# Introduction to Database Systems
# CSE 414

## Lecture 9: Datalog

# Class Overview

- Unit 1: Intro
- Unit 2: Relational Data Models and Query Languages
  - Data models, SQL, Relational Algebra, 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

acts on relational algebra tables (first normal form)

# 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

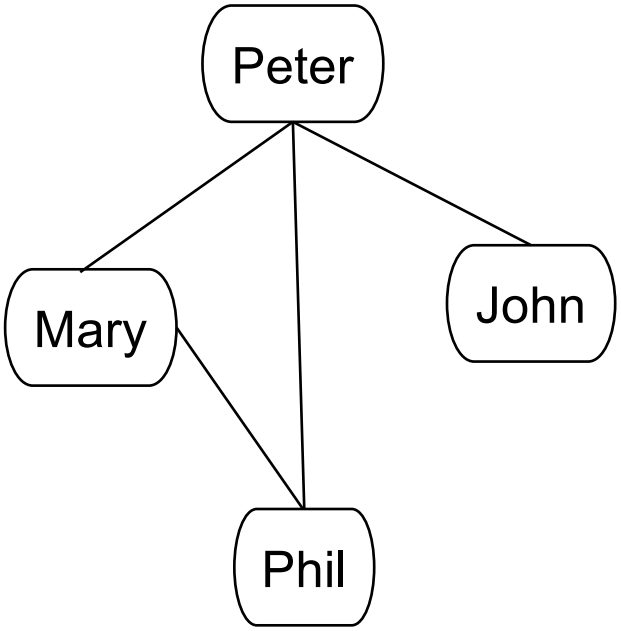

- Open-source implementation of Datalog DBMS
- Under active development
- Commercial implementations are available
  - More difficult to set up and use
- "sqlite" of Datalog
  - Set-based rather than bag-based

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

# Why bother with *yet* another relational query language?

particularly well suited for work on data networks (graphs)

# 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)`

my friends

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

My own friends

my friends of 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…

recursion would be ideal…

Datalog allows us to write *recursive queries* easily

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

# Datalog: Facts and Rules

Facts = tuples in the database

Rules = queries

schema : still relational model

```
.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

what do we want to be true of the output of our query

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

generates a new relation following the relational algebra functions we discussed earlier

y is the information we want returned as part of this new relation

essentially, when we define this rule we are defining all the tuples we want inserted into our new schema, NOT redefining Q1

So
Q1 :- conditions
Q1 :- other conditions

the results of the first rule would NOT be overwritten after the second rule, but rather this performs a union of the tuples found in each rules separately.
Thus, when we perform this recursively, all our old tuples stick around!

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

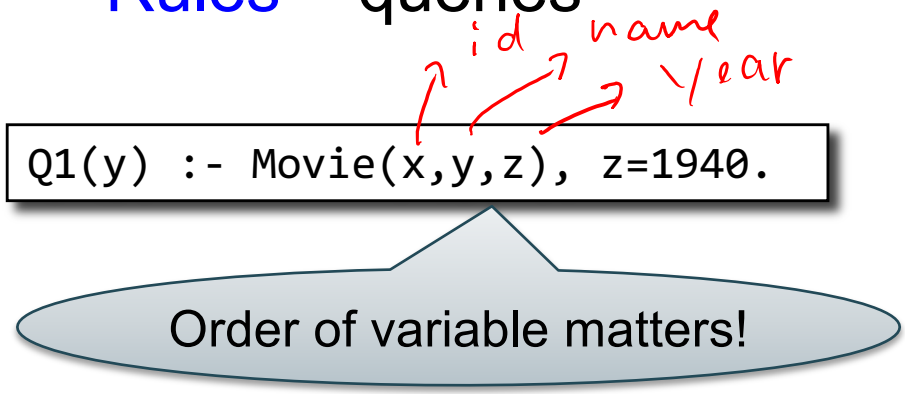
Actor(id, fname, lname)
Casts(pid, mid)
Movie(id, name, year)

# 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




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).
```

joining tables together: reuse the same variable name for variables that are connected to each other.

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).
```

i.e. checks for movie tuples that have 1940 in their third attribute

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

```
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.
```

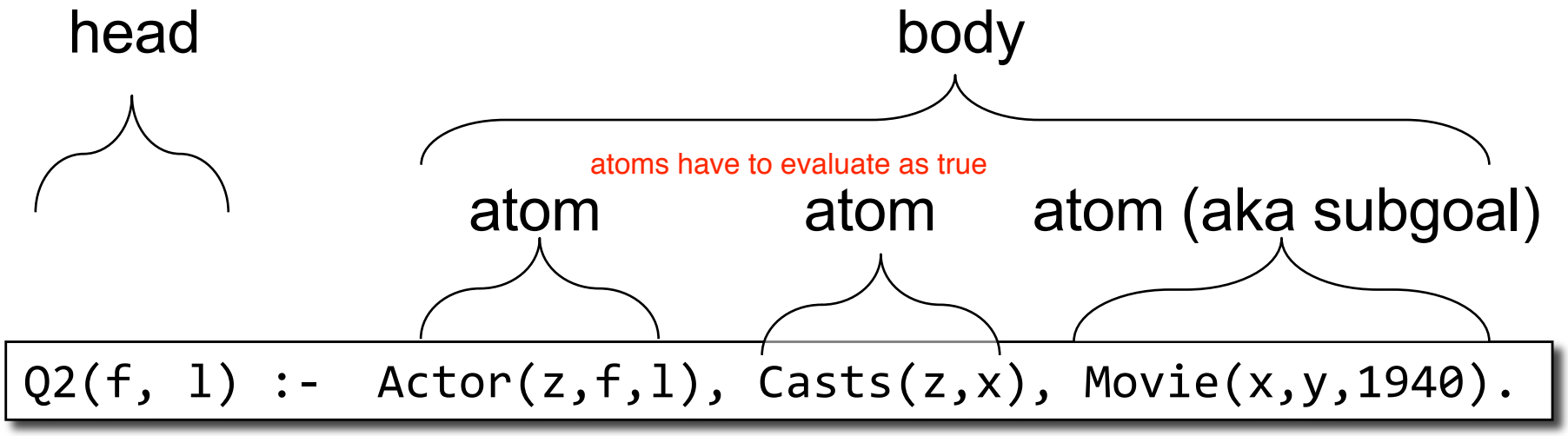
```
Q2(f,l) :- Actor(z,f,l), Casts(z,x),
           Movie(x,y,1940).
```

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

Extensional Database Predicates = EDB = Actor, Casts, Movie

Intensional Database Predicates = IDB = Q1, Q2, Q3

# Datalog: Terminology




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 ,

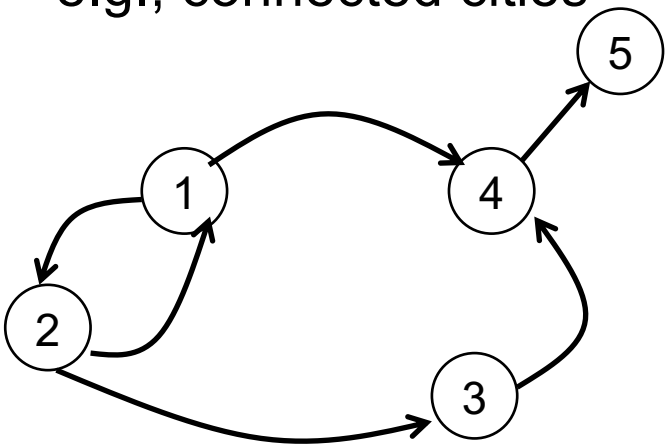
```
Q(args) :- R1(args) AND R2(args) ...
```

# 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

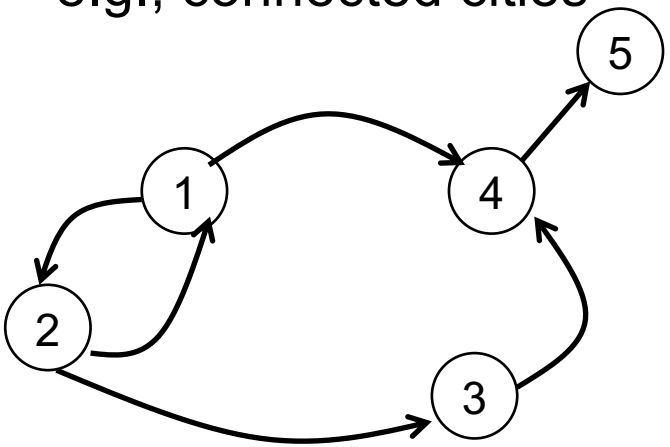



R=

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

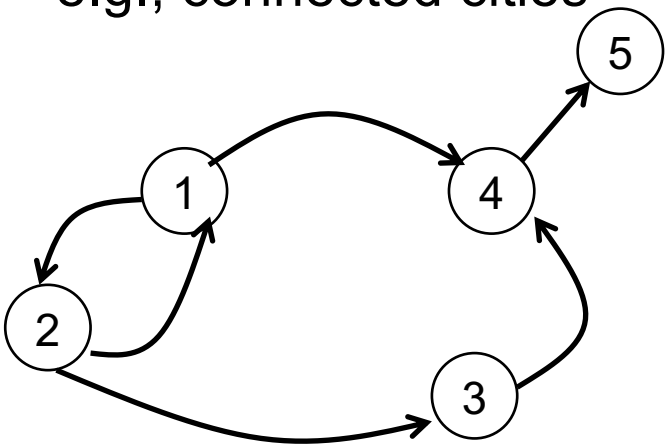
```
T(x,y) :- R(x,y).
T(x,y) :- R(x,z), T(z,y).
```

Multiple rules for the same IDB means OR

What does it compute?

# Example

R encodes a graph
e.g., connected cities




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

What does it compute?

iteratively goes through this query until T stops changing
—> fixed point semantics

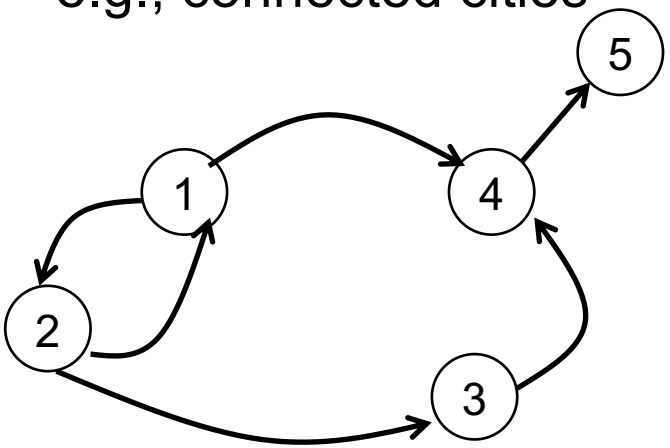
R=

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




R=

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

Initially:
T is empty.

```
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?

First iteration:
T =

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

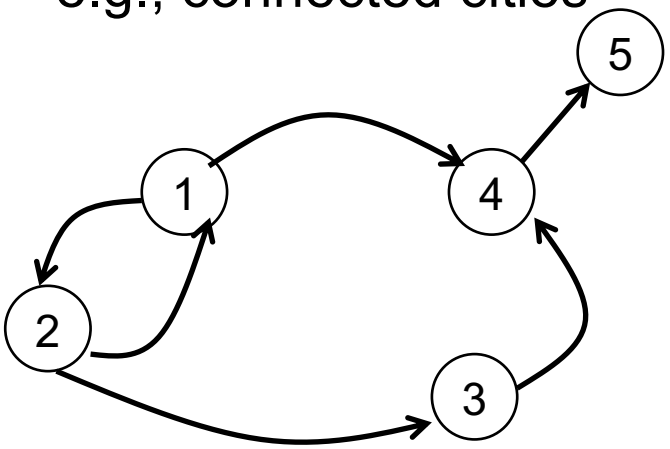
gives tuples representing paths of length 1

First rule generates this

Second rule
generates nothing
(because T is empty)

# Example

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.

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

What does it compute?

gives tuples representing start/stop nodes for paths of length 1 or length 2

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 |

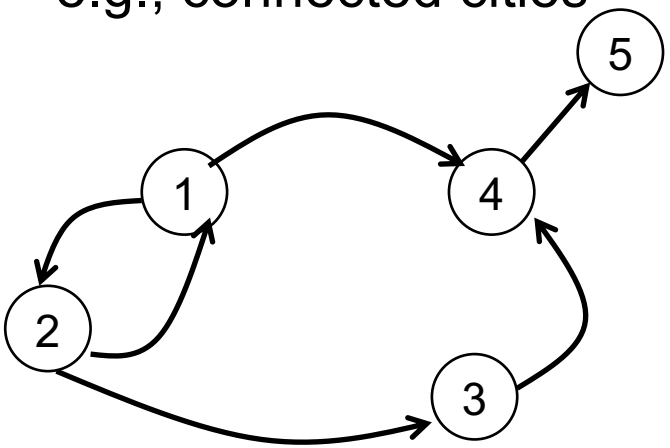
First rule generates this

Second rule generates this

New facts

# Example

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.

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

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

What does it compute?

Finds all the possible nodes that each node can reach via some directed path

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

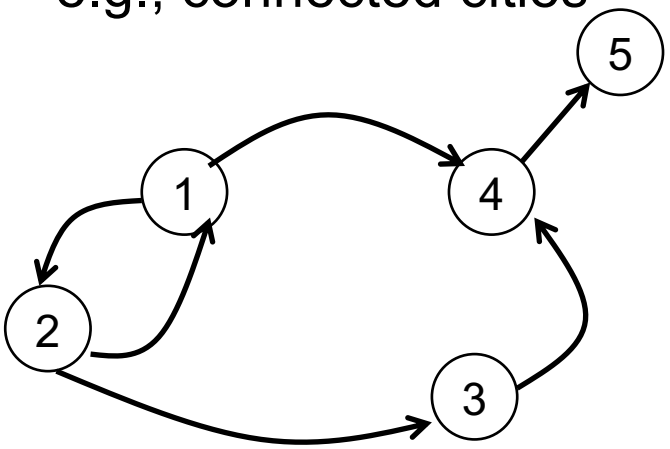
New fact

gives start/stop tuples of all nodes that are connected by a pat of length 1, 2, or 3

Fixpoint semantics: continue applying this recursive rule until T does not change after another iteration

# 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).
```

What does it compute?

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

Number of iterations required = max path length for shortest path between 2 nodes

# 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

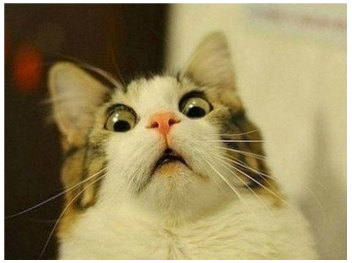
[aggregate name] <var> : { [relation to compute aggregate on] }

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

head

```
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(_,_,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
```

D(p,c) :- ParentChild(p,c)
D(p,x) :- D(p,c), ParentChild(c,x)

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) }.
```

group by parent from D table

for each such parent, count # tuples (i.e. # 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) }.

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

# 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).
```

same child x, but NOT parent = Bob

Be careful not to create duplicate tuples!!!!
list of all people in same generation

SG(x,y): ParentChild(p,x), ParentChild(p,y), x > y

// recursive case
SG(): ParentChild(p,x), ParentChild(q,y), SG(p,q), x > y

ParentChild(p,c)

# 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)
```

ParentChild(p,c)

# Safe Datalog Rules

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

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

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

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

ParentChild(p,c)

# Safe Datalog Rules

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

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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)

ParentChild(p,c)

# Safe Datalog Rules

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

```
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```

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

A datalog rule is *safe* if every variable appears in some positive relational atom

positive = not negated

# 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).
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Stratum 1

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```

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