Logic Programming: Prolog

COMS W4115

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Logic

All Caltech graduates are nerds.
Stephen is a Caltech graduate.
Is Stephen a nerd?

Prolog

All Caltech graduates are nerds. \( \text{nerd}(X) \leftarrow \text{techer}(X) \).
Stephen is a Caltech graduate. \( \text{techer}(\text{stephen}) \).
Is Stephen a nerd? \( \text{?- nerd}(\text{stephen}). \)

More Logic

“My Enemy’s Enemy is My Friend.”

friend(X, Z) :-
    enemy(X, Y), enemy(Y, Z).

enemy(\text{stephen}, \text{ryan}).
enemy(\text{ryan}, \text{jordan}).
enemy(\text{jordan}, \text{jacob}).

?- friend(\text{stephen}, \text{jordan}).

?- friend(\text{stephen}, X).

?- friend(X, \text{stephen}).

X = \text{jordan}
X = \text{stephen Y = jordan}
X = \text{ryan Y = jacob}

More Logic

“The Basic Idea of Prolog

- AI programs often involve searching for the solution to a problem.
- Why not provide this search capability as the underlying idea of the language?
- Result: Prolog

The Basic Idea of Prolog

Prolog

Mostly declarative.
Program looks like a declaration of facts plus rules for deducing things.
“Running” the program involves answering questions that refer to the facts or can be deduced from them.
More formally, you provide the axioms, and Prolog tries to prove theorems.

Prolog

简单搜索

Starts with the query:

?- \text{nerd}(\text{stephen}).

Can we convince ourselves that \text{nerd}(\text{stephen}) is true given the facts we have?

\text{techer}(\text{stephen}).
\text{nerd}(X) \leftarrow \text{techer}(X).

First says \text{techer}(\text{stephen}) is true. Not helpful.
Second says that we can conclude \text{nerd}(X) is true if we can conclude \text{techer}(X) is true. More promising.

Prolog

Prolog Execution

Facts

\text{nerd}(X) \leftarrow \text{techer}(X).
\text{techer}(\text{stephen}).

Query

?- \text{nerd}(\text{stephen}).

Search (Execution)

Result

yes

Prolog

Simple Searching

\text{techer}(\text{stephen}).
\text{nerd}(X) \leftarrow \text{techer}(X).

?- \text{nerd}(\text{stephen}).

Unifying \text{nerd}(\text{stephen}) with the head of the second rule, \text{nerd}(X), we conclude that \( X = \text{stephen} \).
We’re not done: for the rule to be true, we must find that all its conditions are true. \( X = \text{stephen} \), so we want \text{techer}(\text{stephen}) to hold.
This is exactly the first clause in the database; we’re satisfied. The query is simply true.
More Clever Searching

`techer(stephen).`  
`techer(todd).`  
`nerd(X) :- techer(X).`  

`?- nerd(X).`  

"Tell me about everybody who’s provably a nerd."

As before, start with query. Rule only interesting thing.

Unifying `nerd(X)` with `nerd(X)` is vacuously true, so we need to establish `techer(X)`.

Unifying `techer(X)` with `techer(stephen)` succeeds, setting `X = stephen`, but we're not done yet.

Unifying `techer(X)` with `techer(todd)` also succeeds, setting `X = todd`, but we're still not done.

Unifying `techer(X)` with `nerd(X) :- techer(X)` fails, returning no.

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Order Matters

> `/tmp/beta-prolog/bp`  
`?- [user].`  
`| :techer(todd).`  
`| :techer(stephen).`  
`| :nerd(X) :- techer(X).`  
`| :D`  
`yes`  
`| ?- nerd(X).`  
`X = stephen?;`  
`X = todd?;`  
`no`  
`| `-`  

Searching and Backtracking

Unification

Part of the search procedure that matches patterns.

The search attempts to match a goal with a rule in the database by unifying them.

Recursive rules:

- A constant only unifies with itself
- Two structures unify if they have the same functor, the same number of arguments, and the corresponding arguments unify
- A variable unifies with anything but forces an equivalence

Unification Examples

The `=` operator checks whether two structures unify:

| ?- a = a.       | % Constant unifies with itself  
| yes              |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |�
| yes              |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |�
| ?- a = b.        | % Mismatched constants  
| yes              |       |       |       |       |       |       |       |       |�
| no               | % Mismatched constants  
| ?- 5.3 = a.      | % Variables unify  
| yes              |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |�
| no               |       |       |       |       |       |       |       |�
| ?- 5.3 = X       | % Mismatched constants  
| yes              |       |�
| no               |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |�
| ?- foo(a, X) = foo(X, b). | % X=a required, but inconsistent  
| yes              |       |       |       |�
| no               |       |       |       |       |       |       |       |�
| ?- foo(a, X) = foo(a, Y). | % X=a is consistent  
| yes              |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |�
| no               |       |       |       |       |       |       |       |       |       |       |�
| ?- foo(X, b) = foo(a, Y). | % X=b required, but inconsistent  
| yes              |       |       |       |       |�
| no               |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |�

The Prolog Environment

Database consists of clauses.

Each clause consists of terms, which may be constants, variables, or structures.

Constants: `foo my_const + 1.43`

Variables: `X Y Everybody My_var`

Structures: `rainy(rochester)`  
`teaches(edwards, cs4115)`

Structures and Functors

A structure consists of a functor followed by an open parenthesis, a list of comma-separated terms, and a close parenthesis:

```
bin_tree( foo, bin_tree(bar, glarch) )
```

What's a structure? Whatever you like.

A predicate `nerd(stephen)`  
A relationship `teaches(edwards, cs4115)`  
A data structure `bin(+, bin(-, 1, 3), 4)`
The Searching Algorithm

search(goal \( g \), variables \( e \))

for each clause \( h :- t_1, \ldots, t_n \) in the database
\( e = \text{unify}(g, h, e) \)
if successful,
for each term \( t_1, \ldots, t_n \),
\( e = \text{search}(t_k, e) \)
if all successful, return \( e \)
return \text{no}

Order matters

search(goal \( g \), variables \( e \)) In the order they appear
for each clause \( h :- t_1, \ldots, t_n \) in the database
\( e = \text{unify}(g, h, e) \)
if successful, In the order they appear
for each term \( t_1, \ldots, t_n \),
\( e = \text{search}(t_k, e) \)
if all successful, return \( e \)
return \text{no}

Order Affects Efficiency

Consider the query
\( \text{?- path(a, a)}. \)

Good programming practice: Put the easily-satisfied clauses first.

Order Affect Efficiency

\begin{align*}
\text{edge}(a, b). & \quad \text{edge}(b, c). \\
\text{edge}(c, d). & \quad \text{edge}(d, e). \\
\text{edge}(b, e). & \quad \text{edge}(d, f). \\
\text{path}(X, Y) :- & \quad \text{path}(X, Z), \text{edge}(Z, Y). \\
\text{path}(X, X). &
\end{align*}

Consider the query
\( \text{?- path(a, a)}. \)

Will eventually produce the right answer, but will spend much more time doing so.

Order can cause Infinite Recursion

\begin{align*}
\text{edge}(a, b). & \quad \text{edge}(b, c). \\
\text{edge}(c, d). & \quad \text{edge}(d, e). \\
\text{edge}(b, e). & \quad \text{edge}(d, f). \\
\text{path}(X, Y) :- & \quad \text{path}(X, Z), \text{edge}(Z, Y). \\
\text{path}(X, X). &
\end{align*}

Consider the query
\( \text{?- path(a, a)}. \)

Like LL(k) grammars.

Bill and Ted in Prolog

\begin{align*}
\text{super_band}(X) :- & \quad \text{on_guitar}(X, \text{eddie_van_halen}). \\
\text{on_guitar}(X, \text{eddie_van_halen}) :- & \quad \text{triumphant_video}(X). \\
\text{triumphant_video}(X) :- & \quad \text{decent_instruments}(X). \\
\text{decent_instruments}(X) :- & \quad \text{know_how_to_play}(X). \\
\text{know_how_to_play}(X) :- & \quad \text{on_guitar}(X, \text{eddie_van_halen}). \\
\text{super_band}(\text{wyld_stallyns}). &
\end{align*}

What will Bill and Ted do?

Prolog as an Imperative Language

A declarative statement such as
\( P \text{ if } Q \text{ and } R \text{ and } S \)
can also be interpreted procedurally as
To solve \( P \), solve \( Q \), then \( R \), then \( S \).

This is the problem with the last path example.
\( \text{path}(X, Y) :- \text{path}(X, Z), \text{edge}(Z, Y). \)

“To solve \( P \), solve \( P \ldots \)"

Prolog as an Imperative Language

\begin{align*}
\text{go} :- & \quad \text{print}(\text{hello}_{}), \text{print}(\text{world}). \\
\text{?- go}. &
\end{align*}

Hello world

yes

Cuts

Ways to shape the behavior of the search:
- Modify clause and term order.
  Can affect efficiency, termination.
- “Cuts”
  Explicitly forbidding further backtracking.
When the search reaches a cut (!), it does no more backtracking.

```
teacher(stephen) :- !.
teacher(todd).
nerd(X) :- teacher(X).
?- nerd(X).
X = stephen; no
```

## Controlling Search Order

Prolog's ability to control search order is crude, yet often critical for both efficiency and termination.

- **Clause order**
- **Term order**
- **Cuts**

Often very difficult to force the search algorithm to do what you want.

### Elegant Solution Often Less Efficient

Natural definition of sorting is inefficient:

```
sort(L1, L2) :- permute(L1, L2), sorted(L2).
permute([], []).
permute([H|T]) :- append(P, [H|S], L), append(P, S, W), permute(W).

?- sort([1, 2, 3, 4, 5], L).
L = [1, 2, 3, 4, 5].
```

Instead, need to make algorithm more explicit:

```
qsort([], []).
qsort([A|L1, L2) :- part(A, L1, P1, S1), qsort(P1, P2), qsort(S1, S2), append(P2, [A|S2], L2).
part(A, [], [], []).
part(A, [H|T], [H|P], S) :- A >= H, part(A, T, P S).
```