Prolog and Logic Programming

The Rule-Based Paradigm

- An important programming paradigm is to express a program as a set of rules
- The rules are independent and often unordered
- CFGs can be thought of as a rule based system
- We'll take a brief look at a particular sub-paradigm, Logic Programming
- And at Prolog, the most successful of the logic programming languages

History

- Logic Programming has roots going back to early AI researchers like John McCarthy in the 50s & 60s
- Alain Colmerauer (France) designed Prolog as the first LP language in the early 1970s
- Bob Kowalski and colleagues in the UK evolved the language to its current form in the late 70s
- It' s been widely used for many AI systems, but also for systems that need a fast, efficient and clean rule based engine
- The prolog model has also influenced the database community – see datalog

Computation as Deduction

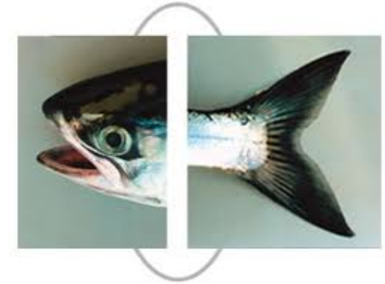
- Logic programming offers a slightly different paradigm for computation: *computation is logical deduction*
- It uses the language of logic to express data and programs.

  Forall X,Y: *X is the father of Y* if *X is a parent of Y* and *X is male*
- Current logic programming languages use FOL
- Prolog and other LP languages include extra features that enable programmers to go beyond FOL (e.g., calling procedures, negation as failure, constraints)

Theorem Proving

- Logic Programming uses the notion of an *automatic theorem prover* as an interpreter.
- The theorem prover derives a desired solution from an initial set of axioms.
- The proof must be a "constructive" one so that more than a true/false answer can be obtained
- E.G. The answer to $\exists X \; X = sqrt(16)$ should be $X = 4$ *or* $X = -4$ rather than *true*

A Declarative Example



- Here's a simple way to specify what has to be true if X is the smallest number in a list of numbers L
    1. X has to be a member of the list L
    2. There can't be list member X2 such that X2<X
- We need to say how we determine that some X is a member of a list
    1. No X is a member of the empty list
    2. X is a member of list L if it is equal to L's head
    3. X is a member of list L if it is a member of L's tail.

A Simple Prolog Model

Think of Prolog as a system which has a database composed of two components:

- **facts:** statements about true relations which hold between particular objects in the world, e.g.:

```
parent(adam, able).   % adam is a parent of able
parent(eve, able).    % eve is a parent of able
male(adam).           % adam is male.
```

- **rules:** statements about relations between objects in the world using variables to express generalizations

% X is the father of Y **if** X is a parent of Y **and** X is male

father(X,Y) :- parent(X, Y), male(X).

% X is a sibling of Y **if** X and Y share a parent

sibling(X,Y) :- parent(P,X), parent(P,Y)

Nomenclature and Syntax

- A prolog rule is called a **clause**
- A clause has a head, a neck and a body:

father(X,Y) :- parent(X,Y) , male(X) .

head *neck* *body*

- the head is a single predicate -- the rule's conclusion
- The body is a a sequence of zero or more predicates that are the rule's premise or condition
- An empty body means the rule's head is a fact.
- note:
  - read :- as IF
  - read , as AND between predicates
  - a . marks the end of input

Prolog Database

```
parent(adam,able)
parent(adam,cain)
male(adam)
...
```

Facts comprising the "extensional database"

```
father(X,Y) :- parent(X,Y),
               male(X).
sibling(X,Y) :- ...
```

Rules comprising the "intensional database"

Queries

- We also have queries in addition to having facts and rules
- The Prolog REPL interprets input as queries
- A simple query is just a predicate that might have variables in it:
  - parent(adam, cain)
  - parent(adam, X)

Extensional vs. Intensional

The terms *extensional* and *intensional* are borrowed from the language philosophers use for *epistemology*.

- *Extension* refers to whatever *extends*, i.e., "is quantifiable in space as well as in time".
- *Intension* is an antonym of extension, referring to "that class of existence which may be quantifiable in time but not in space."
- NOT *intentional* with a "t", which has to do with "will, volition, desire, plan, …"

For KBs and DBs we use

- *extensional* to refer to that which is explicitly represented (e.g., a fact), and
- *intensional* to refer to that which is represented abstractly, e.g., by a rule of inference.

Prolog Database

```
parent(adam,able)
parent(adam,cain)
male(adam)
...
```

Facts comprising the "extensional database"

```
father(X,Y) :- parent(X,Y),
               male(X).
sibling(X,Y) :- ...
```

Rules comprising the "intensional database"

Epistemology is "a branch of philosophy that investigates the origin, nature, methods, and limits of knowledge"

Running prolog

- A good free version of prolog is swi-prolog
- GL has a commercial version (sicstus prolog) you can invoke with the command "sicstus"

```
[finin@linux2 ~]$ sicstus
SICStus 3.7.1 (Linux-2.2.5-15-i686): Wed Aug 11 16:30:39 CEST 1999
Licensed to umbc.edu
| ?- assert(parent(adam,able)).

yes

| ?- parent(adam,P).

P = able ?

yes

| ?-
```

A Simple Prolog Session

```
| ?- assert(parent(adam,able)).
yes
| ?- assert(parent(eve,able)).
yes
| ?- assert(male(adam)).
yes
| ?- parent(adam,able).
yes
| ?- parent(adam,X).
X = able
yes
```

```
| ?- parent(X,able).
X = adam ;
X = eve ;
no
| ?- parent(X,able) , male(X).
X = adam ;
no
```

A Prolog Session

```
| ?- [user].
| female(eve).
| parent(adam,cain).
| parent(eve,cain).
| father(X,Y) :- parent(X,Y), male(X).
| mother(X,Y) :- parent(X,Y), female(X).
| ^Zuser consulted 356 bytes 0.0666673
   sec.
yes
| ?- mother(Who,cain).
Who = eve
yes
```

```
| ?- mother(eve,Who).
Who = cain
yes
| ?- trace, mother(Who,cain).
  (2) 1 Call: mother(_0,cain) ?
  (3) 2   Call: parent(_0,cain) ?
  (3) 2   Exit: parent(adam,cain)
  (4) 2   Call: female(adam) ?
  (4) 2   Fail: female(adam)
  (3) 2   Back to: parent(_0,cain) ?
  (3) 2   Exit: parent(eve,cain)
  (5) 2   Call: female(eve) ?
  (5) 2   Exit: female(eve)
  (2) 1 Exit: mother(eve,cain)
Who = eve
yes
```

```
| ?- [user].
| sibling(X,Y) :-
|   father(Pa,X),
|   father(Pa,Y),
|   mother(Ma,X),
|   mother(Ma,Y),
|   X \= Y.
^Zuser consulted 152 bytes 0.0500008 sec.
yes
| ?- sibling(X,Y).
X = able
Y = cain ;
X = cain
Y = able ;
```

```
trace,sibling(X,Y).
(2) 1 Call: sibling(_0,_1) ?
(3) 2  Call: father(_65643,_0) ?
(4) 3   Call: parent(_65643,_0) ?
(4) 3   Exit: parent(adam,able)
(5) 3   Call: male(adam) ?
(5) 3   Exit: male(adam)
(3) 2  Exit: father(adam,able)
(6) 2  Call: father(adam,_1) ?
(7) 3   Call: parent(adam,_1) ?
(7) 3   Exit: parent(adam,able)
(8) 3   Call: male(adam) ?
(8) 3   Exit: male(adam)
(6) 2  Exit: father(adam,able)
(9) 2  Call: mother(_65644,able) ?
(10) 3  Call: parent(_65644,able) ?
(10) 3  Exit: parent(adam,able)
(11) 3  Call: female(adam) ?
(11) 3  Fail: female(adam)
(10) 3  Back to: parent(_65644,able) ?
(10) 3  Exit: parent(eve,able)
(12) 3  Call: female(eve) ?
(12) 3  Exit: female(eve)
(9) 2  Exit: mother(eve,able)
(13) 2 Call: mother(eve,able) ?
(14) 3  Call: parent(eve,able) ?
(14) 3  Exit: parent(eve,able)
(15) 3  Call: female(eve) ?
(15) 3  Exit: female(eve)
(13) 2 Exit: mother(eve,able)
(16) 2 Call: not able=able ?
(17) 3  Call: able=able ?
(17) 3  exit: able=able
(16) 2 Back to: not able=able ?
(16) 2 Fail: not able=able
(15) 3  Back to: female(eve) ?
(15) 3  Fail: female(eve)
(14) 3  Back to: parent(eve,able) ?
(14) 3  Fail: parent(eve,able)
(13) 2 Back to: mother(eve,able) ?
(13) 2 Fail: mother(eve,able)
(12) 3  Back to: female(eve) ?
(12) 3  Fail: female(eve)
(10) 3  Back to: parent(_65644,able) ?
(10) 3  Fail: parent(_65644,able)
(9) 2  Back to: mother(_65644,able) ?
(9) 2  Fail: mother(_65644,able)
(8) 3   Back to: male(adam) ?
(8) 3   Fail: male(adam)
(7) 3   Back to: parent(adam,_1) ?
(7) 3   Exit: parent(adam,cain)
(18) 3  Call: male(adam) ?
(18) 3  Exit: male(adam)
(6) 2  Exit: father(adam,cain)
(19) 2 Call: mother(_65644,able) ?
(20) 3  Call: parent(_65644,able) ?
(20) 3  Exit: parent(adam,able)
(21) 3  Call: female(adam) ?
(21) 3  Fail: female(adam)
(20) 3  Back to: parent(_65644,able) ?
(20) 3  Exit: parent(eve,able)
(22) 3  Call: female(eve) ?
(22) 3  Exit: female(eve)
(19) 2 Exit: mother(eve,able)
(23) 2 Call: mother(eve,cain) ?
(24) 3  Call: parent(eve,cain) ?
(24) 3  Exit: parent(eve,cain)
(25) 3  Call: female(eve) ?
(25) 3  Exit: female(eve)
(23) 2 Exit: mother(eve,cain)
(26) 2 Call: not able=cain ?
(27) 3  Call: able=cain ?
(27) 3  Fail: able=cain
(26) 2 Exit: not able=cain
(2) 1 Exit: sibling(able,cain)
X = able
Y = cain
yes no
| ?-
```

Program files

Typically you put your assertions (fact and rules) into a file and load it

```
| ?- [genesis].
{consulting /afs/umbc.edu/users/f/i/finin/home/genesis.pl...}
{/afs/umbc.edu/users/f/i/finin/home/genesis.pl consulted, 0 msec 2720 bytes}
yes
| ?- male(adam).
yes
| ?- sibling(P1, P2).
P1 = cain,
P2 = cain ? ;
P1 = cain,
P2 = able ? ;
P1 = cain,
P2 = cain ? ;
P1 = cain,
P2 = able ? ;
P1 = able,
P2 = cain ? ;
P1 = able,
P2 = able ? ;
P1 = able,
P2 = cain ? ;
P1 = able,
P2 = able ? ;
no
| ?-
```

```
[finin@linux2 ~]$ more genesis.pl
% prolog example
% facts
male(adam).
female(eve).
parent(adam,cain).
parent(eve,cain).
parent(adam,able).
parent(eve,able).
% rules
father(X,Y) :-
   parent(X,Y),
   male(X).
mother(X,Y) :-
   parent(X,Y),
   female(X).
sibling(X,Y) :-
   parent(P, X),
   parent(P, Y).
child(X, Y) :- parent(Y, X).
```

How to Satisfy a Goal

Here is an informal description of how Prolog satisfies a goal (like father(adam,X)). Suppose the goal is G:

- if G = P,Q then first satisfy P, carry any variable bindings forward to Q, and then satiety Q.
- if G = P;Q then satisfy P. If that fails, then try to satisfy Q.
- if G = \+ (P) then try to satisfy P. If this succeeds, then fail and if it fails, then succeed.
- if G is a simple goal, then look for a fact in the DB that unifies with G look for a rule whose conclusion unifies with G and try to satisfy its body

Note

- Two basic conditions are true, which always succeeds, and fail, which always fails.
- Comma (,) represents conjunction (i.e., and).
- Semi-colon represents disjunction (i.e., or):

```
grandParent(X,Y) :-
   grandFather(X,Y);
   grandMother(X,Y).
```

- No real distinction between rules and facts. A fact is just a rule whose body is the trivial condition true. These are equivalent:
  – *parent(adam,cain).*
  – *parent(adam,cain) :- true.*

Note

- Goals can usually be posed with any of several combination of variables and constants:
  - parent(cain,able) - is Cain Able's parent?
  - parent(cain,X) - Who is a child of Cain?
  - parent(X,cain) - Who is Cain a child of?
  - parent(X,Y) - What two people have a parent/child relationship?

Terms

- The term is the basic data structure in Prolog.
- The term is to Prolog what the s-expression is to Lisp.
- A term is either:
  - a constant - e.g.
    - john , 13, 3.1415, +, 'a constant'
  - a variable - e.g.
    - X, Var, _, _foo
  - a compound term - e.g.
    - part(arm,body)
    - part(arm(john),body(john))

Compound Terms

- A compound term can be thought of as a relation between one or more terms:
  - part_of(finger,hand)

and is written as:

  - the relation name (called the principle functor) which must be a constant.
  - An open parenthesis
  - The arguments - one or more terms separated by commas.
  - A closing parenthesis.
- The number of arguments of a compound terms is called its arity.

Term	arity
f	0
f(a)	1
f(a,b)	2
f(g(a),b)	2

Lists

- Lists are so useful there is special syntax to support them, tho they are just terms
- It's like Python: [1, [2, 3], 4, foo]
- But matching is special
  - If *L = [1,2,3,4]* then *L = [Head | Tail]* results in Head being bound to *1* and Tail to *[2,3,4]*
  - If *L = [4]* then *L = [Head | Tail]* results in Head being bound to *4* and Tail to *[]*

member

% member(X,L) is true if X is a member of list L.

```
member(X, [X|Tail]).
member(X, [Head|Tail]) :- member(X, Tail).
```

min

% min(X, L) is true if X is the smallest member
% of a list of numbers L

```
min(X, L) :-
    member(X, L),
    \+ (member(Y,L), Y>X).
```

- \+ is Prolog's negation operator
- It's really "negation as failure"
- \+ G is false if goal G can be proven
- \+ G is true if G can not be proven
- i.e., assume its false if you can not prove it to be true

Computations

- Numerical computations can be done in logic, but its messy and inefficient
- Prolog provides a simple limited way to do computations
- <variable> is <expression> succeeds if <variable> can be unified with the value produced by <expression>

```
?- X=2, Y=4, Z is X+Y.
X = 2,
Y = 4,
Z = 6.

?- X=2, Y=4, X is X+Y.
false.
```

From Functions to Relations

- Prolog facts and rules define *relations*, not *functions*
- Consider age as:
  - A function: calling *age(john)* returns 22
  - As a relation: querying *age(john, 22)* returns true, *age(john, X)* binds X to 22, and *age(john, X)* is false for every $X \neq 22$
- Relations are more general than functions
- The typical way to define a function **f** with inputs $\mathbf{i_1 \ldots i_n}$ and output **o** is as: $\mathbf{f(i_1,i_2,\ldots i_n,o)}$

A numerical example

- Here's how we might define the factorial relation in Prolog.

```
fact(1,1).
fact(N,M) :-
    N > 1,
    N1 is N-1,
    fact(N1,M1),
    M is M1*N.
```

```
def fact(n):
  if n==1:
    return 1
  else:
    n1 = n-1
    m1 = fact(n1)
    m = m1 * n
    return m
```

Another example:

```
square(X,Y) :- Y is X*X.
```

Prolog = PROgramming in LOGic

- Prolog is as much a programming language as it is a theorem prover
- It has a simple, well defined and controllable reasoning strategy that programmers can exploit for efficiency and predictability
- It has basic data structures (e.g., Lists) and can link to routines in other languages
- It's a great tool for many problems