## Introduction to Database Systems
## CSE 414

Lecture 8: Datalog

## Announcements

- HW3 posted (1 week)
  - Same dataset, more challenging queries
  - We have sent out all Azure codes if you filled out the form earlier
  - Make sure you use the cheapest tier
    - aka READ THE HW INSTRUCTIONS
  - You should first run on sqlite in any case!

## 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

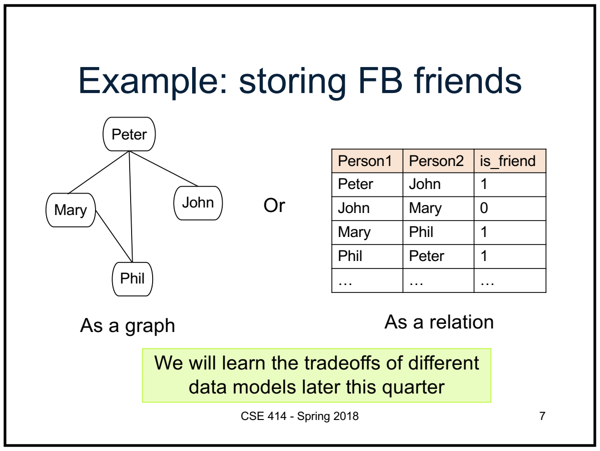
## What is Datalog?

- 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)
  - Eve http://witheve.com/
  - Differential datalog https://github.com/frankmcsherry/differential-dataflow
  - 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

Peter
Mary
John
Phil

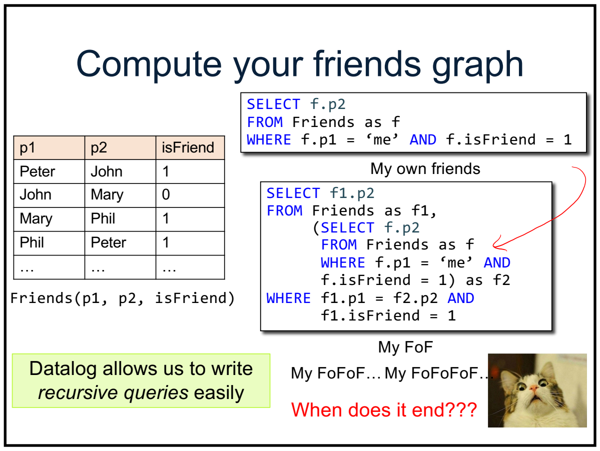
Or

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

As a graph

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

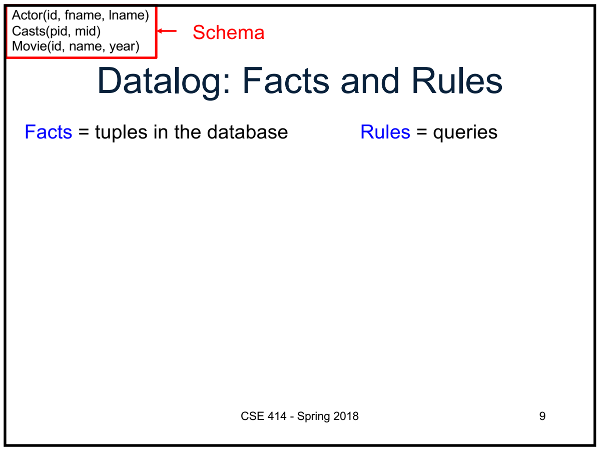
```
SELECT f1.p2
FROM Friends as f1,
     (SELECT f.p2
      FROM Friends as f
      WHERE f.p1 = ‘me’ AND
      f.isFriend = 1) as f2
WHERE f1.p1 = f2.p2 AND
      f1.isFriend = 1
```

My FoF

Datalog allows us to write *recursive queries* easily

My FoFoF… My FoFoFoF…

When does it end???



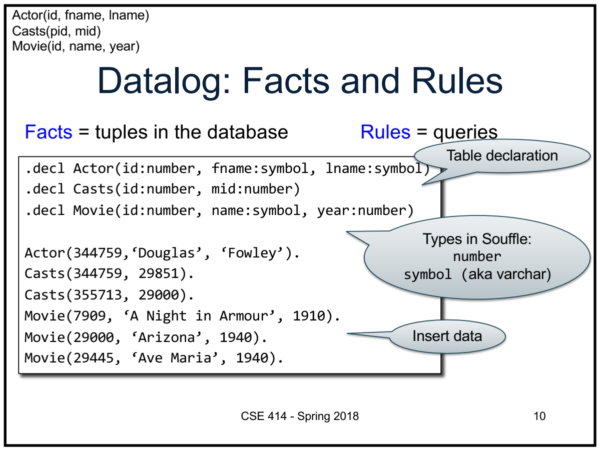
Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

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

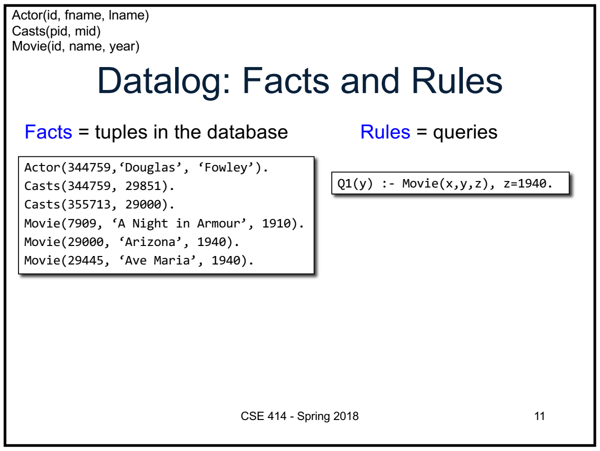
```
.decl Actor(id:number, fname:symbol, lname:symbol)
.decl Casts(id:number, mid:number)
.decl Movie(id:number, name:symbol, year:number)

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

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```
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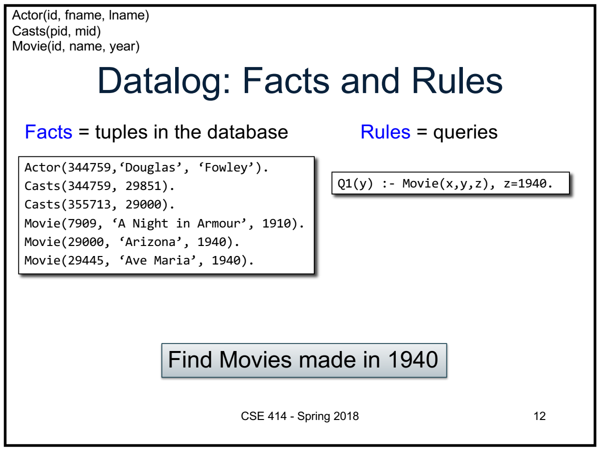
```

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



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

## Datalog: Facts and Rules

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```
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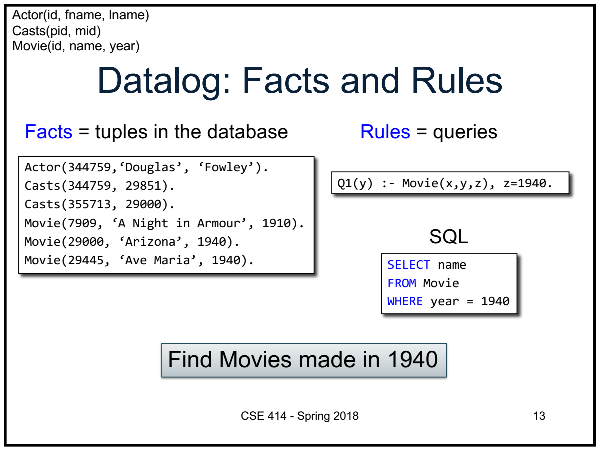
```

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

Find Movies made in 1940


Actor(id, fname, lname)
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## Datalog: Facts and Rules

Facts = tuples in the database

Rules = queries

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Movie(29000, ‘Arizona’, 1940).
Movie(29445, ‘Ave Maria’, 1940).
```

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

SQL

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

Find Movies made in 1940

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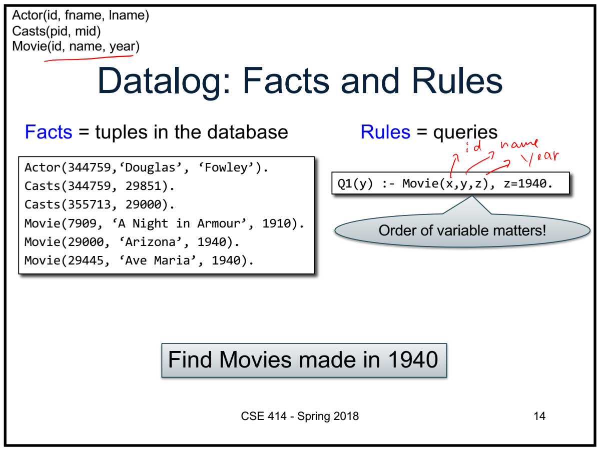
Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

## Datalog: Facts and Rules

Facts = tuples in the database

Rules = queries

```
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Movie(7909, ‘A Night in Armour’, 1910).
Movie(29000, ‘Arizona’, 1940).
Movie(29445, ‘Ave Maria’, 1940).
```

id name year

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

Order of variable matters!

Find Movies made in 1940

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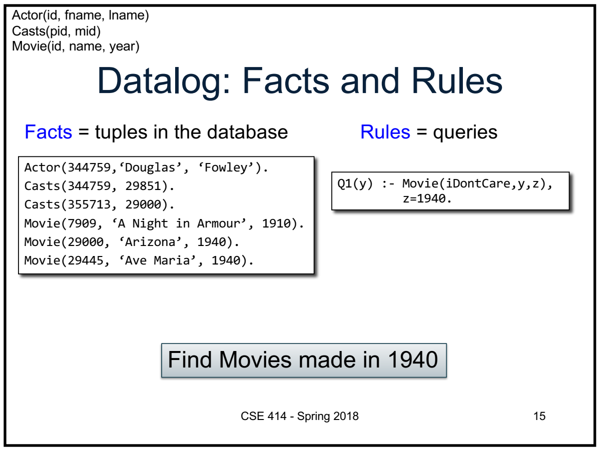
Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

## Datalog: Facts and Rules

Facts = tuples in the database

Rules = queries

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

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

Find Movies made in 1940

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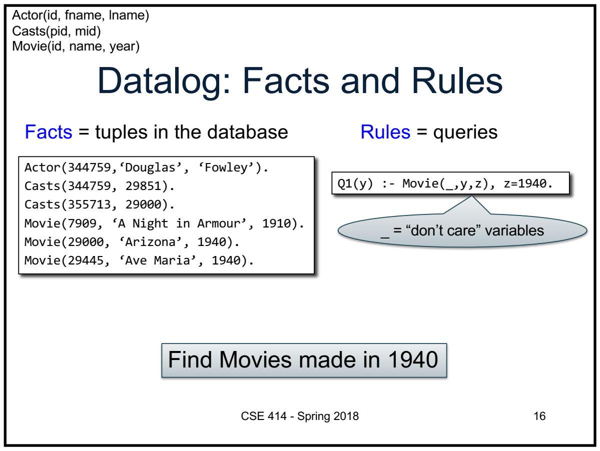
Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

## 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(_,y,z), z=1940.
```

_ = “don’t care” variables

Find Movies made in 1940

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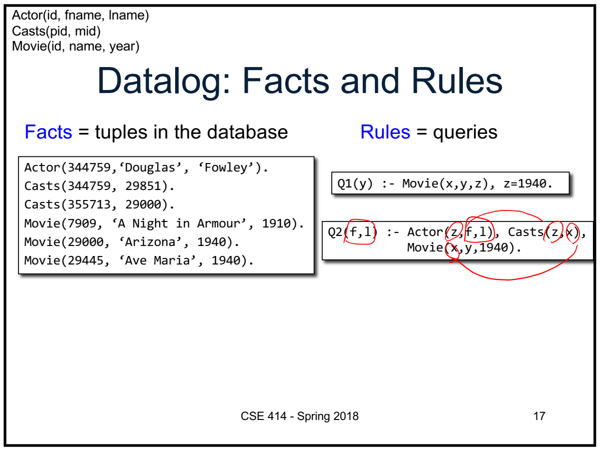
Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

## 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).
```

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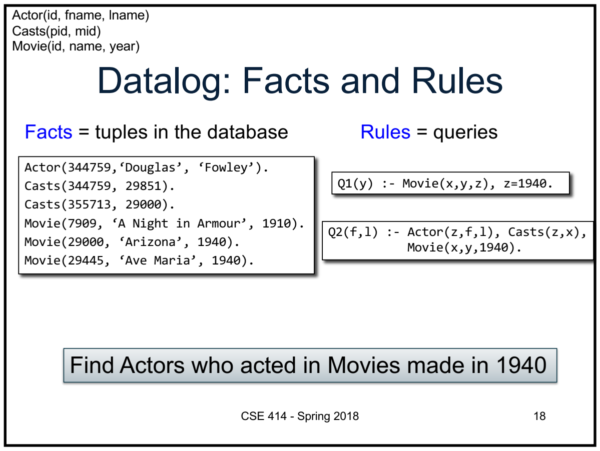
Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

## Datalog: Facts and Rules

Facts = tuples in the database

Rules = queries

```
Actor(344759,‘Douglas’, ‘Fowley’).
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```

```
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

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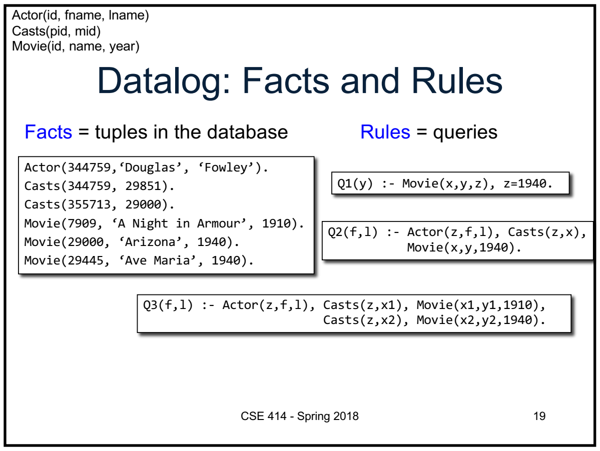

Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

## Datalog: Facts and Rules

Facts = tuples in the database

Rules = queries

```
Actor(344759,‘Douglas’, ‘Fowley’).
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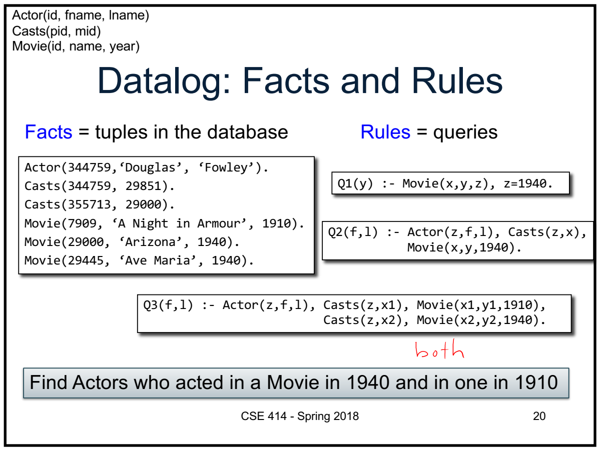
```

```
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

Rules = queries

```
Actor(344759,‘Douglas’, ‘Fowley’).
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```

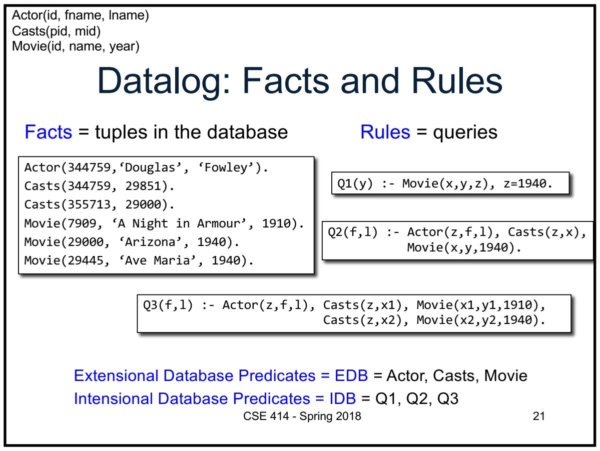
```
Q1(y) :- Movie(x,y,z), z=1940.
```

```
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).
```

both

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).
```

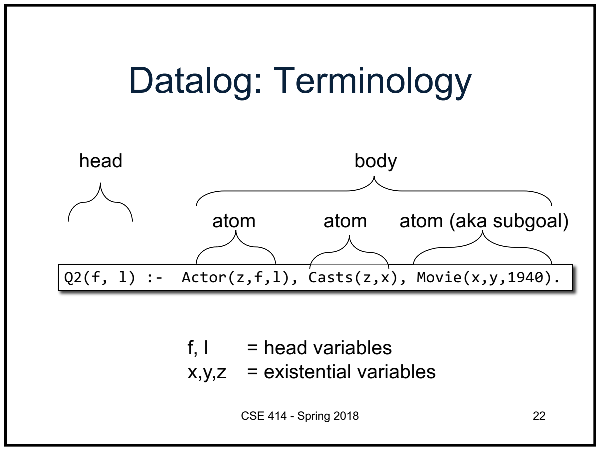
```
Q1(y) :- Movie(x,y,z), z=1940.
```

```
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

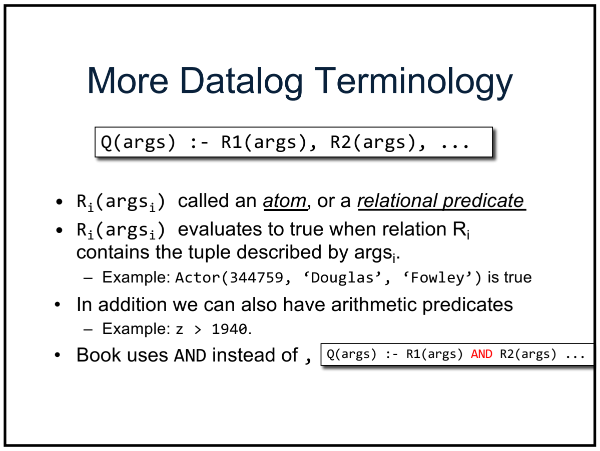
Intensional Database Predicates = IDB = Q1, Q2, Q3



## Datalog: Terminology

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

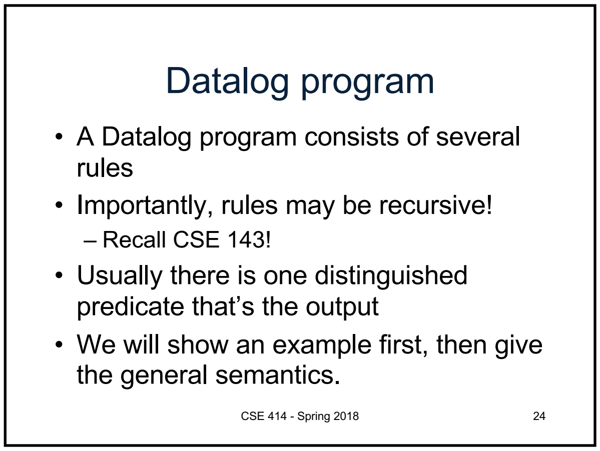
f, l = head variables
x,y,z = existential variables



## More Datalog Terminology

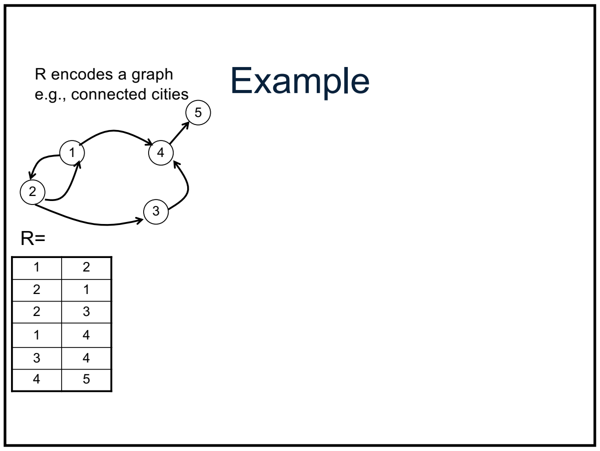
```
Q(args) :- R1(args), R2(args), ...
```

- $R_i(args_i)$ 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.

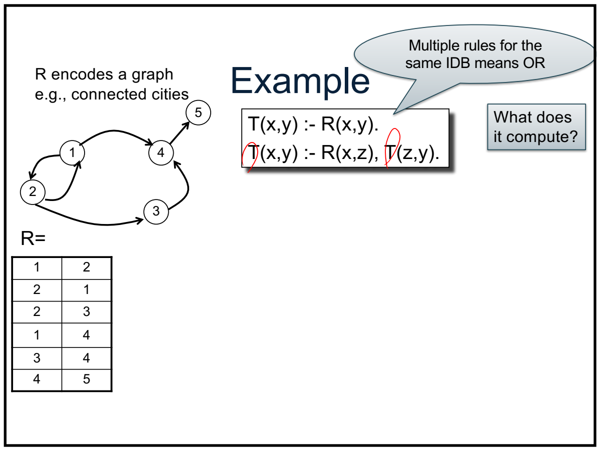


R encodes a graph
e.g., connected cities

# Example

R=

|   |   |
|---|---|
| 1 | 2 |
| 2 | 1 |
| 2 | 3 |
| 1 | 4 |
| 3 | 4 |
| 4 | 5 |



R encodes a graph
e.g., connected cities

# Example

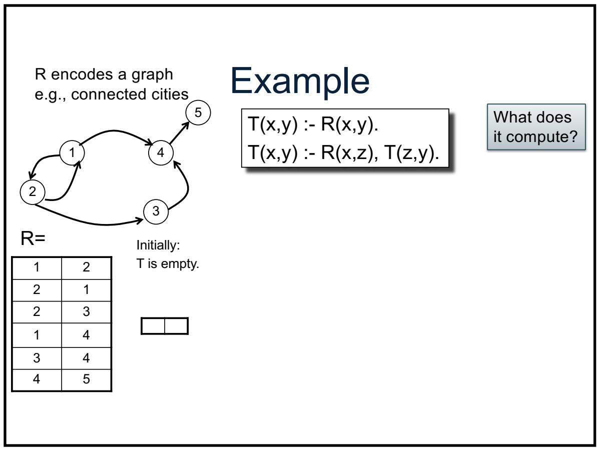
Multiple rules for the same IDB means OR

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 |



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

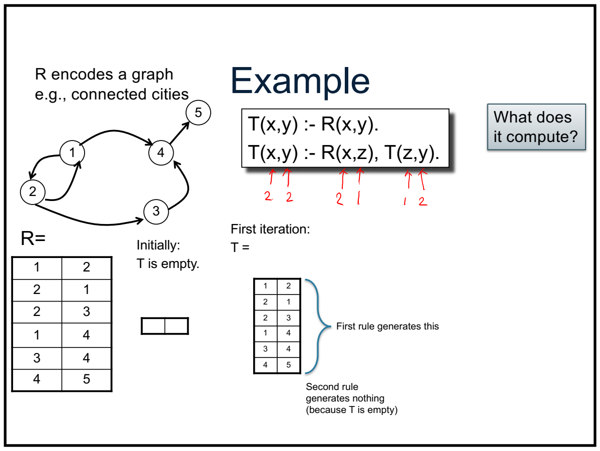
What does it compute?

R=

|   |   |
|---|---|
| 1 | 2 |
| 2 | 1 |
| 2 | 3 |
| 1 | 4 |
| 3 | 4 |
| 4 | 5 |

Initially:
T is empty.

|   |   |
|---|---|



R encodes a graph
e.g., connected cities

# Example

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

2 2 2 1 1 2

What does it compute?

R=

|   |   |
|---|---|
| 1 | 2 |
| 2 | 1 |
| 2 | 3 |
| 1 | 4 |
| 3 | 4 |
| 4 | 5 |

Initially:
T is empty.

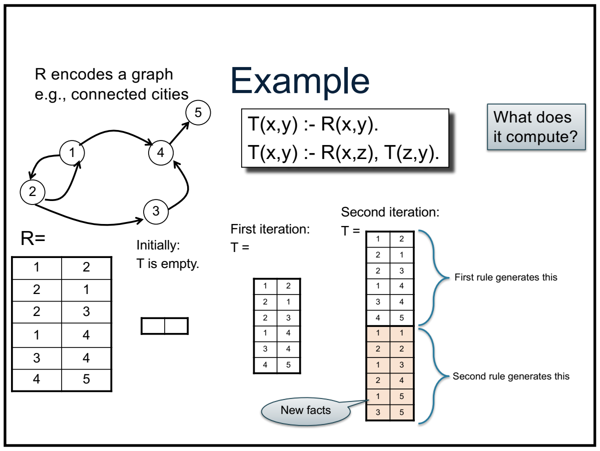
|   |   |
|---|---|

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)



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 |

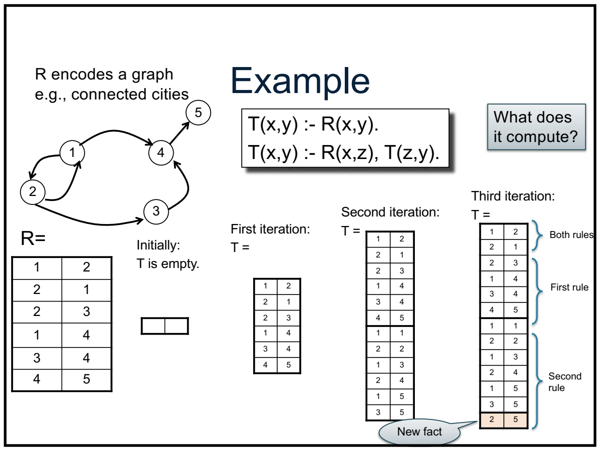
Second iteration:
T =

|   |   |
|---|---|
| 1 | 2 |
| 2 | 1 |
| 2 | 3 |
| 1 | 4 |
| 3 | 4 |
| 4 | 5 |
| 1 | 1 |
| 2 | 2 |
| 1 | 3 |
| 2 | 4 |
| 1 | 5 |
| 3 | 5 |

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 |

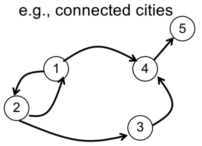
Both rules

First rule

Second rule

New fact

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 |

Fourth iteration
T =
(same)

No new facts.
DONE

# Datalog Semantics

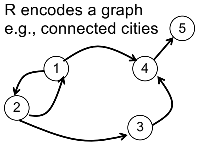
Fixpoint semantics

- 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?)

# 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)

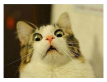
# Aggregates

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

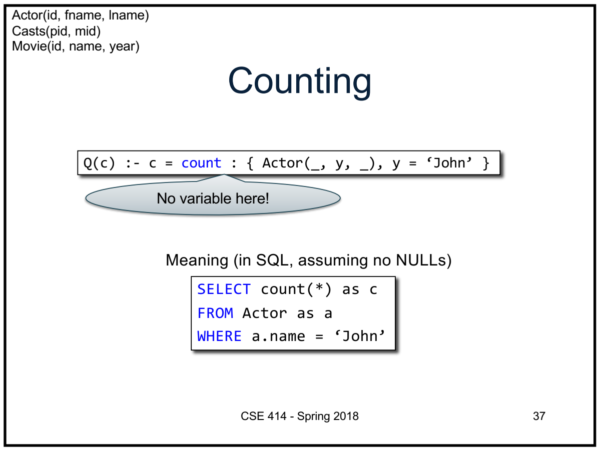
```
min x : { Actor(x, y, _), y = ‘John’ }
```

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

What does this even mean???



Can’t use variable that are not aggregated in the outer /head atoms



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

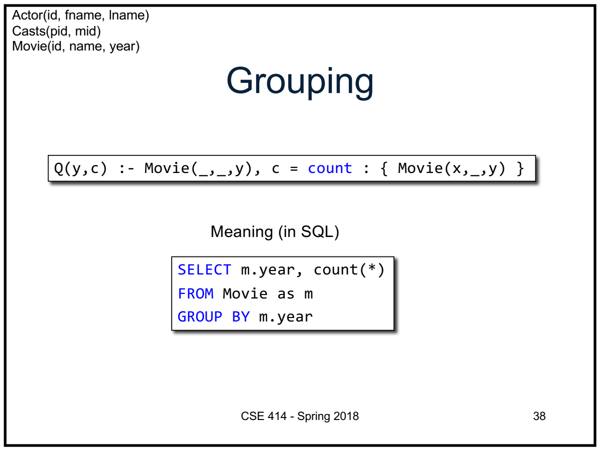
## Counting

```
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'
```



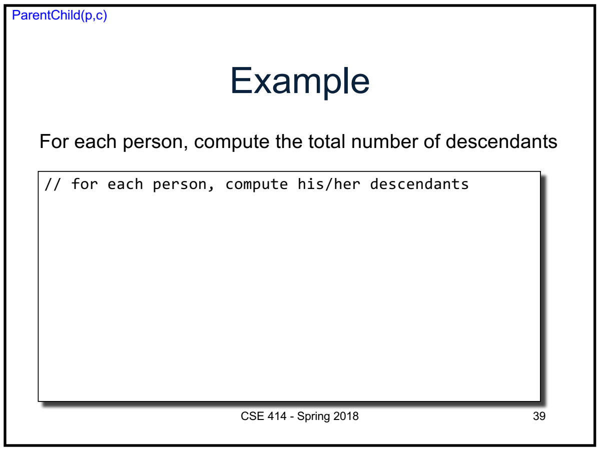
Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

## Grouping

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

Meaning (in SQL)

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

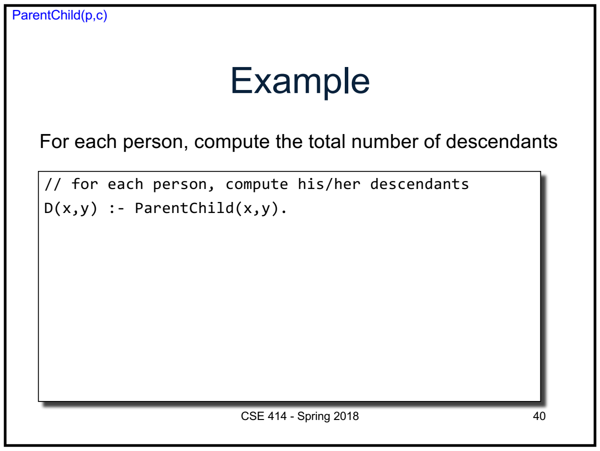


ParentChild(p,c)

## Example

For each person, compute the total number of descendants

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

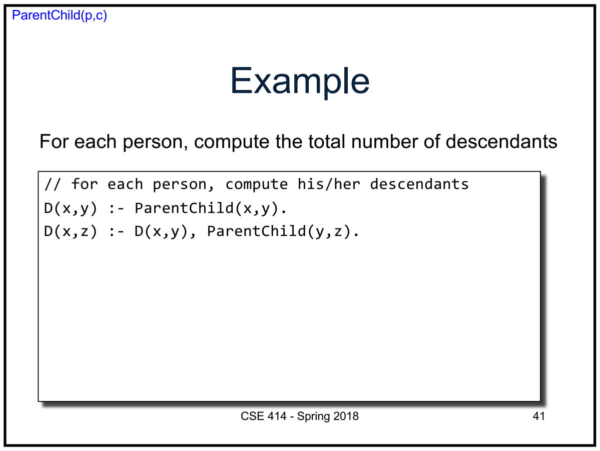


ParentChild(p,c)

## Example

For each person, compute the total number of descendants

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

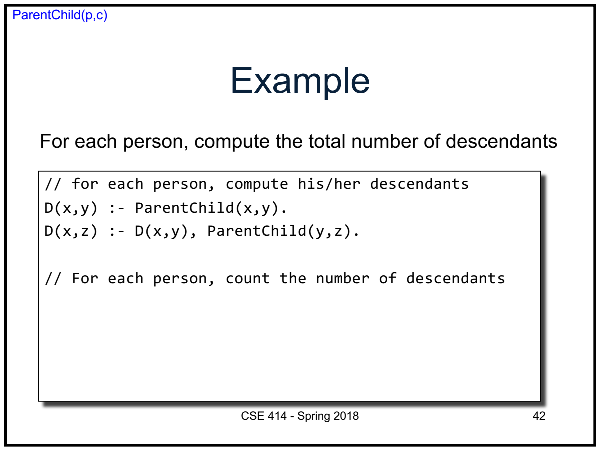


ParentChild(p,c)

## Example

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).
```



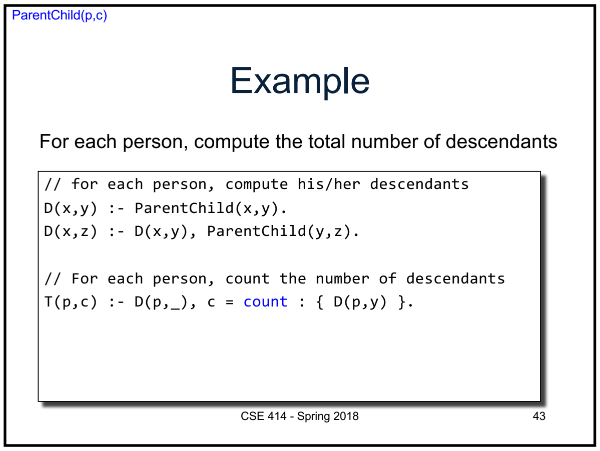
ParentChild(p,c)

## Example

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
```



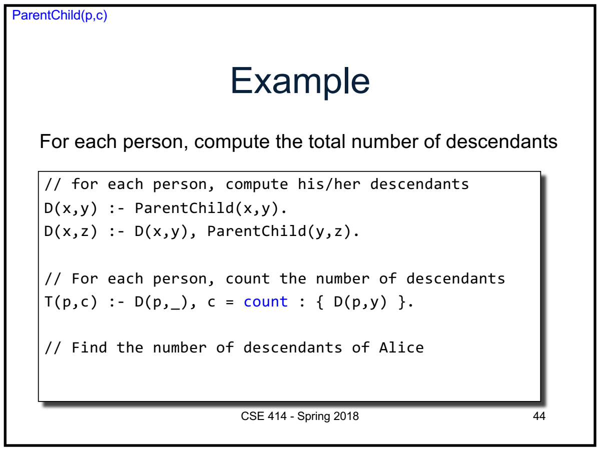
ParentChild(p,c)

## Example

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) }.
```



ParentChild(p,c)

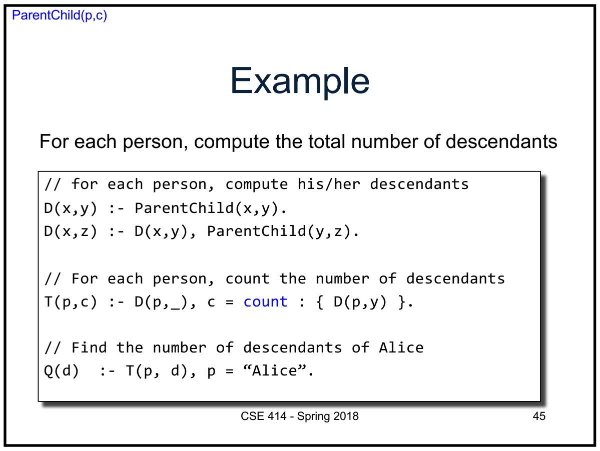
## Example

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) }.

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



ParentChild(p,c)

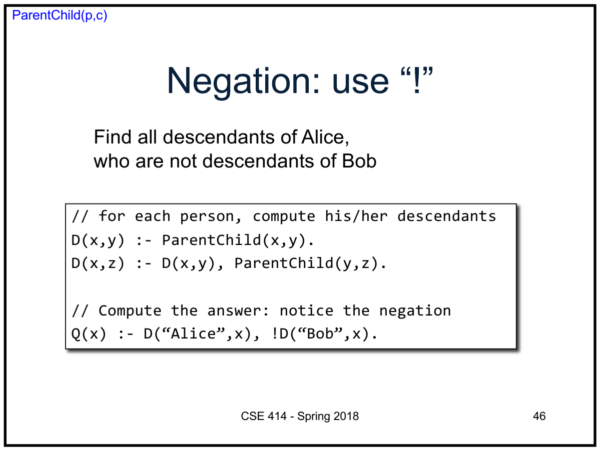
## Example

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) }.

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



ParentChild(p,c)

## Negation: use “!”

Find all descendants of Alice,
who are not descendants of Bob

```
// 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(“Alice”,x), !D(“Bob”,x).
```