Computational Logic

CLP Semantics and Fundamental Results
Constraint Domains

- Semantics parameterized by the constraint domain: CLP(\(\mathcal{X}\)), where \(\mathcal{X} \equiv (\Sigma, D, L, T)\)

- Signature \(\Sigma\): set of predicate and function symbols, together with their arity

- \(L \subseteq \Sigma\)–formulae: constraints

- \(D\) is the set of actual elements in the domain

- \(\Sigma\)–structure \(D\): gives the meaning of predicate and function symbols (and hence, constraints).

- \(T\) a first–order theory (axiomatizes some properties of \(D\))

- \((D, L)\) is a constraint domain

- Assumptions:
  - \(L\) built upon a first–order language
  - \(=\in \Sigma\) is identity in \(D\)
  - There are identically false and identically true constraints in \(L\)
  - \(L\) is closed w.r.t. renaming, conjunction and existential quantification
Domains (I)

- $\Sigma = \{0, 1, +, *, =, <, \leq\}$, $D = \mathbb{R}$, $D$ interprets $\Sigma$ as usual, $\mathcal{R} = (D, \mathcal{L})$
  - Arithmetic over the reals
  - Eg.: $x^2 + 2xy < \frac{y}{x} \land x > 0$ ($\equiv xxx + xxy + xxy < y \land 0 < x$)

- Question: is 0 needed? How can it be represented?

- Let us assume $\Sigma' = \{0, 1, +, =, <, \leq\}$, $\mathcal{R}_{Lin} = (D', \mathcal{L}')$
  - Linear arithmetic
  - Eg.: $3x - y < 3$ ($\equiv x + x + x < 1 + 1 + 1 + y$)

- Let us assume $\Sigma'' = \{0, 1, +, =\}$, $\mathcal{R}_{LinEq} = (D'', \mathcal{L}'')$
  - Linear equations
  - Eg.: $3x + y = 5 \land y = 2x$
Domains (II)

- $\Sigma = \{ <\text{constant and function symbols}>, = \}$
- $D = \{ \text{finite trees} \}$
- $D$ interprets $\Sigma$ as tree constructors
- Each $f \in \Sigma$ with arity $n$ maps $n$ trees to a tree with root labeled $f$ and whose subtrees are the arguments of the mapping
- Constraints: syntactic tree equality
- $\mathcal{FT} = (D, \mathcal{L})$
  - Constraints over the Herbrand domain
  - Eg.: $g(h(Z), Y) = g(Y, h(a))$
- $LP \equiv CLP(\mathcal{FT})$
Domains (III)

- $\Sigma = \{<\text{constants}>, \lambda, ., ::, =\}$
- $D = \{\text{finite strings of constants}\}$
- $D$ interprets $.\text{ as string concatenation, :: as string length}$
  - Equations over strings of constants
  - Eg.: $X.A.X = X.A$

- $\Sigma = \{0, 1, \neg, \land, =\}$
- $D = \{\text{true, false}\}$
- $D$ interprets symbols in $\Sigma$ as boolean functions
- $BOOL = (D, \mathcal{L})$
  - Boolean constraints
  - Eg.: $\neg(x \land y) = 1$
CLP(\mathcal{X}) Programs

- Recall that:
  - $\Sigma$ is a set of predicate and function symbols
  - $\mathcal{L} \subseteq \Sigma$—formulae are the constraints
- $\Pi$: set of predicate symbols definable by a program
- Atom: $p(t_1, t_2, \ldots, t_n)$, where $t_1, t_2, \ldots, t_n$ are terms and $p \in \Pi$
- Primitive constraint: $p(t_1, t_2, \ldots, t_n)$, where $t_1, t_2, \ldots, t_n$ are terms and $p \in \Sigma$ is a predicate symbol
- Every constraint is a (first–order) formula built from primitive constraints
- The class of constraints will vary (generally only a subset of formulas are considered constraints)
- A CLP program is a collection of rules of the form $a \leftarrow b_1, \ldots, b_n$ where $a$ is an atom and the $b_i$’s are atoms or constraints
- A fact is a rule $a \leftarrow c$ where $c$ is a constraint
- A goal (or query) $G$ is a conjunction of constraints and atoms
Basic Operations on Constraints

• Constraint domains are expected to support some basic operations on constraints

1. Consistency (or satisfiability) test: \( \mathcal{D} \models \exists c \)
2. Implication or entailment: \( \mathcal{D} \models c_0 \rightarrow c_1 \)
3. Projection of a constraint \( c_0 \) onto variables \( \tilde{x} \) to obtain a constraint \( c_1 \) such that \( \mathcal{D} \models c_1 \leftrightarrow \exists_{\tilde{x}} c_0 \)
4. Detection of uniqueness of variable value: \( \mathcal{D} \models c(x, \tilde{z}) \land c(y, \tilde{w}) \rightarrow x = y \)

• Actually, only the first one is really required

• In actual implementations, some of these operations—in particular the test of consistency—may be incomplete

• Examples:
  ◦ \( x \ast x < 0 \) is inconsistent in \( \mathbb{R} \) (because \( \neg \exists x \in \mathbb{R} : x \ast x < 0 \))
  ◦ \( \mathcal{D} \models (x \land y = 1) \rightarrow (x \lor y = 1) \) in \( \text{BOOL} \)
  ◦ In \( \mathcal{T} \), the projection of \( x = f(y) \land y = f(z) \) on \( \{x, z\} \) is \( x = f(f(z)) \)
  ◦ In \( \mathcal{WE} \), \( \mathcal{D} \models x.a.x = x.a \land y.b.y = y.b \rightarrow x = y \)

• Prove the last assertion!
Properties of CLP Languages

• $\mathcal{T}$ axiomatizes some of the properties of $\mathcal{D}$

• For a given $\Sigma$, let $(\mathcal{D}, \mathcal{L})$ be a constraint domain with signature $\Sigma$, and $\mathcal{T}$ a $\Sigma$–theory.

• $\mathcal{D}$ and $\mathcal{T}$ correspond on $\mathcal{L}$ if:
  ◦ $\mathcal{D}$ is a model of $\mathcal{T}$, and
  ◦ for every constraint $c \in \mathcal{L}$, $\mathcal{D} \models \exists c$ iff $\mathcal{T} \models \exists c$.

• $\mathcal{T}$ is *satisfaction complete* with respect to $\mathcal{L}$ if for every constraint $c \in \mathcal{L}$, either $\mathcal{T} \models \exists c$ or $\mathcal{T} \models \neg \exists c$.

• $(\mathcal{D}, \mathcal{L})$ is *solution compact* if

  $$\forall c \exists \{c_i\}_{i \in I} : \mathcal{D} \models \forall \bar{x} \neg c(\bar{x}) \iff \bigvee_{i \in I} c_i(\bar{x})$$

  i.e., any negated constraint in $\mathcal{L}$ can be expressed as a (in)finite disjunction of constraints.
Solution Compactness

- Important to lift SLDNF results to CLP($\mathcal{X}$)
- We have to deal only with user predicates
- E.g.
  - $x \not\geq y$ in CLP($\mathcal{R}$) is $x < y$
  - $x \neq y$ in CLP($\mathcal{R}$) is $x < y \lor y < x$
  - $\mathcal{R}_{Lin}$ with constraint $x \neq \pi$ is not s.c.
- How can we express $x \neq y$ in CLP($\mathcal{FT}$)?
Logical Semantics (I)

- Two common logical semantics exist.
- The first one interprets a rule

\[ p(\tilde{x}) \leftarrow b_1, \ldots, b_n \]

as the logic formula

\[ \forall \tilde{x}, \tilde{y} \ p(\tilde{x}) \lor \neg b_1 \lor \ldots \lor \neg b_n \]
Logical Semantics (II)

- The second one associates a logic formula to each predicate in \( \Pi \)
  
  - If the set of rules of \( P \) with \( p \) in the head is:

    \[
    \begin{align*}
    p(\tilde{x}) & \leftarrow B_1 \\
    p(\tilde{x}) & \leftarrow B_2 \\
    & \vdots \\
    p(\tilde{x}) & \leftarrow B_n
    \end{align*}
    \]

    then the formula associated with \( p \) is:

    \[
    \forall \tilde{x} \ p(\tilde{x}) \iff \exists \tilde{y}_1 B_1 \\
    \lor \exists \tilde{y}_2 B_2 \\
    \vdots \\
    \lor \exists \tilde{y}_n B_n
    \]

  - If \( p \) does not occur in the head of a rule of \( P \), the formula is:

    \[
    \forall \tilde{x} \neg p(\tilde{x})
    \]

  - The collection of all such formulas is the \textit{Clark completion} of \( P \) (denoted by \( P^* \))

- These two semantics differ on the treatment of the treatment of the negation
Logical Semantics (III)

- A *valuation* is a mapping from variables to $D$, and the natural extension which maps terms to $D$ and formulas to closed $L^*$–formulas.

- A $\mathcal{D}$–interpretation of a formula is an interpretation of the formula with the same domain as $\mathcal{D}$ and the same interpretation for the symbols in $\Sigma$ as $\mathcal{D}$.

- It can be represented as a subset of $B_\mathcal{D}$ where

$$B_\mathcal{D} = \{ p(\tilde{d}) \mid p \in \Pi, \tilde{d} \in D^k \}$$

- A $\mathcal{D}$–model of a closed formula is a $\mathcal{D}$–interpretation which is a model of the formula.

- The usual logical semantics is based on the $\mathcal{D}$–models of $P$ and the models of $P^*, \mathcal{T}$.

- The least $\mathcal{D}$–model of a formula $Q$ is denoted by $lm(Q, \mathcal{D})$.

- A *solution* to a query $G$ is a valuation $v$ such that $v(G) \subseteq lm(P, \mathcal{D})$. 
Fixpoint Semantics

- Based on one-step consequence operator $T^D_P$ (also called “immediate consequence operator”).
- Take as semantics $\text{lfp}(T^D_P)$, where:

\[
T^D_P(I) = \{ p(\tilde{d}) \mid p(\tilde{x}) \leftarrow c, b_1, \ldots, b_n \in P, a_i \in I, \]
\[
D \models v(c), v(\tilde{x}) = \tilde{d}, v(b_i) = a_i \}
\]
- Theorems:
  1. $T^D_P \uparrow \omega = \text{lfp}(T^D_P)$
  2. $\text{lm}(P, D) = \text{lfp}(T^D_P)$
Top–Down Operational Semantics (I)

- General framework for operational semantics
- Formalized as a transition system on *states*
- State: a 3–tuple $\langle A, C, S \rangle$, or *fail*, where
  - $A$ is a multiset of atoms and constraints,
  - $C \cup S$ multiset of constraints,
  - $C$, active constraints (awake)
  - $S$, passive constraints (asleep)
- *Computation* and *Selection* rules depend on $A$
- Transition system: parameterized by a predicate *consistent* and a function *infer*:
  - *consistent*(C) checks the consistency of a constraint store
  - Usually “*consistent*(C) iff $\mathcal{D} \models \exists c$”, but sometimes “if $\mathcal{D} \models \exists c$ then *consistent*(C)”
  - *infer*(C, S) computes a new set of active and passive constraints
Top–Down Operational Semantics (II)

- **Transition $r$:** computation step; rewriting using user predicates
  \[
  \langle A \cup a, C, S \rangle \rightarrow_r \langle A \cup B, C, S \cup (a = h) \rangle
  \]
  if $h \leftarrow B \in P$, and $a$ and $h$ have the same predicate symbol, or
  \[
  \langle A \cup a, C, S \rangle \rightarrow_r \text{fail}
  \]
  if there is no rule $h \leftarrow B$ of $P$ such that $a$ and $h$ have the same predicate symbol
  ($a = h$ is a set of argument–wise equations) if $a$ is a predicate symbol selected by
  the computation rule

- **Transition $c$:** selects constraints
  \[
  \langle A \cup c, C, S \rangle \rightarrow_c \langle A, C, S \cup c \rangle
  \]
  if $c$ is a constraint selected by the computation rule

- **Transition $i$:** infers new constraints
  \[
  \langle A, C, S \rangle \rightarrow_i \langle A, C', S' \rangle \text{ if } (C', S') = \text{infer}(C, S)
  \]
  ◦ In particular, may turn passive constraints into active ones

- **Transition $s$:** checks satisfiability
  \[
  \langle A, C, S \rangle \rightarrow_s \begin{cases} 
  \langle A, C, S' \rangle & \text{if } \text{consistent}(C) \\
  \text{fail} & \text{if } \neg \text{consistent}(C')
  \end{cases}
  \]
Top–Down Operational Semantics (III)

- Initial state: \( \langle G, \emptyset, \emptyset \rangle \)
- Derivation: \( \langle A_1, C_1, S_1 \rangle \rightarrow \ldots \rightarrow \langle A_i, C_i, S_i \rangle \rightarrow \ldots \)
- Final state: \( E \rightarrow E \)
- **Successful derivation**: final state \( \langle \emptyset, C, S \rangle \)
- A derivation *flounders* if finite and the final state is \( \langle A, C, S \rangle \) with \( A \neq \emptyset \)
- A derivation is *failed* if it is finite and the final state is fail
- **Answer**: \( \exists_{\tilde{x}} C \land S \), where \( \tilde{x} \) are the variables in the initial goal
- A derivation is *fair* if it is failed or, for every \( i \) and every \( a \in A_i \), \( a \) is rewritten in a later transition
- A computation rule is fair if it gives rise only to fair derivations
• **Computation tree** for goal $G$ and program $P$:
  ◦ Nodes labeled with states
  ◦ Edges labeled with $\rightarrow_r$, $\rightarrow_c$, $\rightarrow_i$ or $\rightarrow_s$
  ◦ Root labeled by $\langle G, \emptyset, \emptyset \rangle$
  ◦ All sons of a given node have the same label
  ◦ Only one son with transitions $\rightarrow_c$, $\rightarrow_i$ or $\rightarrow_s$
  ◦ A son per program clause with transition $\rightarrow_r$
• Consider the program
  \[ p(X + 3, X) \leftarrow X < 3. \]
  \[ p(X + 3, X) \leftarrow X > 3, p(X, Y). \]
  and the goal \( \leftarrow p(5, X) \)
• A possible computation tree is:

  \[
  \langle \{X < 3\}, \emptyset, \{5 = X + 3\} \rangle \langle \{X > 3, p(X, Y)\}, \emptyset, \{5 = X + 3\} \rangle
  \]

  \[
  \langle \{X < 3\}, \{X = 2\}, \emptyset \rangle \langle \{X > 3, p(X, Y)\}, \{X = 2\}, \emptyset \rangle
  \]

  \[
  \langle \emptyset, \{X = 2\}, \{X < 3\} \rangle \langle \{p(X, Y), X = 2\}, \{X > 3\} \rangle
  \]

  \[
  \langle \emptyset, \{X = 2\}, \emptyset \rangle \langle \{p(X, Y), X = 2, X > 3\}, \emptyset \rangle
  \]

  \[
  \text{fail}
  \]

• Dotted rectangle: previous state was final as well
Types of CLP(\mathcal{X}) Systems

- **Quick-checking** CLP(\mathcal{X}) system: its operational semantics can be described by 
  \[
  \rightarrow_{ris} \equiv \rightarrow_r \rightarrow_i \rightarrow_s \quad \text{and} \quad \rightarrow_{cis} \equiv \rightarrow_c \rightarrow_i \rightarrow_s
  \]
  
  i.e., always selects either an atom or a constraint, infers and checks consistency

- **Progressive** CLP system: for all \( \langle A, C, S \rangle \) with \( A \neq \emptyset \), every derivation from that state either fails or contains a \( \rightarrow_r \) or \( \rightarrow_c \) transition

- **Ideal** CLP system:
  - Quick-checking
  - Progressive
  - \( infer(C, S) = (C \cup S, \emptyset) \)
  - \( consistent(C) \) holds iff \( \mathcal{D} \models \exists c \)
Soundness and Completeness Results

- Success set: the set of queries plus constraints which have a successful derivation in the program:
  \[ SS(P) = \{ p(\tilde{x}) \leftarrow c \mid \langle p(\tilde{x}), \emptyset, \emptyset \rangle \rightarrow^* \langle \emptyset, c', c'' \rangle, \mathcal{D} \models c \leftrightarrow \exists \tilde{x} c' \land c'' \} \]

- Consider a program \( P \) in the CLP language determined by a 4–tuple \((\Sigma, \mathcal{D}, \mathcal{L}, \mathcal{T})\) and executing on an ideal CLP system. Then:
  1. \([SS(P)]_\mathcal{D} = lm(P, D)\), where
     \[ [SS(P)]_\mathcal{D} = \{ v(a) \mid (a \leftarrow c) \in SS(P), \mathcal{D} \models v(c) \} \]
  2. \( SS(P) = lfp(S_P^\mathcal{D}) \)
  3. (Soundness) if the goal \( G \) has a successful derivation with answer constraint \( c \), then \( P, \mathcal{T} \models c \rightarrow G \)
  4. (Completeness) if \( P, \mathcal{T} \models c \rightarrow G \) then there are derivations for the goal \( G \) with answer constraints \( c_1, \ldots, c_n \) such that \( \mathcal{T} \models c \rightarrow \lor_{i=1}^n c_i \)
  5. Assume \( \mathcal{T} \) is satisfaction complete w.r.t. \( \mathcal{L} \). Then the goal \( G \) is finitely failed for \( P \) iff \( P^*, \mathcal{T} \models \neg G \).
Negation in CLP($\mathcal{X}$)

- Most LP results can be lifted to CLP($\mathcal{X}$)
- In particular, negation as failure (à la SLDNF) is still valid using:
  - Satisfiability instead of unification
  - Variable elimination instead of groundness
- Added bonus: if the system is *solution compact*, then negated constraints can be expressed in terms of primitive constraints
- Less chances of a floundered / incorrect computation