Computational Logic

Fundamentals (of Definite Programs):

Syntax and Semantics
Towards Logic Programming

- 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 Greene'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 *Clauses*.
  - A clause has the form:
    
    $\{conc_1, ..., conc_m\} \leftarrow \{cond_1, ..., cond_n\}$
    
    where
    
    $conc_1, ..., conc_m$ “or”
    
    are literals, and are the *conclusions* and *conditions* of a rule:
    
    $\{conc_1, ..., conc_m\} \leftarrow \{cond_1, ..., cond_n\}$
    
    “conclusions” “conditions”

  - All variables are implicitly universally quantified: (if $X_1, ..., X_k$ are the variables)
    
    $\forall X_1, ..., X_k \ conc_1 \lor ... \lor conc_m \leftarrow cond_1 \land ... \land cond_n$

- 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 *Horn Clause* then has the form:
  
  $conc_1 \leftarrow \{cond_1, ..., cond_n\}$

  where $n$ can be zero and possibly $conc_1$ empty.
Some Logic Programming Terminology – “Syntax” of Logic Programs

• **Definite Program**: a set of positive Horn clauses
  \[ \text{head} \leftarrow \text{goal}_1, ..., \text{goal}_n \]
  - The single conclusion is called the **head**.
  - The conditions are called “goals” or “procedure calls”.
  - \( \text{goal}_1, ..., \text{goal}_n \) (\( n \geq 0 \)) 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 $A$,

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

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:

$$P = \{ p(f(X)) \leftarrow p(X) \quad p(a) \quad q(a) \quad q(b) \}$$

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

$$B_P = \{ p(a), p(b), q(a), q(b), p(f(a)), p(f(b)), q(f(a)), \ldots \}$$
Herbrand Interpretations and Models

- 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., \( H_P \)). (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 \( H_P \subseteq M \).

- A logic program is **complete** if \( M \subseteq H_P \).

- 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 $\theta$

$\text{father}(\text{john}, \text{mary}) \leftarrow$
$\text{grandfather}(X, Y) \leftarrow \text{father}(X, Z), \text{mother}(Z, Y)$

$\theta = \{X/\text{john}, Z/\text{mary}\}$
• 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')
• 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
  ←
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 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 \((H_P)\) ≡ “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

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

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’, first solve ‘goal}_1’ and then ‘goal}_2’ and then ... and 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
CONTROL: Procedural reading of a logic program (Contd.)

- 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 $T : X \rightarrow X$ 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 $lfp(T)$
- Powers of a monotonic operator (successive applications):
  \[
  T \uparrow 0(x) = x \\
  T \uparrow n(x) = T(T \uparrow (n-1)(x))(n \text{ is a successor ordinal}) \\
  T \uparrow \omega(x) = \square\{T \uparrow n(x) | n < \omega\}
  \]
  We abbreviate $T \uparrow \alpha(\perp)$ as $T \uparrow \alpha$
- There is some $\omega$ such that $T \uparrow \omega = lfp(T)$. The sequence $T \uparrow 0, T \uparrow 1, ..., lfp T$ is the **Kleene sequence** for $T$
- In a finite lattice the Kleene sequence for a monotonic operator $T$ is finite
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*).
Example:

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

\[ U_P = \{ a, b, f(a), f(b), f(f(a)), f(f(b)), \ldots \} \]
\[ B_P = \{ p(a), p(b), q(a), q(b), p(f(a)), p(f(b)), q(f(a)), \ldots \} \]
\[ I_P = \text{all subsets of } B \]
\[ H_P = \{ q(a), q(b), p(a), p(f(a)), p(f(f(a))), \ldots \} \]

\[ T_P \uparrow 0 = \{ p(a), q(a), q(b) \} \]
\[ T_P \uparrow 1 = \{ p(a), q(a), q(b), p(f(a)) \} \]
\[ T_P \uparrow 2 = \{ p(a), q(a), q(b), p(f(a)), p(f(f(a))) \} \]
\[ \ldots \]
\[ T_P \uparrow \omega = H_P \]