Lecture 6: Prolog

2-AIN-108 Computational Logic

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Example

Logic Program:

$$
\begin{array}{rcl}
father(abraham, isaac) & \leftarrow & \\
mother(sarah, isaac) & \leftarrow & \\
father(isaac, jacob) & \leftarrow & \\
parent(X, Y) & \leftarrow & father(X, Y) \\
parent(X, Y) & \leftarrow & mother(X, Y) \\
grandparent(X, Z) & \leftarrow & parent(X, Y), parent(Y, Z) \\
ancestor(X, Y) & \leftarrow & parent(X, Y) \\
ancestor(X, Z) & \leftarrow & parent(X, Y), ancestor(Y, Z)
\end{array}
$$

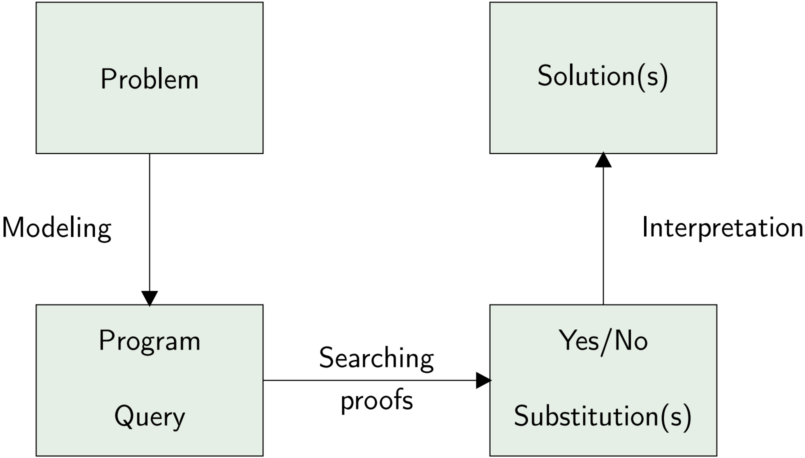
Query:

$$(\exists X)(\exists Y) ancestor(X, Y)?$$

Answer:

Yes for $X = abraham, Y = isaac; X = sarah, Y = isaac;$
$X = abraham, Y = jacob.$

Programming with Prolog



SLD-resolution $\equiv$ Linear resolution with Selection function for Definite clauses.

Definition (Resolvent)

Let G be a definite goal $A_1 \wedge \cdots \wedge A_{k-1} \wedge A_k \wedge A_{k+1} \wedge \cdots \wedge A_m$, A_k be a selected atom, and r be a definite rule $B_0 \leftarrow B_1 \wedge \cdots \wedge B_n$. We say that a definite goal G' is a resolvent derived from G and r using θ if θ is the most general unifier of A_k and B_0 and G' has the form $\leftarrow (A_1 \wedge \cdots \wedge A_{k-1} \wedge B_1 \wedge \cdots \wedge B_n \wedge A_{k+1} \wedge \cdots \wedge A_m)\theta$.

SLD-Derivation

Definition (SLD-derivation)

Let P be a definite logic program and G be a definite goal. An SLD-derivation of $P \cup \{G\}$ is a (posibly infinite) sequence of goals $G = G_0, \ldots, G_i, \ldots,$ where each G_{i+1} is a resolvent obtained from G_i and a rule r_{i+1} from P using θ_{i+1}.

Definition (Successful, Failed, and Infinite Derivation)

A successful derivation ends in empty goal $\leftarrow$. A failed derivation ends in non-empty goal with the property that all atoms does not unify with the head of any rule. An infinite derivation is an infinite sequence of goals.

SLD-Tree

Definition (SLD-Tree)

Let P be a definite logic program and G be a definite goal.
An SLD-tree for $P \cup \{G\}$ is a minimal tree satisfying the following:

- Each node of the tree is a (possibly empty) definite goal
- The root is G
- If G' is a node of the tree and G'' is a resolvent derived from G', then G' has a child G''

Standard Prolog

- selects the first literal in the goal
- chooses rules for unification in order as they appear in the logic program
- uses depth-first search strategy

Answer

Definition (Correct Answer)

Let P be a definite logic program and G be a definite goal. An answer for $P \cup \{G\}$ is a substitution for variables in G. An answer θ for $P \cup \{G\}$ is correct iff $P \models (A_1 \wedge \cdots \wedge A_n)\theta$ where $G = \leftarrow A_1 \wedge \cdots \wedge A_n$.

Definition (Computed Answer)

Let $G_0, \ldots, G_n$ be a successful derivation using $\theta_1, \ldots, \theta_n$. Then $\theta_1 \ldots \theta_n$ restricted to the variables of G is the computed answer.

Soundness and Completeness

Theorem (Soundness)

Let P be a definite logic program and G be a definite goal. Every computed answer for $P \cup \{G\}$ is a correct answer for $P \cup \{G\}$.

Theorem (Completeness)

Let P be a definite logic program and G be a definite goal. For every correct answer θ for $P \cup \{G\}$ there exists a computed answer σ for $P \cup \{G\}$ and a substitution γ such that $\theta = \sigma\gamma$.

Fact (Termination)

SLD-resolution may not terminate.

SLDNF-Resolution

SLD-resolution augmented by the negation as failure rule.

Definition (Resolvent)

Let G be a normal goal $L_1 \wedge \cdots \wedge L_{k-1} \wedge L_k \wedge L_{k+1} \wedge \cdots \wedge L_m$, L_k be a selected atom A, and r be a normal rule $B \leftarrow M_1 \wedge \cdots \wedge M_n$. We say that a normal goal G' is a resolvent derived from G and r using θ if θ is the most general unifier of A and B and G' has the form $\leftarrow (L_1 \wedge \cdots \wedge L_{k-1} \wedge M_1 \wedge \cdots \wedge M_n \wedge L_{k+1} \wedge \cdots \wedge L_m)\theta$.

Definition (Negation as Failure Rule)

Let G be a normal goal $L_1 \wedge \cdots \wedge L_{k-1} \wedge L_k \wedge L_{k+1} \wedge \cdots \wedge L_m$ and L_k be a selected negated atom $\sim A$. We say that a normal goal G' is obtained from G using negation as failure rule if $P \cup \{\leftarrow A\}$ has finitely failed SLDNF-tree and G' has the form
$\leftarrow L_1 \wedge \cdots \wedge L_{k-1} \wedge L_{k+1} \wedge \cdots \wedge L_m$.

SLDNF-Derivation

Definition (SLDNF-Derivation)

Let P be a normal logic program and G be a normal goal.
An SLDNF-derivation of $P \cup \{G\}$ is a (possibly infinite) sequence of goals $G = G_0, \ldots, G_i, \ldots$ where each G_{i+1}

- is derived from G_i and a rule r_{i+1} from P using θ_{i+1}, or
- is obtained from G_i using negation as failure rule on selected literal $\sim A$. In such case, $r_{i+1} = \leftarrow A$ and θ_{i+1} is identity.

Definition (Successful, Failed, and Infinite Derivation)

A successful derivation ends in empty goal $\leftarrow$. A failed derivation ends in non-empty goal with the property that the selected literal is

- an atom which do not unify with the head of any rule, or
- a negated atom which do not have finitely failed SLDNF-tree.

An infinite derivation is an infinite sequence of goals.

SLDNF-Tree

Definition (SLDNF-Tree)

Let P be a normal logic program and G be a normal goal.
An SLDNF-tree for $P \cup \{G\}$ is a minimal tree satisfying the following:

- Each node of the tree is a (possibly empty) normal goal
- The root is G
- If G' is a node of the tree and G'' is a resolvent derived from G', then G' has a child G''
- If G' is a node of the tree and G'' is obtained from G' using negation as failure rule, then G' has a child G''

Definition (Finitely Failed SLDNF-Tree)

A finitely failed SLDNF-tree is finite and has only failed branches.

SLDNF-Derivation and SLDNF-Tree

Please note, that SLDNF-tree is defined in terms of SLDNF-derivation, and SLDNF-derivation is defined in terms of SLDNF-tree. Such cyclic definitions are not correct. Proper definitions are much more complex, although they capture the same idea. They can be found in:

Lloyd, J. W. (1987). Foundations of Logic Programming. Springer.

Answer

Definition (Correct Answer)

Let P be a normal logic program and G be a normal goal. An answer for $P \cup \{G\}$ is a substitution for variables in G. An answer θ for $P \cup \{G\}$ is correct iff $Comp(P) \models (L_1 \wedge \cdots \wedge L_n)\theta$ where $G = \leftarrow L_1 \wedge \cdots \wedge L_n$.

Definition (Computed Answer)

Let $G_0, \ldots, G_n$ be a successful derivation using $\theta_1, \ldots, \theta_n$. Then $\theta_1 \ldots \theta_n$ restricted to the variables of G is the computed answer.

Soundness and Completeness

Theorem (Soundness)

Let P be a normal logic program and G be a normal goal. Every computed answer for $P \cup \{G\}$ is a correct answer for $P \cup \{G\}$.

Fact (Termination)

SLDNF-resolution may not terminate.

Fact (Completeness)

SLDNF-resolution is not complete. Even if it terminates, it may not compute all answers (see floundering).

Floundering

```
man(dilbert). man(bill).
husband(bill).
single(X) :- man(X), not(husband(X)).

? single(X).
X = dilbert; No

man(dilbert). man(bill).
husband(bill).
single(X) :- not(husband(X)), man(X).

? single(X).
No
```

Ordering of Rules Matters

```
reverse([], []).
reverse([X|Xs], Zs) :- reverse(Xs, Ys),
                       append(Ys, [X], Zs).

? reverse(Xs, [3,2,1]).
Xs = [1,2,3];
...

reverse([X|Xs], Zs) :- reverse(Xs, Ys),
                       append(Ys, [X], Zs).
reverse([], []).

? reverse(Xs, [3,2,1]).
...
```

Ordering of Literals Matters

```
reverse([], []).
reverse([X|Xs], Zs) :- reverse(Xs, Ys),
                       append(Ys, [X], Zs).

? reverse([1,2,2], Zs).
Zs = [3,2,1];
No

reverse([], []).
reverse([X|Xs], Zs) :- append(Ys, [X], Zs),
                       reverse(Xs, Ys).

? reverse([1,2,3], Zs).
Zs = [3,2,1];
...
```