Computational Logic

Fundamentals of Definite Programs: Syntax and Semantics
Conclusion: resolution is a complete and effective deduction mechanism using:
- Horn clauses (related to “Definite programs”),
- Linear, Input strategy
- Breadth-first exploration of the tree (or an equivalent approach)
  (possibly ordered clauses, but not required – see Selection rule later)
- Very close to what is generally referred to as SLD-resolution (see later)
- This allows to some extent realizing Green’s dream (within the theoretical limits of the formal method), and efficiently!
Towards Logic Programming (Contd.)

- Given these results, why not use logic as a general purpose *programming language*? [Kowalski 74]

- A “logic program” would have two interpretations:
  - *Declarative* (“LOGIC”): the logical reading (facts, statements, knowledge)
  - *Procedural* (“CONTROL”): what resolution does with the program

- ALGORITHM = LOGIC + CONTROL

- Specify these components separately

- Often, worrying about control is not needed at all (thanks to resolution)

- Control can be effectively provided through the ordering of the literals in the clauses
Towards Logic Programming: Another (more compact) Clausal Form

- All formulas are transformed into a set of \textit{Clauses}.

  - A clause has the form:

    \[
    \begin{array}{c}
    \text{conc}_1, \ldots, \text{conc}_m \leftarrow \text{cond}_1, \ldots, \text{cond}_n \\
    \end{array}
    \]

    where \( \text{conc}_1, \ldots, \text{conc}_m \) \( \lor \) \( \text{cond}_1, \ldots, \text{cond}_n \) are literals, and are the \textit{conclusions} and \textit{conditions} of a rule:

    \[
    \begin{array}{c}
    \text{conc}_1, \ldots, \text{conc}_m \leftarrow \text{cond}_1, \ldots, \text{cond}_n \\
    \end{array}
    \]

    \textit{“conclusions”} \( \lor \) \textit{“conditions”}

  - All variables are implicitly universally quantified: (if \( X_1, \ldots, X_k \) are the variables)

    \[
    \forall X_1, \ldots, X_k \quad \text{conc}_1 \lor \ldots \lor \text{conc}_m \leftarrow \text{cond}_1 \land \ldots \land \text{cond}_n
    \]

- More compact than the traditional clausal form:

  - no connectives, just commas

  - no need to repeat negations: all negated atoms on one side, non-negated ones on the other

- A \textit{Horn Clause} then has the form:

  \[
  \begin{array}{c}
  \text{conc}_1 \leftarrow \text{cond}_1, \ldots, \text{cond}_n \\
  \end{array}
  \]

  where \( n \) can be zero and possibly \( \text{conc}_1 \) empty.
Some Logic Programming Terminology – “Syntax” of Logic Programs

- **Definite Program**: a set of positive Horn clauses
  \[
  \text{head} \leftarrow \text{goal}_1, \ldots, \text{goal}_n
  \]
- The single *conclusion* is called the *head*.
- The conditions are called “goals” or “procedure calls”.
- \( \text{goal}_1, \ldots, \text{goal}_n \) \((n \geq 0)\) is called the “body”.
- If \( n = 0 \) the clause is called a “fact” (and the arrow is normally deleted)
- Otherwise it is called a “rule”
- **Query** (question): a negative Horn clause (a “headless” clause)
- A procedure is a set of rules and facts in which the heads have the same predicate symbol and arity.
- Terms in a goal are also called “arguments”.


• Examples:
  grandfather(X,Y) ← father(X,Z), mother(Z,Y).
  grandfather(X,Y) ← .
  grandfather(X,Y).
  ← grandfather(X,Y).
• A rule (has head and body)

\[ \text{head} \leftarrow \text{goal}_1, \ldots, \text{goal}_n. \]

which contains variables \( X_1, \ldots, X_k \) can be read as
for all \( X_1, \ldots, X_k \):
“head” is true if “goal_1” and ... and “goal_n” are true

• A fact n=0 (has only head)

\[ \text{head}. \]

for all \( X_1, \ldots, X_k \): “head” is true (always)

• A query (the headless clause)

\[ \leftarrow \text{goal}_1, \ldots, \text{goal}_n \]

can be read as:
for which \( X_1, \ldots, X_k \) are “goal_1” and ... and “goal_n” true?
• Given a first-order language $L$, with a non-empty set of variables, constants, function symbols, relation symbols, connectives, quantifiers, etc. and given a syntactic object $A$,

$$\text{ground}(A) = \{A\theta \mid \exists \theta \in \text{Subst}, \text{var}(A\theta) = \emptyset\}$$

i.e. the set of all “ground instances” of $A$.

• Given $L$, $U_L$ (*Herbrand universe*) is the set of all ground terms of $L$.

• $B_L$ (*Herbrand Base*) is the set of all ground atoms of $L$.

• Similarly, for the language $L_P$ associated with a given program $P$ we define $U_P$, and $B_P$.

• Example:

$$P = \{ p(f(X)) \leftarrow p(X). \ p(a). \ q(a). \ q(b). \}$$
$$U_P = \{a, b, f(a), f(b), f(f(a)), f(f(b)), \ldots\}$$
$$B_P = \{p(a), p(b), q(a), q(b), p(f(a)), p(f(b)), q(f(a)), \ldots\}$$
A *Herbrand Interpretation* is a subset of $B_L$, i.e. the set of all Herbrand interpretations $I_L = \wp(B_L)$.

(Note that $I_L$ forms a *complete lattice* under $\subseteq$ – important for fixpoint operations to be introduced later).

**Example:** $P = \{ \ p(f(X)) \leftarrow p(X). \ p(a). \ q(a). \ q(b). \ \}$

$U_P = \{ a, b, f(a), f(b), f(f(a)), f(f(b)), \ldots \}$

$B_P = \{ p(a), p(b), q(a), q(b), p(f(a)), p(f(b)), q(f(a)), \ldots \}$

$I_P = \text{all subsets of } B_P$

A *Herbrand Model* is a Herbrand interpretation which contains all logical consequences of the program.

The *Minimal Herbrand Model* $H_P$ is the smallest Herbrand interpretation which contains all logical consequences of the program. (It is unique.)

**Example:**

$H_P = \{ q(a), q(b), p(a), p(f(a)), p(f(f(a))), \ldots \}$
Declarative Semantics, Completeness, Correctness

- **Declarative semantics of a logic program** $P$:
  the set of ground facts which are logical consequences of the program (i.e., $HP$).
  (Also called the “least model” semantics of $P$).

- **Intended meaning of a logic program** $P$:
  the set $M$ of ground facts that the user expects to be logical consequences of the program.

- A logic program is **correct** if $HP \subseteq M$.

- A logic program is **complete** if $M \subseteq HP$.

- Example:
  father(john,peter).
  father(john,mary).
  mother(mary,mike).
  grandfather(X,Y) ← father(X,Z), father(Z,Y).

  with the usual intended meaning is **correct** but **incomplete**.
We now turn to the *operational semantics* of logic programs, given by a concrete operational procedure: *Linear (Input) Resolution*.

- Complementary literals:
  - in two different clauses
  - on different sides of $\leftarrow$
  - unifiable with unifier $\theta$

\[
\begin{align*}
\text{father}(\text{john}, \text{mary}) & \leftarrow \\
\text{grandfather}(X, Y) & \leftarrow \text{father}(X, Z), \text{mother}(Z, Y)
\end{align*}
\]

\[
\theta = \{X/\text{john}, Z/\text{mary}\}
\]
• Resolution step (linear, input, ...):

  ◇ given a clause and a resolvent, we can build a new resolvent which follows from them by:

  * renaming apart the clause (“standardization apart” step)
  * putting all the conclusions to the left of the ←
  * putting all the conditions to the right of the ←

  * if there are complementary literals (unifying literals at different sides of the arrow in the two clauses), eliminating them and applying $\theta$ to the new resolvent

• LD-Resolution: linear (and input) resolution, applied to definite programs

  Note that then all resolvents are negative Horn clauses (like the query).
Example

• from
  father(john,peter) ←
  mother(mary,david) ←
  we can infer
  father(john,peter), mother(mary,david) ←

• from
  father(john,mary) ←
  grandfather(X,Y) ← father(X,Z), mother(Z,Y)
  we can infer
  grandfather(john, Y′) ← mother(mary, Y′)
CONTROL: A proof using LD-Resolution

- Prove “grandfather(john,david) ←” using the set of axioms:
  1. father(john,peter) ←
  2. father(john,mary) ←
  3. father(peter,mike) ←
  4. mother(mary,david) ←
  5. grandfather(L,M) ← father (L,N), father(N,M)
  6. grandfather(X,Y) ← father (X,Z), mother(Z,Y)

- We introduce the predicate to prove (negated!)
  7. ← grandfather(john,david)

- We start resolution: e.g. 6 and 7
  8. ← father(john,Z₁), mother(Z₁,david) X₁/john, Y₁/david

- using 2 and 8
  9. ← mother(mary,david) Z₁/mary

- using 4 and 9
  ←
CONTROL: Rules and SLD-Resolution

- Two control-related issues are still left open in LD-resolution. Given a current resolvent $R$ and a set of clauses $K$:
  - given a clause $C$ in $K$, several of the literals in $R$ may unify the non-negated a complementary literal in $C$
  - given a literal $L$ in $R$, it may unify with complementary literals in several clauses in $K$

- A *Computation* (or *Selection* rule) is a function which, given a resolvent (and possibly the proof tree up to that point) returns (selects) a literal from it. This is the goal that will be used next in the resolution process.

- A *Search* rule is a function which, given a literal and a set of clauses (and possibly the proof tree up to that point), returns a clause from the set. This is the clause that will be used next in the resolution process.
• SLD-resolution: Linear resolution for Definite programs with Selection rule.

• An SLD-resolution method is given by the combination of a computation (or selection) rule and a search rule.

• Independence of the computation rule: Completeness does not depend on the choice of the computation rule.

• Example: a “left-to-right” rule (as in ordered resolution) does not impair completeness – this coincides with the completeness result for ordered resolution.

• Fundamental result:
  “Declarative” semantics ($H_P$) $\equiv$ “operational” semantics (SLD-resolution)
  I.e., all the facts in $H_P$ can be deduced using SLD-resolution.
CONTROL: Procedural reading of a logic program

- Given a rule

\[ \text{head} \leftarrow \text{goal}_1, \ldots, \text{goal}_n. \]

it can be seen as a description of the goals the solver (resolution method) has to execute in order to solve “head”

- Possible, given computation and search rules.

- In general, “In order to solve ‘head’, solve ‘goal}_1’ and ... and solve ‘goal}_n’ ”

- If ordered resolution is used (left-to-right computation rule), then read “In order to solve ‘head’, \textit{first} solve ‘goal}_1’ and \textit{then} ‘goal}_2’ and \textit{then} ... and \textit{finally} solve ‘goal}_n’ ”

- Thus the “control” part corresponding to the computation rule is often associated with the order of the goals in the body of a clause

- Another part (corresponding to the search rule) is often associated with the order of clauses
Example – read “procedurally”:

father(john,peter).
father(john,mary).
father(peter,mike).
father(X,Y) ← mother(Z,Y), married(X,Z).
Towards a Fixpoint Semantics for LP – Fixpoint Basics

• A fixpoint for an operator $T : X \to X$ is an element of $x \in X$ such that $x = T(x)$.

• If $X$ is a poset, $T$ is monotonic if $\forall x, y \in X, \ x \leq y \Rightarrow T(x) \leq T(y)$

• If $X$ is a complete lattice and $T$ is monotonic the set of fixpoints of $T$ is also a complete lattice [Tarski]

• The least element of the lattice is the least fixpoint of $T$, denoted $\text{lfp } T$

• Powers of a monotonic operator (successive applications):
  \[
  T \uparrow 0(x) = x \\
  T \uparrow n(x) = T(T \uparrow (n - 1)(x))(n \text{ is a successor ordinal}) \\
  T \uparrow \omega(x) = \bigsqcup \{T \uparrow n(x) | n < \omega \}
  \]
  We abbreviate $T \uparrow \alpha(\bot)$ as $T \uparrow \alpha$

• There is some $\omega$ such that $T \uparrow \omega = \text{lfp } T$. The sequence $T \uparrow 0, T \uparrow 1, ..., \text{lfp } T$ is the Kleene sequence for $T$

• In a finite lattice the Kleene sequence for a monotonic operator $T$ is finite
Towards a Fixpoint Semantics for LP – Fixpoint Basics (Contd.)

- A subset $Y$ of a poset $X$ is an (ascending) chain iff $\forall y, y' \in Y, y \leq y' \lor y' \leq y$
- A complete lattice $X$ is *ascending chain finite* (or *Noetherian*) if all ascending chains are finite
- In an ascending chain finite lattice the Kleene sequence for a monotonic operator $T$ is finite
Lattice Structures

finite

finite_depth

ascending chain finite
A Fixpoint Semantics for Logic Programs, and Equivalences

- The *Immediate consequence operator* $T_P$ is a mapping: $T_P : I_P \rightarrow I_P$ defined by: $T_P(I) = \{ A \in B_P | \exists C \in \text{ground}(P), C = A \leftarrow L_1, \ldots, L_n \text{ and } L_1, \ldots L_n \in I \}$ (in particular, if $(A \leftarrow) \in P$, then every element of $\text{ground}(A)$ is in $T_P(I)$, $\forall I$).

- $T_P$ is monotonic, so it has a least fixpoint $I^*$ so that $T_P(I^*) = I^*$, which can be obtained by applying $T_P$ iteratively starting from the bottom element of the lattice (the empty interpretation).

- (Characterization Theorem) [Van Emden and Kowalski]
  A program $P$ has a Herbrand model $H_P$ such that:
  - $H_P$ is the least Herbrand Model of $P$.
  - $H_P$ is the least fixpoint of $T_P$ ($\text{lfp } T_P$).
  - $H_P = T_P \uparrow \omega$.
  I.e., *least model semantics* ($H_P$) $\equiv$ *fixpoint semantics* ($\text{lfp } T_P$)

- Because it gives us some intuition on how to build $H_P$, the least fixpoint semantics can in some cases (e.g., finite models) also be an operational semantics (e.g., in *deductive databases*).
A Fixpoint Semantics for Logic Programs: Example

- Example:

\[ P = \{ \ p(f(X)) \leftarrow p(X). \]
\[ p(a). \]
\[ q(a). \]
\[ q(b). \} \]

\[ U_P = \{ a, b, f(a), f(b), f(f(a)), f(f(b)), \ldots \} \]

\[ B_P = \{ p(a), p(b), q(a), q(b), p(f(a)), p(f(b)), q(f(a)), \ldots \} \]

\[ I_P = \text{all subsets of } B \]

\[ H_P = \{ q(a), q(b), p(a), p(f(a)), p(f(f(a))), \ldots \} \]

\[ T_P \uparrow 0 = \{ p(a), q(a), q(b) \} \]

\[ T_P \uparrow 1 = \{ p(a), q(a), q(b), p(f(a)) \} \]

\[ T_P \uparrow 2 = \{ p(a), q(a), q(b), p(f(a)), p(f(f(a))) \} \]

\[ \ldots \]

\[ T_P \uparrow \omega = H_P \]