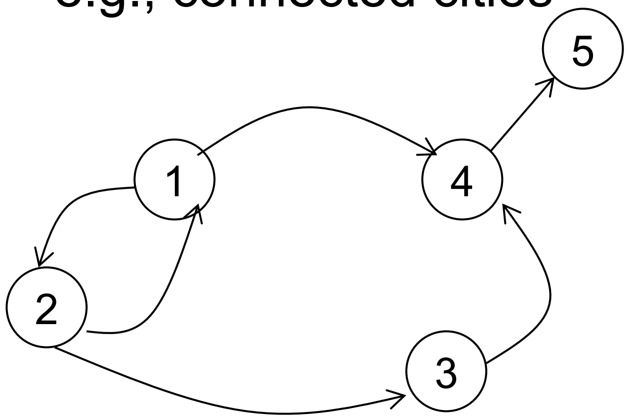
First rule

Second rule

New fact

Example

R encodes a graph
e.g., connected cities



$$T(x,y) \text{ :- } R(x,y).$$
$$T(x,y) \text{ :- } R(x,z),\ T(z,y).$$

What does it compute?

R=

1	2
2	1
2	3
1	4
3	4
4	5

Initially:
T is empty.

First iteration:
T =

1	2
2	1
2	3
1	4
3	4
4	5

Second iteration:
T =

1	2
2	1
2	3
1	4
3	4
4	5
1	1
2	2
1	3
2	4
1	5
3	5

Third iteration:
T =

1	2
2	1
2	3
1	4
3	4
4	5
1	1
2	2
1	3
2	4
1	5
3	5
2	5

Fourth iteration
T =
(same)

No new facts.
DONE

Datalog Semantics

Fixpoint semantics

- Start:

  IDB_0 = empty relations

  $t = 0$

  Repeat:

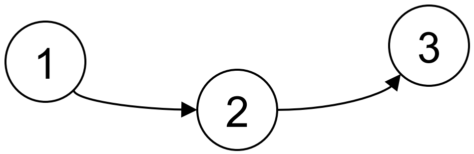
  IDB_{t+1} = Compute Rules(EDB, IDB_t)

  $t = t+1$

  Until $IDB_t = IDB_{t-1}$

- Remark: since rules are monotone:
  $\emptyset = IDB_0 \subseteq IDB_1 \subseteq IDB_2 \subseteq \ldots$
- It follows that a datalog program w/o functions (+, *, ...) always terminates. (Why?)

Model of Datalog Program

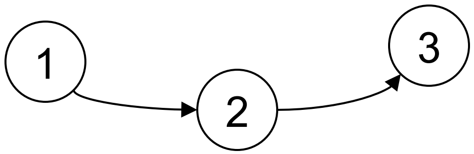



```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

R=

1	2
2	3

Model of Datalog Program



R=

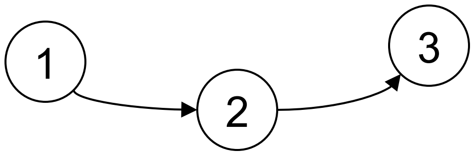
1	2
2	3

```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

A relation instance T is called a *model* if it satisfies these logical formulas:

$$\forall x\ \forall y\ (R(x,y) \rightarrow T(x,y))$$
$$\forall x\ \forall y\ \forall z\ (R(x,z) \wedge T(z,y) \rightarrow T(x,y)$$

Model of Datalog Program



R=

1	2
2	3

T(x,y) :- R(x,y).

T(x,y) :- R(x,z), T(z,y).

A relation instance T is called a *model* if it satisfies these logical formulas:

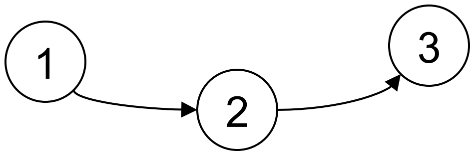
$\forall x\ \forall y\ (R(x,y) \rightarrow T(x,y))$

$\forall x\ \forall y\ \forall z\ (R(x,z) \wedge T(z,y) \rightarrow T(x,y)$

Equivalent to:

$\forall x\ \forall y\ (\exists z\ R(x,z) \wedge T(z,y) \rightarrow T(x,y)$

Model of Datalog Program



R=

1	2
2	3

```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

A relation instance T is called a *model* if it satisfies these logical formulas:

$$\forall x\ \forall y\ (R(x,y) \rightarrow T(x,y))$$

$$\forall x\ \forall y\ \forall z\ (R(x,z) \wedge T(z,y) \rightarrow T(x,y)$$

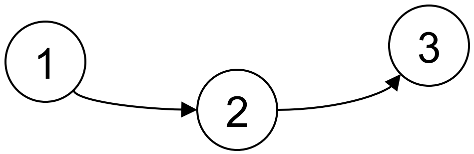
Equivalent to:
$\forall x\ \forall y\ (\exists z\ R(x,z) \wedge T(z,y) \rightarrow T(x,y)$

Which tables T are models?

T=

1	2
2	3

Model of Datalog Program



R=

1	2
2	3

T(x,y) :- R(x,y).

T(x,y) :- R(x,z), T(z,y).

A relation instance T is called a *model* if it satisfies these logical formulas:

$\forall x\ \forall y\ (R(x,y) \rightarrow T(x,y))$

$\forall x\ \forall y\ \forall z\ (R(x,z) \wedge T(z,y) \rightarrow T(x,y)$

Equivalent to:

$\forall x\ \forall y\ (\exists z\ R(x,z) \wedge T(z,y) \rightarrow T(x,y)$

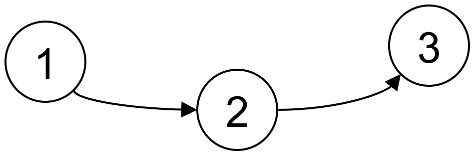
Which tables T are models?

T=

1	2
2	3

No

Model of Datalog Program



R=

1	2
2	3

```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

A relation instance T is called a *model* if it satisfies these logical formulas:

$$\forall x\ \forall y\ (R(x,y) \rightarrow T(x,y))$$
$$\forall x\ \forall y\ \forall z\ (R(x,z) \land T(z,y) \rightarrow T(x,y)$$

Equivalent to:
$\forall x\ \forall y\ (\exists z\ R(x,z) \land T(z,y) \rightarrow T(x,y)$

Which tables T are models?

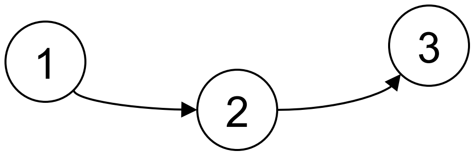
T=

1	2
2	3

1	2
2	3
1	3

No

Model of Datalog Program



R=

1	2
2	3

```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

A relation instance T is called a *model* if it satisfies these logical formulas:

$$\forall x\ \forall y\ (R(x,y) \rightarrow T(x,y))$$
$$\forall x\ \forall y\ \forall z\ (R(x,z) \wedge T(z,y) \rightarrow T(x,y)$$

Equivalent to:
$\forall x\ \forall y\ (\exists z\ R(x,z) \wedge T(z,y) \rightarrow T(x,y)$

Which tables T are models?

T=

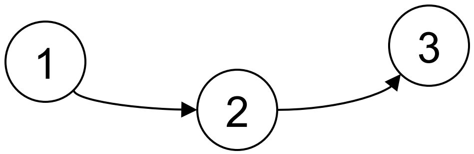
1	2
2	3

No

1	2
2	3
1	3

Yes

Model of Datalog Program



R=

1	2
2	3

```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

A relation instance T is called a *model* if it satisfies these logical formulas:

$$\forall x\ \forall y\ (R(x,y) \rightarrow T(x,y))$$
$$\forall x\ \forall y\ \forall z\ (R(x,z) \wedge T(z,y) \rightarrow T(x,y)$$

Equivalent to:
$\forall x\ \forall y\ (\exists z\ R(x,z) \wedge T(z,y) \rightarrow T(x,y)$

Which tables T are models?

T=

1	2
2	3

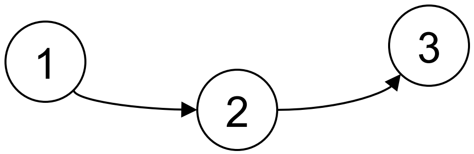
No

1	2
2	3
1	3

Yes

1	2
2	3
1	3
3	1

Model of Datalog Program




```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

A relation instance T is called a *model* if it satisfies these logical formulas:

R=

1	2
2	3

$$\forall x\ \forall y\ (R(x,y) \rightarrow T(x,y))$$
$$\forall x\ \forall y\ \forall z\ (R(x,z) \land T(z,y) \rightarrow T(x,y)$$

Equivalent to:
$\forall x\ \forall y\ (\exists z\ R(x,z) \land T(z,y) \rightarrow T(x,y)$

Which tables T are models?

T=

1	2
2	3

No

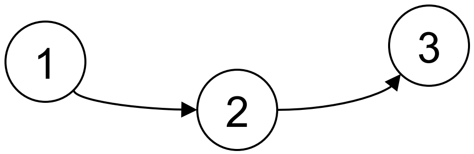
1	2
2	3
1	3

Yes

1	2
2	3
1	3
3	1

No

Model of Datalog Program



R=

1	2
2	3

```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

A relation instance T is called a *model* if it satisfies these logical formulas:

$$\forall x\ \forall y\ (R(x,y) \rightarrow T(x,y))$$

$$\forall x\ \forall y\ \forall z\ (R(x,z) \wedge T(z,y) \rightarrow T(x,y)$$

Equivalent to:

$$\forall x\ \forall y\ (\exists z\ R(x,z) \wedge T(z,y) \rightarrow T(x,y)$$

Which tables T are models?

T=

1	2
2	3

No

1	2
2	3
1	3

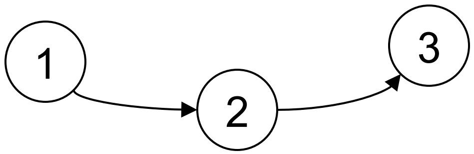
Yes

1	2
2	3
1	3
3	1

No

1	1
1	2
1	3
2	1
2	2
2	3
3	1
3	2
3	3

Model of Datalog Program



R=

1	2
2	3

```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

A relation instance T is called a <u>*model*</u> if it satisfies these logical formulas:

$$\forall x\ \forall y\ (R(x,y) \rightarrow T(x,y))$$
$$\forall x\ \forall y\ \forall z\ (R(x,z) \wedge T(z,y) \rightarrow T(x,y)$$

Equivalent to:
$\forall x\ \forall y\ (\exists z\ R(x,z) \wedge T(z,y) \rightarrow T(x,y)$

Which tables T are models?

T=

1	2
2	3

No

1	2
2	3
1	3

Yes

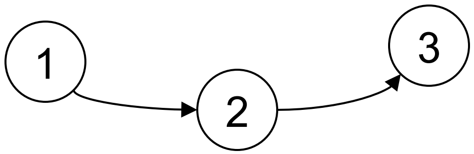
1	2
2	3
1	3
3	1

No

1	1
1	2
1	3
2	1
2	2
2	3
3	1
3	2
3	3

Yes

Model of Datalog Program



R=

1	2
2	3

```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

A relation instance T is called a *model* if it satisfies these logical formulas:

$$\forall x\ \forall y\ (R(x,y) \rightarrow T(x,y))$$
$$\forall x\ \forall y\ \forall z\ (R(x,z) \wedge T(z,y) \rightarrow T(x,y)$$

Equivalent to:
$\forall x\ \forall y\ (\exists z\ R(x,z) \wedge T(z,y) \rightarrow T(x,y)$

Which tables T are models?

T=

1	2
2	3

No

1	2
2	3
1	3

Yes

1	2
2	3
1	3
3	1

No

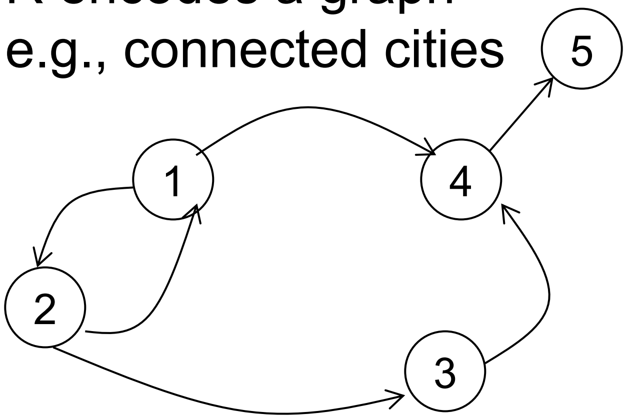
1	1
1	2
1	3
2	1
2	2
2	3
3	1
3	2
3	3

Yes

Notice: the datalog program always computes the *minimal model*

Three Equivalent Programs

R encodes a graph
e.g., connected cities



R=

1	2
2	1
2	3
1	4
3	4
4	5

T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).

Right linear

T(x,y) :- R(x,y).
T(x,y) :- T(x,z), R(z,y).

Left linear

T(x,y) :- R(x,y).
T(x,y) :- T(x,z), T(z,y).

Non-linear

Question: which terminates in fewest iterations?

More Features

- Aggregates
- Grouping
- Negation

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Aggregates

[aggregate name] <var> : { [relation to compute aggregate on] }

```
min x : { Actor(x, y, _), y = 'John' }
```

```
Q(minId) :- minId = min x : { Actor(x, y, _), y = 'John' }
```

Assign variable to
the value of the aggregate

Meaning (in SQL)

```
SELECT min(id) as minId
FROM Actor as a
WHERE a.name = 'John'
```

Aggregates in Souffle:

- `count`
- `min`
- `max`
- `sum`

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Counting

```
Q(c) :- c = count : { Actor(_, y, _), y = 'John' }
```

No variable here!

Meaning (in SQL, assuming no NULLs)

```
SELECT count(*) as c
FROM Actor as a
WHERE a.name = 'John'
```

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

Grouping

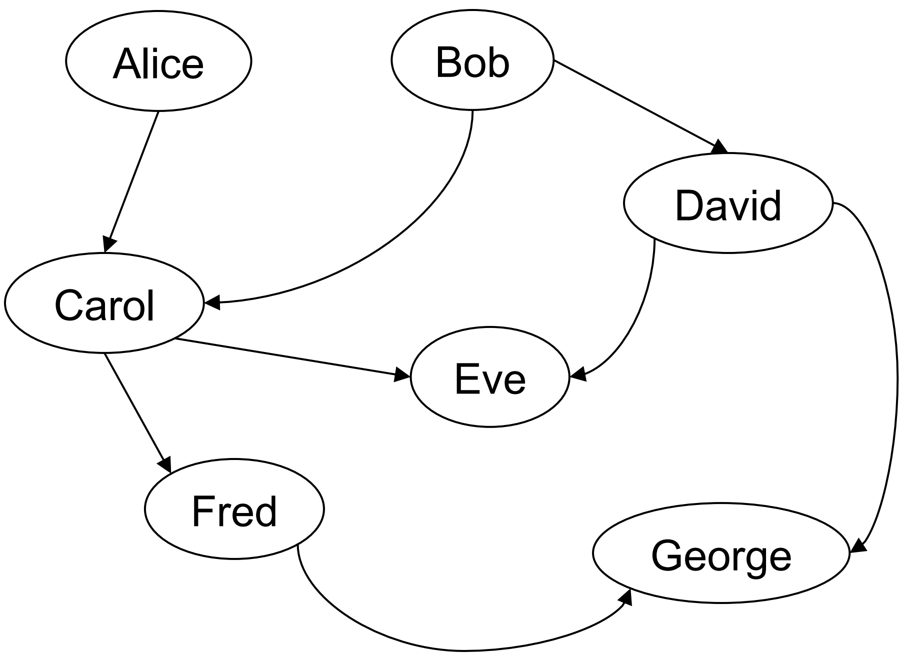
```
Q(y,c) :- Movie(_,_,y), c = count : { Movie(_,_,y) }
```

Meaning (in SQL)

```
SELECT m.year, count(*)
FROM Movie as m
GROUP BY m.year
```

Examples

A genealogy database (parent/child)



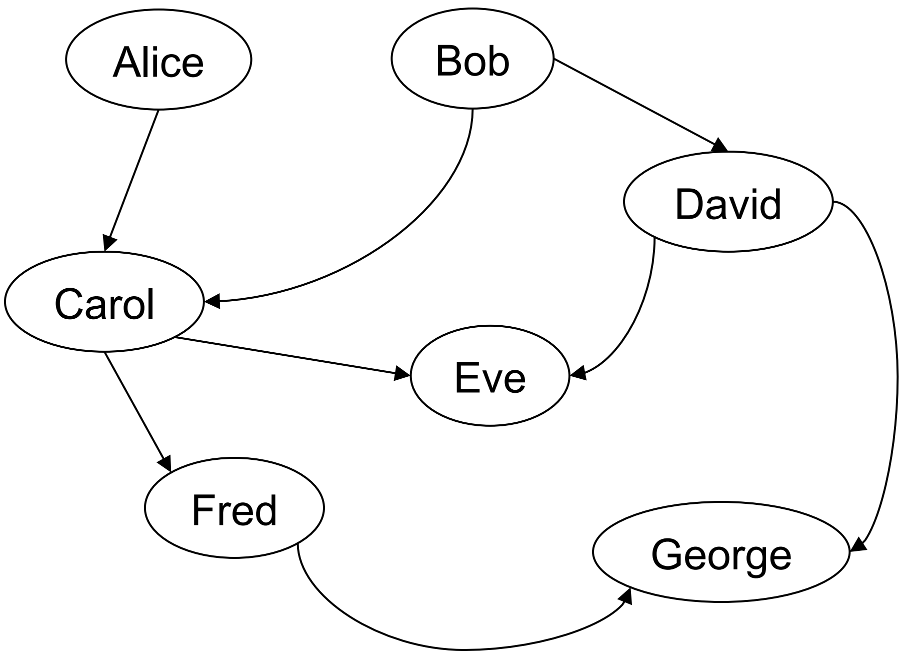
ParentChild

p	c
Alice	Carol
Bob	Carol
Bob	David
Carol	Eve
…	

ParentChild(p,c)

Count Descendants

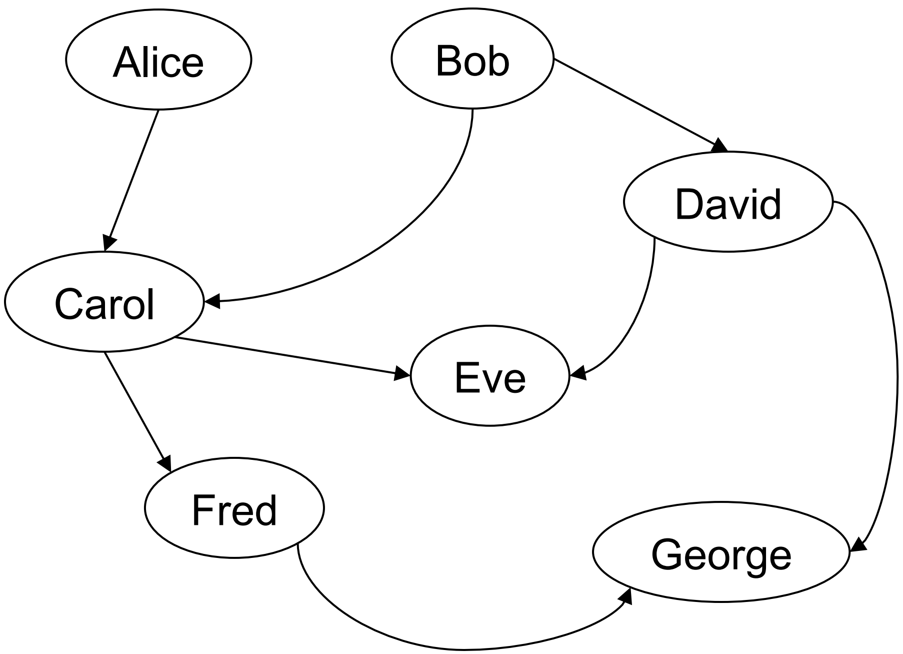
For each person, count his/her descendants



ParentChild(p,c)

Count Descendants

For each person, count his/her descendants

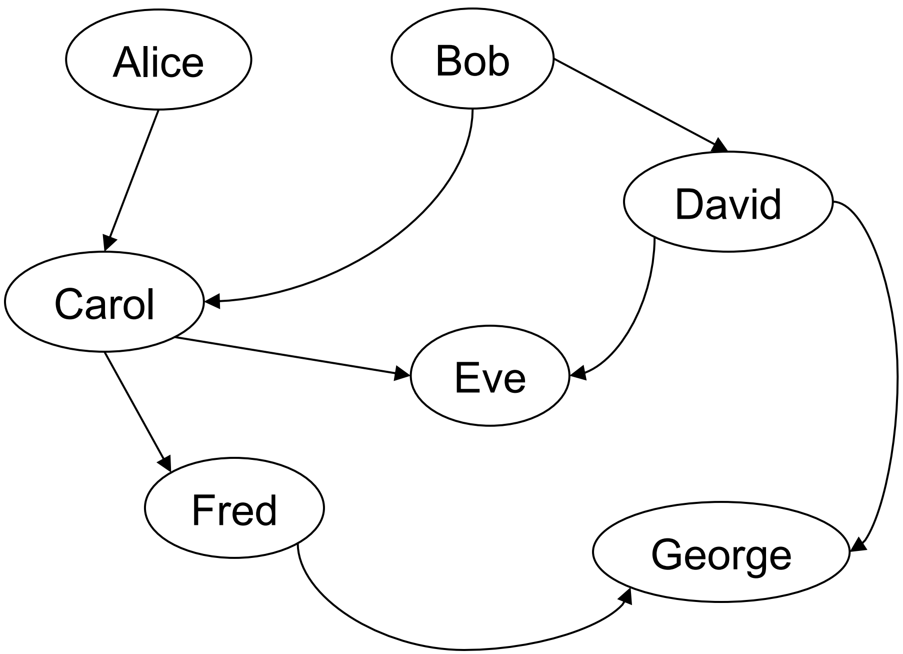


Answer

p	cnt
Alice	4
Bob	5
Carol	3
David	2
Fred	1

Count Descendants

For each person, count his/her descendants



Answer

p	cnt
Alice	4
Bob	5
Carol	3
David	2
Fred	1

Note: Eve and George do not appear in the answer (why?)

Count Descendants

For each person, compute the total number of descendants

```
// for each person, compute his/her descendants
```

Count Descendants

For each person, compute the total number of descendants

```
// for each person, compute his/her descendants
D(x,y) :- ParentChild(x,y).
```

Count Descendants

For each person, compute the total number of descendants

```
// for each person, compute his/her descendants
D(x,y) :- ParentChild(x,y).
D(x,z) :- D(x,y), ParentChild(y,z).
```

Count Descendants

For each person, compute the total number of descendants

```
// for each person, compute his/her descendants
D(x,y) :- ParentChild(x,y).
D(x,z) :- D(x,y), ParentChild(y,z).

// For each person, count the number of descendants
```

Count Descendants

For each person, compute the total number of descendants

```
// for each person, compute his/her descendants
D(x,y) :- ParentChild(x,y).
D(x,z) :- D(x,y), ParentChild(y,z).

// For each person, count the number of descendants
T(p,c) :- D(p,_), c = count : { D(p,y) }.
```

Count Descendants

How many descendants does Alice have?

```
// for each person, compute his/her descendants
D(x,y) :- ParentChild(x,y).
D(x,z) :- D(x,y), ParentChild(y,z).

// For each person, count the number of descendants
T(p,c) :- D(p,_), c = count : { D(p,y) }.
```

Count Descendants

How many descendants does Alice have?

```
// for each person, compute his/her descendants
D(x,y) :- ParentChild(x,y).
D(x,z) :- D(x,y), ParentChild(y,z).

// For each person, count the number of descendants
T(p,c) :- D(p,_), c = count : { D(p,y) }.

// Find the number of descendants of Alice
```

Count Descendants

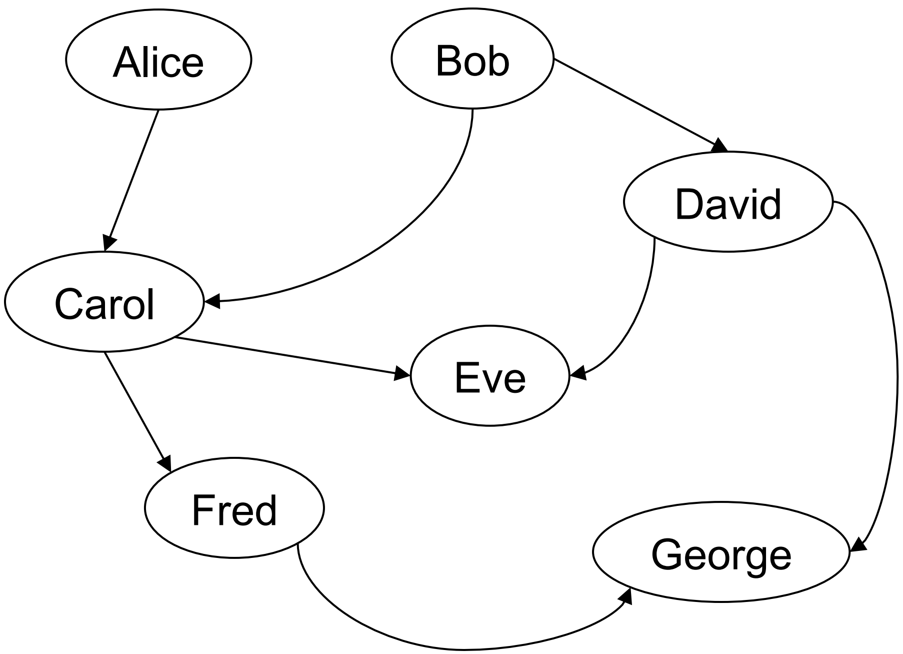
How many descendants does Alice have?

```
// for each person, compute his/her descendants
D(x,y) :- ParentChild(x,y).
D(x,z) :- D(x,y), ParentChild(y,z).

// For each person, count the number of descendants
T(p,c) :- D(p,_), c = count : { D(p,y) }.

// Find the number of descendants of Alice
Q(d) :- T(p,d), p = “Alice”.
```

ParentChild(p,c)

Negation: use "!"

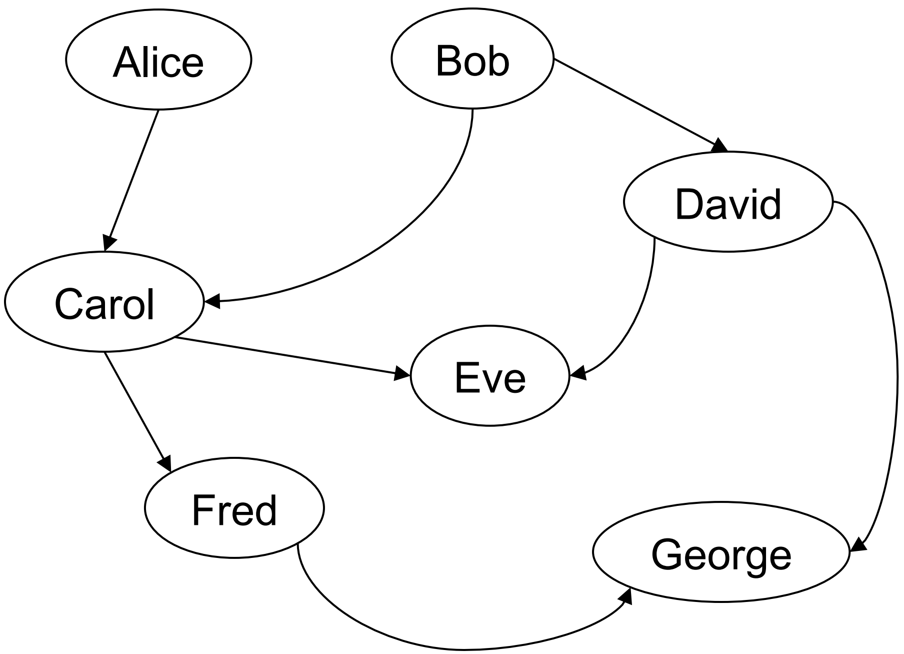
Find all descendants of Bob that are not descendants of Alice



ParentChild(p,c)

Negation: use “!”

Find all descendants of Bob that are not descendants of Alice



Answer

x
David

Negation: use "!"

Find all descendants of Bob that are not descendants of Alice

```
// for each person, compute his/her descendants
D(x,y) :- ParentChild(x,y).
D(x,z) :- D(x,y), ParentChild(y,z).
```

Negation: use “!”

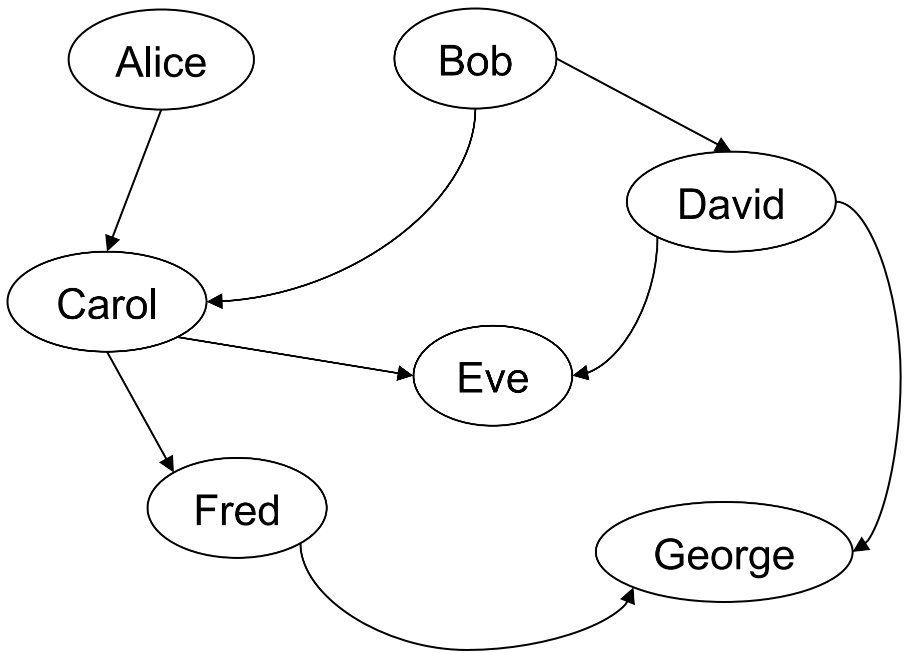
Find all descendants of Bob that are not descendants of Alice

```
// for each person, compute his/her descendants
D(x,y) :- ParentChild(x,y).
D(x,z) :- D(x,y), ParentChild(y,z).

// Compute the answer: notice the negation
Q(x) :- D(“Bob”,x), !D(“Alice”,x).
```

ParentChild(p,c)

Same Generation

Two people are in the *same generation* if they are descendants at the same generation of some common ancestor



SG

p1	p2
Carol	David
Eve	George
Fred	George
Fred	Eve

ParentChild(p,c)

Same Generation

Compute pairs of people at the same generation

```
// common parent
```

Same Generation

Compute pairs of people at the same generation

```
// common parent
SG(x,y) :- ParentChild(p,x), ParentChild(p,y)
```

ParentChild(p,c)

Same Generation

Compute pairs of people at the same generation

```
// common parent
SG(x,y) :- ParentChild(p,x), ParentChild(p,y)

// parents at the same generation
```

Same Generation

Compute pairs of people at the same generation

```
// common parent
SG(x,y) :- ParentChild(p,x), ParentChild(p,y)

// parents at the same generation
SG(x,y) :- ParentChild(p,x), ParentChild(q,y), SG(p,q)
```

Same Generation

Compute pairs of people at the same generation

```
// common parent
SG(x,y) :- ParentChild(p,x), ParentChild(p,y)

// parents at the same generation
SG(x,y) :- ParentChild(p,x), ParentChild(q,y), SG(p,q)
```

Problem: this includes answers like SG(Carol, Carol)

And also SG(Eve, George), SG(George, Eve)

How to fix?

ParentChild(p,c)

Same Generation

Compute pairs of people at the same generation

```
// common parent
SG(x,y) :- ParentChild(p,x), ParentChild(p,y), x < y

// parents at the same generation
SG(x,y) :- ParentChild(p,x), ParentChild(q,y),
          SG(p,q),  x < y
```

Safe Datalog Rules

Here are *unsafe* datalog rules. What's "unsafe" about them ?

```
U1(x,y) :- ParentChild("Alice",x), y != "Bob"
```

```
U2(x) :- ParentChild("Alice",x), !ParentChild(x,y)
```

```
U3(minId, y) :- minId = min x : { Actor(x, y, _) }
```

ParentChild(p,c)

Safe Datalog Rules

Holds for
every y other than "Bob"
U1 = infinite!

Here are *unsafe* datalog rules. What's "unsafe" about them ?

```
U1(x,y) :- ParentChild("Alice",x), y != "Bob"
```

```
U2(x) :- ParentChild("Alice",x), !ParentChild(x,y)
```

```
U3(minId, y) :- minId = min x : { Actor(x, y, _) }
```

ParentChild(p,c)

Safe Datalog Rules

Holds for
every y other than "Bob"
U1 = infinite!

Here are *unsafe* datalog rules. What's "unsafe" about them ?

```
U1(x,y) :- ParentChild("Alice",x), y != "Bob"
```

```
U2(x) :- ParentChild("Alice",x), !ParentChild(x,y)
```

Want Alice's childless children,
but we get all children x (because
there exists some y that x is not parent of y)

```
U3(minId, y) :- minId = min x : { Actor(x, y, _) }
```

Safe Datalog Rules

Here are *unsafe* datalog rules. What's "unsafe" about them ?

Holds for
every y other than "Bob"
U1 = infinite!

```
U1(x,y) :- ParentChild("Alice",x), y != "Bob"
```

```
U2(x) :- ParentChild("Alice",x), !ParentChild(x,y)
```

Want Alice's childless children,
but we get all children x (because
there exists some y that x is not parent of y)

```
U3(minId, y) :- minId = min x : { Actor(x, y, _) }
```

Unclear what y is

Safe Datalog Rules

Here are *unsafe* datalog rules. What's "unsafe" about them ?

```
U1(x,y) :- ParentChild("Alice",x), y != "Bob"
```

```
U2(x) :- ParentChild("Alice",x), !ParentChild(x,y)
```

A datalog rule is *safe* if every variable appears in some positive, non-aggregated relational atom

```
U3(minId, y) :- minId = min x : { Actor(x, y, _) }
```

Stratified Datalog

- Recursion does not cope well with aggregates or negation
- Example: what does this mean?

```
A() :- !B().
B() :- !A().
```

- A datalog program is ***stratified*** if it can be partitioned into *strata*
  - Only IDB predicates defined in strata 1, 2, ..., n may appear under ! or agg in stratum n+1.

- Many Datalog DBMSs (including souffle) accepts only stratified Datalog.

Stratified Datalog

```
D(x,y) :- ParentChild(x,y).
D(x,z) :- D(x,y), ParentChild(y,z).
```

Stratum 1

```
T(p,c) :- D(p,_), c = count : { D(p,y) }.
Q(d) :- T(p,d), p = "Alice".
```

Stratum 2

May use D
in an agg since it was
defined in previous
stratum

Stratified Datalog

```
D(x,y) :- ParentChild(x,y).
D(x,z) :- D(x,y), ParentChild(y,z).
```
Stratum 1

```
T(p,c) :- D(p,_), c = count : { D(p,y) }.
Q(d) :- T(p,d), p = “Alice”.
```
Stratum 2

May use D in an agg since it was defined in previous stratum

```
D(x,y) :- ParentChild(x,y).
D(x,z) :- D(x,y), ParentChild(y,z).
```
Stratum 1

```
Q(x) :- D(“Alice”,x), !D(“Bob”,x).
```
Stratum 2

May use !D

```
A() :- !B().
B() :- !A().
```
Non-stratified

Cannot use !A

Stratified Datalog

- If we don't use aggregates or negation, then the Datalog program is already stratified
- If we do use aggregates or negation, it is usually quite natural to write the program in a stratified way