Prolog

- Logic programming (declarative)
  - Goals and subgoals
- Prolog Syntax
- Database example
  - rule order, subgoal order, argument invertibility, backtracking model of execution, negation by failure, variables
- Data structures (lists, trees)
  - Recursive Functions: append, member
  - Lazy evaluation, terms as trees, Prolog search trees
- Models of execution
  - Goal-oriented semantics
  - Procedural view

Intro to Logic Programming

- Specifies relations between objects

  larger (2,1), father (tom, jane)
- Separates control in PL from description of desired outcome

  father(X, jane) :- male(X), parent(X, jane).
- Computation engine: theorem proving and recursion
  - Higher-level PL than imperative languages
  - More accessible to non-technical people

Horn Clauses

- Conjunct of 0 or more conditions which are atomic formulae in predicate logic (constants, predicates, functions)

  $h_1 \wedge h_2 \wedge_{\dots} \wedge h_n \rightarrow c$

- Means c if $h_1, h_2, \dots, h_n$ are all true
- Can have variables in the h_i 's or c

  $c(x_1, x_2, \dots, x_m)$ if $h(x_1, x_2, \dots, x_m, y_1, \dots, y_k)$

  means for all objects $x_1, x_2, \dots, x_m$, c holds if there are objects $y_1, \dots, y_k$ such that h holds.

  father(X, jane) :- male(X), parents(X, Y, jane)

Logic Programming

- Goal-oriented semantics
  - goal is true for those values of variables which make each of the subgoals true
    - *father(X, jane)* will be true if *male(X)* and *parents(X,Y, jane)* are true with specific values for *X* and *Y*
  - recursively apply this reasoning until reach rules that are facts.
  - called *backwards chaining*

Logic Programming

- **Nondeterminism**
  - Choice of rule to expand subgoal by
  - Choice of subgoal to explore first

father(X, jane):- male(X), parents(X, Y, jane).
father (X,jane):- father (X,Y), brother(Y, jane).
which rule to use first? which subgoal to explore first?

- **Prolog tries rules in sequential order and proves subgoals from left to right. - Deterministic!**

Victoria Database Program

victoria.pl
from Clocksin and Mellish

predicate

constants

```
male(albert).
male(edward).
female(alice).
female(victoria).
parents(edward,victoria,albert).
parents(alice,victoria,albert).
?- male(albert).
yes
?- male(alice).
no
?-female(X).
X = alice ;
X = victoria ;
no
```

variable

By responding
<cr> you quit the query
; <cr> you continue to find another variable binding that makes the query true.

Victoria Example

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

```
?-female(X).
X = alice    ;
X = victoria   ;
```

a query or proposed fact

; asks for more answers

if user types <cr> 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 capitalized, predicates and constants are lower case

Victoria Example

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

a rule

- Prolog program consists of facts, rules, and queries
- A query is a proposed fact, needing to be proven
  - If query has no variables and is provable, answer is *yes*
  - If query has variables, the proof process causes some variables to be bound to values which are reported (called a *substitution*)

Victoria Example, cont.

```
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

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

first answer from 3.+6.+5.

second answer from 3.+6.+6.

Subgoal order, argument invertibility, backtracking, rule order

Victoria Example, cont.

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

?- sis(X,Y).
```

X = alice

Y = edward ;

no

= means *unifies with*

== means *same in value*

\+ (P) succeeds when P fails; called negation by failure

Negation by Failure

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

if X succeeds in first rule, then the goal fails because of the last term.

if we type ";" the cut (!) will prevent us from backtracking over it or trying the second rule so there is no way to undue the fail.

if X fails in the first rule, then the goal fails because subgoal X fails. the system tries the second rule which succeeds, since "_" unifies with anything.

Procedural Semantics

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

Semantics:

- 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.*

Prolog Syntax in EBNF

15 jane X

<term> → <integer> | <atom> | <variable> |
<functor> (<term> {, <term>})

head :- body

<rule> → <predicate> (<term> {, <term>}):-
<term> {, <term>} . | <fact>

<fact> → <functor> (<term>) {, <term>}).

<query> → ?- <functor>(<term>{,<term>}).

a proposed fact that must be proven

Syntax

- **Names come from first order logic**

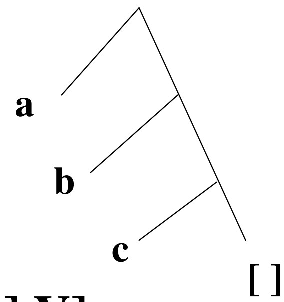
  a(X,Y) :- b (c(Y)), integer(X).

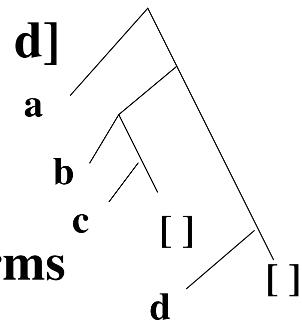
  - **Predicates are evaluated**
  - **Functors with terms are unified**
  - **Call this a clause or rule**

  cf. "Computing with Logic", D. Warren and D. Meyers

Lists

<u>list</u>	<u>head</u>	<u>tail</u>
[a,b,c]	a	[b,c]
[X, [cat], Y]	X	[[cat],Y]
[a, [b, c], d]	a	[[b,c], d]
[X ǀ Y]	X	Y





a list consists of a sequence of terms

Unifying Lists

[X,Y,Z] = [john, likes, fish]

X = john, Y = likes, Z = fish

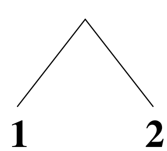
[cat] = [X ǀ Y]

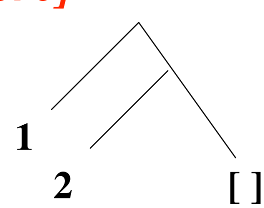
X = cat, Y = [ ]

[[the, Y] ǀ Z] = [[X, hare] ǀ [is, here]]

X = the, Y = hare, Z = [is , here]

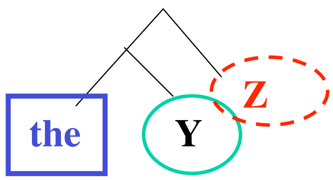
[1 ǀ 2] versus [1, 2]

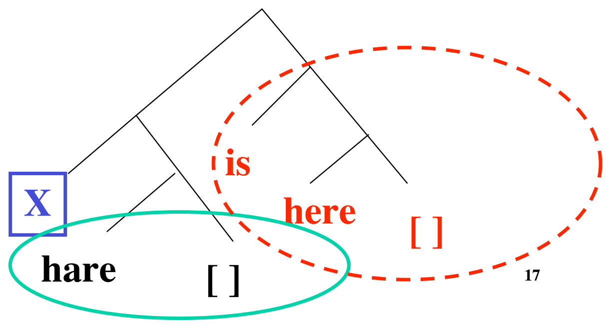




Lists

- Sequence of elements separated by commas, or
- [first element | rest_of_list]
  - [car(list) | cdr(list)] notation
- [[the | Y] | Z] = [[X, hare] | [is, here]]

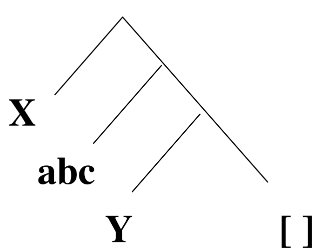


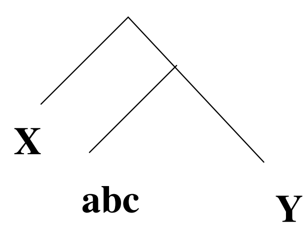


Lists

[X, abc, Y] =? [X, abc | Y]

thre is no value binding for Y, to make these two trees isomorphic.





Lists

don't care variable unifies with anything

[a,b | Z] =? [X | Y]

X = a, Y = [b | Z], Z = _

look at the trees to see why this works!

[a, b, c] = [X | Y]

X = a, Y = [b,c] ;

no

Member_of Function

member(A, [A | B]).

member(A, [B | C]) :- member (A, C).

goal-oriented semantics: can get value assignment for goal member(A,[B|C]) by showing truth of subgoal member(A,C) and retaining value bindings of the variables

procedural semantics: think of head of clause as procedure entry, terms as parameters. then body consists of calls within this procedure to do the calculation. variables bindings are like "returned values".

Example

```
?- member(a,[a,b]).
   yes
?- member(a,[b,c]).
   no
?- member(X,[a,b,c]).
   X = a  ;
   X = b ;
   X = c ;
   no
```

Invertibility of Prolog arguments

1. member(A, [A | B]).
2. member(A, [B | C]) :- member (A, C).

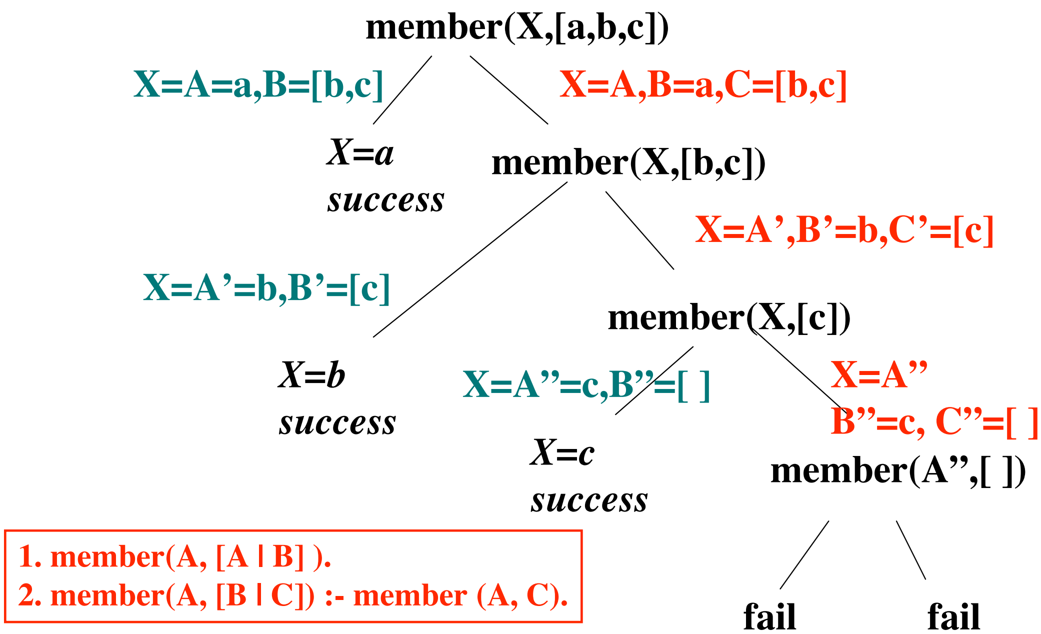
Example

```
?- member(a,[b, c, X]).
   X= a  ;
   no
?- member(X,Y).
   X = _123
   Y = [ X | _124] ) ;
   X = _123
   Y = [_125, X | _126]  ;
   X = _123
   Y =  [ _127, _128, X |_129]
```

1. member(A, [A | B]).
2. member(A, [B | C]) :- member (A, C).

Lazy evaluation of *a priori* unbounded list structure. Unbound X variableis first element, then second element, then third element, in a sequence of generated lists of increasing length.

Prolog Search Tree



1. member(A, [A | B]).
2. member(A, [B | C]) :- member (A, C).

?- member(X, [a,b,c]).

match rule 1. member(A, [A | B]) so X = A = a, B = [b,c]

X = a ;

match rule 2. member(A, [B | C]) so X = A, B = a, C = [b,c]

then evaluate subgoal member(X, [b,c])

match rule 1. member(A’,[A’ | B’]) so X = b, B’ = [c]

X = b ;

match rule 2. member(A’,[B’ | C’]) so X = A’, B’ = b, C’ = [c]

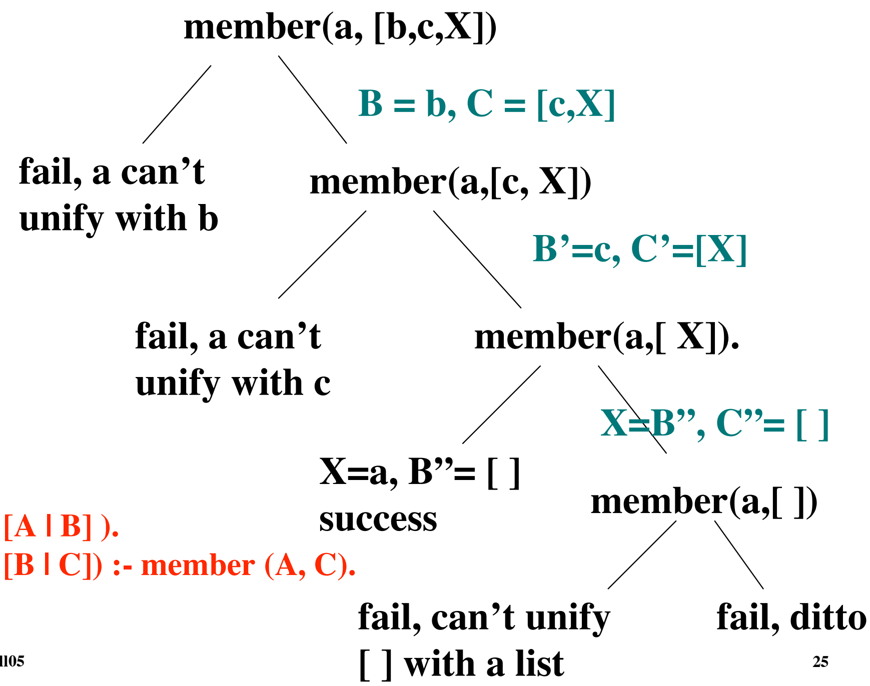
then evaluate subgoal member(X, [c])

match rule 1. member(A”,[A” | B”]) so X=A”= c, B”=[ ]

X = c ;

match rule 2. member(A”,[B” | C”]) so X=A”, B”=c, C”=[ ], but member(X, [ ]) is unsatisfiable, *no*

Another Search Tree



1. member(A, [A | B]).
2. member(A, [B | C]) :- member (A, C).

Prolog Search Trees

- Really have built an evaluation tree for the query `member(X,[a,b,c]).`
- Search trees provide a formalism to consider all possible computation paths
- Leaves are success nodes or failures where computation can proceed no further
  - Can have more than 1 of each type of node
- By convention, to model Prolog, leftmost subgoal is tried first

Prolog Search Trees, cont.

- **Label edges with variable bindings that occur by *unification***
- **There can be infinite branches in the tree, representing non-terminating computations (performed lazily by Prolog);**
  - ***Lazy evaluation* implies only generate a node when needed.**

Another Member_of Function

Equivalent set of rules:

```
mem(A,[A|_] ).
mem(A,[_| C]) :- mem(A,C).
```

Can examine search tree and see the variables which have been excised were auxiliary variables in the clauses.

Append Function

```
append ([ ],A,A).
append([A|B],C,[A|D]):- append(B,C,D).
```

- Build a list

  `?- append([a],[b],Y).`

  Y = [a,b]

- Break a list into constituent parts

  `?- append(X,[b],[a,b]).`

  X = [a]

  `?- append([a],Y,[a,b]).`

  Y = [b]

More Append

`?- append(X, Y, [a,b]).`

X = [ ]

Y = [a, b] ;

X = [a]

Y = [b] ;

X = [a,b]

Y = [ ] ;

no

```
append ([ ],A,A).
append([A|B],C,[A|D]):- append(B,C,D).
```

Still More Append

- **Generating an unbounded number of lists**

```
?- append(X, [b], Y).
```

X = [ ]

Y = [b]   ;

X = [_169]

Y = [_169, b]   ;

X = [_169, _170]

Y = [_169, _170, b] ;

etc.

```
append ([ ],A,A).
append([A|B],C,[A|D]):- append(B,C,D).
```


Common Beginner's Errors

- **Compile-time**
  - Forget ending "."
  - Misspelled functors
  - Need to override precedences with (..)
- **Runtime**
  - Infinite loops - check your recursion
  - Variables instantiated with unexpected values
  - Circular definitions
  - Giving wrong numbers of arguments to a clause

Examples Online on Paul

- /grad/users/ryder/prolog/programs/ contains examples of Prolog programs
- /grad/users/ryder/prolog/newtraces/ contains traces of runs of these programs
- Remember, to run these you need to copy them to your own working directory so you can write on them