Introduction to Data Management CSE 344

Lecture 14: Datalog

(guest lecturer Dan Suciu)

Announcements

- WQ 4 and HW 4 due on Thursday
- Midterm next Monday in class
- This week:
  - Today: RC + Datalog
  - Wed: NoSQL (a taste of non relational data model)
  - Thurs: Midterm review

Review: Relational Calculus

Query Q:

$Q(x_1, \ldots, x_k) = P$

This means: $(x_1, \ldots, x_k)$ is in Q if P is true

Relational predicate P is a formula given by this grammar:

$P ::= \text{atom} \mid P \wedge P \mid P \vee P \mid P \Rightarrow P \mid \text{not}(P) \mid \forall x.P \mid \exists x.P$

Atomic predicate is either a relational or interpreted predicate:

$\text{atom} ::= R(x_1, \ldots, x_k) \mid x = y \mid x > c \mid \ldots$

R(x,y) means (x,y) is in R

Review:
Domain independence

- Consider Q(x) = not R(x) R(x) contains {1,2}
  - If domain of x is {1,2,3,4} then Q(x) = ?
  - What if domain of x is {1,2,3,4,5}?

Results differ!!

- Definition: a query is **domain independent** if it returns the same result regardless of its variables' domain

- How to fix? Bound the range of x!
  - Q(x) = not R(x) $\wedge$ S(x) (many other possibilities)

Review: Domain independence

- Let's be a bit more formal:
  - Active domain of Q consists of all tuples from the relation instances referenced in Q (along with any constants in Q)
  - Ex: AD(Q) = {1,2} for query on previous slide

- If eval(Q, AD(Q)) = eval(Q, D), where D is a domain that is larger than or equal to AD(Q), then Q is **domain independent** (dependent otherwise)

- We will see an analog of this in Datalog

- Make sure you understand the examples from last lecture!

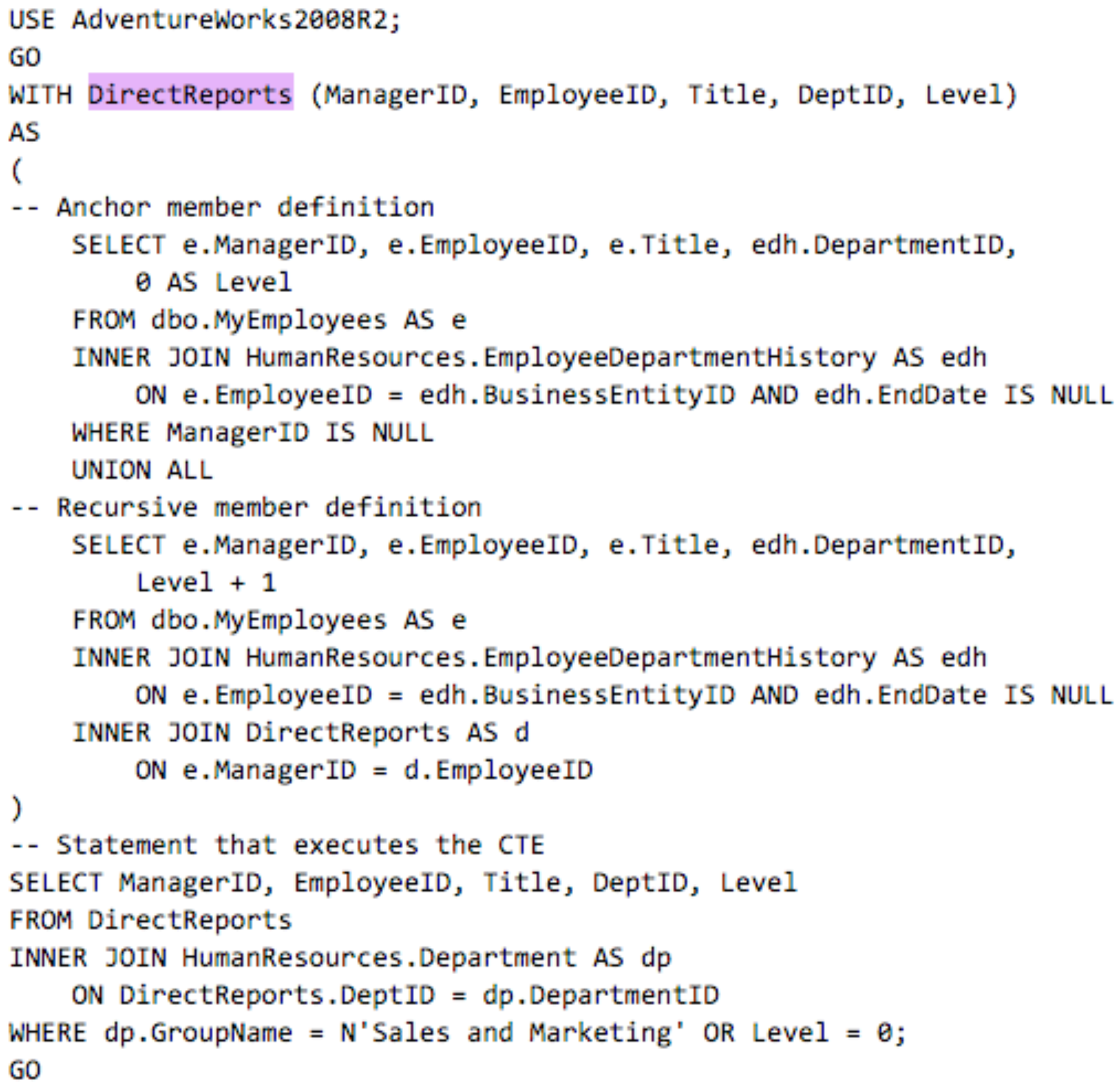
Datalog

What is Datalog?

- Another query language for relational model
  - Simple and elegant
  - Initially designed for *recursive* queries
- Today:
  - Some companies use datalog for data analytics, e.g., LogicBlox
  - Increased interest due to recursive analytics
- We discuss only *recursion-free* or *non-recursive* datalog and add negation

Why Do We Learn Datalog?

- A query language that is closest to mathematical logic
  - Good language to reason about query properties
- Datalog can be translated to SQL (practice at home!)
  - Helps to express complex SQL as we will see next lecture
  - Can also translate back and forth between datalog and RA
- Fact: relational algebra, non-recursive datalog with negation, and relational calculus all have the same expressive power!



```
USE AdventureWorks2008R2;
GO
WITH DirectReports (ManagerID, EmployeeID, Title, DeptID, Level)
AS
(
-- Anchor member definition
    SELECT e.ManagerID, e.EmployeeID, e.Title, edh.DepartmentID,
        0 AS Level
    FROM dbo.MyEmployees AS e
    INNER JOIN HumanResources.EmployeeDepartmentHistory AS edh
        ON e.EmployeeID = edh.BusinessEntityID AND edh.EndDate IS NULL
    WHERE ManagerID IS NULL
    UNION ALL
-- Recursive member definition
    SELECT e.ManagerID, e.EmployeeID, e.Title, edh.DepartmentID,
        Level + 1
    FROM dbo.MyEmployees AS e
    INNER JOIN HumanResources.EmployeeDepartmentHistory AS edh
        ON e.EmployeeID = edh.BusinessEntityID AND edh.EndDate IS NULL
    INNER JOIN DirectReports AS d
        ON e.ManagerID = d.EmployeeID
)
-- Statement that executes the CTE
SELECT ManagerID, EmployeeID, Title, DeptID, Level
FROM DirectReports
INNER JOIN HumanResources.Department AS dp
    ON DirectReports.DeptID = dp.DepartmentID
WHERE dp.GroupName = N'Sales and Marketing' OR Level = 0;
GO
```

```
DirectReports(eid, 0) :-
            Employee(eid),
            not Manages(_, eid)
DirectReports(eid, level+1) :-
            DirectReports(mid, level),
            Manages(mid, eid)
```

SQL Query vs Datalog
(which would you rather write?)

Datalog

We do not run datalog in 344; to try out on you own:

- Download DLV (http://www.dbai.tuwien.ac.at/proj/dlv/) Run DLV on this file
- Or IRIS

http://www.iris-reasoner.org/demo

- Or pydatalog

(https://sites.google.com/site/pydatalog/home)

- Or DrRacket

http://www.racket-lang.org/

```
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)

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

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

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```

Rules = queries

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

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

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```

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

Rules = queries

No need for $\exists x\ \exists z$

```
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

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

Rules = queries

No need for ∃x ∃z

```
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).
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Movie(7909, ‘A Night in Armour’, 1910).
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```

Rules = queries

No need for ∃x ∃z

```
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

No need for ∃x ∃z

```
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

No need for ∃x ∃z

```
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

```
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

No need for ∃x ∃z

```
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

$$\overbrace{\text{Q2(f, l)}}^{\text{head}}\text{ :- }\overbrace{\overbrace{\text{Actor(z,f,l)}}^{\text{atom}}\text{, }\overbrace{\text{Casts(z,x)}}^{\text{atom}}\text{, }\overbrace{\text{Movie(x,y,'1940')}}^{\text{atom (aka subgoal)}}}^{\text{body}}\text{.}$$

f, l = head variables

x,y,z = existential variables

More Datalog Terminology

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

Your book uses:
Q(args) :- R1(args) AND R2(args) AND ....

- $R_i(args_i)$ is 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 to relational predicates, we can also have arithmetic predicates
  - Example: z=‘1940’.

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

Semantics

- Meaning of a datalog rule = a logical statement !

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

- Means:
  - $\forall$x. $\forall$y. $\forall$z. [(Movie(x,y,z) and z='1940') $\Rightarrow$ Q1(y)]
  - and Q1 is the **smallest** relation that has this property

- Note: logically equivalent to:
  - $\forall$ y. [($\exists$x. $\exists$ z. Movie(x,y,z) and z='1940') $\Rightarrow$ Q1(y)]
  - That's why vars not in head are called "existential variables".

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

Datalog program

A datalog program is a collection of one or more rules

Each rule tells how to infer its relations from others

Example: Find all actors with Bacon number ≤ 2

```
B0(x) :- Actor(x,'Kevin', 'Bacon')
B1(x) :- Actor(x,f,l), Casts(x,z), Casts(y,z), B0(y)
B2(x) :- Actor(x,f,l), Casts(x,z), Casts(y,z), B1(y)
 Q4(x) :- B0(x)
 Q4(x) :- B1(x)
 Q4(x) :- B2(x)
```

Note: Q4 means the *union* of B0 and B2

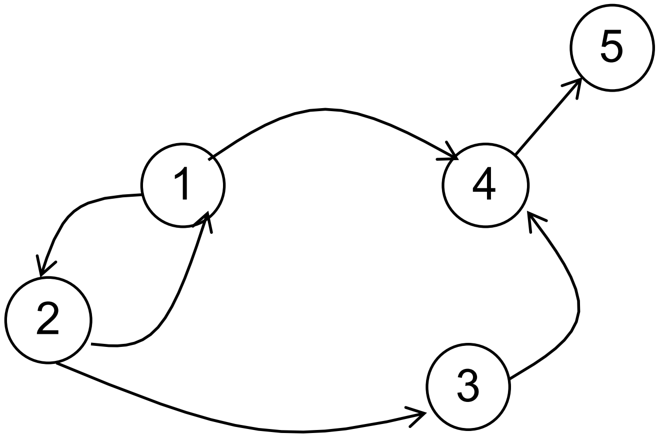
We actually don’t need Q4(x) :- B0(x) and Q4(x) :- B1(x)

Recursive Datalog

- In datalog, rules can be recursive

```
Path(x, y) :- Edge(x, y).
Path(x, y) :- Path(x, z), Edge (z, y).
```

- We study only on non-recursive datalog



Edge encodes a graph
Path finds all paths

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

Datalog with negation

Find all actors who do not have a Bacon number >= 2

```
B0(x) :- Actor(x,'Kevin', 'Bacon')
B1(x) :- Actor(x,f,l), Casts(x,z), Casts(y,z), B0(y)
Q6(x) :- Actor(x,f,l), not B1(x), not B0(x)
```

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

Simpler than in relational calculus

R(A,B,C)
S(D,E,F)
T(G,H)

RA to Datalog by Examples

Union R(A,B,C) ∪ S(D,E,F)

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

R(A,B,C)
S(D,E,F)
T(G,H)

RA to Datalog by Examples

Intersection R(A,B,C) ∩ S(D,E,F)

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

R(A,B,C)
S(D,E,F)
T(G,H)

RA to Datalog by Examples

Selection: $\sigma_{x>100 \text{ and } y=\text{'foo'}}(R)$

L(x,y,z) :- R(x,y,z), x > 100, y='foo'

Selection $\sigma_{x>100 \textbf{ or } y=\text{'foo'}}(R)$

L(x,y,z) :- R(x,y,z), x > 100

L(x,y,z) :- R(x,y,z), y='foo'

R(A,B,C)
S(D,E,F)
T(G,H)

RA to Datalog by Examples

Equi-join: $R \bowtie_{R.A=S.D \text{ and } R.B=S.E} S$

J(x,y,z,q) :- R(x,y,z), S(x,y,q)

R(A,B,C)
S(D,E,F)
T(G,H)

RA to Datalog by Examples

Projection

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

R(A,B,C)
S(D,E,F)
T(G,H)

RA to Datalog by Examples

To express difference, we add negation

D(x,y,z) :- R(x,y,z), NOT S(x,y,z)

Examples

R(A,B,C)

S(D,E,F)

T(G,H)

Translate: $\Pi_A(\sigma_{B=3}$ (R))

A(a) :- R(a,3,_)

Underscore used to denote an "anonymous variable”

Each such variable is unique

Examples

R(A,B,C)

S(D,E,F)

T(G,H)

Translate: $\Pi_{A}(\sigma_{B=3}(R) \bowtie_{R.A=S.D} \sigma_{E=5}(S))$

A(a) :- R(a,3,_), S(a,5,_)

Datalog Summary

- EDB (base relations) and IDB (derived relations)
- Datalog program = set of rules
- Datalog is recursive
  - But we only focused on non-recursive datalog

- Some reminders about semantics:
  - Multiple atoms in a rule mean join (or intersection)
  - Variables with the same name are join variables
  - Multiple rules with same head mean union

Using what we have learned

How to write a complex SQL query:

- Write it in RC
- Translate RC to datalog
- Translate datalog to SQL

Take shortcuts when you know what you’re doing