Answer Set Based Design of Autonomous, Rational Agents

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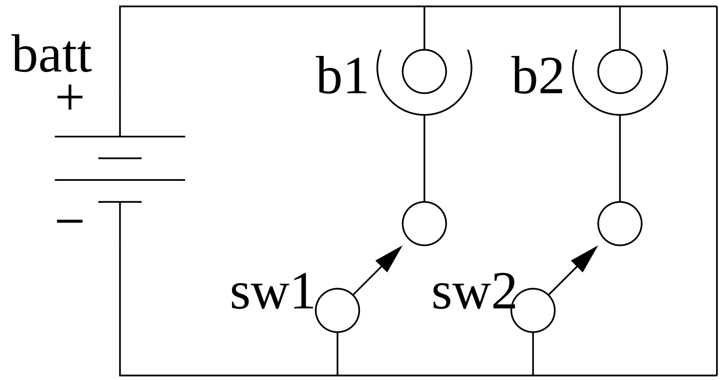
Our Goal

To design an agent capable of
rational, autonomous interaction with the environment.

Example of Agent Behavior

A Physical System



Domain Properties

- $closed(SW)$
- $lit(Bulb)$
- $ab(Bulb)$
- $ab(batt)$

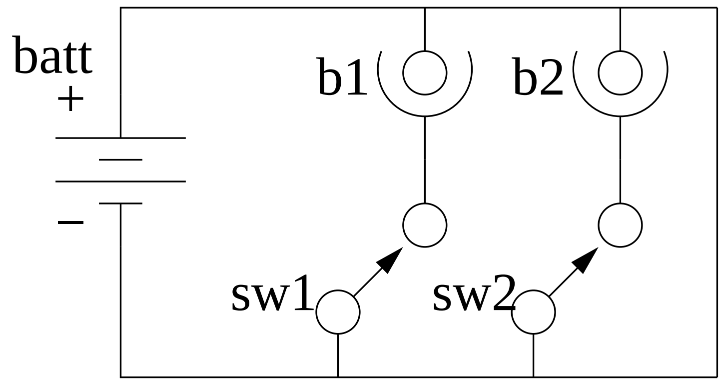
Agent Actions

- $flip(SW)$
- $replace(Bulb)$
- $replace(batt)$

Exogenous Actions

- $blow\_up(Bulb)$

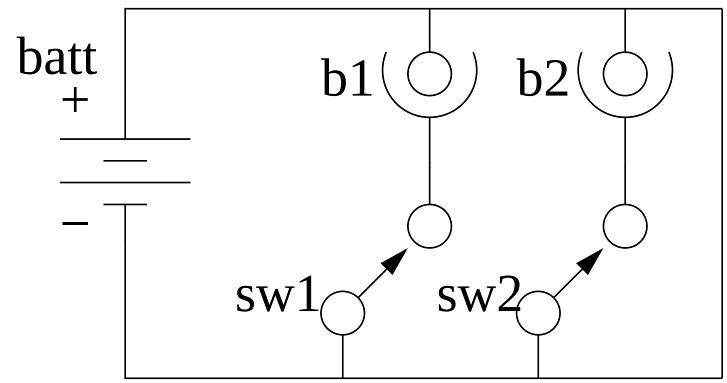
Planning



Agent's goal: $lit(b_1)$

- **Observes**: switches open; bulbs off; components ok
- **Finds plan**: $flip(sw_1)$
- **Executes**: $flip(sw_1)$
- **Observes**: ...?

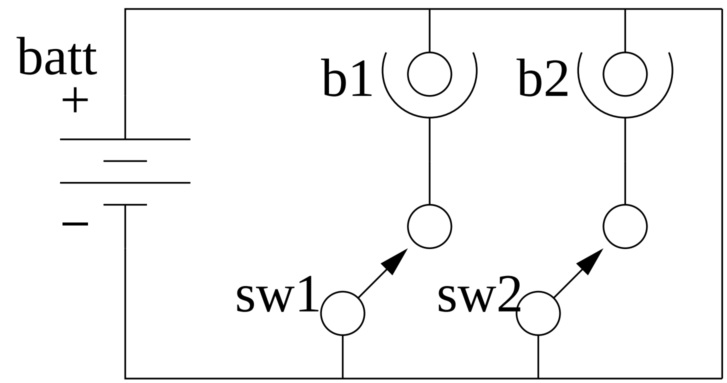
Diagnosis



[. . .]

- **Executes**: $flip(sw_1)$
- **Observes**: $\neg lit(b_1)$ $\Leftarrow$ **UNEXPECTED!!!**
- **Explains**: $blow\_up(b_1)$ occurred *concurrently* with $flip(sw_1)$
- **Tests**: is $ab(b_1)$ true?
- **Answer**: . . .?

Recovery

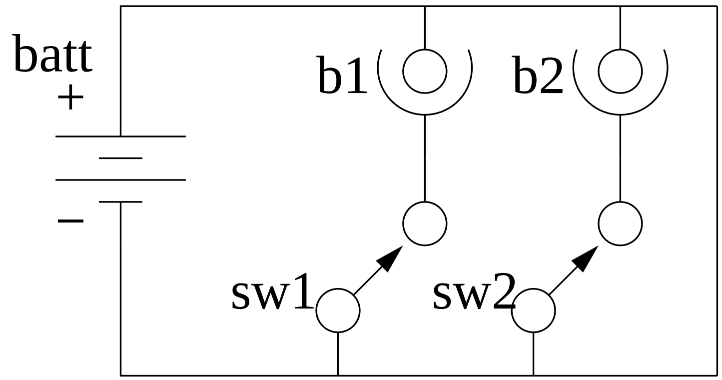


[. . .]

- **Tests**: is $ab(b_1)$ true?
- **Answer**: $ab(b_1)$ true
- **Finds plan**: $replace(b_1)$
- **Executes**: $replace(b_1)$
- **Observes**: $lit(b_1)$ $\Leftarrow$ **SUCCESS!!!**

Beyond Diagnosis

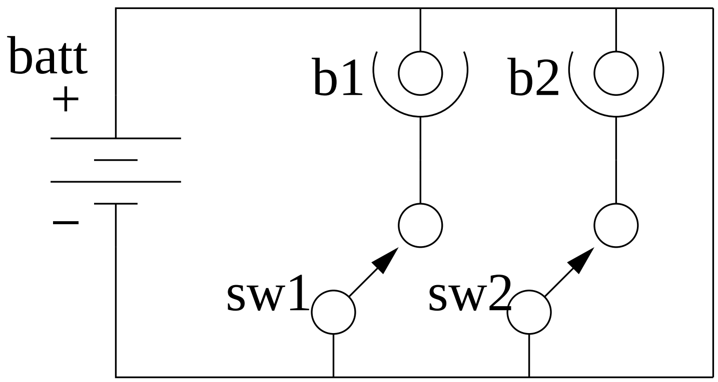
What if...?



Receives new goal: $lit(b_2)$

- **Finds plan**: $flip(sw_2)$
- **Executes**: $flip(sw_2)$
- **Observes**: $\neg lit(b_2)$ $\Leftarrow$ **UNEXPECTED!!!**
- **Explains**: $blow\_up(b_2)$ occurred (e.g. with $flip(sw_2)$)
- **Tests**: is $ab(b_2)$ true?
- **Answer**: $ab(b_2)$ **false**!!! $\Leftarrow$ **NO DIAGNOSES LEFT**

Learning

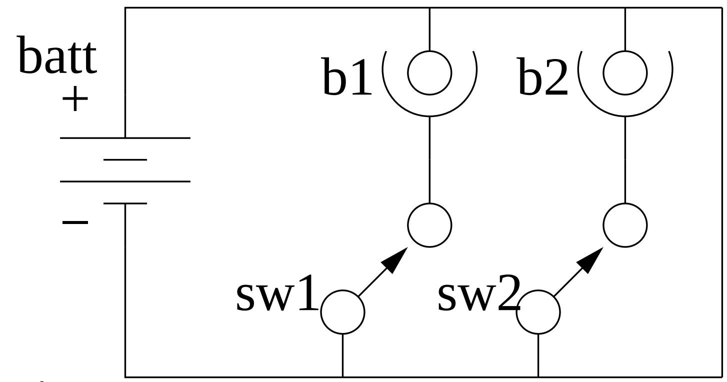


[. . .]

- **Explains**: "if sw_1, sw_2 are closed, $batt$ becomes faulty"

- **Tests**: is $ab(batt)$ true?
- **Answer**: $ab(batt)$ true
- **Finds plan**: . . .?

Recovery



[. . .]

- **Finds plan**: $flip(sw_1)$; $replace(batt)$
- **Executes**: $flip(sw_1)$
- **Observes**: sw_1 open
- **Executes**: $replace(batt)$
- **Observes**: $lit(b_2)$ $\Leftarrow$ **SUCCESS!!!**

How Do We Build It?

Key Elements

- Control loop
  - ◇ Simple procedural code
- Domain model
  - ◇ Encoded in action language $\mathcal{AL}$; automatically translated to A-Prolog
- Reasoning modules
  - ◇ Written in A-Prolog

⇒ Features:

- ◇ Reasoning modules, control loop provably correct
- ◇ Writing domain models, reasoning modules, control knowledge: easy

Control Loop: Observe–Think–Act loop

1. observe the world;
2. interpret the observations *(if needed)*:
   - ◇ diagnose;
   - ◇ learn;
3. select a goal;
4. plan;
5. execute part of the plan.

Domain Model

Action Description AD

%% Flipping SW causes SW to become
%% closed if it was open and vice-versa.
%%
d_1 : $flip(SW)$ causes $closed(SW)$ if $\neg closed(SW)$.
d_2 : $flip(SW)$ causes $\neg closed(SW)$ if $closed(SW)$.

s_1 : $lit(b_1)$ if $closed(sw_1),\ \neg ab(b_1)$.
$[\ldots]$

d_3 : $blow\_up(B)$ causes $ab(B)$.

d_4 : $replace(batt)$ causes $\neg ab(batt)$.
$[\ldots]$

Recorded History H^{cT}

Initial Situation:

$obs(\neg closed(sw_1), 0)$, $obs(\neg closed(sw_2), 0)$,
$obs(\neg lit(b_1), 0)$, $obs(\neg lit(b_2), 0)$,
$obs(\neg ab(b_1), 0)$, $obs(\neg ab(b_2), 0)$,
$obs(\neg ab(batt), 0)$,

Agent Actions at step 0:

$hpd(flip(sw_1), 0)$,

Observations at step 1:

$obs(closed(sw_1), 1)$, $obs(\neg lit(b_1), 1)$

A-Prolog

Language Features

- Knowledge representation language
- Roots: logic programming, non-monotonic reasoning
- Intuitive reading of statements closely matches formal semantics

◇ High-level specification language, *but also...*

◇ ...close to implementation level

- Programs are compact and easy to understand.

Simple Examples

"If it is raining and you do not have a rain coat, take an umbrella."

$$take\_umbrella \leftarrow raining, \neg have\_raincoat.$$

"It is raining. You do not have a rain coat."

$$raining. \quad \neg have\_raincoat.$$

Conclusion: $take\_umbrella$ $\Leftarrow$ the agent take an umbrella.

Simple Examples

"If I am a good student, I do not have any B's."

$$\neg have\_B \leftarrow good\_student.$$

"I have B's, but I am a good student."

$$have\_B. \quad good\_student.$$

Contradiction: conclusion $\neg have\_B$ contradicts $have\_B$.

The program is **inconsistent**.

A-Prolog with Variables

"If switch SW is closed, SW is connected to bulb B, and B is not malfunctioning, then B is lit."

$$lit(B) \leftarrow closed(SW), connected(SW, B), \neg ab(B).$$

"Switches sw_1, sw_2, sw_3 are closed and connected to b_1, b_2, b_3, respectively. Only b_2 is malfunctioning.

$$closed(sw_1). \quad closed(sw_2). \quad closed(sw_3).$$
$$connected(sw_1, b_1). \; connected(sw_2, b_2). \; connected(sw_3, b_3).$$
$$\neg ab(b_1). \quad ab(b_2). \quad \neg ab(b_3).$$

Answer Set: $\{lit(b_1), lit(b_3)\}$.

Set Notation

"If you behave, some of these toys may be yours."

$$\{X \mid have(X)\} \subseteq \{X \mid toy(X)\} \leftarrow behave.$$

Given facts: $behave,\ toy(t_1),\ toy(t_2)$

Answer Sets:

$\{have(t_1), have(t_2)\}$
$\{have(t_1)\}$
$\{have(t_2)\}$
$\{\}$ $\Leftarrow$ *agent does not get any toys*

Abbreviation: $\{have(X)\ :\ toy(X)\} \leftarrow behave.$

Translation of AD in A-Prolog, $\alpha(AD)$

Dynamic Law of $\mathcal{AL}$

d_1 : $flip(sw_1)$ causes $closed(sw_1)$ if $\neg closed(sw_1)$.

α-Translation:

% d_1 is a dynamic law
$dlaw(d_1)$.

% The head of d_1 is $closed(sw_1)$
$head(d_1, closed(sw_1))$.

% The action of d_1 is $flip(sw_1)$
$action(d_1, flip(sw_1))$.

% Precondition #1 of d_1 is $\neg closed(sw_1)$
$prec(d_1, 1, \neg closed(sw_1))$.

Translating State Constraints

Law:

$$lit(b_1) \text{ if } closed(sw_1),\ \neg ab(b_1)$$

α-**Translation**:

$$\left\{\begin{array}{l}
\%\ s_1 \text{ is a state constraint} \\
slaw(s_1). \\
\\
\%\ \text{The head of } s_1 \text{ is } lit(b_1) \\
head(s_1, lit(b_1)). \\
\\
\%\ \text{The preconditions of } s_1 \text{ are } closed(sw_1) \text{ and } \neg ab(b_1) \\
prec(s_1, 1, closed(sw_1)). \\
prec(s_1, 2, \neg ab(b_1)).
\end{array}\right.$$

Projecting the Effects of Actions

$$
\begin{array}{ll}
holds(L, T+1) \leftarrow & dlaw(D), \\
 & head(D, L), \\
 & action(D, A), \\
 & occurs(A, T), \\
 & all\_prec\_hold(D, T).
\end{array}
$$

$\ldots$

$$
\begin{array}{ll}
prec\_n\_holds(D, N, T) \leftarrow & prec(D, N, P), \\
 & holds(P, T).
\end{array}
$$

Planning

Overview

- Agent's Goal: set of fluent literals, e.g.

$$\{\ have(lots\_of(money)),\quad \neg in(jail)\ \}.$$

- Approach: generate and test.
- *Generation*: possible occurrences of actions are generated.
- *Testing*: constraint ensuring that solutions achieve the goal.

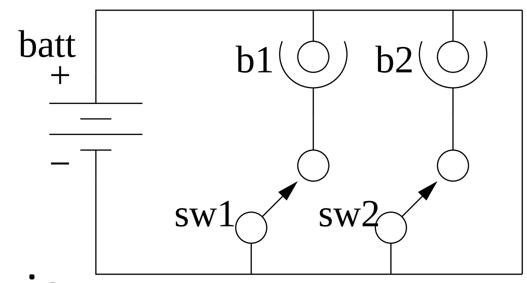
Planning Module

Consists of $\alpha(\langle AD, H^{cT}\rangle)$ together with:

$$PGEN : \begin{cases} \text{\%\% select occurrences of actions for each step} \\ \{occurs(A,T) \ : \ ag\_action(A)\} \leftarrow T \geq cT. \\ \\ \text{\%\% goal achieved if required literals eventually hold} \\ goal\_achieved \leftarrow holds(g_1,T), \\ \qquad\qquad\qquad\qquad \ldots, \\ \qquad\qquad\qquad\qquad holds(g_m,T). \\ \\ \text{\%\% plans achieve the goal} \\ \leftarrow \text{not } goal\_achieved. \end{cases}$$

Example

- H^{cT}: $\begin{cases} obs(\neg closed(sw_1), 0),\ obs(\neg closed(sw_2), 0), \\ obs(\neg lit(b_1), 0),\ obs(\neg lit(b_2), 0), \\ obs(\neg ab(b_1), 0),\ obs(\neg ab(b_2), 0), \\ obs(\neg ab(batt), 0) \end{cases}$



- Goal: $\{lit(b_1)\}$.
- Generation: possible sequence of actions is:

$$occurs(flip(sw_1), 0).$$

- Testing: according to the model, $occurs(flip(sw_1), 0)$ yields the effect

$$holds(lit(b_1), 1).$$

PLAN FOUND!!

Diagnosis

Basics

- *Symptom*: history H^{cT} with unexpected observations
- H^{cT} is symptom if:

$$\alpha(\langle AD, H^{cT} \rangle) \textit{ is inconsistent}$$

- *Explanation* E: set of statements $hpd(a_e, t)$ such that

$$\alpha(\langle AD, H^{cT} \cup E \rangle) \text{ is consistent.}$$

- *Candidate Diagnosis*: $cD = \langle E, \Delta_E \rangle$, where:
  - ◇ E: explanation
  - ◇ Δ_E: components that may be damaged by actions of E.

Diagnosis

- Approach: generate and test.
- *Generation*: possible occurrences of actions in the past are generated.
- *Testing*: sequences that do not explain the observations are discarded.

Diagnostic Module

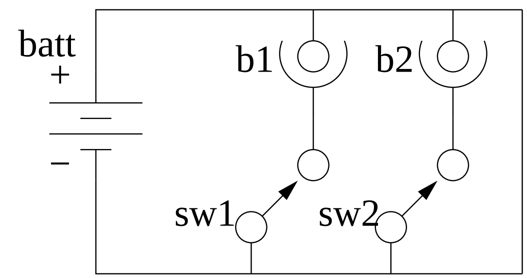
Consists of $\alpha(\langle AD, H^{cT}\rangle)$ together with:

%% Select occurrences of actions for each step in the past
$\{\ occurs(A,T)\ :\ ex\_action(A)\ \} \leftarrow 0 \leq T < cT.$

%% It is impossible for a prediction to
%% disagree with an observation.
$\leftarrow holds(F,T), obs(\neg F,T).$
$\leftarrow holds(\neg F,T), obs(F,T).$

Example: Diagnosing the Circuit

- H^{cT}: $\begin{cases} obs(\neg closed(sw_1),0),\ obs(\neg closed(sw_2),0), \\ obs(\neg lit(b_1),0),\ obs(\neg lit(b_2),0), \\ obs(\neg ab(b_1),0),\ obs(\neg ab(b_2),0),\ obs(\neg ab(batt),0) \\ \\ hpd(flip(sw_1),0) \\ \\ obs(\neg lit(b_1),1) \end{cases}$



- $\alpha(\langle AD, H^{cT}\rangle)$ inconsistent $\Rightarrow$ H^{cT} is *symptom*
- Generation: possible sequence of actions is:

$$occurs(blow\_up(b_1),0)$$

- Testing: according to the model, $occurs(blow\_up(b_1),0)$ justifies:

$$obs(\neg lit(b_1),1).$$

CANDIDATE DIAGNOSIS FOUND!!

Learning

Modification Statements

- *Modification Statements*: $dlaw(w)$, $slaw(w)$, $head(w, l)$, $action(w, a_e)$, $prec(w, n, p)$.
- *Valid* set of Modification Statements, Mod:
  - ◇ for every w, $slaw(w)$ and $dlaw(w)$ cannot be both in Mod;
  - ◇ one $head(w, l)$ statement for every $slaw(w)$ or $dlaw(w)$ in Mod;
  - ◇ one $action(w, l)$ statement for every $dlaw(w)$ in Mod;

Examples

$\{slaw(w), head(w, l_1), prec(w, 1, l_2)\}$ *is valid*;
$\{slaw(w), prec(w, 1, l_2)\}$ is *not* valid (missing $head$);
$\{dlaw(w), head(w, l_1), prec(w, 1, l_2)\}$ is *not* valid (missing $action$).

Candidate Correction

- $upd(AD, Mod)$: *Update* of AD w.r.t. Mod.
  Example
  $upd(AD, \{slaw(w), head(w, l_1), prec(w, 1, l_2)\}) =$

  $$AD \cup \{ \; l_1 \text{ if } l_2 \; \}$$

- *Symptom*: H^{cT} such that $\alpha(\langle AD, H^{cT} \rangle)$ is inconsistent.

- *Modification* of AD for symptom H^{cT}: *valid* Mod such that
  $\alpha(\langle upd(AD, Mod), H^{cT} \rangle)$ is consistent

- *Candidate Correction*: $cC = \langle Mod, \Delta \rangle$, where:
  - ◇ Mod: modification of AD for H^{cT}
  - ◇ Δ: components that may be damaged by actions of H^{cT} according to $upd(AD, Mod)$.

Learning

- Approach: generate and test.
- *Generation*: sets of possible valid modification statements are generated.
- *Testing*: Mod's that do not allow to explain the observations are discarded.

Learning Module

Consists of $\alpha(\langle AD, H^{cT}\rangle)$ together with:

$CGEN$:

% Any Lit can be a precondition of a law
$\{\ prec(W, N, Lit)\ \} \leftarrow law(W).$

% Available law names can be used for new laws
$\{\ new\_law(W) :\ avail\_law\_name(W)\ \}.$

% New laws are either state constr's or dynamic laws
$1\{\ dlaw(W), slaw(W)\ \}1 \leftarrow new\_law(W).$

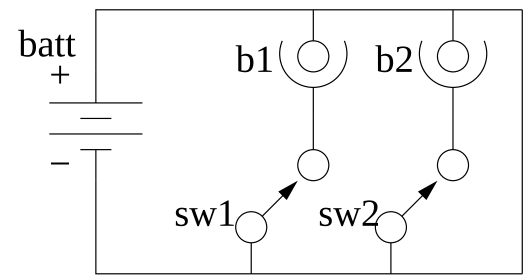
% Any Lit can be the head of a new law
$1\{\ head(W, Lit)\ \}1 \leftarrow new\_law(W).$

% Any action Act can be the trigger of a new dynamic law
$1\{\ action(W, Act)\ \}1 \leftarrow new\_law(W), dlaw(W).$

$\leftarrow holds(F, T), obs(\neg F, T).$
$\leftarrow holds(\neg F, T), obs(F, T).$

Example: Learning about the Circuit

- H^{cT}: $\begin{cases} obs(closed(sw_1),0),\ obs(\neg closed(sw_2),0), \\ obs(lit(b_1),0),\ obs(\neg lit(b_2),0) \\ \\ hpd(flip(sw_2),0) \\ \\ obs(\neg lit(b_2),1) \end{cases}$



- $\alpha(\langle AD, H^{cT}\rangle)$ inconsistent $\Rightarrow$ H^{cT} is *symptom*

- Generation: possible set of modification statements is:
  $slaw(w_0)$,
  $head(w_0, ab(batt))$,
  $prec(w_0, 1, closed(sw_1))$, $prec(w_0, 2, closed(sw_2))$

- Testing: according to the (new) model, $obs(\neg lit(b_2), 1)$ is justified.

CANDIDATE CORRECTION FOUND!!

About the Complete Architecture

- Diagnostic and learning modules *gather further observations* to confirm their hypotheses.
- Extension of A-Prolog (*CR-Prolog*) allows computing:
  - plans that satisfy *at best* a set of requirements
  - *most likely* diagnoses
  - *most reasonable* corrections
- *More powerful encoding of $\mathcal{AL}$ in A-Prolog* allows learning of more general laws, e.g:

$$\begin{array}{lll} ab(batt) & \text{if} & closed(SW_1), \\ & & closed(SW_2), \\ & & SW_1 \neq SW_2. \end{array}$$

Conclusions

Unique features:

- The architecture uniformly combines planning, diagnosis and learning.
- Sophisticated reasoning + use of observations $\Rightarrow$ high degree of autonomy.
- Shared domain model $\Rightarrow$ ease of development, verification, maintainance.
- Directly implementable.

A-Prolog Standpoint

- Demonstration of the flexibility of A-Prolog.
  A-Prolog can be used for:
  - ◇ Axiomatizing models and histories.
  - ◇ Encoding general purpose reasoning modules.
  - ◇ Formalizing control knowledge, i.e. constraints and preferences.
  - ◇ High level specification and direct implementation.

Future Work

- Planning with incomplete information: possible plans and their relation with sensing.
- Automated goal selection (CR-Prolog's preferences?).
- Continue work on confirmation of hypotheses in presence of non-observable fluents.
- Introduce confirmation of hypotheses as a subgoal in the observe-think-act loop.