Prolog

- Language constructs
  - Facts, rules, queries through examples
- Horn clauses
  - Goal-oriented semantics
  - Procedural semantics
- How computation is performed?
- Comparison to logic programming

Logic Programming vs Prolog

- Logic programming languages are neither procedural or functional.
- Based on predicate calculus -- represent using predicates/relations:

```
class Student extends Person {int year; float gpa; major}
```

can be represented, among others, as

```
student(_), person(_), inYear(_,_), hasGpa(_,_),...
person(X):- student(X).
student(jane).          %% jane = new Student();
inYear(jane,3).         %% jane.year = 3;
```

Logic Programming vs Prolog

- Separate logic from control:
  - Separate the What (logic) from the How (control)
  - Programmer declares what facts and relations are true
  - System determines how to use facts to solve problems
  - State relationships and query them as in logic

Logic Programming

- Computation engine: theorem-proving
  - Uses unification, resolution, backward chaining, backtracking
- Programming style: uses recursion, like functional paradigm
- Problem description is higher-level than imperative languages

Prolog

- As database management
  - Start with program as a database of facts
  - Simple queries with constants and variables ("binding"), conjunctions and disjunctions
  - Add to program rules to derive additional facts
  - Two interpretations
    - Declarative: based on logic
    - Procedural: searching for answers to queries
      - Search trees and rule firings can be traced

Facts

```
likes(eve, pie).     food(pie).
likes(al, eve).      food(apple).
likes(eve, tom).     person(tom).
likes(eve, eve).
```

predicates

constants

Queries (Asking Questions)

```
likes(eve, pie).      food(pie).
likes(al, eve).       food(apple).
likes(eve, tom).      person(tom).
likes(eve, eve).
```

variable

```
?-likes(al,eve).
yes
?-likes(al, pie)
no
?-likes(eve,al).
no
?-likes(person,food).
no
```

query

answer

```
?-likes(al,Who).
Who=eve
?-likes(eve,W).
W=pie  ;
W=tom  ;
W=eve  ;
no
```

answer with variable binding

force search for more answers

Harder Queries

```
likes(eve, pie).      food(pie).
likes(al, eve).       food(apple).
likes(eve, tom).      person(tom).
likes(eve, eve).
```

```
?-likes(A,B).
A=eve,B=pie ; A=al,B=eve ; …
?-likes(D,D).
D=eve ; no
?-likes(eve,W), person(W).
W=tom
?-likes(al,V), likes(eve,V).
V=eve ;  no
```

and

Harder Queries

```
likes(eve, pie).     food(pie).
likes(al, eve).      food(apple).
likes(eve, tom).     person(tom).
likes(eve, eve).
```

same binding

```
?-likes(eve,W),likes(W,V).
W=eve,V=pie ; W=eve,V=tom ; W=eve,V=eve
?-likes(eve,W),person(W),food(V).
W=tom,V=pie ; W=tom,V=apple
?-likes(eve,V),(person(V);food(V)).
V=pie  ; V=tom ; no
?-likes(eve,W),\+likes(al,W).
W=pie ; W=tom ; no
```

or

not

Rules

```
likes(eve, pie).     food(pie).
likes(al, eve).      food(apple).
likes(eve, tom).     person(tom).
likes(eve, eve).
```

What if you want to ask the same question often? Add a *rule* to the database:

```
rule1:-likes(eve,V),person(V).
```

```
?-rule1.
yes
```

Rules

```
likes(eve, pie).     food(pie).
likes(al, eve).      food(apple).
likes(eve, tom).     person(tom).
likes(eve, eve).
rule1:-likes(eve,V),person(V).
rule2(V):-likes(eve,V),person(V).
```

```
?-rule2(H).
H=tom ; no
?-rule2(pie).
no
```

Note rule1 and rule2 are just like any other predicate!

Queen Victoria Example

cf Clocksin and Mellish

```
male(albert).          a fact
female(alice).         Facts are put in a file.
male(edward).
female(victoria).
parents(edward,victoria,albert).
parents(alice,victoria,albert).
?- [family].           loads file
yes
?- male(albert).       a query
yes
?- male(alice).
no
?- parents(edward,victoria,albert).
yes
?- parents(bullwinkle,victoria,albert).
no
```

Queen Victoria Example, cont.

- Problem: facts alone do not make interesting programs possible. Need variables and deductive rules.

`?-female(X).` *a query or proposed fact*

`X = alice ;` *; asks for more answers*

`X = victoria ;` *if user types <return> then no more answers given*

`no` *when no more answers left, return no*

- Variable X has been unified to all possible values that make `female(X)` true.
  - Performed by pattern match search
- Variables are capitalized, predicates and constants are lower case

Queen Victoria Example, cont.

```
sister_of(X,Y):-
  female(X),parents(X,M,F),parents(Y,M,F).
```

a rule

```
?- sister_of(alice,Y).
Y = edward
?- sister_of(alice, victoria).
no
```

Horn Clauses (logical foundations)

- A Horn Clause is: $c \leftarrow h_1 \wedge h_2 \wedge h_3 \wedge \dots \wedge h_n$
  - *Antecedents*(h's): conjunction of zero or more conditions which are *atomic formulae* in predicate logic
  - *Consequent*(c): an atomic formula in predicate logic
- Meaning of a Horn clause:
  - *The consequent is true if the antecedents are all true*
  - c is true if h_1, h_2 , h_3 , . . . , and h_n are all true

```
likes(calvin,hobbes) ← tiger(hobbes), child(calvin).
```

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Horn Clauses

- In Prolog, a Horn clause $c \leftarrow h_1 \wedge \dots \wedge h_n$ is written `c :- h1 , ... , hn.`
- Horn Clause is a Clause
- Consequent is a Goal or a Head
- Antecedents are Subgoals or Tail
- Horn Clause with No Tail is a Fact

  `male(edward).` *dependent on no other conditions*
- Horn Clause with Tail is a Rule

```
father(albert,edward) :-
  male(edward),parents(edward,M,albert).
```

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Horn Clauses

- Variables may appear in the antecedents and consequent of a Horn clause:
  - $c(X_1, . . . ,X_n)$:- $h(X_1 , . . . ,X_n,Y_1 , . . . ,Y_k)$.
    For all values of $X_1 , . . . ,X_n$, the formula $c(X_1, . . . ,X_n)$ is true if there exist values of $Y_1, . . . ,Y_k$ such that the formula $h(X_1 , . . . ,X_n, Y_1 , . . . ,Y_k)$ is true
  - Call Y_i an auxiliary variable. Its value will be bound to make consequent true, but not reported by Prolog, because it doesn't appear in the consequent.

Declarative Semantics

- Prolog program consists of facts and rules
- Rules like

```
sister_of(X,Y):-
female(X),parents(X,M,F),parents(Y,M,F).
```

correspond to logical formulas

$\forall$X,Y . sister_of(X,Y) $\leftarrow \exists$ M,F . female(X), parents(X,M,F), parents(Y,M,F).

/ X is the sister of Y, if X is female, and there are M and F who are X's parents, and Y's parents */*

- Note that variables not in head are existentially quantified

Declarative Semantics

- A query is a conjunction of atoms, to be proven
  - If query has no variables and is provable, answer is *yes*
  - If query has variables, proof process causes some variables to be bound to values (called a *substitution*); these are reported

Example

```
?-sister_of(X,Y):
   female(X),parents(X,M,F),parents(Y,M,F).
?-sister_of(alice,Y).
Y = edward
?-sister_of(X,Y).
X = alice
Y = edward  ;
X = alice
Y = alice ;
no
```

```
(1)male(albert).
(2)female(alice).
(3)male(edward).
(4)female(victoria).
(5)parents(edward,victoria,albert).
(6)parents(alice,victoria,albert).
```

What's wrong here?

Example shows
-subgoal order of evaluation
-argument invertability
-backtracking
-computation in rule order

Procedural Semantics

```
?-sister_of(X,Y):
  female(X),parents(X,M,F),parents(Y,M,F).
```

- First *find* an `X` to make `female(X)` true
- Second *find* an `M` and `F` to make `parents(X,M,F)` true for that `X`.
- Third *find* a `Y` to make `parents(Y,M,F)` true for those `M,F`
- This algorithm is recursive; each *find* works on a new "copy" of the facts+rules. eventually, each find must be resolved by appealing to facts.
- Process is called *backward chaining.*
- Variables are *local;*
  - (every time rule is used, new names for X,Y,M,F)

Prolog Rule Ordering and Unification

- Rule ordering (from first to last) used in search
- Unification requires all instances of the same variable in a rule to get the same value
- Unification does not require differently named variables to get different values: `sister_of(alice, alice)`
- All rules searched if requested by successive typing of ;

Example

```
sis(X,Y):-female(X),parents(X,M,F),
     parents(Y,M,F),\+(X==Y).
```

`?-sis(X,Y).` *last subgoal disallows X,Y to have same value*

```
X=alice
Y=edward  ;
no
```

= means *unifies with*

== means *same in value*

Negation as Failure

- \+(P) succeeds when P fails
  - Called negation by failure, defined:

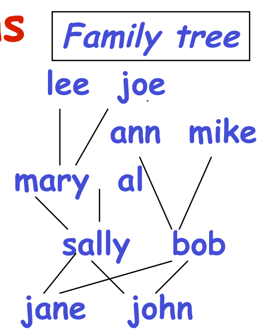
```
not(X):-X,!,fail.
not(_).
```

- Which means
  - if X succeeds in first rule, then the rule is forced to fail by the last subgoal (`fail`).we cannot backtrack over the cut (!) in the first rule, and the cut prevents us from accessing the second rule.
  - if X fails, then the second rule succeeds, because "_" (or don't_care) unifies with anything.

Negation by Failure

- Not equivalent to logical *not* in Prolog
  - Prolog can only assert that something is true
  - Prolog cannot assert that something is false, but only that it cannot be proven with the given rules

Transitive Relations




```
parents(jane,bob,sally).
parents(john,bob,sally).
parents(sally,al,mary).
parents(bob,mike,ann).
parents(mary,joe,lee).
ancestor(X,Y) :- parents(X,Y,_).
ancestor(X,Y) :- parents(X,_,Y).
ancestor(X,Y) :- parents(X,W,_),ancestor(W,Y).
ancestor(X,Y) :- parents(X,_,W), ancestor(W,Y).

?- ancestor(jane,X).
X = bob ;
X = sally ;
X = mike ;
X = ann ;
X= al ;
X = mary ;
X = joe ;
X = lee ;
No
```

Logic Programming vs Prolog

- Logic Programming: Nondeterministic
  - Arbitrarily choose rule to expand first
  - Arbitrarily choose subgoal to explore first
  - Results don't depend on rule and subgoal ordering
- Prolog: Deterministic
  - Expand first rule first
  - Explore first(leftmost) subgoal first
  - Results may depend on rule and subgoal ordering

Minimal Prolog Syntax

<rule> ::= (<head> :- <body> .) | <fact> .

<head> ::= <predicate>

<fact> ::= <predicate>

<body> ::= <predicate> { , <predicate> }

<predicate> ::= <functor> (<term> {
,<term>})

<term> ::= <integer> | <atom> | <variable>|
<predicate>

<query> ::= ?- <predicate>