CSE 544
Principles of Database Management Systems

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Fall 2015

Lecture 4 – Datalog

Announcements

- Project
  - Proposal due next Wednesday
  - Try to include **concrete deliverables** to keep track of progress
  - Talk to staff if you have questions / concerns

- Office hour changes
  - I will cancel OH on 10/20 due to CSE affiliates day (please send email to make appointment)
  - Shumo will have OH on 10/21 (Wed) instead of 10/23 (Fri) for HW1 questions
  - Use discussion board ☺

References

- R&G Chapter 24

- Hellerstein, “The Declarative Imperative,” SIGMOD Record 2010.

Datalog

- Alternative notation for queries
- Designed for *recursive* queries in the 80s
- Modern implementations: commercial (LogicBlox), networking (Overlog), programming languages, …

- Topics
  - Syntax of datalog
  - How to evaluate
  - Datalog semantics

Running Datalog

How to try out datalog quickly:

- Download DLV from: http://www.dlvsystem.com/dlvdb/
- Run DLV on this file:

```
parent(william, john).
parent(john, james).
parent(james, bill).
parent(sue, bill).
parent(james, carol).
parent(sue, carol).

male(john).
male(james).
female(sue).
male(bill).
female(carol).

grandparent(X, Y) :- parent(X, Z), parent(Z, Y).
father(X, Y) :- parent(X, Y), male(X).
mother(X, Y) :- parent(X, Y), female(X).
brother(X, Y) :- parent(P, X), parent(P, Y), male(X), X != Y.
sister(X, Y)  :- parent(P, X), parent(P, Y), female(X), X != Y.
```

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

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)

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)

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)

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'.
```

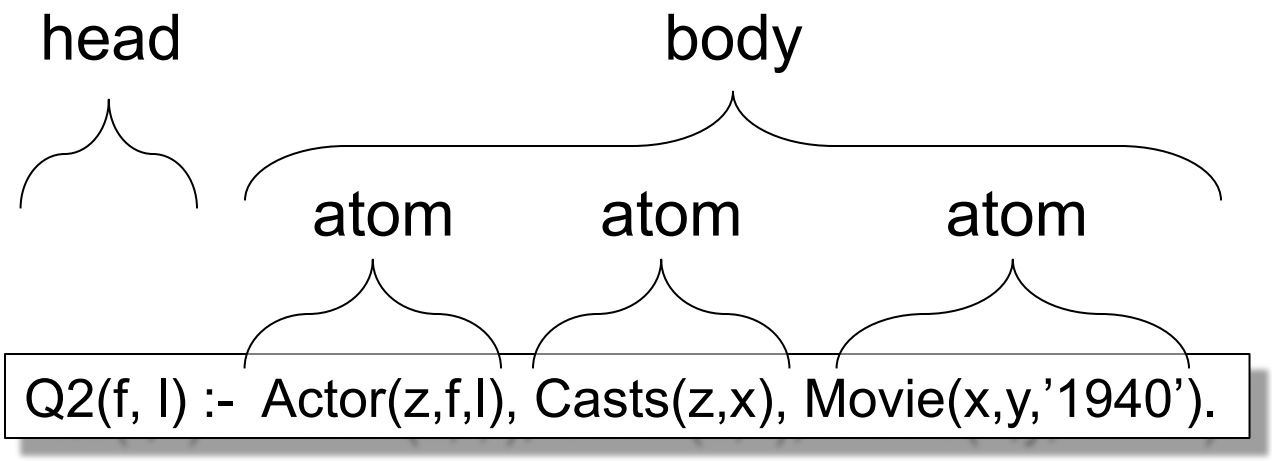
```
Q2(f, l) :-  Actor(z,f,l), Casts(z,x),
             Movie(x,y,'1940').
```

```
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

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

Terminology



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

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

Safe Datalog Rules

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

```
U1(x,y) :- Movie(x,z,1994), y>1910
```

```
U2(x)   :- Movie(x,z,1994), not Casts(u,x)
```

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

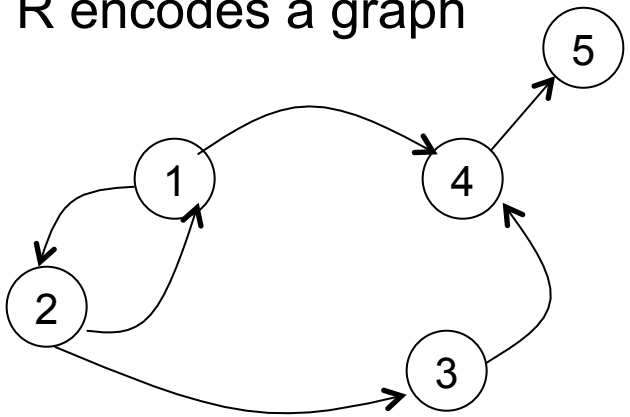
Datalog v.s. SQL

- Non-recursive datalog with negation is a cleaned-up, core of SQL

- You should be able to translate easily between non-recursive datalog with negation and SQL

Simple datalog programs

R encodes a graph




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

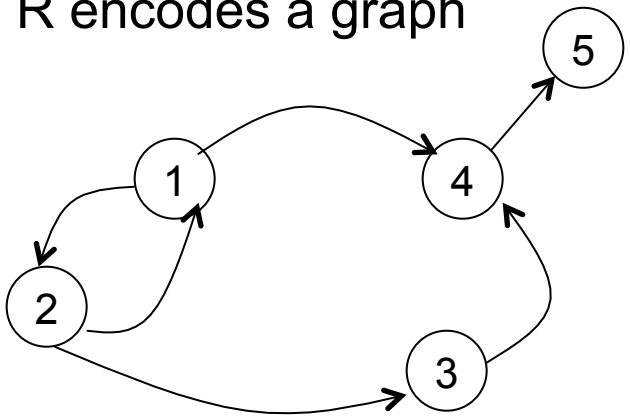
What does it compute?

R=

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

Simple datalog programs

R encodes a graph

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

What does it compute?

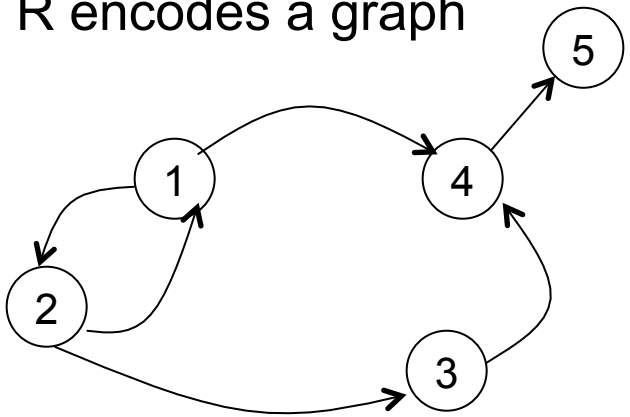
R=

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

Initially:
T is empty.

Simple datalog programs

R encodes a graph




```
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

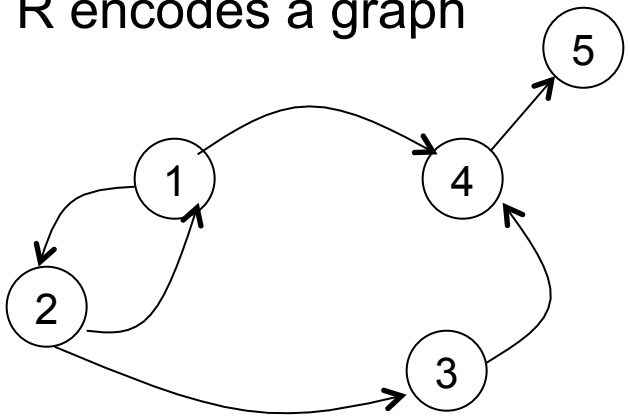
Initially:
T is empty.

First iteration:
T =

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

Simple datalog programs

R encodes a graph




```
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 =

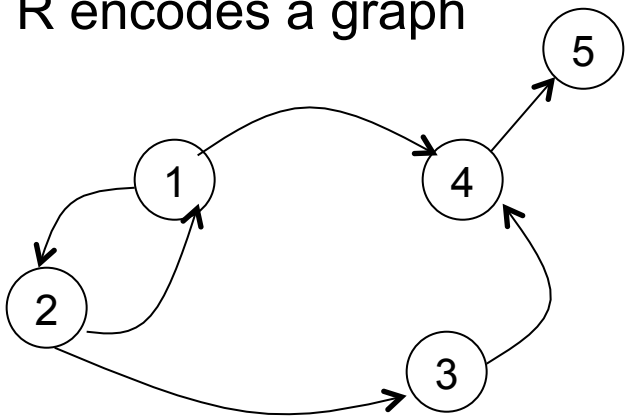
1	2
2	1
2	3
1	4
3	4
4	5

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

Simple datalog programs

R encodes a graph




```
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

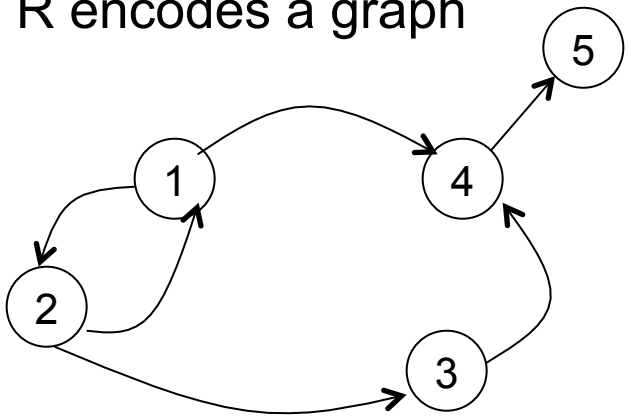
Third iteration:
T =

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

Done

Simple datalog programs

R encodes a graph




```
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

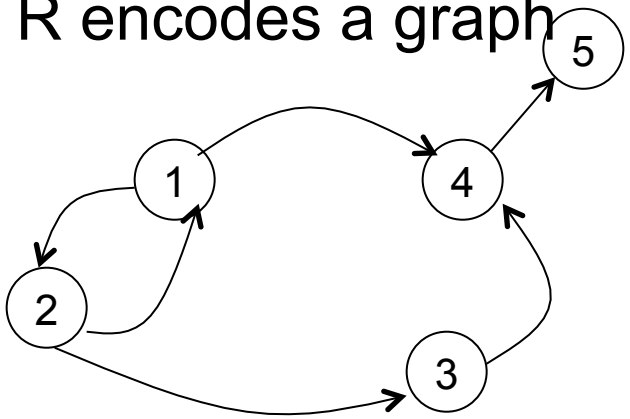
Discovered 3 times!

Discovered twice

Done

Simple datalog programs

R encodes a graph



R=

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

Alternative ways to compute TC:

```
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

What are the pros / cons?

Syntax of Datalog Programs

The schema consists of two sets of relations:

- Extensional Database (EDB): R_1, R_2, …
- Intentional Database (IDB): P_1, P_2, …

A datalog program **P** has the form:

P:

$P_{i1}(x_{11},x_{12},\ldots)$:- $body_1$
$P_{i2}(x_{21},x_{22},\ldots)$:- $body_2$
….

- Each head predicate P_i is an IDB
- Each body is a conjunction of IDB and/or EDB predicates

Note: no negation (yet)! Recursion OK.

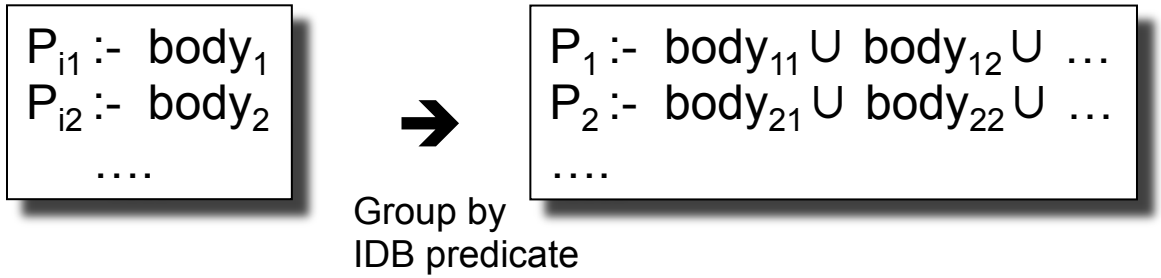
Naïve Datalog Evaluation Algorithm

Datalog program:

P_{i1} :- $body_1$
P_{i2} :- $body_2$
....

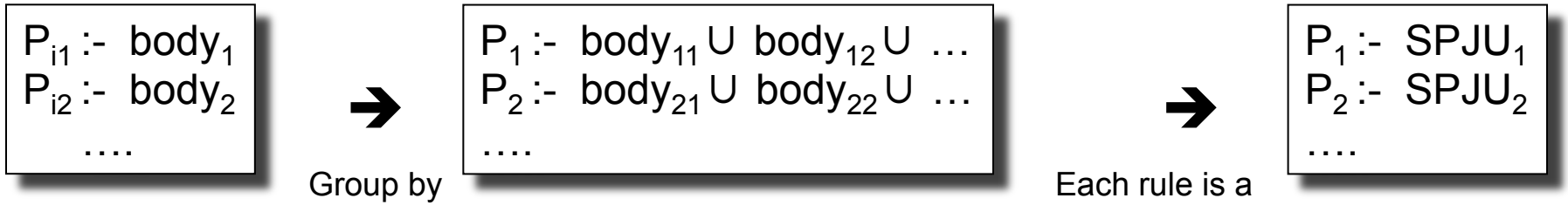
Naïve Datalog Evaluation Algorithm

Datalog program:



Naïve Datalog Evaluation Algorithm

Datalog program:



Naïve Datalog Evaluation Algorithm

Datalog program:

P_{i1} :- $body_1$
P_{i2} :- $body_2$
….

➔ Group by IDB predicate

P_1 :- $body_{11}$ ∪ $body_{12}$ ∪ …
P_2 :- $body_{21}$ ∪ $body_{22}$ ∪ …
….

➔ Each rule is a Select-Project-Join-Union query

P_1 :- $SPJU_1$
P_2 :- $SPJU_2$
….

Example:

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

➔ ?

Naïve Datalog Evaluation Algorithm

Datalog program:

P_{i1} :- $body_1$
P_{i2} :- $body_2$
….

➔ Group by IDB predicate

P_1 :- $body_{11} \cup body_{12} \cup \ldots$
P_2 :- $body_{21} \cup body_{22} \cup \ldots$
….

➔ Each rule is a Select-Project-Join-Union query

P_1 :- $SPJU_1$
P_2 :- $SPJU_2$
….

Example:

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

➔ $T(x,y) :- R(x,y) \cup \Pi_{xy}(R(x,z) \bowtie T(z,y))$

Naïve Datalog Evaluation Algorithm

Datalog program:

P_{i1} :- $body_1$
P_{i2} :- $body_2$
….

➔ Group by IDB predicate

P_1 :- $body_{11} \cup body_{12} \cup \ldots$
P_2 :- $body_{21} \cup body_{22} \cup \ldots$
….

➔ Each rule is a Select-Project-Join-Union query

P_1 :- $SPJU_1$
P_2 :- $SPJU_2$
….

Naïve datalog evaluation algorithm:

$P_1 = P_2 = \ldots = \varnothing$
Loop
  $NewP_1 = SPJU_1$; $NewP_2 = SPJU_2$; …
  if ($NewP_1 = P_1$ and $NewP_2 = P_2$ and …)
    then exit
  $P_1 = NewP_1$; $P_2 = NewP_2$; …
Endloop

Example:

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

➔ $T(x,y) :- R(x,y) \cup \Pi_{xy}(R(x,z) \bowtie T(z,y))$

Naïve Datalog Evaluation Algorithm

Datalog program:

P_{i1} :- $body_1$
P_{i2} :- $body_2$
….

➔ Group by IDB predicate

P_1 :- $body_{11} \cup body_{12} \cup$ …
P_2 :- $body_{21} \cup body_{22} \cup$ …
….

➔ Each rule is a Select-Project-Join-Union query

P_1 :- $SPJU_1$
P_2 :- $SPJU_2$
….

Naïve datalog evaluation algorithm:

$P_1 = P_2 = \ldots = \varnothing$
Loop
  $NewP_1 = SPJU_1$; $NewP_2 = SPJU_2$; …
  if ($NewP_1 = P_1$ and $NewP_2 = P_2$ and …)
    then exit
  $P_1 = NewP_1$; $P_2 = NewP_2$; …
Endloop

Example:

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

➔ $T(x,y) :- R(x,y) \cup \Pi_{xy}(R(x,z) \bowtie T(z,y))$

T= ∅
Loop
  NewT(x,y) = $R(x,y) \cup \Pi_{xy}(R(x,z) \bowtie T(z,y))$
  if (NewT = T)
    then exit
  T = NewT
Endloop

Discussion

- A datalog program *always* terminates (why?)

Problem with the Naïve Algorithm

- The same facts are discovered over and over again
- The *semi-naïve* algorithm tries to reduce the number of facts discovered multiple times

Background: Incremental View Maintenace

Let V be a view computed by one datalog rule (no recursion)

V :- body

If (some of) the relations are updated: $R_1 \leftarrow R_1 \cup \Delta R_1$, $R_1 \leftarrow R_2 \cup \Delta R_2$, …

Then the view is also modified as follows: $V \leftarrow V \cup \Delta V$

Incremental view maintenance:
Compute ΔV without having to recompute V

Background: Incremental View Maintenace

Example 1:

V(x,y) :- R(x,z),S(z,y)

If $R \leftarrow R \cup \Delta R$ then what is $\Delta V(x,y)$?

Background: Incremental View Maintenace

Example 1:

$V(x,y) :- R(x,z),S(z,y)$

If $R \leftarrow R \cup \Delta R$ then what is $\Delta V(x,y)$?

$\Delta V(x,y) :- \Delta R(x,z),S(z,y)$

Background: Incremental View Maintenace

Example 2:

V(x,y) :- R(x,z),S(z,y)

If $R \leftarrow R \cup \Delta R$ and $S \leftarrow S \cup \Delta S$
then what is $\Delta V(x,y)$?

Background: Incremental View Maintenace

Example 2:

$V(x,y) :- R(x,z),S(z,y)$

If $R \leftarrow R \cup \Delta R$ and $S \leftarrow S \cup \Delta S$
then what is $\Delta V(x,y)$?

$\Delta V(x,y) :- \Delta R(x,z),S(z,y)$
$\Delta V(x,y) :- R(x,z), \Delta S(z,y)$
$\Delta V(x,y) :- \Delta R(x,z), \Delta S(z,y)$

Background: Incremental View Maintenace

Example 3:

V(x,y) :- T(x,z),T(z,y)

If $T \leftarrow T \cup \Delta T$
then what is $\Delta V(x,y)$?

Background: Incremental View Maintenace

Example 3:

$V(x,y) :- T(x,z), T(z,y)$

If $T \leftarrow T \cup \Delta T$
then what is $\Delta V(x,y)$?

$\Delta V(x,y) :- \Delta T(x,z), T(z,y)$
$\Delta V(x,y) :- T(x,z), \Delta T(z,y)$
$\Delta V(x,y) :- \Delta T(x,z), \Delta T(z,y)$

Semi-naïve Evaluation Algorithm

Separate the Datalog program into the non-recursive, and the recursive part.
Each P_i defined by non-recursive-$SPJU_i$ and (recursive-)$SPJU_i$.

$P_1 = \Delta P_1$ = non-recursive-$SPJU_1$,
$P_2 = \Delta P_2$ = non-recursive-$SPJU_2$,
…
Loop
    $\Delta P_1 = \Delta$ $SPJU_1$; $\Delta P_2 = \Delta SPJU_2$; …
    if ($\Delta P_1 = \varnothing$ and $\Delta P_2 = \varnothing$ and …)
        then break
    $P_1 = P_1 \cup \Delta P_1$; $P_2 = P_2 \cup \Delta P_2$; …
Endloop

Semi-naïve Evaluation Algorithm

Separate the Datalog program into the non-recursive, and the recursive part.
Each P_i defined by non-recursive-$SPJU_i$ and (recursive-)$SPJU_i$.

$P_1 = \Delta P_1$ = non-recursive-$SPJU_1$, $P_2 = \Delta P_2$ = non-recursive-$SPJU_2$, …
Loop
  $\Delta P_1 = \Delta\ SPJU_1$; $\Delta P_2 = \Delta SPJU_2$; …
  if ($\Delta P_1 = \varnothing$ and $\Delta P_2 = \varnothing$ and …)
    then break
  $P_1 = P_1 \cup \Delta P_1$; $P_2 = P_2 \cup \Delta P_2$; …
Endloop

Example:

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

T= ΔT = **? (non-recursive rule)**
Loop
  ΔT(x,y) = **? (recursive Δ-rule)**
  if (ΔT = ∅)
    then break
  T = TUΔT
Endloop

Semi-naïve Evaluation Algorithm

Separate the Datalog program into the non-recursive, and the recursive part.
Each P_i defined by non-recursive-$SPJU_i$ and (recursive-)$SPJU_i$.

$P_1 = \Delta P_1$ = non-recursive-$SPJU_1$, $P_2 = \Delta P_2$ = non-recursive-$SPJU_2$, …
Loop
  $\Delta P_1 = \Delta\ SPJU_1$; $\Delta P_2 = \Delta SPJU_2$; …
  if ($\Delta P_1 = \varnothing$ and $\Delta P_2 = \varnothing$ and …)
    then break
  $P_1 = P_1 \cup \Delta P_1$; $P_2 = P_2 \cup \Delta P_2$; …
Endloop

Example:

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

T(x,y) = R(x,y), ΔT(x,y) = R(x,y)
Loop
  ΔT(x,y) = R(x,z), ΔT(z,y)
  if (ΔT = ∅)
    then break
  T = T∪ΔT
Endloop

Semi-naïve Evaluation Algorithm

Separate the Datalog program into the non-recursive, and the recursive part.
Each P_i defined by non-recursive-$SPJU_i$ and (recursive-)$SPJU_i$.

$P_1 = \Delta P_1$ = non-recursive-$SPJU_1$, $P_2 = \Delta P_2$ = non-recursive-$SPJU_2$, …
Loop
  $\Delta P_1 = \Delta$ $SPJU_1$; $\Delta P_2 = \Delta SPJU_2$; …
  if ($\Delta P_1 = \varnothing$ and $\Delta P_2 = \varnothing$ and …)
    then break
  $P_1 = P_1 \cup \Delta P_1$; $P_2 = P_2 \cup \Delta P_2$; …
Endloop

Example:

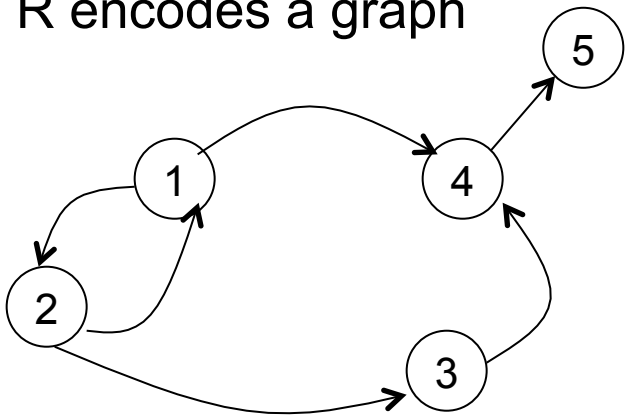
T(x,y) :- R(x,y)
T(x,y) :- R(x,z), T(z,y)

T(x,y) = R(x,y), ΔT(x,y) = R(x,y)
Loop
  ΔT(x,y) = R(x,z), ΔT(z,y)
  if (ΔT = ∅)
    then break
  T = TUΔT
Endloop

Note: for any linear datalog programs, the semi-naïve algorithm has only one Δ-rule for each rule!

Simple datalog programs

R encodes a graph




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

```
T= R,  ΔT = R
Loop
  ΔT(x,y)  = R(x,z),  ΔT(z,y)
  if (ΔT = ∅)
        then break
  T = TUΔT
Endloop
```

R=

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

Initially:

ΔT=

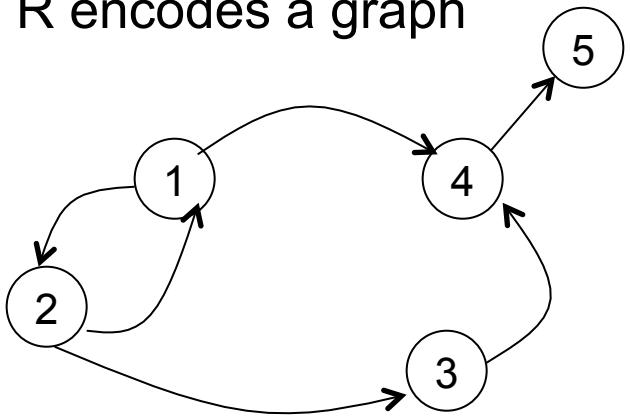
1	2
1	4
2	1
2	3
3	4
4	5

T=

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

Simple datalog programs

R encodes a graph



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

```
T= R,  ΔT = R
Loop
  ΔT(x,y)  = R(x,z),  ΔT(z,y)
  if (ΔT = ∅)
        then break
  T = TUΔT
Endloop
```

R=

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

Initially:

ΔT=

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

T=

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

First iteration:

ΔT= paths of length 2

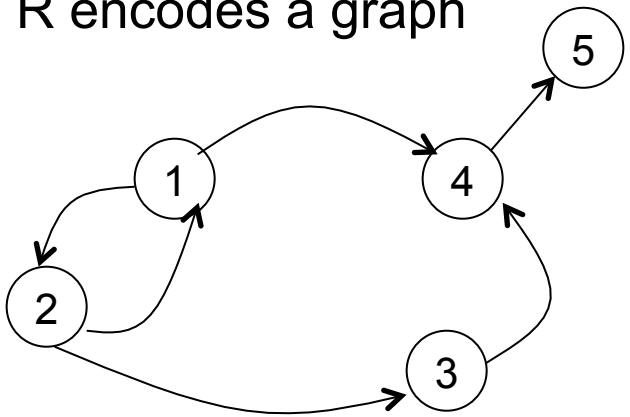
1	1
1	3
1	5
2	2
2	4
3	5

T=

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

Simple datalog programs

R encodes a graph




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

```
T= R,  ΔT = R
Loop
  ΔT(x,y)  = R(x,z),  ΔT(z,y)
  if (ΔT = ∅)
        then break
  T = TUΔT
Endloop
```

R=

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

Initially:

ΔT=

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

T=

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

First iteration:

ΔT= paths of length 2

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

T=

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

Second iteration:

ΔT= paths of length 3

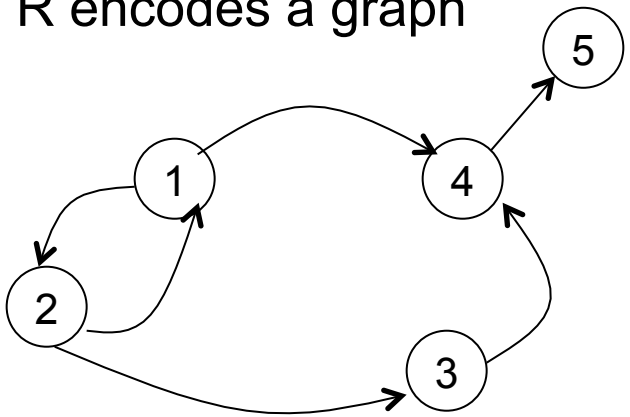
1	2
1	4
2	1
2	3
2	5

T=

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

Simple datalog programs

R encodes a graph




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

```
T= R,  ΔT = R
Loop
  ΔT(x,y)  = R(x,z),  ΔT(z,y)
  if (ΔT = ∅)
        then break
  T = TUΔT
Endloop
```

R=

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

Initially:

ΔT=

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

T=

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

First iteration:

ΔT= paths of length 2

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

T=

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

Second iteration:

ΔT= paths of length 3

1	2
1	4
2	1
2	3
2	5

T=

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

Third iteration:

ΔT= paths of length 4

Discussion of Semi-Naïve Algorithm

- Avoids re-computing some tuples, but not all tuples
- Easy to implement, no disadvantage over naïve

- A rule is called *linear* if its body contains only one recursive IDB predicate:
  - A linear rule always results in a single incremental rule
  - A non-linear rule may result in multiple incremental rules

Discussion

The *Declarative Imperative* paper:

- What are the extensions to datalog in Dedalus?
- What is the main usage of Dedalus described in the paper?
- What are the applications of Dedalus?
- What could you have used Dedalus for?