Lecture 1: Introduction

Outline

1. Declarative problem solving
2. Answer set programming
3. Some prerequisites

1. DECLARATIVE PROBLEM SOLVING

- Declarative programming languages allow the specification of *what* is to be computed rather than *how* the computation takes place.
- PROLOG (*PRO*gramming in *LOG*ic) is a prototypical language that was developed for declarative programming.

```
Nat(0). Nat(s(X)) :- Nat(X).
```

- Programming in a *procedural* language such as Pascal, C, or Java is much about *controlling* the execution order of commands.

```
unsigned int f(unsigned int x) {
  if(x == 0 || x==1)
    return 1;
  else return x*f(x-1);
}
```


Conceptual Model

A problem is solved using a declarative programming language by

1. *modelling* the problem domain using the language,
2. performing actual *computation* steps to produce output, and
3. *extracting* a solution for the problem from the output.

$$\begin{array}{ccc} \boxed{\text{Problem}} & & \boxed{\text{Solution}} \\ \downarrow & & \uparrow \\ \boxed{\text{Model}} & \longrightarrow & \boxed{\text{Output}} \end{array}$$

Compilers and/or interpreters can be used to execute the model.

Basic Requirements

Any declarative language should

- have a clear declarative *semantics*,
- enable *concise* formalization of a variety of problem domains,
- lend itself to *modular* program development, and
- provide sufficient *performance* and *scalability*.

Remark. The last two requirements may endanger the declarative nature of programming (cf. the use of *cuts* "!" in PROLOG), i.e., a form of control necessary for efficiency reasons.

2. ANSWER SET PROGRAMMING

Answer set programming (ASP) is a paradigm for declarative programming that effectively emerged in the late nineties.

- A rule-based language is used for problem encodings.
- Every program P, i.e., a set of rules, has a clearly defined *semantics* (the set of answer sets associated with P).
- The order of rules and the order of individual conditions in rules is irrelevant which gives a declarative nature for answer sets.
- Dedicated search engines—*answer set solvers*—are used to compute an answer set or several answer sets for a program.

Revising the Conceptual Model for ASP

A problem is encoded so that the answer sets of the respective program and the solutions of the problem are in a tight correspondence.

$$\begin{array}{ccc} \boxed{\text{Problem}} & & \boxed{\text{Solution}} \\ \downarrow & & \uparrow \\ \boxed{\text{Set of rules}} & \longrightarrow & \boxed{\text{Answer set}} \end{array}$$

Current answer set solvers expect *ground* programs as their input which implies a preprocessing step in order to remove variables.

Example: Graph Coloring

```
edge(a,b). edge(b,c). edge(c,a).       % Edges

node(X) :- edge(X,Y).                  % Extract nodes
node(Y) :- edge(X,Y).

r(X) :- not g(X), not b(X), node(X).   % Red
g(X) :- not b(X), not r(X), node(X).   % Green
b(X) :- not r(X), not g(X), node(X).   % Blue

:- r(X), r(Y), edge(X,Y).              % Constraints
:- g(X), g(Y), edge(X,Y).
:- b(X), b(Y), edge(X,Y).
```


Example. The program for 3-coloring graphs is used as follows:

```
$ lparse color.lp > color.sm
$ lplist color.sm | less
$ smodels 1 < color.sm
Answer: 1
Stable Model: r(a) g(c) b(b) edge(c,a) edge(b,c) edge(a,b) \
node(c) node(b) node(a)
True
Duration: 0.004
Number of choice points: 2
Number of wrong choices: 0
Number of atoms: 16
Number of rules: 24
Number of picked atoms: 22
Number of forced atoms: 0
Number of truth assignments: 77
Size of searchspace (removed): 9 (0)
```

Roots of ASP

- Knowledge representation and reasoning
- Databases (SQL)
- Deductive databases
- Logic programming (PROLOG)
  - SLD-Resolution
  - Negation as failure to prove
  - Clark's completion and supported models
- Constraint programming

Example: SuDoku Puzzle

```
number(1). number(2). number(3). number(4). number(5).
number(6). number(7). number(8). number(9).

border(1). border(4). border(7).

region(X,Y) :- border(X), border(Y).

1 { value(X,Y,N):number(X):number(Y):
    X1<=X:X<=X1+2:Y1<=Y:Y<=Y1+2 } 1
  :- number(N), region(X1,Y1).

:- 2 {value(X,Y,N):number(N)}, number(X), number(Y).
:- 2 {value(X,Y,N):number(Y)}, number(N), number(X).
:- 2 {value(X,Y,N):number(X)}, number(N), number(Y).
```


Example. Royle's SuDoku puzzle with 16 clues gets solved in 52 ms.

```
$ lparse sudoku.lp royle.lp | smodels 1
smodels version 2.32. Reading...done
Answer: 1
Stable Model: value(8,8,1) value(4,7,1) ... value(3,1,9)
True
Duration: 0.052
Number of choice points: 1
Number of wrong choices: 0
Number of atoms: 1156
Number of rules: 928
Number of picked atoms: 321
Number of forced atoms: 51
Number of truth assignments: 8017
Size of searchspace (removed): 36 (0)
```


Example. The corresponding solution can be extracted from the answer set and then visualized as a solved SuDoku puzzle:

1	9	3	8	6	7	4	2	**5**
4	6	8	5	**3**	2	9	1	7
7	5	**2**	1	**4**	9	6	8	3
6	2	1	4	7	3	5	9	8
5	**3**	**4**	9	1	8	**7**	6	2
9	8	7	**2**	5	**6**	3	4	**1**
2	1	6	3	9	**5**	8	7	4
8	**7**	5	6	2	4	1	**3**	9
3	4	9	7	8	**1**	2	5	6

Example. Actually, there are 2 solutions for this 16 clue puzzle. The other is obtained by exchanging the occurrences of 8 and 9:

1	8	3	9	6	7	4	2	**5**
4	6	9	5	**3**	2	8	1	7
7	5	**2**	1	**4**	8	6	9	3
6	2	1	4	7	3	5	8	9
5	**3**	**4**	8	1	9	**7**	6	2
8	9	7	**2**	5	**6**	3	4	**1**
2	1	6	3	8	**5**	9	7	4
9	**7**	5	6	2	4	1	**3**	8
3	4	8	7	9	**1**	2	5	6

Applications of ASP

- **Product configuration**
- **Combinatorial problems**
  Graph problems, combinatorial auctions, ...
- **AI Planning**
  Contingency plans for the NASA space shuttle
- **Verification and analysis**
  Communication protocols, security protocols, ...
- **Information and data integration**
  Semantic web

Factors Behind the Success of ASP

- The performance of computers has increased remarkably.
- Implementation techniques have advanced rapidly.
- Many efficient solvers are publicly available:
  `smodels`, `clasp`, `cmodels`, `dlv`, ...
- Rule-based languages are highly expressive—enabling concise encodings for a wide variety of problems.
- ASP languages lend themselves to fast prototyping with little programming effort.

3. SOME PREREQUISITES

- Propositional languages
- Interpretations and models
- Logical entailment
- First-order languages
- Structures
- Herbrand bases
- Herbrand structures and models
- Relational operations

Propositional Languages

- Any set of *atomic sentences* $\mathcal{P} \neq \emptyset$, or *atoms* for short, induces a propositional language $\mathcal{L}$— the set of well-formed sentences.
- Sentences are built using the atoms of $\mathcal{P}$ and propositional connectives $\neg$ (negation), $\wedge$ (conjunction), $\vee$ (disjunction), $\rightarrow$ (implication), and $\leftrightarrow$ (equivalence).
  1. Atomic sentences are *sentences*.
  2. If α and β are sentences, then expressions of the forms $(\neg\alpha)$, $(\alpha \vee \beta)$, $(\alpha \wedge \beta)$, $(\alpha \rightarrow \beta)$, $(\alpha \leftrightarrow \beta)$ are also *sentences*.
- *Propositional theories* T are defined as subsets of $\mathcal{L}$.

Example. The theory $T = \{r \vee g \vee b,\ \neg r \vee \neg g,\ \neg g \vee \neg b,\ \neg b \vee \neg r\}$ describes the 3-coloring of a single node in a graph.

Interpretations and Models

- An *interpretation* I for $\mathcal{L}$ is defined as any subset of $\mathcal{P}$:
  1. atoms in I are considered to be *true* and
  2. atoms in $\mathcal{P} \setminus I$ are *false*.
- If $\mathcal{P}$ is finite, there are $|\mathbf{2}^{\mathcal{P}}| = 2^{|\mathcal{P}|}$ different interpretations, each of which represents of a unique state of the world described in $\mathcal{L}$.
- The satisfaction $I \models \alpha$ of a sentence $\alpha \in \mathcal{L}$ in an interpretation I is defined in the standard way.
- An interpretation I is a *model* of a theory T iff $I \models T$, i.e., $I \models \alpha$ holds for every $\alpha \in T$.

Example. The theory $T = \{r \vee g \vee b,\ \neg r \vee \neg g,\ \neg g \vee \neg b,\ \neg b \vee \neg r\}$ based on $\mathcal{P} = \{r, g, b\}$ has models $M_1 = \{r\}$, $M_2 = \{g\}$, and $M_3 = \{b\}$.

Logical Entailment

- A sentence α is a *logical consequence* of a theory T, denoted $T \models \alpha$, iff $M \models \alpha$ for every model $M \models T$.
- The set of logical consequences $\mathrm{Cn}(T) = \{\alpha \in \mathcal{L} \mid T \models \alpha\}$.
- The operator $\mathrm{Cn}(\cdot)$ has the properties of a *closure operator*. For any T_1 and T_2,
  1. $T_1 \subseteq \mathrm{Cn}(T_1)$,
  2. $T_1 \subseteq T_2 \implies \mathrm{Cn}(T_1) \subseteq \mathrm{Cn}(T_2)$, and
  3. $\mathrm{Cn}(\mathrm{Cn}(T_1)) = \mathrm{Cn}(T_1)$.

Example. Consider the theory $T = \{a,\ a \rightarrow b,\ \neg b \vee c,\ d \rightarrow \neg c\}$ based on $\mathcal{P} = \{a, b, c, d\}$. The theory has a unique model $M = \{a, b, c\}$.

$\implies \mathrm{Cn}(T) = \{a,\ a \rightarrow b,\ b,\ \neg b \vee c,\ c,\ d \rightarrow \neg c,\ \neg d,\ c \vee d, \ldots\}$.

First-Order Languages (I)

- A first-order language $\mathcal{L}$ is based on mutually disjoint sets of
  - *constant* symbols $\mathcal{C}$,
  - *variable* symbols $\mathcal{V}$,
  - *function* symbols $\mathcal{F}$, and
  - *relation* symbols $\mathcal{R}$.
- A *term* is either
  1. a constant symbol c from $\mathcal{C}$,
  2. a variable symbol v from $\mathcal{V}$, or
  3. an expression of the form $f(t_1, \ldots, t_n)$ where f is a function symbol of *arity* $n > 0$ from $\mathcal{F}$ and $t_1, \ldots, t_n$ are *terms*.

Remark. Constants represent function symbols of arity 0.

First-Order Languages (II)

- An *atomic formula* is an expression of the form
  1. R for each relation symbol of arity 0 from $\mathcal{R}$,
  2. $t_1 = t_2$ where t_1 and t_2 are terms, or
  3. $R(t_1,\ldots,t_n)$ where R is a relation symbol of arity $n > 0$ from $\mathcal{R}$ and $t_1,\ldots,t_n$ are terms.
- Atomic formulas are *formulas*.
- If α and β are formulas and v is a variable from $\mathcal{V}$, then expressions of the forms

  $(\neg\alpha)$, $(\alpha \vee \beta)$, $(\alpha \wedge \beta)$, $(\alpha \rightarrow \beta)$, $(\alpha \leftrightarrow \beta)$, $(\forall v\alpha)$, and $(\exists v\alpha)$

  are also *formulas*.
- A *sentence* is a formula having no *free occurrences* of variables.

Structures (I)

- An interpretation for a first-order language $\mathcal{L}$ is a *structure* S based on a *universe* U which is any non-empty set and
  1. each $c \in \mathcal{C}$ is mapped to an element $c^S \in U$,
  2. each $v \in \mathcal{V}$ is mapped to an element $v^S \in U$,
  3. each $f \in \mathcal{F}$ is mapped to a function $f^S : U^n \rightarrow U$ where n is the arity of f, and
  4. each $R \in \mathcal{R}$ with an arity n is mapped to a relation $R^S \subseteq U^n$.
- Given a structure S, each term t is mapped to an element $t^s \in U$.

Example. Given a constant symbol 0 and a *unary* (of arity 1) function symbol s we may define a structure S based on $U = \{0,1,2,\ldots\}$ by setting $0^S = 0$ and $s^S : x \mapsto x+1$. Thus $(s(s(s(0))))^S = 3$.

Structures (II)

- Atomic formulas R, $t_1 = t_2$, and $R(t_1,\ldots,t_n)$ are satisfied by S iff $\langle\rangle \in R^S$, $(t_1)^S = (t_2)^S$, and $\langle (t_1)^S,\ldots,(t_n)^S\rangle \in R^S$, respectively.
- The satisfaction of a first order formula/sentence α in a structure is defined in the standard way.
- Structures that are *models* of sentences ($S \models \alpha$) and theories ($S \models T$) are distinguished in analogy to propositional logic.
- Moreover, the definition of $T \models \alpha$, i.e., whether a sentence α is a *logical consequence* of a theory T, remains unchanged.

Example. For $T = \{E(0),\ \forall x(E(x) \rightarrow O(s(x))),\ \forall x(O(x) \rightarrow E(s(x)))\}$ formalizing *even* natural numbers: $T \models E(s(s(0)))$ but $T \not\models \neg E(s(0))$.

Herbrand Bases

- A *ground term* is a term having no occurrences of variables.
- Given the sets $\mathcal{C}$ and $\mathcal{F}$ (see above), the *Herbrand universe* is the set of ground terms constructible using the symbols of $\mathcal{C}$ and $\mathcal{F}$.
- Given the set $\mathcal{R}$, the *Herbrand base* consists of *atomic sentences* $R(t_1,\ldots,t_n)$ where $R \in \mathcal{R}$ is of arity n and each t_i is a ground term.
- A *Herbrand instance* of an atomic *formula* $R(t_1,\ldots,t_n)$ is obtained by substituting ground terms for variables occurring in $t_1,\ldots,t_n$.
- We may also define the Herbrand base $\mathrm{Hb}(T)$ of a theory T by inspecting which constant/function symbols occur in T.

Example. For the previous theory T formalizing even natural numbers, we have $\mathrm{Hb}(T) = \{E(0), O(0), E(s(0)), O(s(0)), \ldots\}$.

Herbrand Structures and Models

- A *Herbrand structure* S is based on a fixed interpretation of constant and function symbols over the Herbrand universe:
  1. Each $c \in \mathcal{C}$ is mapped to $c^S = c$.
  2. Each $f \in \mathcal{F}$ is mapped to $f^S : \langle t_1, \ldots, t_n \rangle \mapsto f(t_1, \ldots, t_n)$.

  $\Longrightarrow$ Only interpretations of variables and predicates can vary!
- Any Herbrand structure S can be viewed as a propositional interpretation $I = \{R(t_1, \ldots, t_n) \in \mathrm{Hb}(T) \mid S \models R(t_1, \ldots, t_n)\}$.
- A *Herbrand model* M of a theory T is a Herbrand structure that satisfies all sentences of T.

Example. For the theory T formalizing even natural numbers, we have a Herbrand model $M = \{E(0), O(s(0)), E(s(s(0))), O(s(s(s(0)))), \ldots\}$.

Relational operations

Assume that R_1 and R_2 are *binary relations* (of arity 2) over a fixed universe U, i.e., $R_1 \subseteq U^2$ and $R_2 \subseteq U^2$.

1. The *union* of R_1 and R_2 is
   $R_1 \cup R_2 = \{\langle x, y \rangle \in U^2 \mid \langle x, y \rangle \in R_1 \text{ or } \langle x, y \rangle \in R_2\}$.
2. The *intersection* of R_1 and R_2 is
   $R_1 \cap R_2 = \{\langle x, y \rangle \in U^2 \mid \langle x, y \rangle \in R_1 \text{ and } \langle x, y \rangle \in R_2\}$.
3. The *projections* of R_1 w.r.t. the first/second arguments are
   $P_1 = \{x \in U \mid \langle x, y \rangle \in R_1\}$ and $P_2 = \{y \in U \mid \langle x, y \rangle \in R_1\}$.
4. The *composition* of R_1 of R_2 is
   $R_1 \circ R_2 = \{\langle x, y \rangle \in U^2 \mid \langle x, z \rangle \in R_1 \text{ and } \langle z, y \rangle \in R_2\}$.

OBJECTIVES

- You have the necessary premises for the course, i.e., you are familiar with the syntax and semantics of classical logic.
- You know the main characteristics of declarative programming languages and understand the difference w.r.t. procedural ones.
- You understand the conceptual model of answer set programming.
- You are able to list the basic steps which are required to to apply ASP in declarative problem solving.

TIME TO PONDER

Definition. The set of classical models associated with a propositional theory T is $\mathrm{CM}(T) = \{M \subseteq \mathrm{Hb}(T) \mid M \models T\}$.

Problem. Let T_1 and T_2 be arbitrary propositional theories.

Which one of the following is correct in general?

1. $\mathrm{CM}(T_1 \cup T_2) = \mathrm{CM}(T_1) \cap \mathrm{CM}(T_2)$.
2. $\mathrm{CM}(T_1 \cup T_2) = \{M_1 \cup M_2 \mid M_1 \in \mathrm{CM}(T_1) \text{ and } M_2 \in \mathrm{CM}(T_2)\}$.
3. $\mathrm{CM}(T_1 \cup T_2) =$
   $\{M_1 \cup M_2 \mid M_1 \in \mathrm{CM}(T_1),\ M_2 \in \mathrm{CM}(T_2), \text{ and } M_1 \cap H = M_2 \cap H\}$
   where $H = \mathrm{Hb}(T_1) \cap \mathrm{Hb}(T_2)$.