Answer Set Based Design of Autonomous, Rational Agents

Marcello Balduccini

Knowledge Representation Lab
Computer Science Department
Texas Tech University

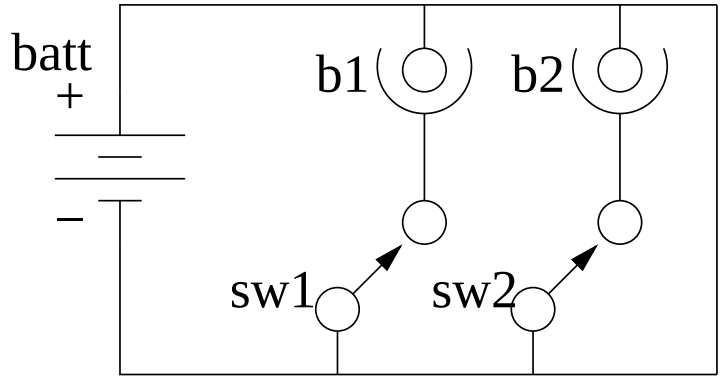
November 18, 2005

Our Goal

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

Example of Agent Behavior

A Physical System



Domain Properties

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

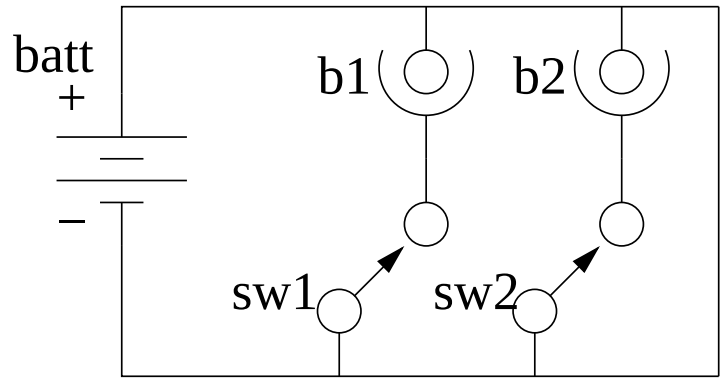
Agent Actions

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

Exogenous Actions

- $blow\_up(Bulb)$

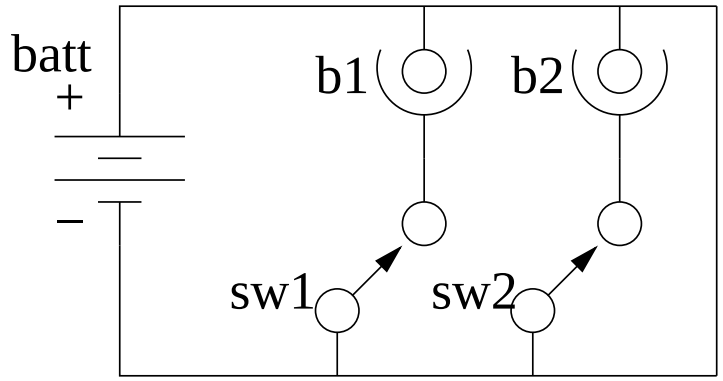
Planning



Agent's goal: $lit(b_1)$

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

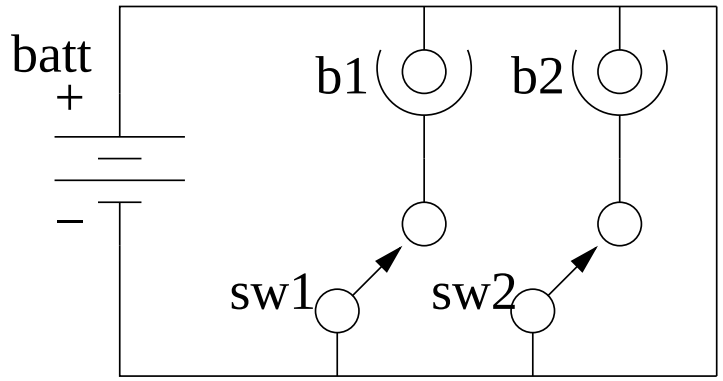
Diagnosis



[...]

- **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

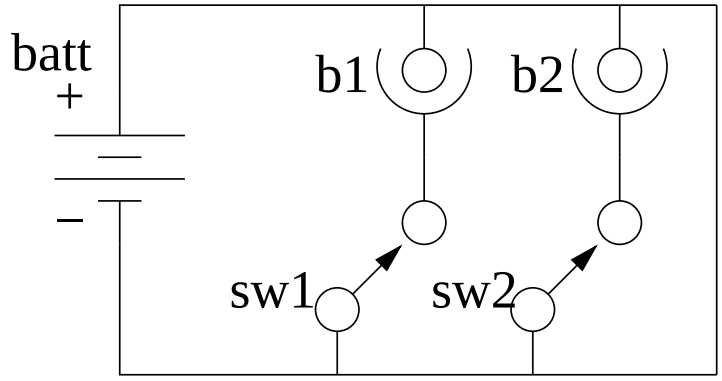


[...]

- **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

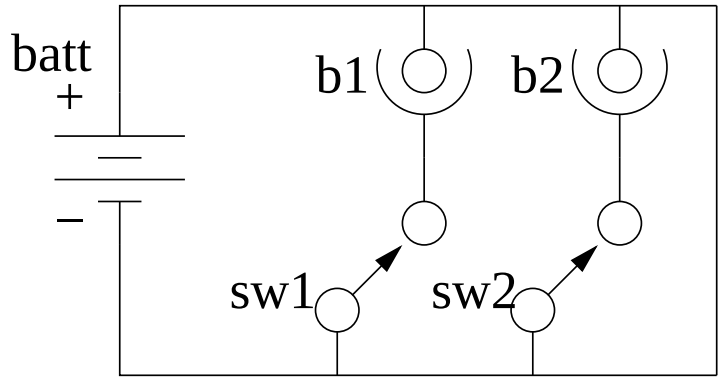
What if...?



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**

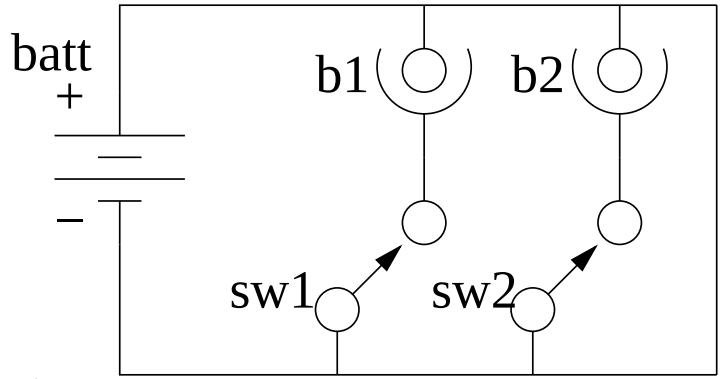
Learning



[...]

- **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

$\Rightarrow$ 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 $closed(sw_1),\ \neg ab(b_1)$.
[...]

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

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

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: $take\_umbrella \quad \Leftarrow$ 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.

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

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**:

% s_1 is a state constraint
$slaw(s_1)$.

% The head of s_1 is $lit(b_1)$
$head(s_1, lit(b_1))$.

% The preconditions of s_1 are $closed(sw_1)$ and $\neg ab(b_1)$
$prec(s_1, 1, closed(sw_1))$.
$prec(s_1, 2, \neg ab(b_1))$.

Projecting the Effects of Actions

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

...

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

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.

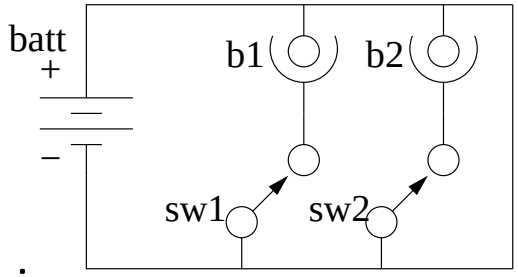
Planning Module

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:
  - $\diamond$ E: explanation
  - $\diamond$ 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

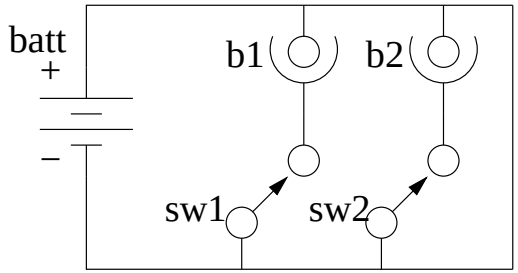
Consists of $\alpha(\langle AD, H^{cT}\rangle)$ together with:

%% 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
$1\{\ dlaw(W), slaw(W)\ \}1 \leftarrow new\_law(W).$

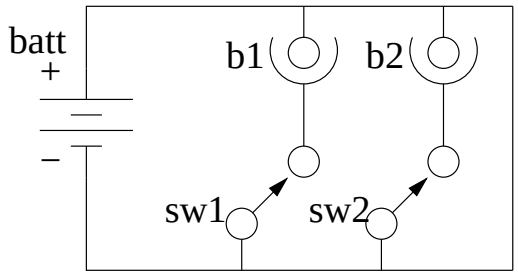
% Any Lit can be the head of a new law
$1\{\ head(W, Lit)\ \}1 \leftarrow new\_law(W).$

% 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:

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

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.