Introduction to Data Management CSE 344

Lecture 13: Datalog

(Ch 5.3–5.4)

Announcements

- HW3 is due Tomorrow

Spent	Count
$0	7
$1	7
$2	10
$3	7
$4	9
$6	1
$21	1

Announcements

- HW3 is due Tomorrow
- WQ4 is due next Monday
  - it will be useful review for the midterm
  - finish it early if you have time
- Midterm on Friday, July 21h, in class…
  - All the web quizes are open if that helps you study

Midterm

- Content
  - Lectures 1 through 13 (today / Monday)
  - HW 1–3, WQ 1–4
- Closed book. No computers, phones, watches, etc.!
- Can bring one letter-sized piece of paper with notes, but…
  - test will not be about memorization
  - formulas provided for join algorithms & selectivity
  - can ask me during test about anything you could look up
- Similar in format & content to CSE 344 17wi midterm
  - Previous midterms on course webpage

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)
IsBeer(beer)
IsBar(bar)

Domain independence

- $Q(x) = \forall y.\ Likes(x,y)$ is domain dependent
  - Suppose Likes = { (d1,b1), (d1,b2) }
  - What if we evaluate y over { b1, b2 }? Q(x) { d1 }
  - What about { b1, b2, b3 }? – None

- $Q(x) = \exists y.\ Likes(x,y)$ is domain independent
  - What if we evaluate y over { b1, b2 }?
  - What about { b1, b2, b3 }?

- $Q(x) = IsBar(x) \wedge \forall y.\ Serves(x,y) \Rightarrow IsBeer(y)$ is domain independent
  - Let IsBeer = { b1, b2 }, IsBar = { bar1 }, and Serves = { (bar1, b1), (bar1, b2) }
  - What if we evaluate y over { b1, b2 }? { b1, b2, b3 }?

Today: YAQL

(Yet Another Query Language

Datalog

What is Datalog?

- Another query language for relational model
  - Simple and elegant
  - Initially designed for *recursive* queries
  - 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

Datalog

- See book: 5.3 – 5.4
- See also: Query Language primer
  - article by Dan Suciu
  - covers relational calculus as well

```sql
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?)

Why Do We Learn Datalog?

- Datalog can be translated to SQL
  - Helps to express complex queries

- Increase in datalog interest due to recursive analytics

- A query language that is closest to mathematical logic
  - Good language to reason about query properties
  - Can show that:

1. Non-recursive datalog & RA have **equivalent power**
2. Recursive datalog is strictly more powerful than RA
3. Extended RA & SQL92 is strictly more powerful than datalog

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
- Can also try Flix
  (http://flix.github.io/try/)
- 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.
```

Similar to Prolog - logical programing language

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

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

Book writes:
$Q(args)$:- $R1(args)$ 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(pid, fname, lname)
Casts(pid, mid)
Movie(mid, name, year)

Datalog: Facts and Rules

Find Movies made in 1940

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,'1940').

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

Datalog: Facts and Rules

Find Actors who acted in Movies made in 1940

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,'1940').
```

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

Q2(f, l) = Movie(x, y, '1940')
Cast(z, x) Actor(z, f, l)

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

Datalog: Facts and Rules

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

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,'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(pid, fname, lname)
Casts(pid, mid)
Movie(mid, 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,'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)

Semantics

- Meaning of a datalog rule = a logical statement !

$$\boxed{Q1(y) \text{ :- } Movie(x,y,z), z=\text{'1940'}.}$$

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

- Note: logically equivalent to:
  - $\forall\ y.\ [(\exists x. \exists\ z.\ Movie(x,y,z) \text{ and } z=\text{'1940'}) \Rightarrow Q1(y)]$
  - 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** expresses the idea that, from certain combinations of tuples in certain relations, we may **infer** that some other tuple must be in some other relation or in the query answer

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)
```

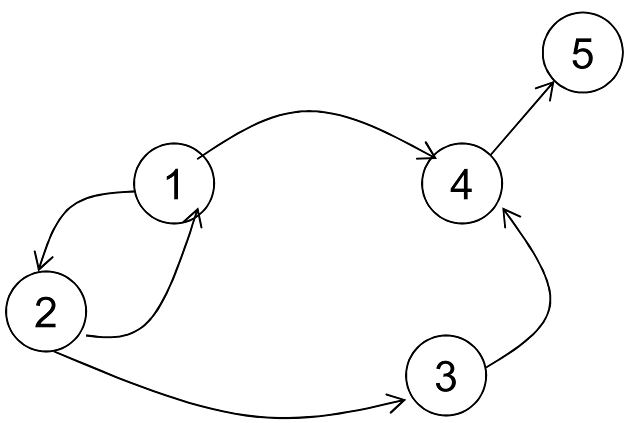
Note: Q4 means the *union* of B0, B1, & B2

Recursive Datalog

- In datalog, rules can be recursive

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

- We'll focus on non-recursive datalog



4, 5
2 1
1 2

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 ?

U0(x) :- y > 1910

arithmetic

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

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

, ~~Cast(w, x)~~

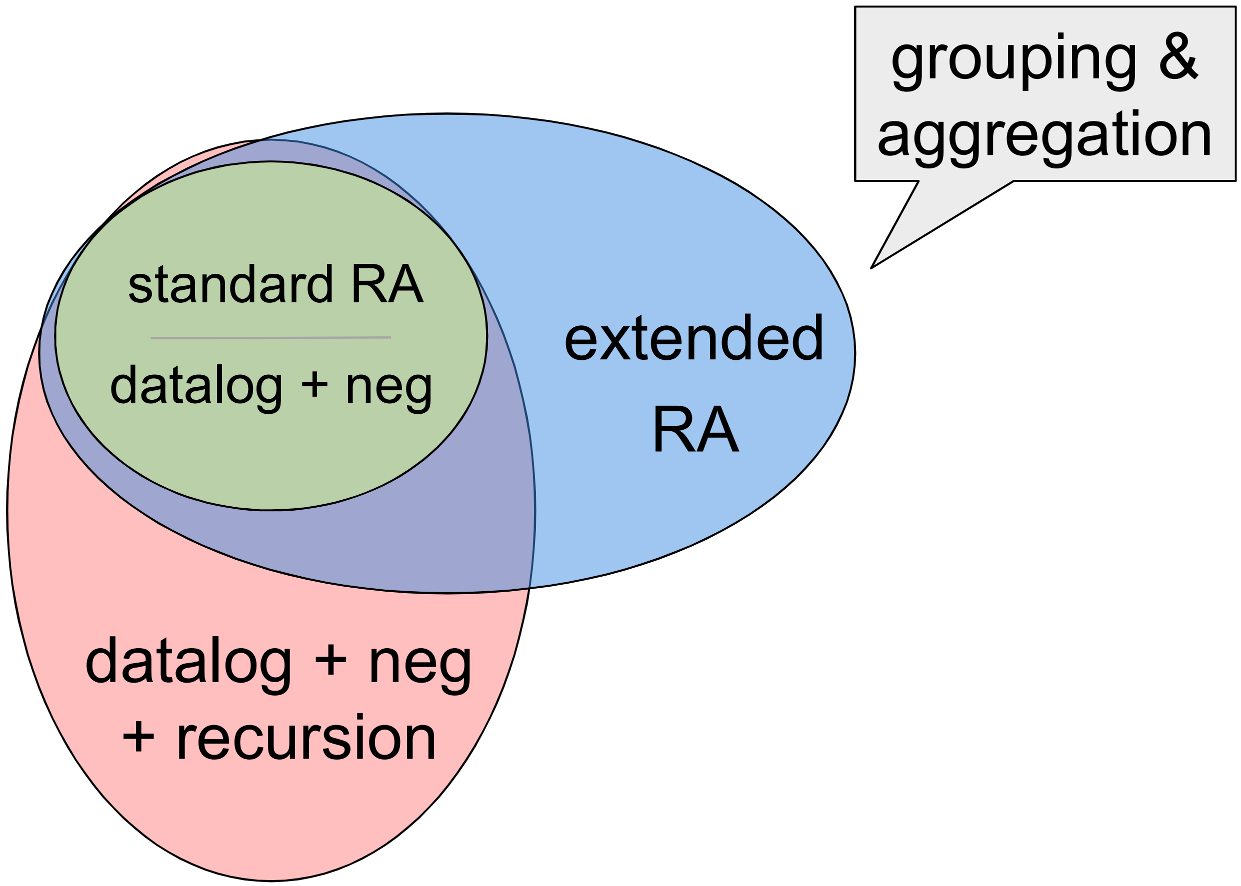
, Cast(u, v)

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

Datalog vs Relational Algebra

- Every expression in standard relational algebra can be expressed as a Datalog query
- But operations in the extended relational algebra (grouping, aggregation, and sorting) have no corresponding features in the version of datalog that we discussed today
- Similarly, datalog can express recursion, which relational algebra cannot

Datalog vs Relational Algebra



RA to Datalog by Examples

Schema for our examples:

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)

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)

What does this do?

Cross Product

I(x,y,z) :- R(x,y,z), S(a,b,~~y~~c)

RA to Datalog by Examples

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

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

Selection x>100 **or** y='some string'

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

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

RA to Datalog by Examples

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

J(x,y,z,u,v,w) :- R(x,y,z), S(u,v,w), x=u, y=v

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

(x, y, z, x, y, w)

RA to Datalog by Examples

Projection $\pi_x(R)$

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

RA to Datalog by Examples

To express set difference R – S,
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: $\Pi_A(\sigma_{B=3}(R))$
B(a,b,c) :- R(a,b,c), b=3
A(a) :- B(a,b,c)

B(a,b,c) :- R(a,3,c)

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”, a variable that appears only once.

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,_)

Friend(name1, name2)
Enemy(name1, name2)

More Examples

Find Joe's friends, and Joe's friends of friends.

A(x) := Friend("Joe", x)
A(x) := Friend("Joe", y) Friend(y, x)

A(x) :- Friend('Joe', x)
A(x) :- Friend('Joe', z), Friend(z, x), x != 'Joe'

:-

Friend(name1, name2)
Enemy(name1, name2)

More Examples

Find all of Joe's friends who do not have any friends except for Joe:

```
JoeFriends(x) :- Friend('Joe',x)
NonAns(x) :- Friend(y,x), y != ‘Joe’
A(x) :- JoeFriends(x), not NonAns(x)
```

Friend(name1, name2)

Enemy(name1, name2)

More Examples

Find all people such that all their enemies' enemies are their friends

- Q: if someone doesn't have any enemies nor friends, do we want them in the answer?
- A: Yes!

```
Everyone(x) :- Friend(x,y)
Everyone(x) :- Friend(y,x)
Everyone(x) :- Enemy(x,y)
Everyone(x) :- Enemy(y,x)
NonAns(x) :- Enemy(x,y),Enemy(y,z), NOT Friend(x,z)
A(x) :- Everyone(x), NOT NonAns(x)
```

Friend(name1, name2)
Enemy(name1, name2)

More Examples

Find all persons x that have **only** friends **all** of whose enemies are x's enemies.

what's wrong with this?

```
NonAns(x) :- Friend(x,y), Enemy(y,z), not Enemy(x,z)
A(x) :- not NonAns(x)
```

```
NonAns(x) :- Friend(x,y), Enemy(y,z), not Enemy(x,z)
A(x) :- Everyone(x), not NonAns(x)
```

Datalog Summary

- facts (extensional relations - EDBs) and rules (intensional relations - IDBs)
  - rules can use relations, arithmetic, union, intersect, …
- As with SQL, existential quantifiers are easier
  - use negation to handle universal

Datalog Summary

- Everything expressible in RA is expressible in non-recursive datalog and vice versa
  - recursive datalog can express more than (extended) RA
  - extended RA can express more than 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

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

From RC to Datalog$^{\neg}$ to SQL

Query: Find drinkers that like some beer so much that they frequent all bars that serve it

$$Q(x) = \exists y.\ Likes(x, y) \land \forall z.(Serves(z,y) \Rightarrow Frequents(x,z))$$

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

From RC to Datalog$^{\neg}$ to SQL

Query: Find drinkers that like some beer so much that they frequent all bars that serve it

$Q(x) = \exists y.\ \text{Likes}(x, y) \wedge \forall z.(\text{Serves}(z,y) \Rightarrow \text{Frequents}(x,z))$

$P \Rightarrow Q$ same as $\neg P \vee Q$

$\forall x\ P(x)$ same as $\neg \exists x\ \neg P(x)$

Step 1: Replace $\forall$ with $\exists$ using de Morgan's Laws

$\neg(\neg P \vee Q)$ same as $P \wedge \neg Q$

$Q(x) = \exists y.\ \text{Likes}(x, y) \wedge \neg \exists z.(\text{Serves}(z,y) \wedge \neg \text{Frequents}(x,z))$

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

From RC to Datalog$^{\neg}$ to SQL

Query: Find drinkers that like some beer so much that they frequent all bars that serve it

$$Q(x) = \exists y.\ Likes(x, y) \wedge \forall z.(Serves(z,y) \Rightarrow Frequents(x,z))$$

P ⇒ Q same as ¬P ∨ Q

∀x P(x) same as ¬∃x ¬P(x)

Step 1: Replace ∀ with ∃ using de Morgan's Laws

¬(¬P∨Q) same as P∧ ¬ Q

$$Q(x) = \exists y.\ Likes(x, y) \wedge \neg\exists z.(Serves(z,y) \wedge \neg Frequents(x,z))$$

Step 2: Make sure the query is domain independent

$$Q(x) = \exists y.\ Likes(x, y) \wedge \neg\exists z.(Likes(x,y) \wedge Serves(z,y) \wedge \neg Frequents(x,z))$$

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

From RC to Datalog$^{\neg}$ to SQL

$$Q(x) = \exists y.\ Likes(x, y) \wedge \neg\ \underbrace{\exists z.(Likes(x,y) \wedge Serves(z,y) \wedge \neg Frequents(x,z))}_{H(x,y)}$$

Step 3: Create a datalog rule for each subexpression;
(shortcut: only for "important" subexpressions)

```
H(x,y)   :- Likes(x,y),Serves(z,y), not Frequents(x,z)
Q(x)     :- Likes(x,y), not H(x,y)
```

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

From RC to Datalog$^{\neg}$ to SQL

```
H(x,y)   :- Likes(x,y),Serves(z,y), not Frequents(x,z)
Q(x)     :- Likes(x,y), not H(x,y)
```

Step 4: Write it in SQL

```
SELECT DISTINCT L.drinker FROM Likes L
WHERE not exists
  (SELECT * FROM Likes L2, Serves S
   WHERE … …)
```

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

From RC to Datalog$^{\neg}$ to SQL

```
H(x,y)  :- Likes(x,y),Serves(z,y), not Frequents(x,z)
Q(x)    :- Likes(x,y), not H(x,y)
```

Step 4: Write it in SQL

```
SELECT DISTINCT L.drinker FROM Likes L
WHERE not exists
  (SELECT * FROM Likes L2, Serves S
   WHERE L2.drinker=L.drinker and L2.beer=L.beer
         and L2.beer=S.beer
         and not exists (SELECT * FROM Frequents F
                         WHERE F.drinker=L2.drinker
                           and F.bar=S.bar))
```

Likes(drinker, beer)
Frequents(drinker, bar)
Serves(bar, beer)

From RC to Datalog$^{\neg}$ to SQL

H(x,y)	:- ~~Likes(x,y)~~,Serves(z,y), not Frequents(x,z)
Q(x)	:- Likes(x,y), not H(x,y)

Unsafe rule

Improve the SQL query by using an unsafe datalog rule

```
SELECT DISTINCT L.drinker FROM Likes L
WHERE not exists
  (SELECT * FROM Serves S
   WHERE L.beer=S.beer
        and not exists (SELECT * FROM Frequents F
                        WHERE F.drinker=L.drinker
                           and F.bar=S.bar))
```

Summary: all these formalisms are equivalent!

- We have seen these translations:
  - RA → datalog¬
  - RC → datalog¬
- Practice at home, and read *Query Language Primer:*
  - Nonrecursive datalog¬ → RA
  - RA → RC
- Summary:
  - RA, RC, and non-recursive datalog¬ can express the same class of queries, called Relational Queries