Logical Modeling using Answer Set Programming

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Answer Set Programming
What is ASP?

- ASP is a *declarative problem solving approach*.  
  Syntactically similar to Prolog, but truly declarative.

- For a given ASP “program”, we compute *models* representing a solution for the encoded problem.

- Very efficient implementations are available, for computing models.

- We will use the Potassco tools Gringo, Clasp and Clingo.
  
Sudoku

The famous number riddle Sudoku represents a constraint problem, typically defined on a $9 \times 9$ board, where numbers $1 \ldots 9$ are placed on each cell. The goal is to complete a given board such that in each row, column, and square the numbers $1 \ldots 9$ occur exactly once.
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Unsolved Sudoku

Solved Sudoku
Sudoku
How to start modeling?

Declarative means we *declare* and *describe* the things we know;
Sudoku
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- The game board, cells, rows, columns and squares.
Sudoku
How to start modeling?

Declarative means we *declare* and *describe* the things we know; i.e. the notion of

- The game board, cells, rows, columns and squares.
- The rules, in detail
  - On each cell there is exactly one number from \( \{1 \ldots 9\} \).
  - In each row every number occurs exactly once.
  - In each column every number occurs exactly once.
  - In each square every number occurs exactly once.
Sudoku
How to start modeling?

Declarative means we *declare* and *describe* the things we know; i.e. the notion of

- The game board, cells, rows, columns and squares.
- The rules, in detail
  - On each cell there is exactly one number from \( \{1 \ldots 9\} \).
  - In each row every number occurs exactly once.
  - In each column every number occurs exactly once.
  - In each square every number occurs exactly once.

And there is no need to specify an algorithm on how to solve Sudokus.
We encode the board via facts:

```prolog
number(1..9). row(0..8). column(0..8).
square(0, 0..2, 0..2). square(1, 0..2, 3..5). square(2, 0..2, 6..8).
square(3, 3..5, 0..2). square(4, 3..5, 3..5). square(5, 3..5, 6..8).
square(6, 6..8, 0..2). square(7, 6..8, 3..5). square(8, 6..8, 6..8).
```
Sudoku Board Encoding

Alternatively, via rules:

\[
\begin{align*}
\text{square}(0, X, Y) & :\text{ row}(X), \text{ column}(Y), X < 3, Y < 3. \\
\text{square}(1, X, Y) & :\text{ row}(X), \text{ column}(Y), X < 3, Y > 2, Y < 6. \\
\text{square}(2, X, Y) & :\text{ row}(X), \text{ column}(Y), X < 3, Y > 5. \\
\text{square}(3, X, Y) & :\text{ row}(X), \text{ column}(Y), X > 2, X < 6, Y < 3. \\
\text{square}(4, X, Y) & :\text{ row}(X), \text{ column}(Y), X > 2, X < 6, Y > 2, Y < 6. \\
\text{square}(5, X, Y) & :\text{ row}(X), \text{ column}(Y), X > 2, X < 6, Y > 5. \\
\text{square}(6, X, Y) & :\text{ row}(X), \text{ column}(Y), X > 5, Y < 3. \\
\text{square}(7, X, Y) & :\text{ row}(X), \text{ column}(Y), X > 5, Y > 2, Y < 6. \\
\text{square}(8, X, Y) & :\text{ row}(X), \text{ column}(Y), X > 5, Y > 5.
\end{align*}
\]
Grounding the program via

```
gringo sudoku.lp ---text
```

Yields instantiated `square` atoms (beside the known facts):

```
square(0,0,0). square(0,0,1). square(0,0,2). ...
square(1,0,3). square(1,0,4). square(1,0,5). ...
square(2,0,6). square(2,0,7). square(2,0,8). ...
...```
Sudoku
Rules Encoding

On each cell there is exactly one number from \{1 \ldots 9\}.

\[
\text{cell}(X, Y, 1) \quad \text{:-} \quad \text{row}(X), \; \text{column}(Y), \;
\text{not cell}(X, Y, 2), \; \text{not cell}(X, Y, 3), \; \text{not cell}(X, Y, 4), \;
\text{not cell}(X, Y, 5), \; \text{not cell}(X, Y, 6), \; \text{not cell}(X, Y, 7), \;
\text{not cell}(X, Y, 8), \; \text{not cell}(X, Y, 9). \]

\[
\text{cell}(X, Y, 2) \quad \text{:-} \quad \text{row}(X), \; \text{column}(Y), \;
\text{not cell}(X, Y, 1), \; \text{not cell}(X, Y, 3), \; \text{not cell}(X, Y, 4), \;
\text{not cell}(X, Y, 5), \; \text{not cell}(X, Y, 6), \; \text{not cell}(X, Y, 7), \;
\text{not cell}(X, Y, 8), \; \text{not cell}(X, Y, 9). \]

\[
\ldots
\]

\[
\text{cell}(X, Y, 9) \quad \text{:-} \quad \text{row}(X), \; \text{column}(Y), \;
\text{not cell}(X, Y, 1), \; \text{not cell}(X, Y, 2), \; \text{not cell}(X, Y, 3), \;
\text{not cell}(X, Y, 4), \; \text{not cell}(X, Y, 5), \; \text{not cell}(X, Y, 6), \;
\text{not cell}(X, Y, 7), \; \text{not cell}(X, Y, 8). \]
What is the meaning of these rules?

\[
cell(X, Y, 1) \quad :\quad row(X), \ column(Y), \\
\text{not } cell(X, Y, 2), \text{ not } cell(X, Y, 3), \text{ not } cell(X, Y, 4), \\
\text{not } cell(X, Y, 5), \text{ not } cell(X, Y, 6), \text{ not } cell(X, Y, 7), \\
\text{not } cell(X, Y, 8), \text{ not } cell(X, Y, 9).
\]
What is the meaning of these rules?

\[ cell(X, Y, 1) \ :- \ row(X), \ column(Y), \]
\[ \quad \text{not} \ cell(X, Y, 2), \ \text{not} \ cell(X, Y, 3), \ \text{not} \ cell(X, Y, 4), \]
\[ \quad \text{not} \ cell(X, Y, 5), \ \text{not} \ cell(X, Y, 6), \ \text{not} \ cell(X, Y, 7), \]
\[ \quad \text{not} \ cell(X, Y, 8), \ \text{not} \ cell(X, Y, 9). \]

For the cell at position \((X, Y)\) we can place 1, if \(X\) corresponds to some row and \(Y\) to some column, and we failed to demonstrate that there is already placed one of the other numbers 2...9.
Sudoku
Board Encoding

Since we have one such rule for every number, we can *non-deterministically* choose / guess which number to place on some cell.

We defined the search space with these rules. In fact, without further knowledge, these rules generate all $9^{81}$ combinations of cell numberings; therefore they are called *guessing rules*. 
Sudoku
Board Encoding

Since we have one such rule for every number, we can non-deterministically choose / guess which number to place on some cell.

We defined the search space with these rules. In fact, without further knowledge, these rules generate all $9^{81}$ combinations of cell numberings; therefore they are called guessing rules.

We need to restrict the search space such that only proper numberings are generated.
Each number occurs only once in each row and column.

\[
\begin{align*}
&\text{:- } cell(X, Y_1, N), \ cell(X, Y_2, N), \ Y_1 \neq Y_2. \\
&\text{:- } cell(X_1, Y, N), \ cell(X_2, Y, N), \ X_1 \neq X_2. 
\end{align*}
\]
Each number occurs only once in each row and column.

```prolog
:- cell(X, Y1, N), cell(X, Y2, N), Y1 != Y2.
:- cell(X1, Y, N), cell(X2, Y, N), X1 != X2.
```

Each number occurs only once in each square.

```prolog
in_square(S, N) :- cell(X, Y, N), square(S, X, Y).
:- number(N), not in_square(S, N), square(S, _, _).
```
Sudoku
Grounding and Solving

- We ground the program and call clasp

  gringo sudoku.lp | clasp
Sudoku
Grounding and Solving

Solving...
Answer: 1

cell(8,8,1) cell(8,7,4) cell(8,6,7) cell(8,5,2) cell(8,4,9)
cell(8,3,8) cell(8,2,3) cell(8,1,6) cell(8,0,5) cell(7,8,4)
cell(7,7,2) cell(7,6,9) cell(7,5,1) cell(7,4,8) cell(7,3,7)
cell(7,2,6) cell(7,1,5) cell(7,0,3) cell(6,8,8) cell(6,7,9)
cell(6,6,3) cell(6,5,7) cell(6,4,6) cell(6,3,5) cell(6,2,1)
cell(6,1,4) cell(6,0,2) cell(5,8,2) cell(5,7,1) cell(5,6,8)
cell(5,5,4) cell(5,4,7) cell(5,3,9) cell(5,2,5) cell(5,1,3)
cell(5,0,6) cell(4,8,9) cell(4,7,7) cell(4,6,6) cell(4,5,8)
cell(4,4,5) cell(4,3,3) cell(4,2,4) cell(4,1,2) cell(4,0,1)
cell(3,8,7) cell(3,7,8) cell(3,6,5) cell(3,5,9) cell(3,4,3)
cell(3,3,6) cell(3,2,2) cell(3,1,1) cell(3,0,4) cell(2,8,3)

SATISFIABLE
Models: 1+
Time: 0.043s (Solving: 0.01s 1st Model: 0.01s Unsat: 0.00s)
CPU Time: 0.040s
Sudoku
Grounding and Solving

► We ground the program and call clasp

    gringo sudoku.lp | clasp

► When providing no options clasp will compute one answer set in case of satisfiability. We can request more, e.g. 5, via

    gringo sudoku.lp | clasp ---number 5
Sudoku
Grounding and Solving

- We ground the program and call clasp
  
gringo sudoku.lp | clasp

- When providing no options clasp will compute one answer set in case of satisfiability. We can request more, e.g. 5, via
  
gringo sudoku.lp | clasp ---number 5

Up to now, what are we generating?
Sudoku

Problem Instance

- We add a concrete Sudoku, given as *cell* facts.

  \begin{align*}
  &\text{cell}(0, 0, 3). \text{cell}(0, 4, 8). \text{cell}(0, 6, 6). \text{cell}(0, 8, 7). \\
  &\text{cell}(1, 1, 1). \text{cell}(1, 6, 4). \text{cell}(1, 8, 9). \\
  &\text{cell}(2, 0, 8). \text{cell}(2, 1, 9). \text{cell}(2, 4, 6). \text{cell}(2, 5, 7). \\
  &\text{cell}(3, 1, 6). \text{cell}(3, 3, 1). \text{cell}(3, 4, 9). \text{cell}(3, 6, 7). \\
  &\text{cell}(4, 2, 9). \text{cell}(4, 3, 6). \text{cell}(4, 4, 5). \text{cell}(4, 8, 2). \\
  &\text{cell}(5, 2, 2). \text{cell}(5, 7, 1). \\
  &\text{cell}(6, 1, 5). \text{cell}(6, 4, 4). \text{cell}(6, 8, 3). \\
  &\text{cell}(7, 1, 4). \text{cell}(7, 3, 2). \text{cell}(7, 7, 9). \text{cell}(7, 8, 8). \\
  &\text{cell}(8, 1, 8). \text{cell}(8, 2, 6). \text{cell}(8, 4, 3). \text{cell}(8, 6, 1). \\
  \end{align*}

- There is only one solution, which we can verify by requesting all answer sets

  gringo sudoku.lp sudoku-instance.lp | clasp --number 0
Modeling Paradigm
Guess and Check Programs [?]

For the Sudoku example, we developed two main parts.

- **Problem description**
  Encoding the underlying problem, i.e. the board, rules and constraints.

- **Problem instance**
  Encoding of a concrete instance of the problem; i.e. a partially filled Sudoku.

We can solve any Sudoku with our encoding, the problem description is therefore said to be *uniform*. 
Modeling Paradigm
Guess and Check Programs

Two important aspects in the problem description:

- We defined so-called *guessing rules* to generate prospective solutions.
- We then *constrained* guesses in order to rule out those not representing a solution.

These *guess & check* parts are characteristic for answer set programs.

- Motivated by NP-problems.
- Can be seen as "Design-Pattern"
Traveling Salesman Problem

A salesman is requested to visit some pre-defined cities. In order to be as efficient as possible, he wants to visit every city only once, as well as to travel the shortest roundtrip visiting all cities starting and ending in the same city.
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Traveling Salesman Problem
Problem Separation

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  (a) finding roundtrips beginning from and ending in the same city visiting all other cities only once, and
Traveling Salesman Problem
Problem Separation

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Traveling Salesman Problem

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- In fact, the first is the very well-known NP-complete problem of finding Hamiltonian cycles.
Traveling Salesman Problem
Problem Separation

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  (a) finding roundtrips beginning from and ending in the same city visiting all other cities only once, and
  (b) computing the length of each roundtrip in order to find the shortest.

- In fact, the first is the very well-known NP-complete problem of finding Hamiltonian cycles.

- For the encoding of the Hamiltonian cycle problem we stick to the guess and check paradigm.
Every node in a Hamiltonian cycle has exactly one incoming and one outgoing edge.

\[
\begin{align*}
1 \{ \text{cycle}(X, Y) : \text{edge}(X, Y) \} & 1 :\text{-} \ node(X). \\
1 \{ \text{cycle}(X, Y) : \text{edge}(X, Y) \} & 1 :\text{-} \ node(Y).
\end{align*}
\]
Traveling Salesman Problem
Hamiltonian Cycle Encoding

- Every node in a Hamiltonian cycle has exactly one incoming and one outgoing edge.

\[
\begin{align*}
1 \{ \text{cycle}(X,Y) : \text{edge}(X,Y) \} & \quad 1 :\ :- \quad \text{node}(X). \\
1 \{ \text{cycle}(X,Y) : \text{edge}(X,Y) \} & \quad 1 :\ :- \quad \text{node}(Y).
\end{align*}
\]

- In a Hamiltonian cycle, every node is reachable.

\[
\begin{align*}
\text{reachable}(Y) & \quad :\ :- \quad \text{cycle}(s,Y). \\
\text{reachable}(Y) & \quad :\ :- \quad \text{cycle}(X,Y), \ \text{reachable}(X). \\
& \quad :\ :- \quad \text{node}(X), \ \textbf{not} \ \text{reachable}(X).
\end{align*}
\]
Traveling Salesman Problem
Hamiltonian Cycle Encoding

- Facts for the input graph.
Traveling Salesman Problem
Hamiltonian Cycle Encoding

- Facts for the input graph.

```prolog
node(dresden).
node(bankok).
node(hue).
node(danang).
edge(dresden, hanoi).
edge(frankfurt, bankok).
edge(bankok, hanoi).
edge(hochi, hue).
edge(danang, hue).
edge(Y, X) :- edge(X, Y).
node(frankfurt).
node(hanoi).
node(hochi).
edge(dresden, frankfurt).
edge(frankfurt, hanoi).
edge(frankfurt, hochi).
edge(bankok, hochi).
edge(hochi, danang).
edge(hanoi, hue).
```
Traveling Salesman Problem
Solving - Computing Hamiltonian Cycles

gringo -c s=dresden hamiltonian.lp map.lp | clasp ---n 0

Solving...
Answer: 1
cycle(dresden, hanoi) cycle(hanoi, bankok)
cycle(bankok, hue) cycle(hue, danang)
cycle(danang, hochi) cycle(hochi, frankfurt)
cycle(frankfurt, dresden)
...
SATISFIABLE
Models: 2
Time: 0.002s (Solving: 0.00s 1st Model: 0.00s Unsat: 0.00s)
CPU Time: 0.000s
Traveling Salesman Problem
Hamiltonian Cycle Encoding

- In order to calculate the cycle length, we need the distance information.

\[
\text{distance}(\text{dresden, frankfurt}, 40). \\
\text{distance}(\text{frankfurt, bankok}, 896). \\
\text{distance}(\text{bankok, hochi}, 74). \\
\text{distance}(\text{frankfurt, hanoi}, 872). \\
\text{distance}(\text{hanoi, hue}, 8). \\
\text{distance}(\text{hanoi, bankok}, 834). \\
\text{distance}(\text{bankok, hochi}, 96).
\]

\[
\text{distance}(\text{hochi, danang}, 60). \\
\text{distance}(\text{frankfurt, hochi}, 965). \\
\text{distance}(\text{hanoi, hue}, 54). \\
\text{distance}(\text{hochi, hue}, 64). \\
\]

\[
\text{distance}(X, Y, C) \leftarrow \text{distance}(Y, X, C).
\]
Traveling Salesman Problem
Hamiltonian Cycle Encoding

▶ In order to calculate the cycle length, we need the distance information.

\[
\text{distance}(\text{dresden, frankfurt}, 40). \quad \text{distance}(\text{dresden, hanoi}, 834). \\
\text{distance}(\text{frankfurt, bankok}, 896). \quad \text{distance}(\text{bankok, hanoi}, 96). \\
\text{distance}(\text{bankok, hochi}, 74). \quad \text{distance}(\text{frankfurt, hochi}, 965). \\
\text{distance}(\text{frankfurt, hanoi}, 872). \quad \text{distance}(\text{hanoi, hue}, 54). \\
\text{distance}(\text{hochi, danang}, 60). \quad \text{distance}(\text{hochi, hue}, 64). \\
\text{distance}(\text{danang, hue}, 8). \\
\text{distance}(X, Y, C) :- \text{distance}(Y, X, C).
\]

▶ With a so-called \textit{aggregate function}, we can compute the sum of the edge in a cycle.

\[
\text{circumference}(N) :- N = \#\text{sum } [\text{cycle}(X, Y) : \text{distance}(X, Y, C) = C].
\]
Traveling Salesman Problem
Hamiltonian Cycle Encoding

In example, for \textit{cycle(dresden, frankfurt)} and \textit{cycle(frankfurt, hanoi)}, we obtain the grounded rule

\[
\text{circumference}(912) :- 912 = \#\text{sum}\left[\text{cycle(dresden, frankfurt)} = 40, \text{cycle(frankfurt, hanoi)} = 872\right].
\]
Traveling Salesman Problem
Hamiltonian Cycle Encoding

In example, for \( \text{cycle}( \text{dresden}, \text{frankfurt} ) \) and \( \text{cycle}( \text{frankfurt}, \text{hanoi} ) \), we obtain the grounded rule

\[
\text{circumference}(912) :- 912 = \#\text{sum}[\text{cycle}(\text{dresden}, \text{frankfurt}) = 40, \\
\text{cycle}(\text{frankfurt}, \text{hanoi}) = 872].
\]

We can compute answer sets including one \textit{circumference} atom, via

\[
\text{gringo -c s=dresden \ hamiltonian.lp} \\
\text{map.lp} \\
\text{distances.lp | clasp ---n 0}
\]
Traveling Salesman Problem
Minimization

- Answer sets can be computed and enumerated with respect to some optimization value; i.e. the circumference of our cycles.
Traveling Salesman Problem
Minimization

- Answer sets can be computed and enumerated with respect to some optimization value; i.e. the circumference of our cycles.
- In clasp objective optimization functions are offered, in our case we use minimize.

\[ \#minimize \ [\text{circumference}(N) = N] \].
Traveling Salesman Problem
Minimization

- Answer sets can be computed and enumerated with respect to some optimization value; i.e. the circumference of our cycles.
- In clasp objective optimization functions are offered, in our case we use `minimize`.

\[ \text{#minimize } [\text{circumference}(N) = N]. \]

- Adding the statement to the program yields a minimal hamiltonian cycle of length 1966.
Traveling Salesman Problem
Minimization

Answer: 1
cycle(dresden,hanoi) cycle(hanoi,bankok)
cycle(bankok,hue) cycle(hue,danang)
cycle(danang,hochi) cycle(hochi, frankfurt)
cycle(frankfurt,dresden)
Optimization: 1966
...
OPTIMUM FOUND
Models : 1
Optimization: 1966
Time : 1.358s (Solving: 0.40s 1st Model: 0.01s Unsat: 0.39s)
Traveling Salesman Problem
Minimization

Dresden
Frankfurt
Hanoi
Bankok
Ho Chi Minh
Hue
Da Nang

40
896
965
96
54
8
64
60
872
834
74
64
54
96
60

Further Readings ...

- **Potassco Guide:**
  https://github.com/potassco/guide/releases/
  - META Encoding
  - Multi-Shot Solving
- **Multi-Shot Solving: Ricochet Robots**

Download clingo, or gringo and clasp here:

http://potassco.org
BACKUP
Graph Coloring

\(N\)-Coloring Problem

*Is there some coloring of the vertices of a given graph using \(n\) colors, such that no two adjacent vertices share the same color?*
Graph Coloring

color(green). color(red). color(blue).

coloring(X, green) :- node(X), not coloring(X, red),
not coloring(X, blue).

coloring(X, red) :- node(X), not coloring(X, green),
not coloring(X, blue).

coloring(X, blue) :- node(X), not coloring(X, green),
not coloring(X, red).
Graph Coloring

color(green). color(red). color(blue).

coloring(X, green) :- node(X), not coloring(X, red),
                     not coloring(X, blue).

coloring(X, red)   :- node(X), not coloring(X, green),
                     not coloring(X, blue).

coloring(X, blue) :- node(X), not coloring(X, green),
                     not coloring(X, red).
                     :- coloring(X1, C), coloring(X2, C),
                        edge(X1, X2).
Cannibals and Missionaries

Three missionaries and three cannibals must cross a river using a boat which can carry at most two people, under the constraint that, for both banks, if there are missionaries present on the bank, they cannot be outnumbered by cannibals (if they were, the cannibals would eat the missionaries). The boat cannot cross the river by itself with no people on board.