Knowledge-driven Artificial Intelligence

Torsten Schaub

University of Potsdam & Potassco Solutions GmbH

Outline

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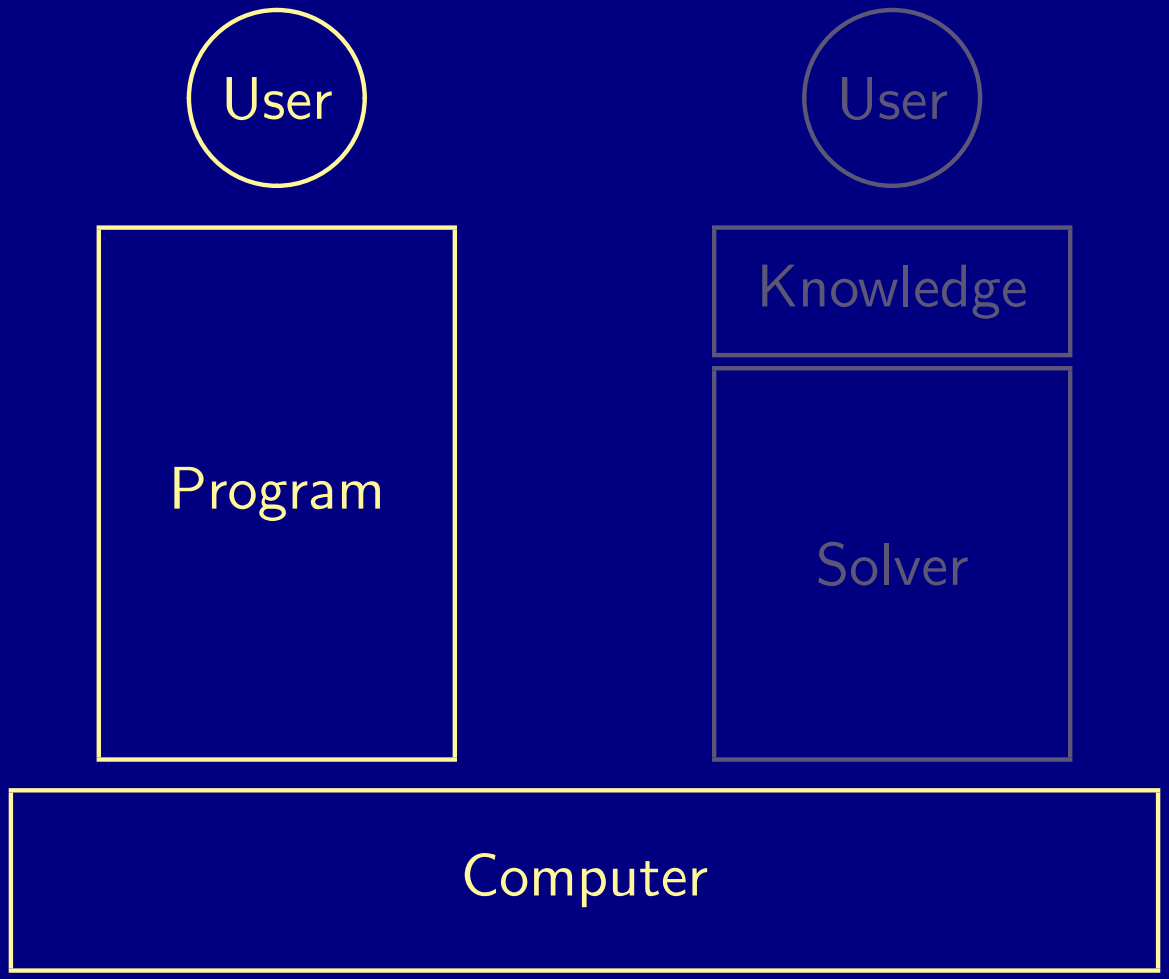
Traditional Software



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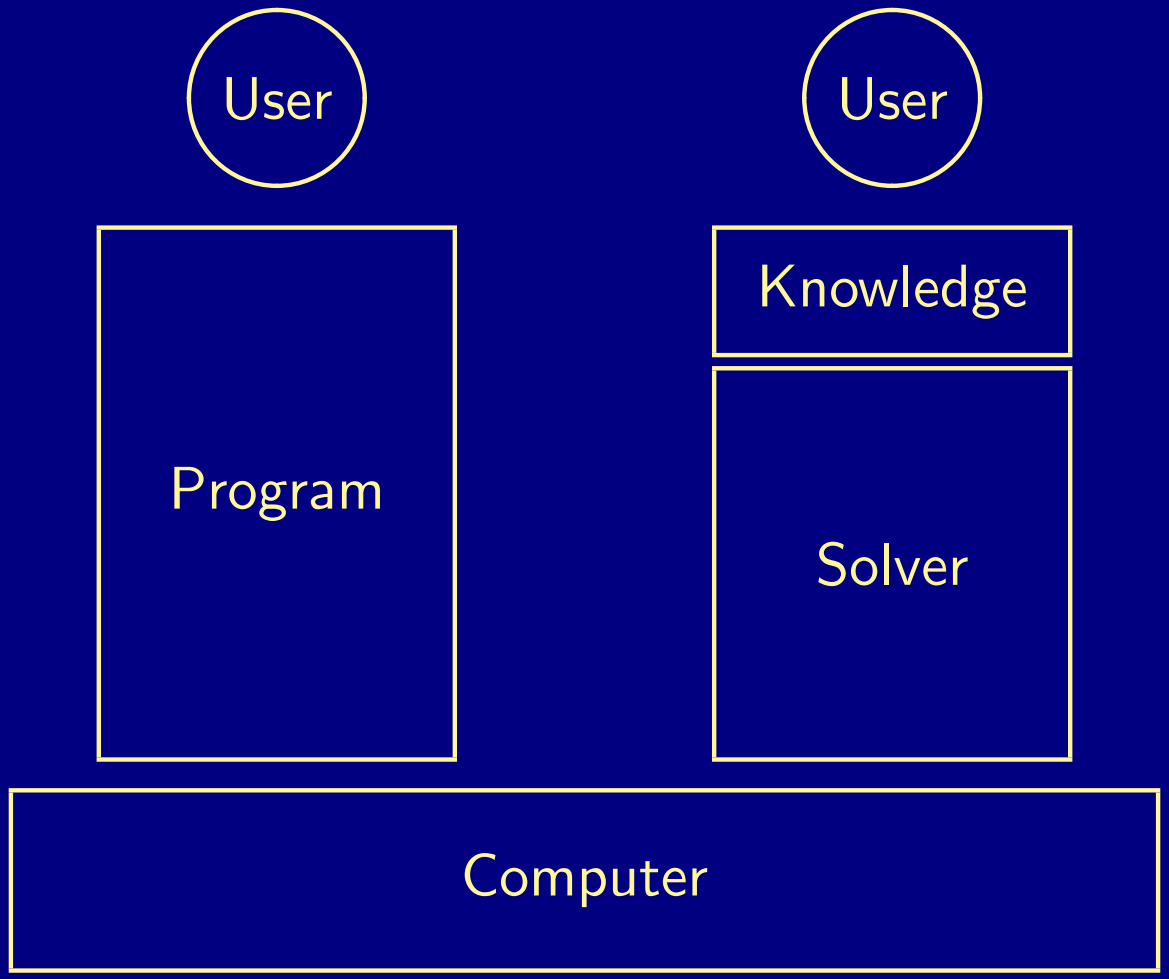

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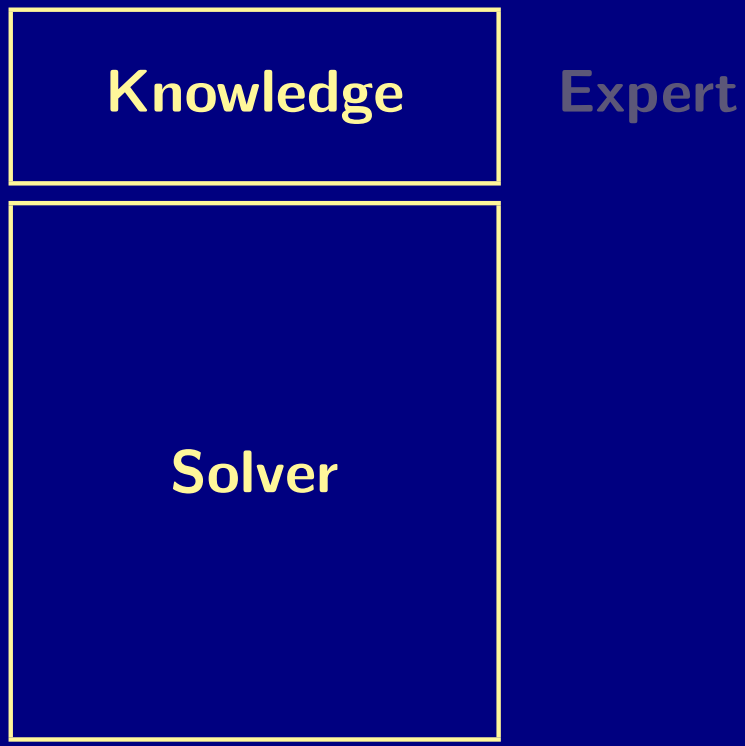
What is the benefit?

+ Transparency
+ Flexibility
+ Maintainability
+ Reliability

+ Generality
+ Efficiency
+ Optimality
+ Availability



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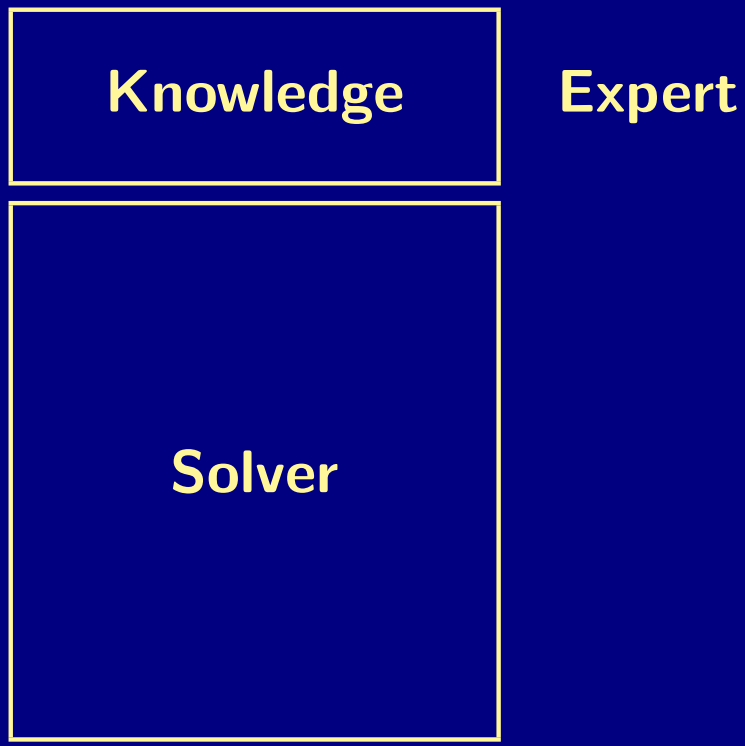

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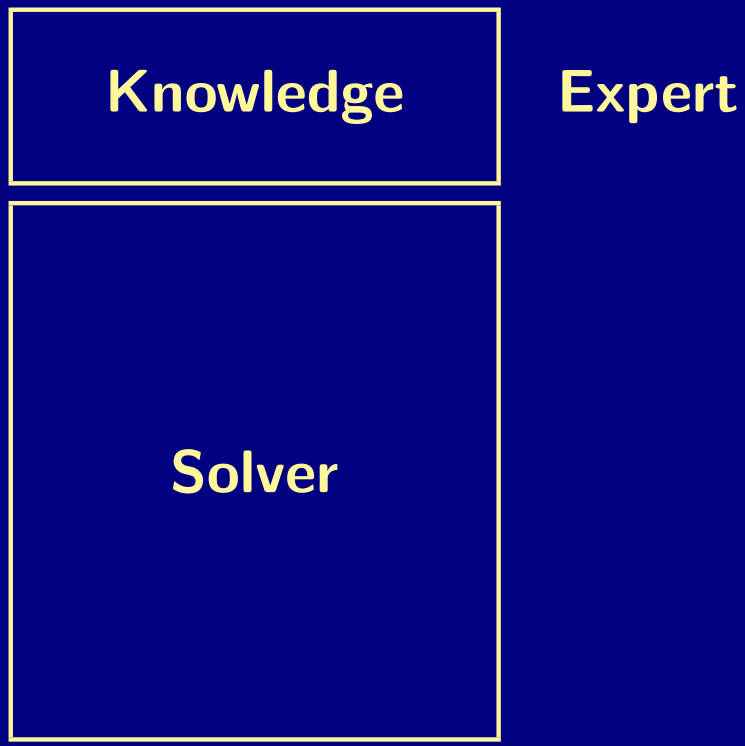

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Industrial impact

Within SIEMENS, constraint technologies have been successfully used for solving configuration problems for more than 25 years. [...] approximately 80 percent of the maintenance costs and more than 60 percent of the development costs for the knowledge representation and reasoning tasks were saved.

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Answer Set Programming (ASP)

- What is ASP?
  ASP is an approach for declarative problem solving

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- What is ASP?
  ASP is an approach for declarative problem solving
- Where is ASP from?
  - Databases
  - Logic programming
  - Knowledge representation and reasoning
  - Satisfiability solving

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Answer Set Programming (ASP)

- What is ASP? **ASP = DB+LP+KR+SAT!**
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Answer Set Programming (ASP)

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- What is ASP good for?
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  Examples Sudoku, Configuration, Diagnosis, Music composition, Planning, System design, Time tabling, etc.

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  - Debian, Ubuntu: Linux package configuration
  - Exeura: Call routing
  - FCC: Radio frequency auction
  - Gioia Tauro: Workforce management
  - NASA: Decision support for Space Shuttle
  - SBB: Train disposition
  - Siemens: Partner units configuration
  - Variantum: Product configuration

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Over 13 months in 2016–17 the US Federal Communications Commission conducted an "incentive auction" to repurpose radio spectrum from broadcast television to wireless internet. In the end, the auction yielded $19.8 billion, $10.05 billion of which was paid to 175 broadcasters for voluntarily relinquishing their licenses across 14 UHF channels. Stations that continued broadcasting were assigned potentially new channels to fit as densely as possible into the channels that remained. The government netted more than $7 billion (used to pay down the national debt) after covering costs. A crucial element of the auction design was the construction of a solver, dubbed SATFC, that determined whether sets of stations could be "repacked" in this way; it needed to run every time a station was given a price quote. This

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- What are ASP's distinguishing features?
  - High level, versatile modeling language
  - High performance solvers
  - Qualitative and quantitative optimization

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- What are ASP's distinguishing features?
  - High level, versatile modeling language
  - High performance solvers
  - Qualitative and quantitative optimization
- Any industrial impact?
  - ASP Tech companies: DLV Systems and **Potassco Solutions**
  - Increasing interest in (large) companies

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Outline

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Some (biased) moments in time

- '80 Capturing incomplete information
- '90 Amalgamation and computation
- '00 Applications and semantic rediscoveries
- '10 Customization and integration

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Some (biased) moments in time

- '80 Capturing incomplete information
  - Databases Closed world assumption
  - Logic programming Negation as failure
  - Non-monotonic reasoning
    Auto-epistemic and Default logics, Circumscription
- '90 Amalgamation and computation
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Some (biased) moments in time

- '80 Capturing incomplete information
- '90 Amalgamation and computation
  - Logic programming semantics
    Well-founded and stable models semantics
  - ASP solving
    "Stable models = Well-founded semantics + Branch"
- '00 Applications and semantic rediscoveries
- '10 Customization and integration

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Some (biased) moments in time

- '80 Capturing incomplete information
- '90 Amalgamation and computation
- '00 Applications and semantic rediscoveries
  - Growing dissemination — see last slides —
  - Constructive logics Equilibrium Logic
- '10 Customization and integration

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Some (biased) moments in time

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  - Complex reasoning modes APIs, multi-shot solving
  - Hybridization Constraint ASP, theory solving

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- '20 Real-world industries
  - Industrial applications
  - Software engineering

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Logic programs

- A logic program, P, over a set $\mathcal{A}$ of atoms is a finite set of rules
- A rule is of the form

$$\mathtt{a}_0 \texttt{ :- } \mathtt{a}_1, \ldots, \mathtt{a}_m, \texttt{ not } \mathtt{a}_{m+1}, \ldots, \texttt{ not } \mathtt{a}_n.$$

  where $0 \leq m \leq n$ and each $a_i \in \mathcal{A}$ is an atom for $0 \leq i \leq n$

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- Semantics given by stable models, informally,
  models of P justifying each true atom by a proof

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  Minimal models in the logic HT (Heyting'30) / G3 (Gödel'32)

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Open and Closed world reasoning

- Open world reasoning
  - if a statement is true, it remains true
  - if a statement is false, it remains false
  - if a statement is unknown, it is either true or false

- Closed world reasoning
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  offers defaults, reachability, succinctness
- ASP offers both open and closed world reasoning by using stable model semantics

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Open and Closed world reasoning

by example

- Alphabet $\{a, b\}$
- The rule
  - a

  has the
  - models $\{a\}, \{a, b\}$
  - minimal models $\{a\}$
  - stable models $\{a\}$

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  - $\neg b \rightarrow a$

  has the
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The logic of Here-and-There (HT)

- Formula $\varphi ::= \bot \mid a \mid \varphi \wedge \varphi \mid \varphi \vee \varphi \mid \varphi \rightarrow \varphi$
- Interpretation A pair $\langle H, T \rangle$ of sets of atoms with $H \subseteq T$
  - H is called "here" and
  - T is called "there"
- Note $\langle H, T \rangle$ is a simplified Kripke structure
- Intuition
  - H represents provably true atoms
  - T represents possibly true atoms
  - atoms not in T are false
- Idea
  - $\langle H, T \rangle \models \varphi \quad \sim \quad \varphi$ is provably true
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Satisfaction

- $\langle H, T\rangle \models a$ if $a \in H$ for any atom a
- $\langle H, T\rangle \models \varphi \wedge \psi$ if $\langle H, T\rangle \models \varphi$ and $\langle H, T\rangle \models \psi$
- $\langle H, T\rangle \models \varphi \vee \psi$ if $\langle H, T\rangle \models \varphi$ or $\langle H, T\rangle \models \psi$
- $\langle H, T\rangle \models \varphi \rightarrow \psi$ if $\langle X, T\rangle \models \varphi$ implies $\langle X, T\rangle \models \psi$ for both $X = H, T$

- Note $\langle H, T\rangle \models \neg\varphi$ if $\langle T, T\rangle \not\models \varphi$ since $\neg\varphi = \varphi \rightarrow \bot$

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Tautologies

H	T	a	$\neg a$	$a \vee \neg a$	$\neg\neg a$	$\neg\neg a \vee \neg a$	$a \leftarrow \neg\neg a$
$\{a\}$	$\{a\}$	**T**	**F**	**T**	**T**	**T**	**T**
$\emptyset$	$\{a\}$	**F**	**F**	**F**	**T**	**T**	**F**
$\emptyset$	$\emptyset$	**F**	**T**	**T**	**F**	**T**	**T**

Tautologies

H	T	a	$\neg a$	$a \vee \neg a$	$\neg\neg a$	$\neg\neg a \vee \neg a$	$a \leftarrow \neg\neg a$
$\{a\}$	$\{a\}$	***T***	***F***	***T***	***T***	***T***	***T***
$\emptyset$	$\{a\}$	***F***	***F***	***F***	***T***	***T***	***F***
$\emptyset$	$\emptyset$	***F***	***T***	***T***	***F***	***T***	***T***

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Equilibrium models

(Pearce'96)

- A total interpretation $\langle T, T\rangle$ is an equilibrium model of a formula φ, if
  1. $\langle T, T\rangle \models \varphi$
  2. $\langle H, T\rangle \not\models \varphi$ for all $H \subset T$
- T is called a stable model of φ
- Note
  - $\langle T, T\rangle$ acts as a classical model
  - $\langle H, T\rangle \models P$ iff $H \models P^T$ (P^T is the reduct of P by T)

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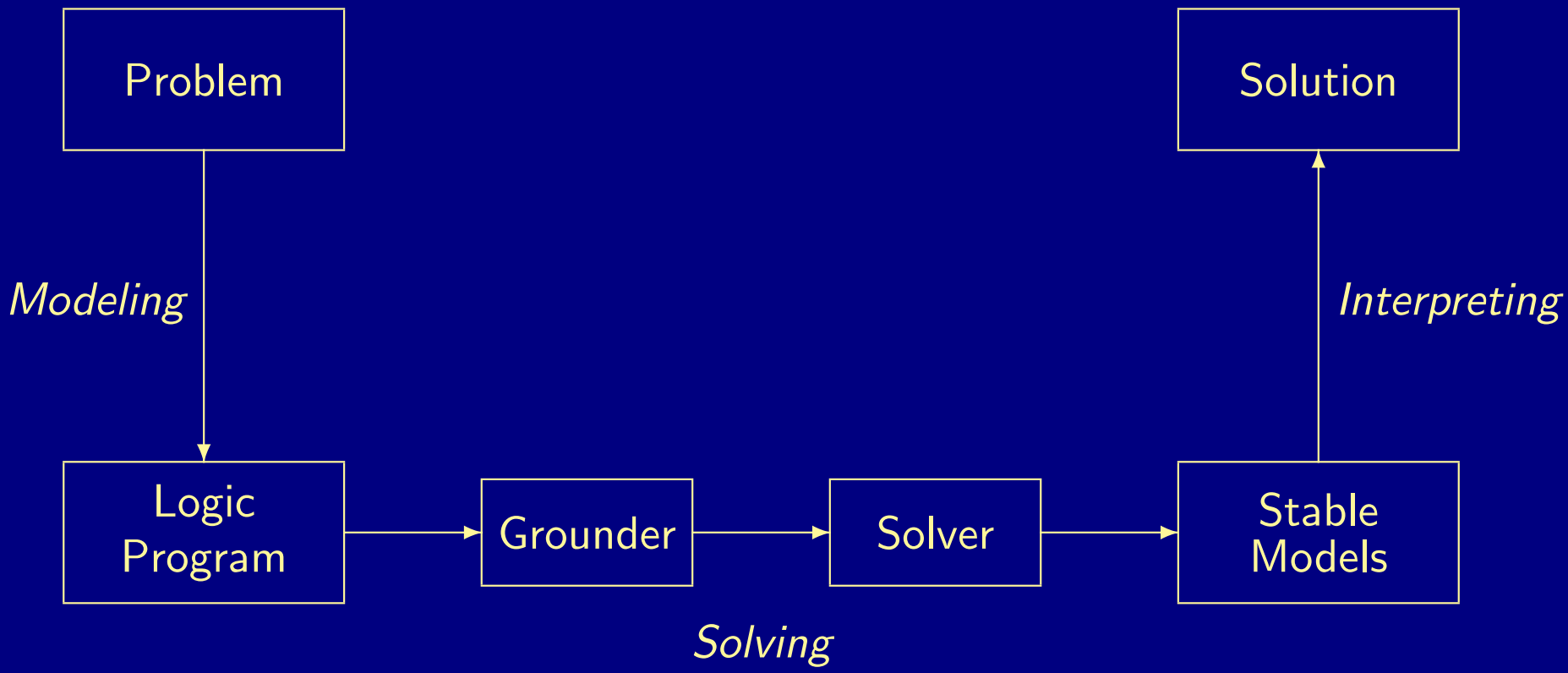
Modeling, grounding, and solving



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Language constructs

- Facts `q(42).`
- Rules `p(X) :- q(X), not r(X).`
- Conditional literals `p :- q(X) : r(X).`
- Disjunction `p(X) ; q(X) :- r(X).`
- Integrity constraints `:- q(X), p(X).`
- Choice `2 { p(X,Y) : q(X) } 7 :- r(Y).`
- Aggregates `s(Y) :- r(Y), 2 #sum{ X : p(X,Y), q(X) } 7.`

- Multi-objective optimization `:~ q(X), p(X,C). [C]`

  `#minimize { C : q(X), p(X,C) }`

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The traveling salesperson problem (TSP)

- Problem Instance A set of cities and distances among them, or simply a weighted graph
- Problem Class What is the shortest possible route visiting each city once and returning to the city of origin?
- Note
  - TSP extends the Hamiltonian cycle problem:
    Is there a cycle in a graph visiting each node exactly once
  - TSP is relevant to applications in logistics, planning, chip design, and the core of the vehicle routing problem

Potassco

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  - TSP is relevant to applications in logistics, planning, chip design, and the core of the vehicle routing problem

Potassco

Traveling salesperson

Problem instance, `cities.lp`

```
start(a).

city(a). city(b). city(c). city(d).

road(a,b,10). road(b,c,20). road(c,d,25). road(d,a,40).
road(b,d,30). road(d,c,25). road(c,a,35).
```

Potassco

Traveling salesperson

Problem encoding, `tsp.lp`

```
{ travel(X,Y) } :- road(X,Y,_).

visited(Y) :- travel(X,Y), start(X).
visited(Y) :- travel(X,Y), visited(X).

:- city(X), not visited(X).

:- city(X), 2 { travel(X,Y) }.
:- city(X), 2 { travel(Y,X) }.
```

Potassco

Traveling salesperson

Problem encoding, `tsp.lp`

```
{ travel(X,Y) } :- road(X,Y,_).

visited(Y) :- travel(X,Y), start(X).
visited(Y) :- travel(X,Y), visited(X).

:- city(X), not visited(X).

:- city(X), 2 { travel(X,Y) }.
:- city(X), 2 { travel(Y,X) }.

:~ travel(X,Y), road(X,Y,D). [D,X,Y]
```

Potassco

Running salesperson

```
$ clingo tsp.lp cities.lp
clingo version 5.3.1
Reading...
Solving...
Answer: 1
start(a) [...] road(c,a,35)
travel(a,b) travel(b,d) travel(d,c) travel(c,a)
visited(b) visited(c) visited(d) visited(a)
Optimization: 100
Answer: 2
start(a) [...] road(c,a,35)
travel(a,b) travel(b,c) travel(c,d) travel(d,a)
visited(b) visited(c) visited(d) visited(a)
Optimization: 95
OPTIMUM FOUND

Models       : 2
  Optimum    : yes
Optimization : 95
Calls        : 1
Time         : 0.005s (Solving: 0.00s 1st Model: 0.00s Unsat: 0.00s)
CPU Time     : 0.002s
```

Potassco

Running salesperson

```
$ clingo tsp.lp cities.lp
clingo version 5.3.1
Reading...
Solving...
Answer: 1
start(a) [...] road(c,a,35)
travel(a,b) travel(b,d) travel(d,c) travel(c,a)
visited(b) visited(c) visited(d) visited(a)
Optimization: 100
Answer: 2
start(a) [...] road(c,a,35)
travel(a,b) travel(b,c) travel(c,d) travel(d,a)
visited(b) visited(c) visited(d) visited(a)
Optimization: 95
OPTIMUM FOUND

Models       : 2
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Calls        : 1
Time         : 0.005s (Solving: 0.00s 1st Model: 0.00s Unsat: 0.00s)
CPU Time     : 0.002s
```

Potassco

Running salesperson

```
$ clingo tsp.lp cities.lp
clingo version 5.3.1
Reading...
Solving...
Answer: 1
start(a) [...] road(c,a,35)
travel(a,b) travel(b,d) travel(d,c) travel(c,a)
visited(b) visited(c) visited(d) visited(a)
Optimization: 100
Answer: 2
start(a) [...] road(c,a,35)
travel(a,b) travel(b,c) travel(c,d) travel(d,a)
visited(b) visited(c) visited(d) visited(a)
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Potassco

Running salesperson

```
$ clingo tsp.lp cities.lp
clingo version 5.3.1
Reading...
Solving...
Answer: 1
start(a) [...] road(c,a,35)
travel(a,b) travel(b,d) travel(d,c) travel(c,a)
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travel(a,b) travel(b,c) travel(c,d) travel(d,a)
visited(b) visited(c) visited(d) visited(a)
Optimization: 95
OPTIMUM FOUND

Models       : 2
  Optimum    : yes
Optimization : 95
Calls        : 1
Time         : 0.005s (Solving: 0.00s 1st Model: 0.00s Unsat: 0.00s)
CPU Time     : 0.002s
```

Potassco

Running salesperson

```
$ clingo tsp.lp cities.lp
clingo version 5.3.1
Reading...
Solving...
Answer: 1
start(a) [...] road(c,a,35)
travel(a,b) travel(b,d) travel(d,c) travel(c,a)
visited(b) visited(c) visited(d) visited(a)
Optimization: 100
Answer: 2
start(a) [...] road(c,a,35)
travel(a,b) travel(b,c) travel(c,d) travel(d,a)
visited(b) visited(c) visited(d) visited(a)
Optimization: 95
OPTIMUM FOUND

Models       : 2
  Optimum    : yes
Optimization : 95
Calls        : 1
Time         : 0.005s (Solving: 0.00s 1st Model: 0.00s Unsat: 0.00s)
CPU Time     : 0.002s
```

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Some of our industrial projects

- Railway companies
  - Shift planning
  - Room planning
  - Maintenance scheduling
  - Train disposition
- Automobile industries
  - Car assembly sequencing
  - Car version configuration
  - Robotic vehicle control
- Logistics industries
  - Delivery optimization
  - Stock optimization
- Manufacturing industries
  - Product configuration
  - Machine configuration
  - Assembly line layout
- Public services
  - University timetabling
  - University study regulations

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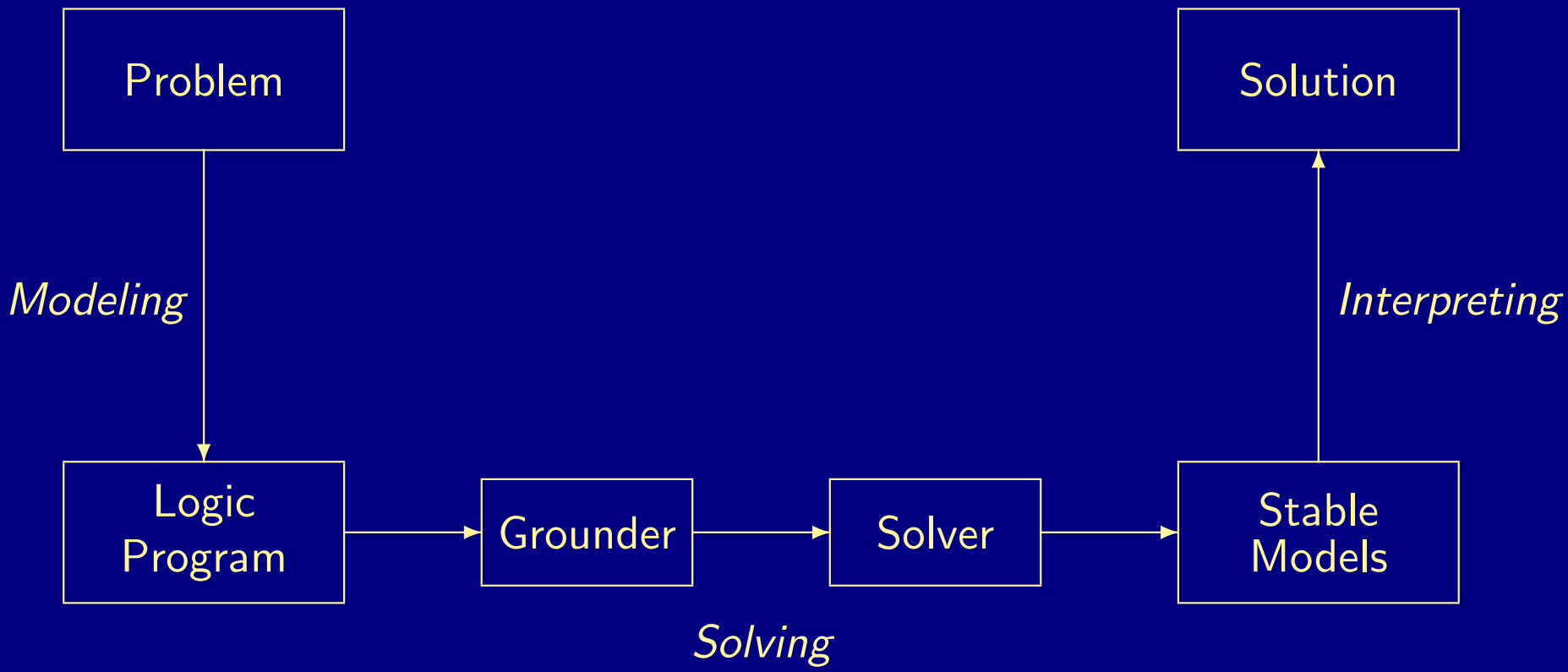
Outline

Potassco

Modeling, grounding, and solving



Potassco

clingraph

Sudoku

Model

ASP Developer

A problem

"A sudoku puzzle"

Visualization encoding

Potassco

clingraph

Sudoku

Model

```
initial(1,4,2). initial(3,3,1).
initial(3,4,3). initial(3,1,4).
```

ASP Developer

Visualization encoding

Potassco

clingraph

Sudoku[1]

Model

```
initial(1,4,2). initial(3,3,1).
initial(3,4,3). initial(3,1,4).
```

ASP Developer


```
  sudoku(X,Y,V) :- initial(X,Y,V).
{ sudoku(X,Y,V) : val(V) } = 1 :- pos(X,Y).
:- sudoku(X,Y,V), sudoku(X',Y,V), X != X'.
:- sudoku(X,Y,V), sudoku(X,Y',V), Y != Y'.
:- sudoku(X,Y,V), sudoku(X',Y',V), (X,Y)!=(X',Y'),
  subgrid(X,Y,S), subgrid(X',Y',S).
```

Visualization encoding

[1] Omitting pos/2, val/1, subgrid/2

Potassco

clingraph

Sudoku

Model

ASP Developer

```
initial(1,4,2). initial(3,3,1).
initial(3,4,3). initial(3,1,4).
```

```
  sudoku(X,Y,V) :- initial(X,Y,V).
{ sudoku(X,Y,V) : val(V) } = 1 :- pos(X,Y).
:- sudoku(X,Y,V), sudoku(X',Y,V), X != X'.
:- sudoku(X,Y,V), sudoku(X,Y',V), Y != Y'.
:- sudoku(X,Y,V), sudoku(X',Y',V), (X,Y)!=(X',Y'),
  subgrid(X,Y,S), subgrid(X',Y',S).
```

```
clingo version 5.7.1
Reading from sudoku.lp ..
Solving...
Answer: 1
sudoku(1,4,2) sudoku(3,3,1)
sudoku(1,2,3) sudoku(3,4,3)
sudoku(3,1,4) sudoku(1,1,1)
sudoku(4,2,1) sudoku(3,2,2)
sudoku(4,1,3) sudoku(1,3,4)
sudoku(4,3,2) sudoku(4,4,4)
sudoku(2,1,2) sudoku(2,4,1)
sudoku(2,3,3) sudoku(2,2,4)
SATISFIABLE

Models : 1+
Calls : 1
Time : 0.007s
CPU Time : 0.003s
```

Visualization encoding

Potassco

clingraph

Sudoku

Model

```
initial(1,4,2). initial(3,3,1).
initial(3,4,3). initial(3,1,4).
```

ASP Developer

```
   sudoku(X,Y,V) :- initial(X,Y,V).
 { sudoku(X,Y,V) : val(V) } = 1 :- pos(X,Y).
:- sudoku(X,Y,V), sudoku(X',Y,V), X != X'.
:- sudoku(X,Y,V), sudoku(X,Y',V), Y != Y'.
:- sudoku(X,Y,V), sudoku(X',Y',V), (X,Y)!=(X',Y'),
   subgrid(X,Y,S), subgrid(X',Y',S).
```

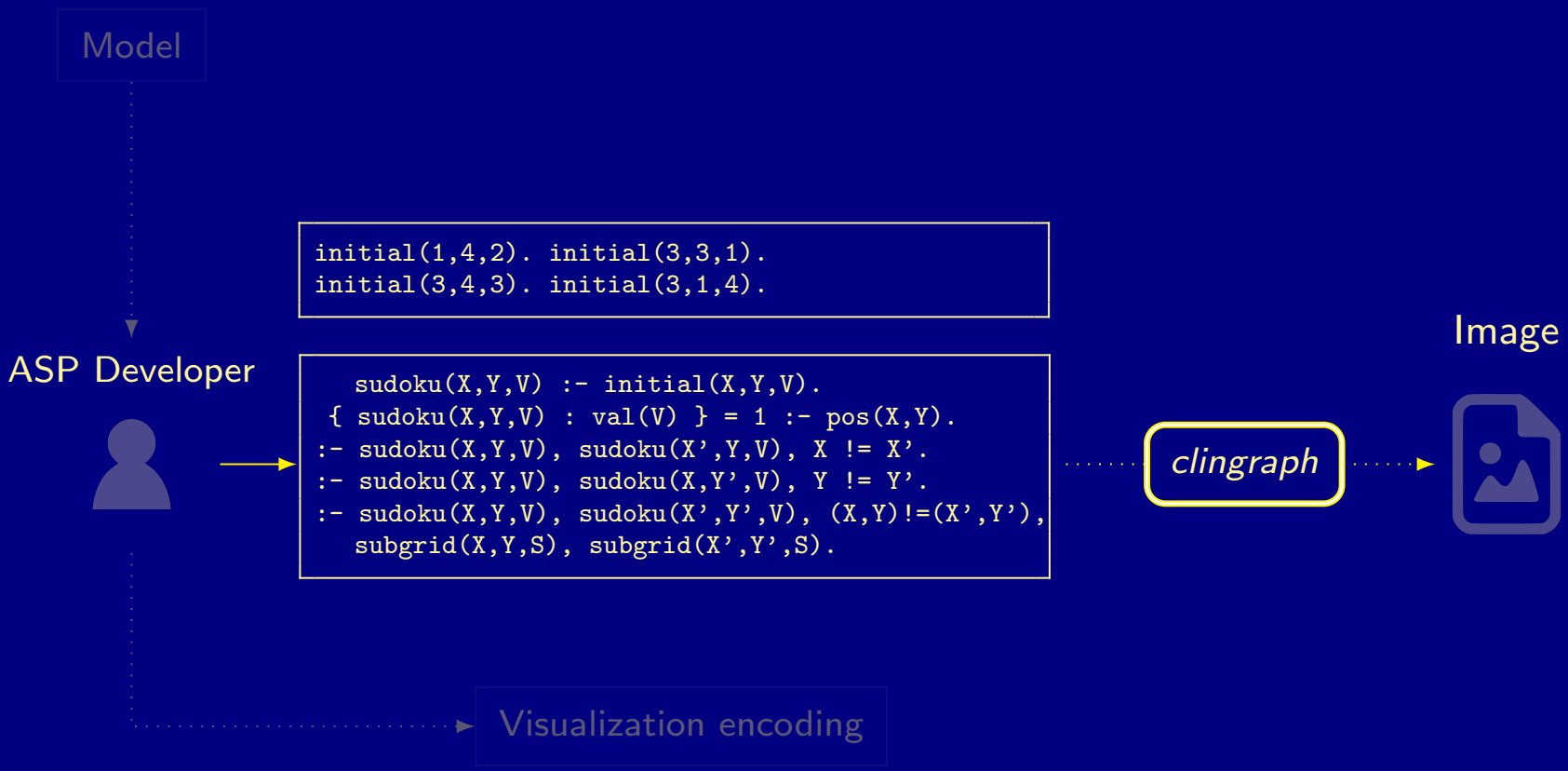
Image

Visualization encoding

Potassco

clingraph

Sudoku



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clingraph

Sudoku

Model

```
initial(1,4,2). initial(3,3,1).
initial(3,4,3). initial(3,1,4).
```

ASP Developer

```
  sudoku(X,Y,V) :- initial(X,Y,V).
{ sudoku(X,Y,V) : val(V) } = 1 :- pos(X,Y).
:- sudoku(X,Y,V), sudoku(X',Y,V), X != X'.
:- sudoku(X,Y,V), sudoku(X,Y',V), Y != Y'.
:- sudoku(X,Y,V), sudoku(X',Y',V), (X,Y)!=(X',Y'),
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```

Image

Visualization encoding

Potassco

clingraph

Sudoku

Model

```
initial(1,4,2). initial(3,3,1).
initial(3,4,3). initial(3,1,4).
```

ASP Developer

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   sudoku(X,Y,V) :- initial(X,Y,V).
 { sudoku(X,Y,V) : val(V) } = 1 :- pos(X,Y).
:- sudoku(X,Y,V), sudoku(X',Y,V), X != X'.
:- sudoku(X,Y,V), sudoku(X,Y',V), Y != Y'.
:- sudoku(X,Y,V), sudoku(X',Y',V), (X,Y)!=(X',Y'),
   subgrid(X,Y,S), subgrid(X',Y',S).
```

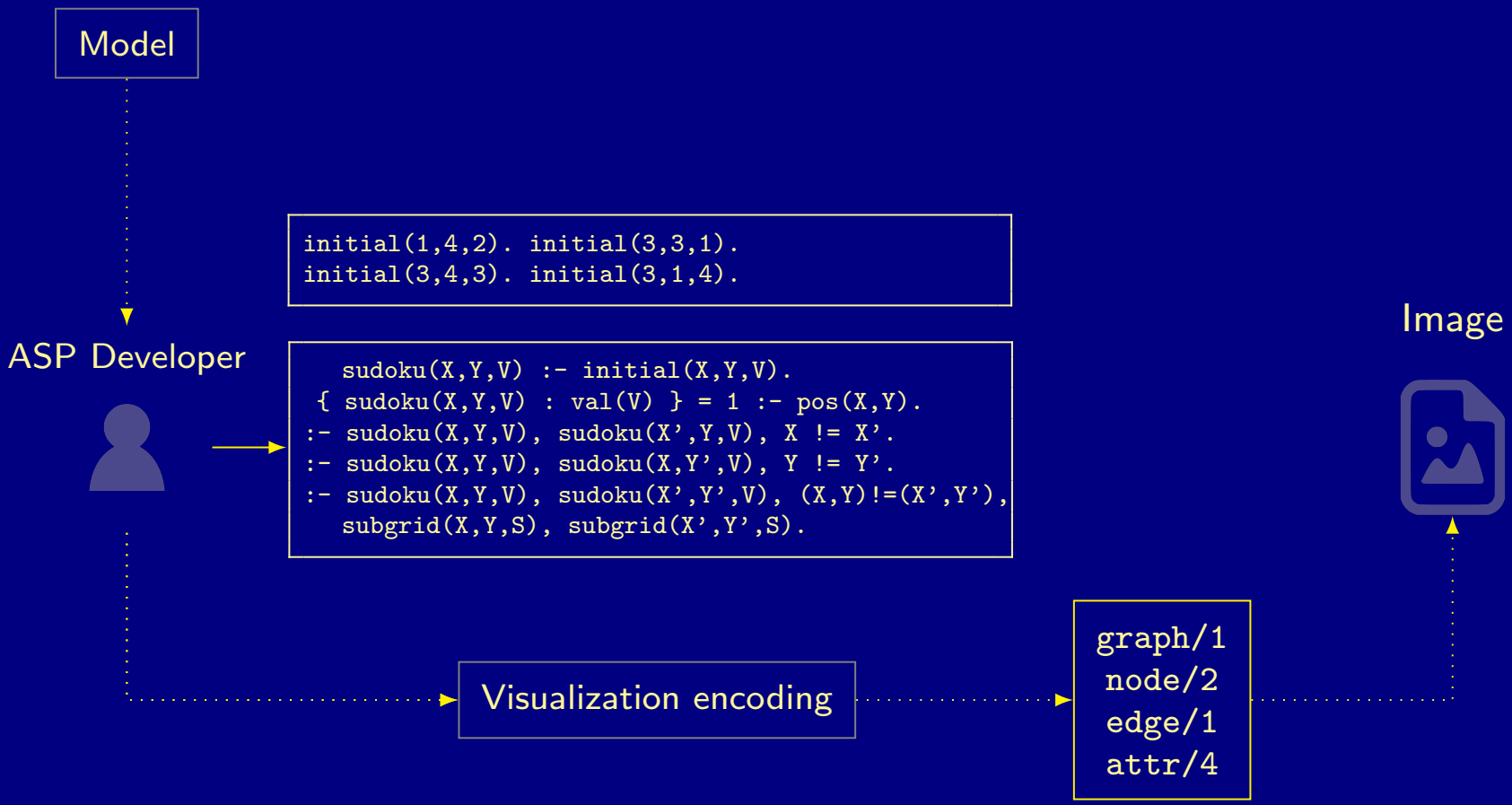
Image

Visualization encoding

Potassco

clingraph

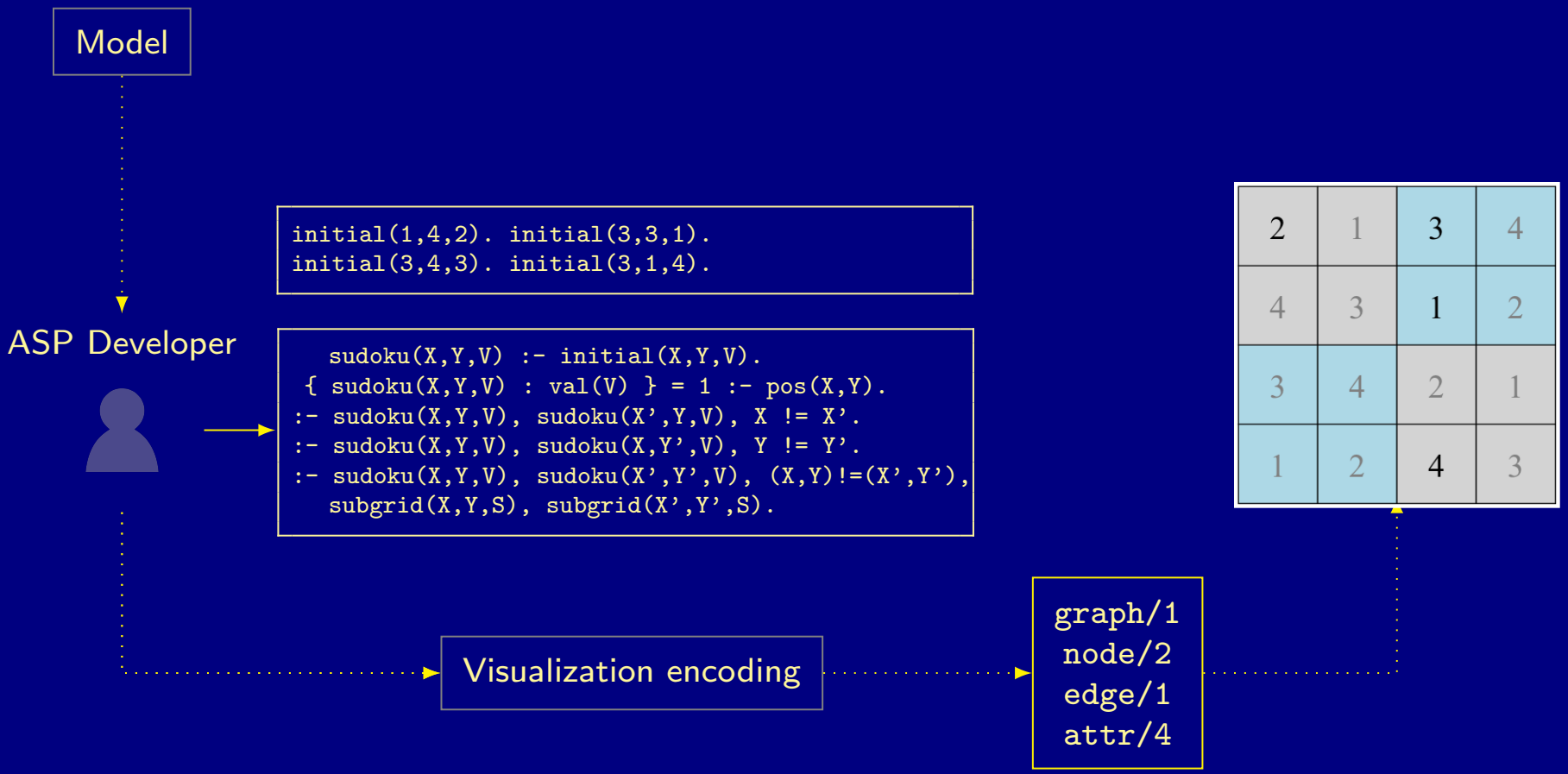
Sudoku



Potassco

clingraph

Sudoku



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Visualization encoding

Sudoku

2	1	3	4
4	3	1	2
3	4	2	1
1	2	4	3

- `graph/1`
- `node/2`
- `edge/1`
- `attr/4`

```
graph(sudoku).

node(pos(X,Y), sudoku) :- pos(X,Y).

attr(node, pos(X,Y), label, V) :- sudoku(X,Y,V).
attr(node, pos(X,Y), shape, square) :- sudoku(X,Y,V).
attr(node, pos(X,Y), style, filled) :- sudoku(X,Y,V).
attr(node, pos(X,Y), fontsize, 30) :- sudoku(X,Y,V).
attr(node, pos(X,Y), width, "1") :- sudoku(X,Y,V).
attr(node, pos(X,Y), pos, @pos(X,Y)) :- pos(X,Y).
attr(node, pos(X,Y), fillcolor, blue) :- pos(X,Y), (((X-1)/dim)+((Y-1)/dim))\2==0.
attr(node, pos(X,Y), fontcolor, gray50) :- sudoku(X,Y,V), not initial(X,Y,_).
```

Potassco

Visualization encoding

Sudoku

2	1	3	4
4	3	1	2
3	4	2	1
1	2	4	3

- `graph/1`
- `node/2`
- `edge/1`
- `attr/4`

```
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attr(node, pos(X,Y), width, "1") :- sudoku(X,Y,V).
attr(node, pos(X,Y), pos, @pos(X,Y)) :- pos(X,Y).
attr(node, pos(X,Y), fillcolor, blue) :- pos(X,Y), (((X-1)/dim)+((Y-1)/dim))\2==0.
attr(node, pos(X,Y), fontcolor, gray50) :- sudoku(X,Y,V), not initial(X,Y,_).
```
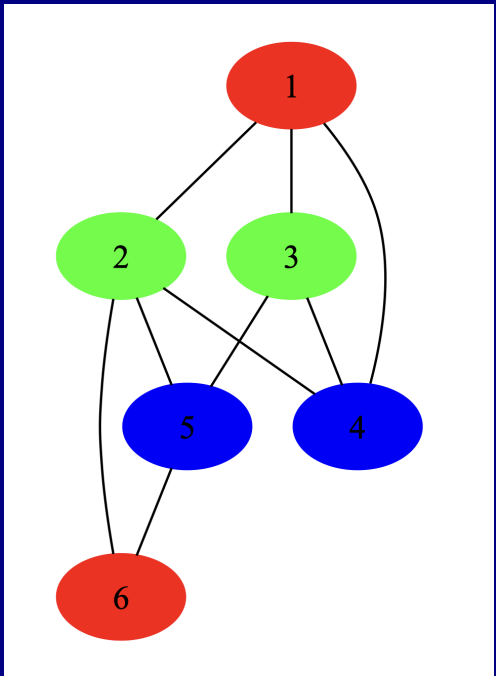

Potassco

Example

Simple graph

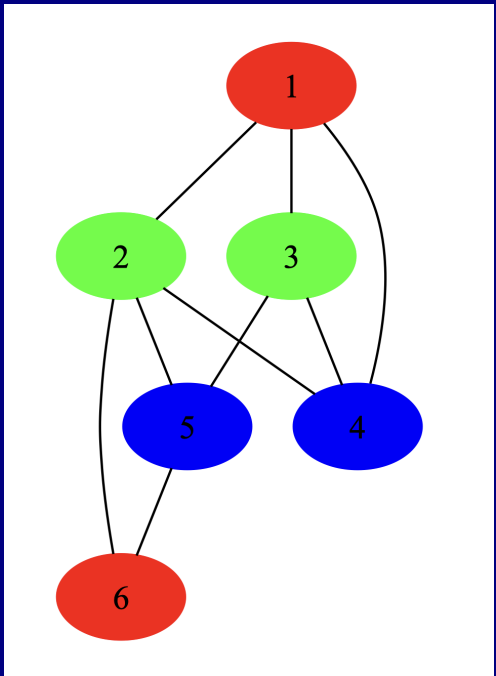



```
#show node/1.
#show edge((N,M)) : edge(N, M).
#show attr(node, N, style, filled): node(N).
#show attr(node, N, color, C) : assign(N, C).
```

Potassco

Example

Simple graph




```
#show node/1.
#show edge((N,M)) : edge(N, M).
#show attr(node, N, style, filled): node(N).
#show attr(node, N, color, C) : assign(N, C).
```

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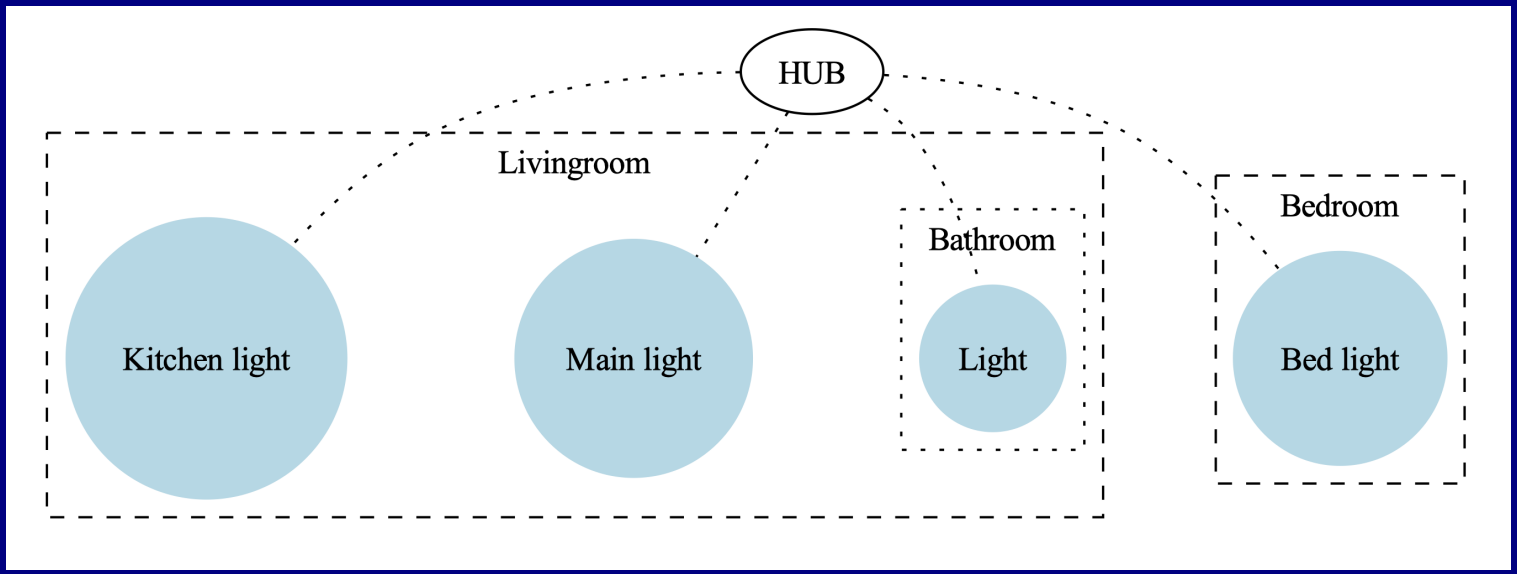
Example

Subgraphs



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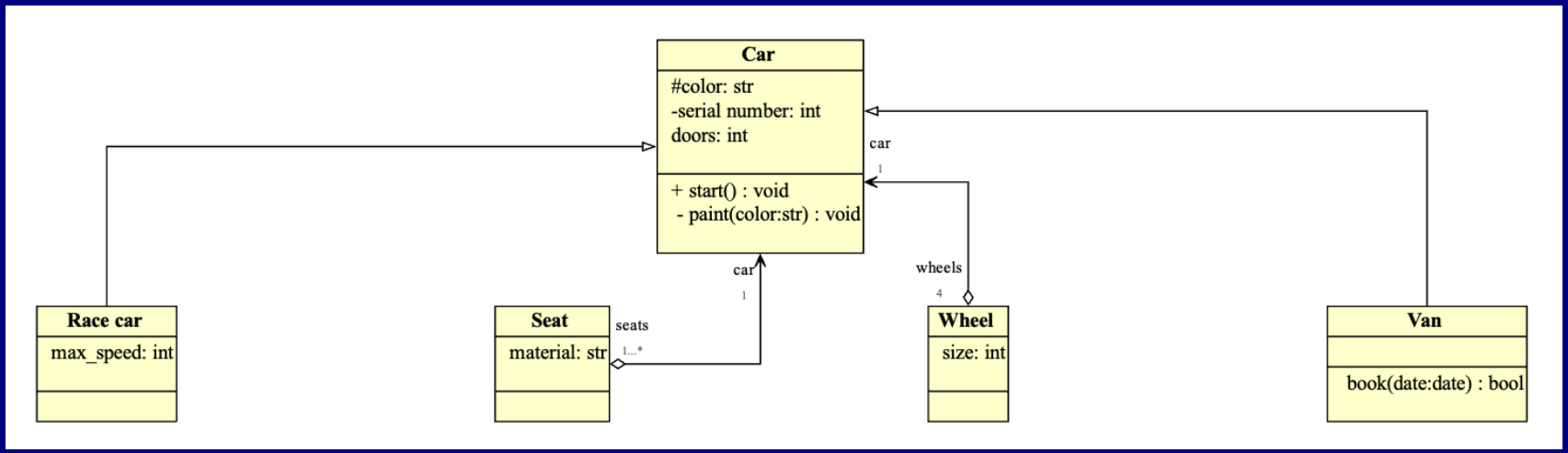
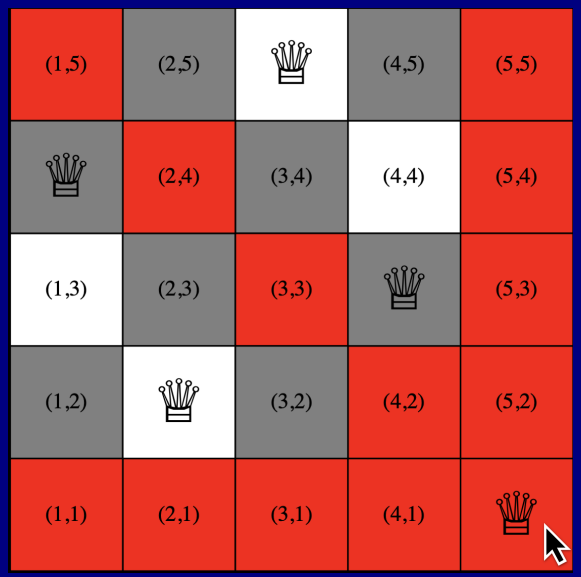
Example

UML



Potassco

Example
SVG



Potassco

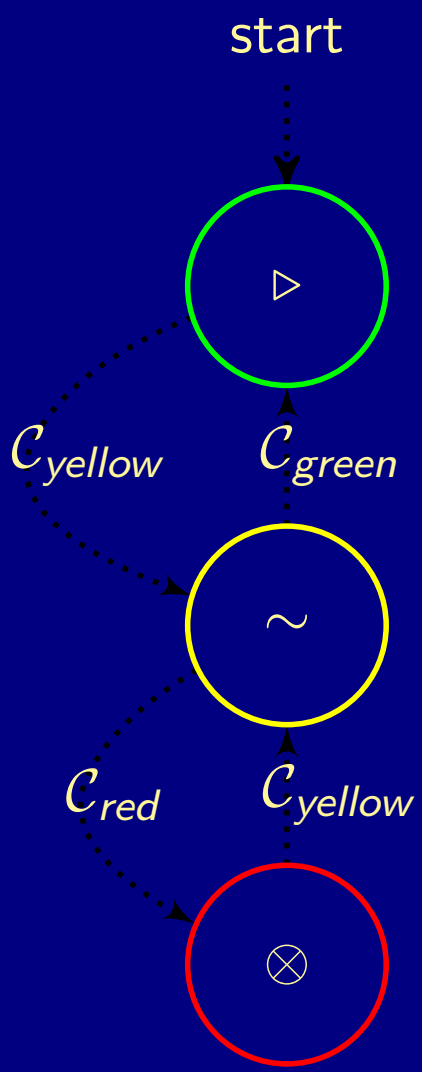
Example

SVG

Potassco

Example

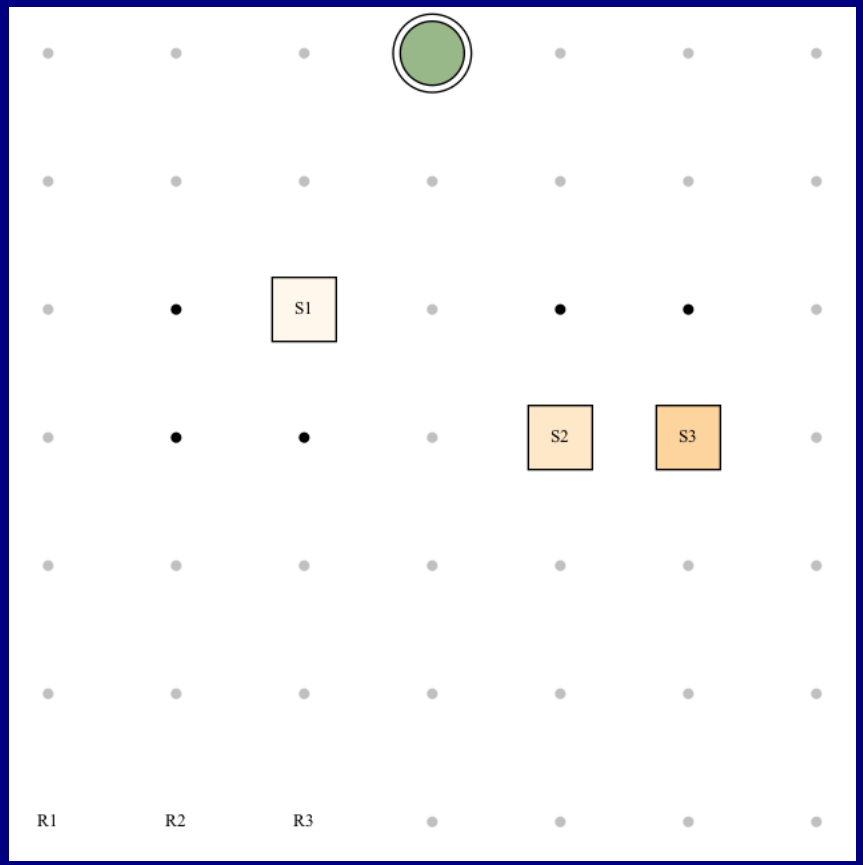
LaTeX



Potassco

Example

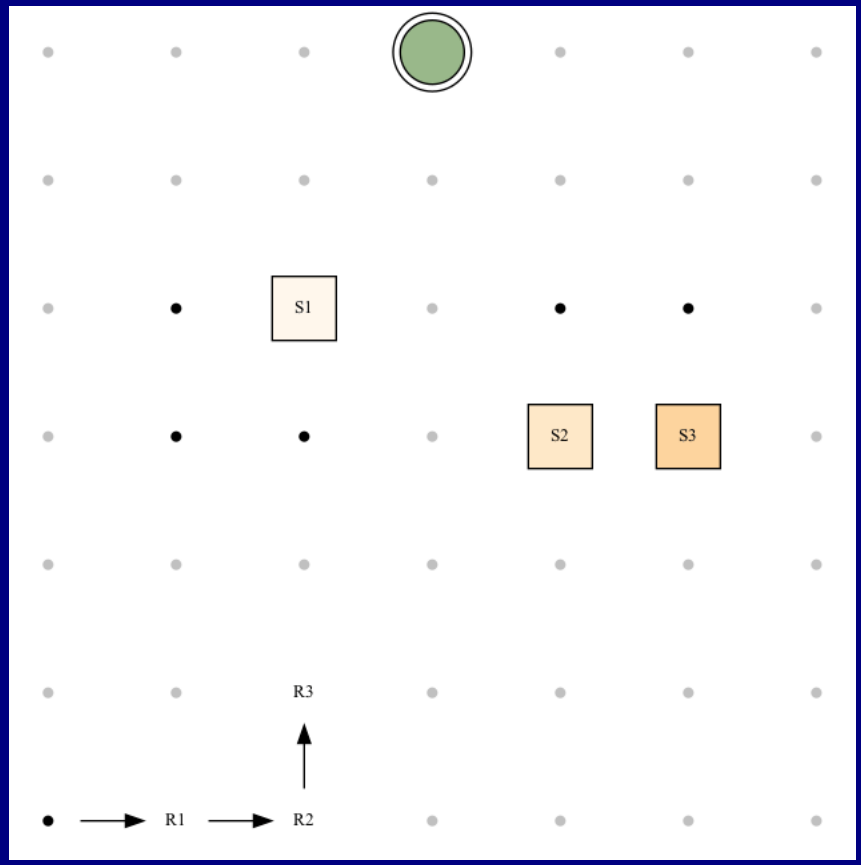
GIF animation



Potassco

Example

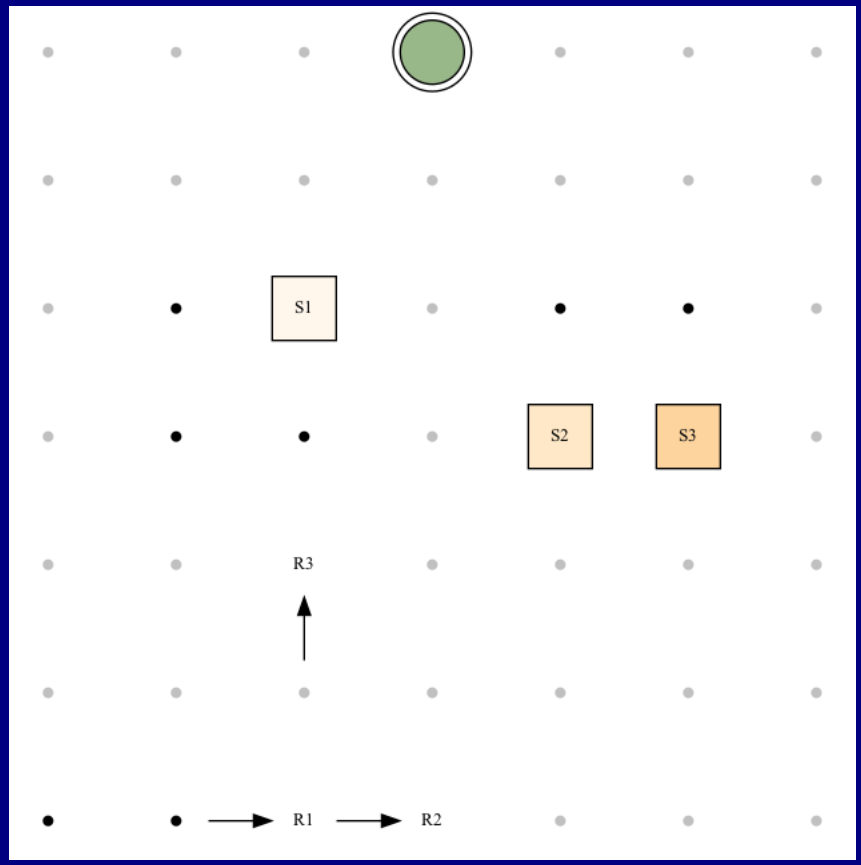
GIF animation



Potassco

Example

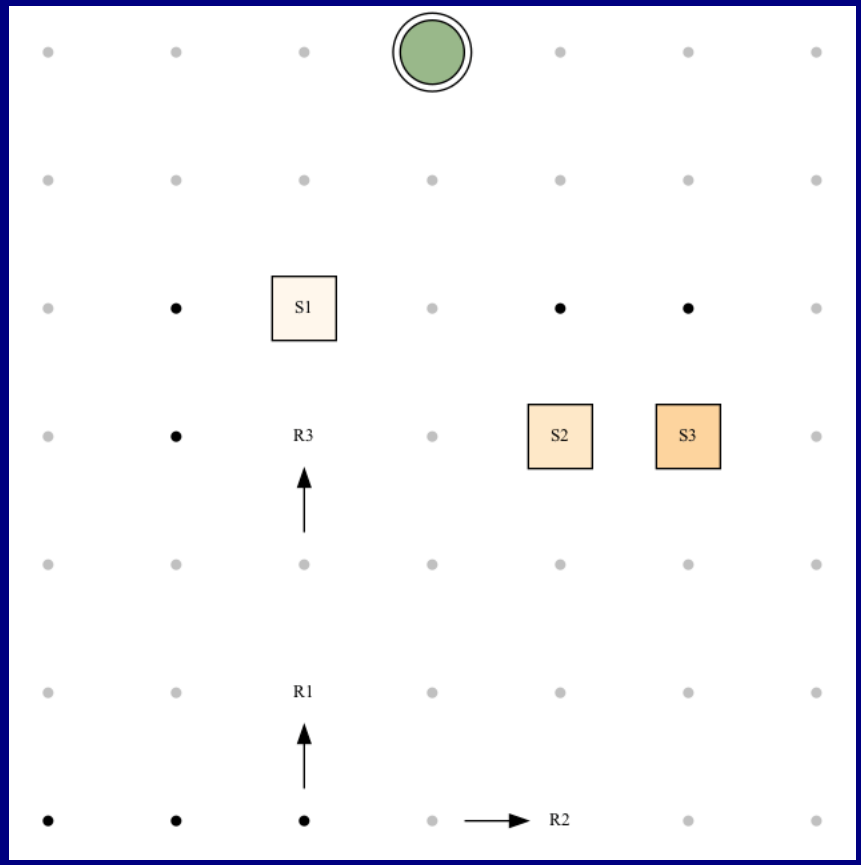
GIF animation



Potassco

Example

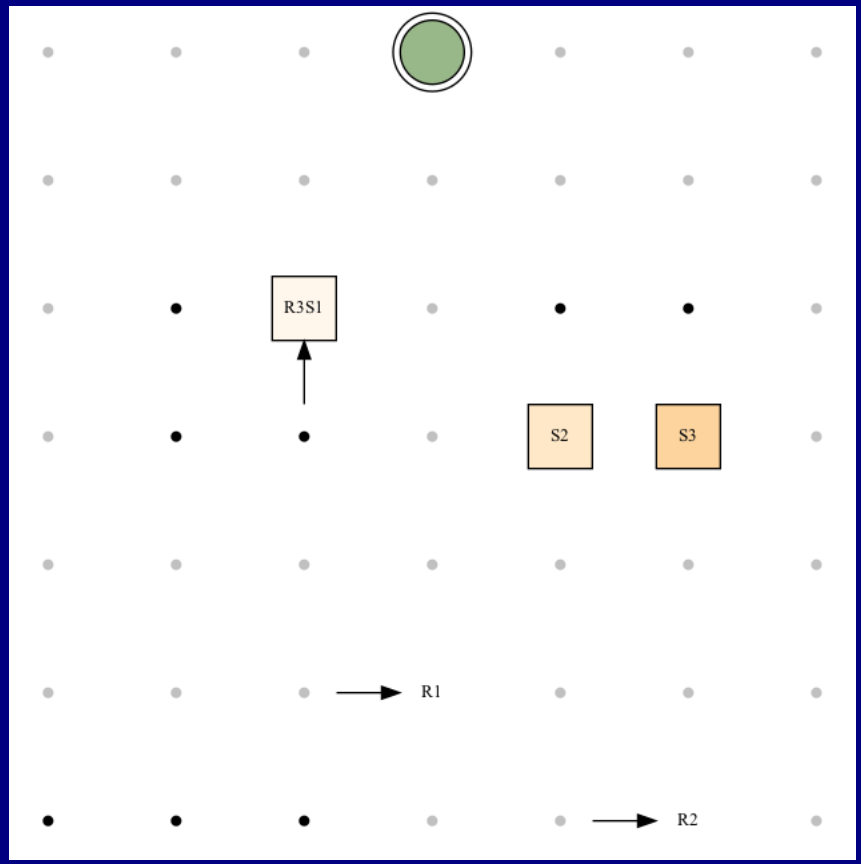
GIF animation



Potassco

Example

GIF animation



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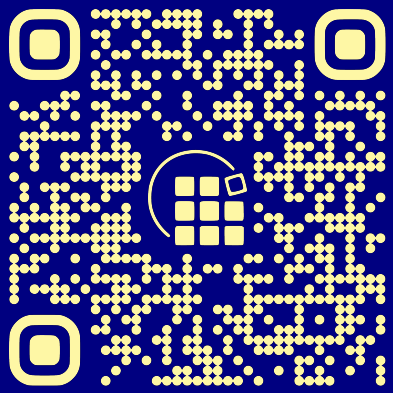
clingraph

- An ASP-based front-end to *graphviz*
  - Define visualizations in terms of ASP
  - Visualize instances, solutions, or even the solving process
  - Extends ASP's rapid prototyping with visualization
- Functionalities
  - Command line usage
  - Python API
  - Different output formats
  - Integration with *clingo*
- Open source software
  - `https://github.com/potassco/clingraph`
  - `https://clingraph.readthedocs.io`



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Outline

Potassco

More features of interest

- Meta programming
- Qualitative and quantitative optimization
- Heuristic programming
- Application interface programming
  - Multi-shot solving
  - Theory solving
- Linear Temporal, Dynamic and Metric reasoning
- Visualization

- Playful? `https://potassco.org`

Potassco

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Potassco

Outline

Potassco

ASP systems and tools

gringo	grounding	*clinsight*	editing
clasp	solving	*xclingo*	explaining
clingo	ASP	*clingo-server*	surfing
metasp	Meta ASP	*acclingo*	tuning
clingcon	ASP+CP	*anthem*	verifying
fclingo	ASP+CP	*asprin*	preferring
clingo[DL]	ASP+CP	*clingraph*	visualizing
clingo[LP]	ASP+CP	*clinguin*	interacting
clingo[LPX]	ASP+CP	*viasp*	visualizing
eclingo	epistemic ASP	*clintest*	testing
plingo	probabilistic ASP	*clorm*	dataing
telingo	temporal ASP	*ngo*	optimizing

Potassco

ASP systems and tools

- *gringo* grounding
- *clasp* solving
- *clingo* ASP
- *metasp* Meta ASP
- *clingcon* ASP+CP
- *fclingo* ASP+CP
- *clingo*[DL] ASP+CP
- *clingo*[LP] ASP+CP
- *clingo*[LPX] ASP+CP
- *eclingo* epistemic ASP
- *plingo* probabilistic ASP
- *telingo* temporal ASP

- *clinsight* editing
- *xclingo* explaining
- *clingo-server* surfing
- *acclingo* tuning
- *anthem* verifying
- *asprin* preferring
- *clingraph* visualizing
- *clinguin* interacting
- *viasp* visualizing
- *clintest* testing
- *clorm* dataing
- *ngo* optimizing

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Application-oriented systems

aspartame	constraint solver
aspcafe	vehicle equipment specification
aspcud	software package configuration
asprilo	warehouse simulation
chasp	music composition
flatzingo	constraint solver
fluto	metabolic network expansion
plasp	planning system
qasp	quantified ASP solver
spa	study planner
teaspoon	university timetabling system
xorro	sampling stable models

Potassco

Outline

Potassco

Take home message

Potassco

Take home message

Modeling + Grounding + Solving

Potassco

Take home message

Modeling + Grounding + Solving

ASP = DB+LP+KR+SAT

Potassco

Take home message

Modeling + Grounding + Solving

ASP = DB+LP+KR+SMT^n

Potassco

Take home message

Modeling + Grounding + Solving

ASP = DB+LP+KR+SMT^n

https://potassco.org

Potassco

Take home message

Modeling + Grounding + Solving

ASP = DB+LP+KR+SMT^n

https://potassco.org

And it's fun !

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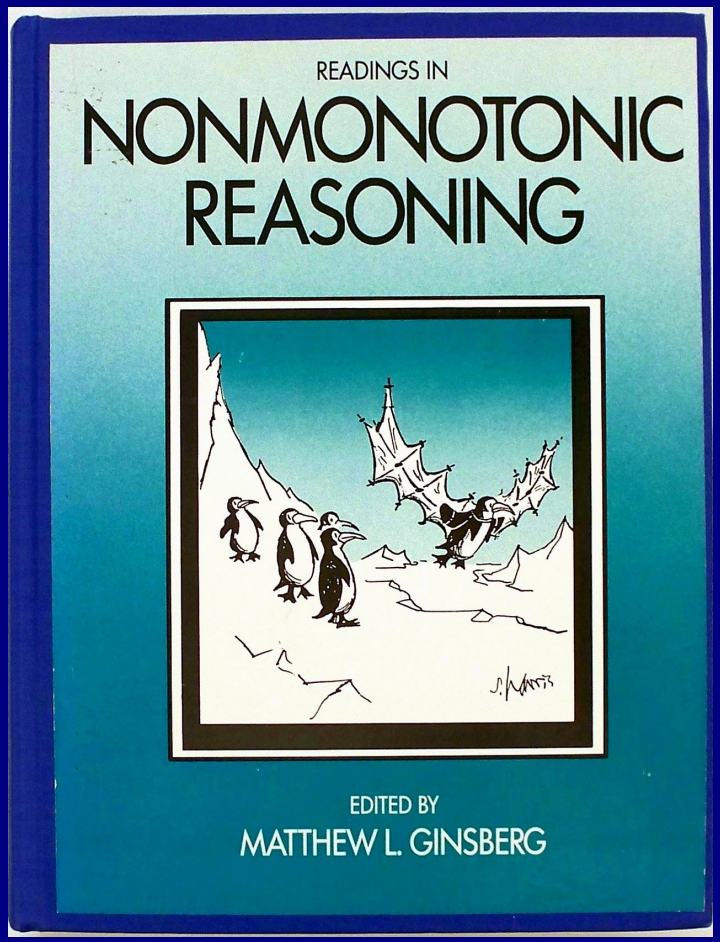
Epilogue

After all, it's all about Tweety!

Epilogue

After all, it's all about Tweety!



'87

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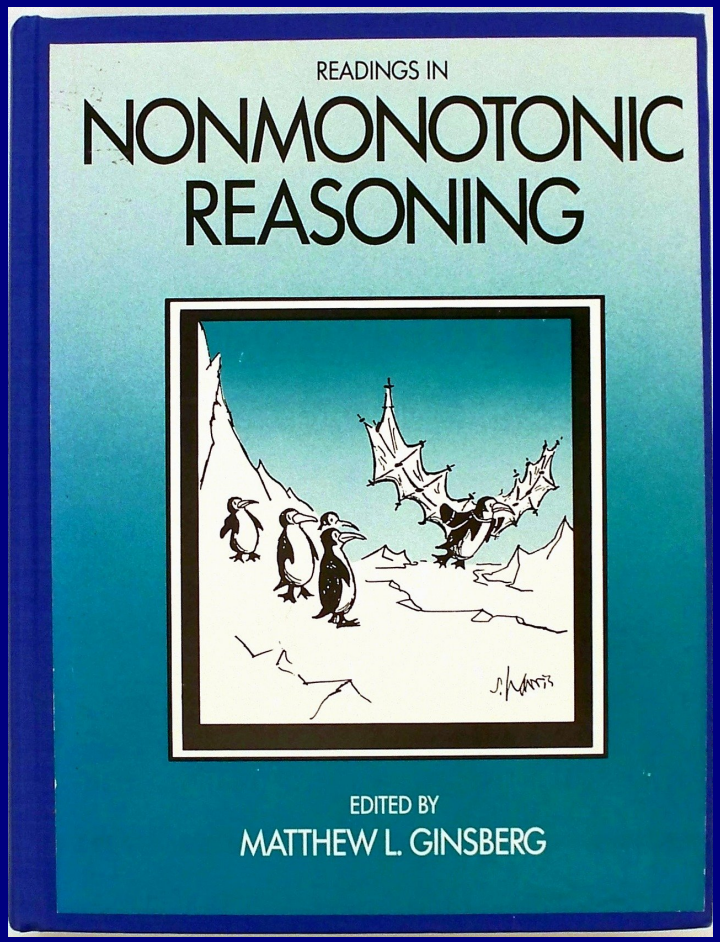
Epilogue

After all, it's all about Tweety!



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