AgentSpeak

EMATM0042 – Intelligent Information Systems

Monday 18 March – Part 1

Previous Lecture…

1. Agents
   - Agent function
   - Agent program
2. Task environments
   - Problem Analysis
   - Properties
3. Types of agents
   - Reactive agents
   - Proactive agents
   - Cognitive agents

This Lecture…

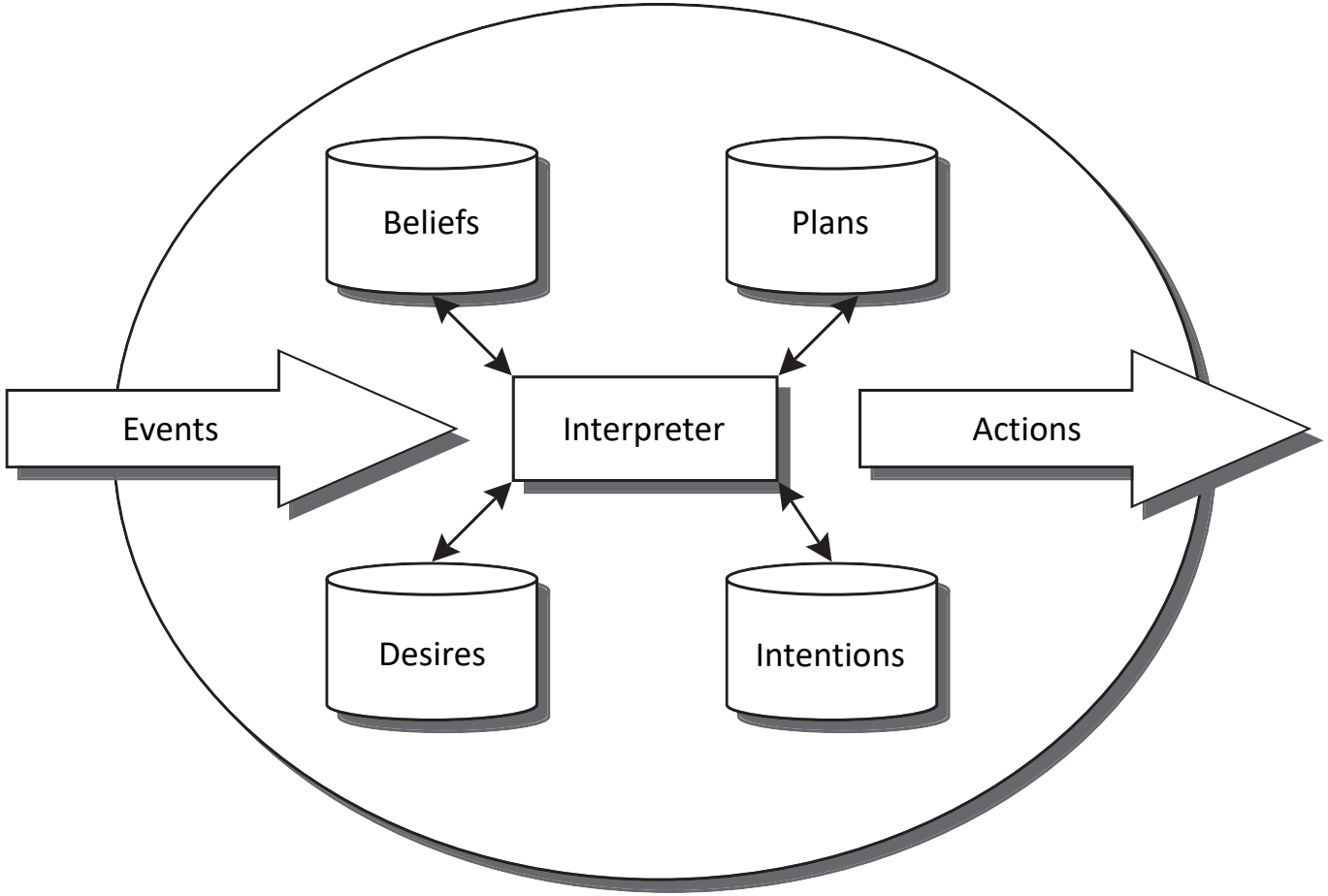
1. Agent-oriented programming
   - PRS
   - AgentSpeak
2. AgentSpeak
   - Logic programming
   - Syntax
   - Semantics
   - Interpreter
   - Programming

Agent-Oriented Programming

A Brief History

Year	Name	Innovation
1987	PRS	First implemented BDI system(?)
1990	AGENT-0	Speech acts
1993	PLACA	Plans
1996	AgentSpeak	Events, intentions
1996	Golog	Action theories, logical specifications
1997	3APL	Practical reasoning rules
2000	JACK	Capabilities
2000	GOAL	Declarative goals
2000	CLAIM	Mobile agents
2002	Jason	AgentSpeak + communication
2003	Jadex	JADE + BDI
2008	2APL	Modules, PG rules

Procedural Reasoning System (PRS)



AgentSpeak

- Influential agent-oriented programming language
  - Numerous language variants and extensions (e.g. Jason, CAN)
  - Mature implementation (i.e. Jason)
  - Used by the Multi-Agent Programming Contest (MAPC)
- Based on
  - Belief-desire-intention (BDI) paradigm
  - Procedural Reasoning System (PRS) architecture
  - Logic programming syntax and inference
- Supports both reactive and pro-active behavior
  - Uses plan library to respond to events
  - Can generate new (sub)goals

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
    <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
    <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
    <- !go_to(Y); pick_up(X).

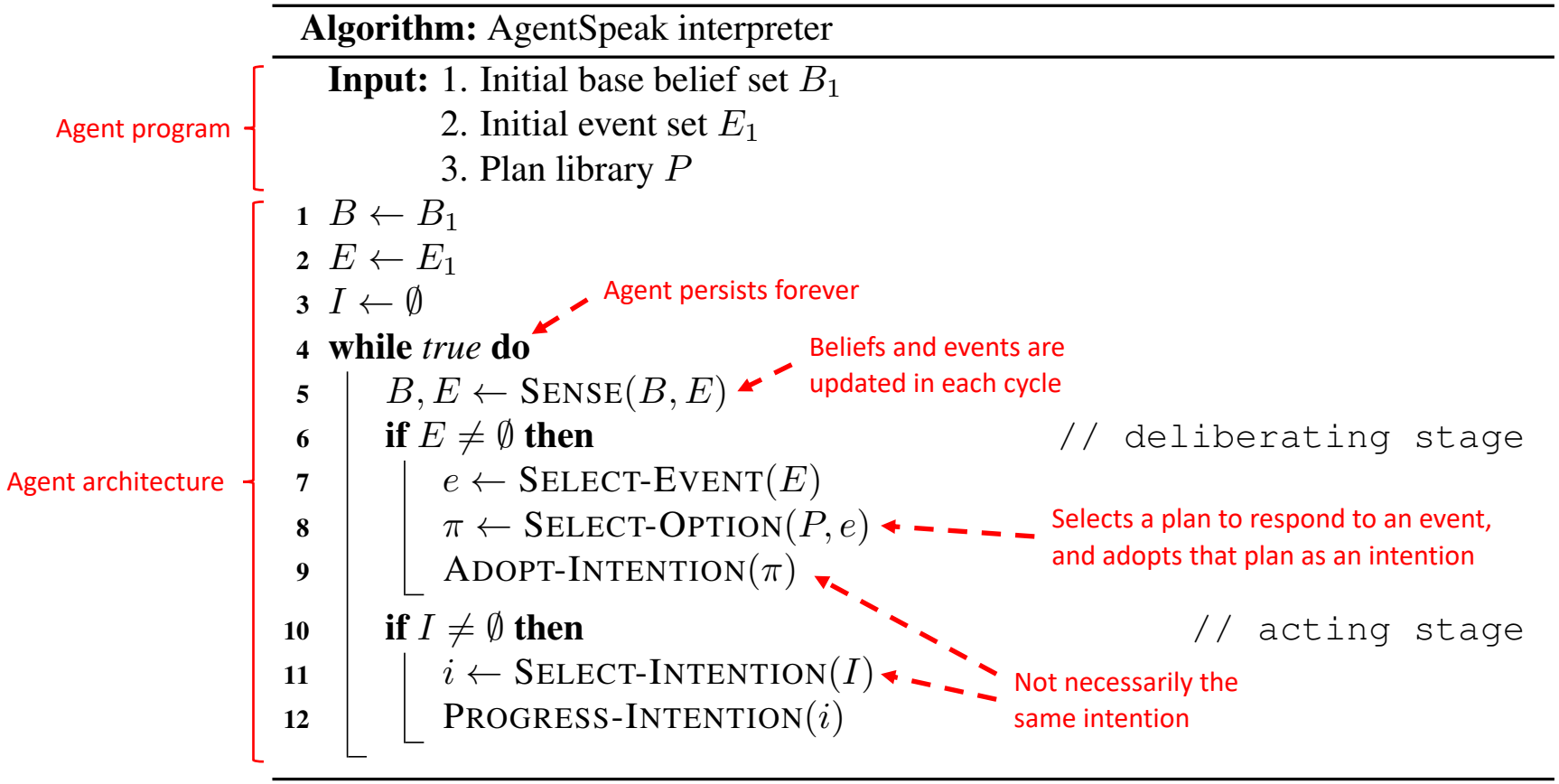
+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
    <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
    <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
    <- move(Y, Z); !go_to(X).
```

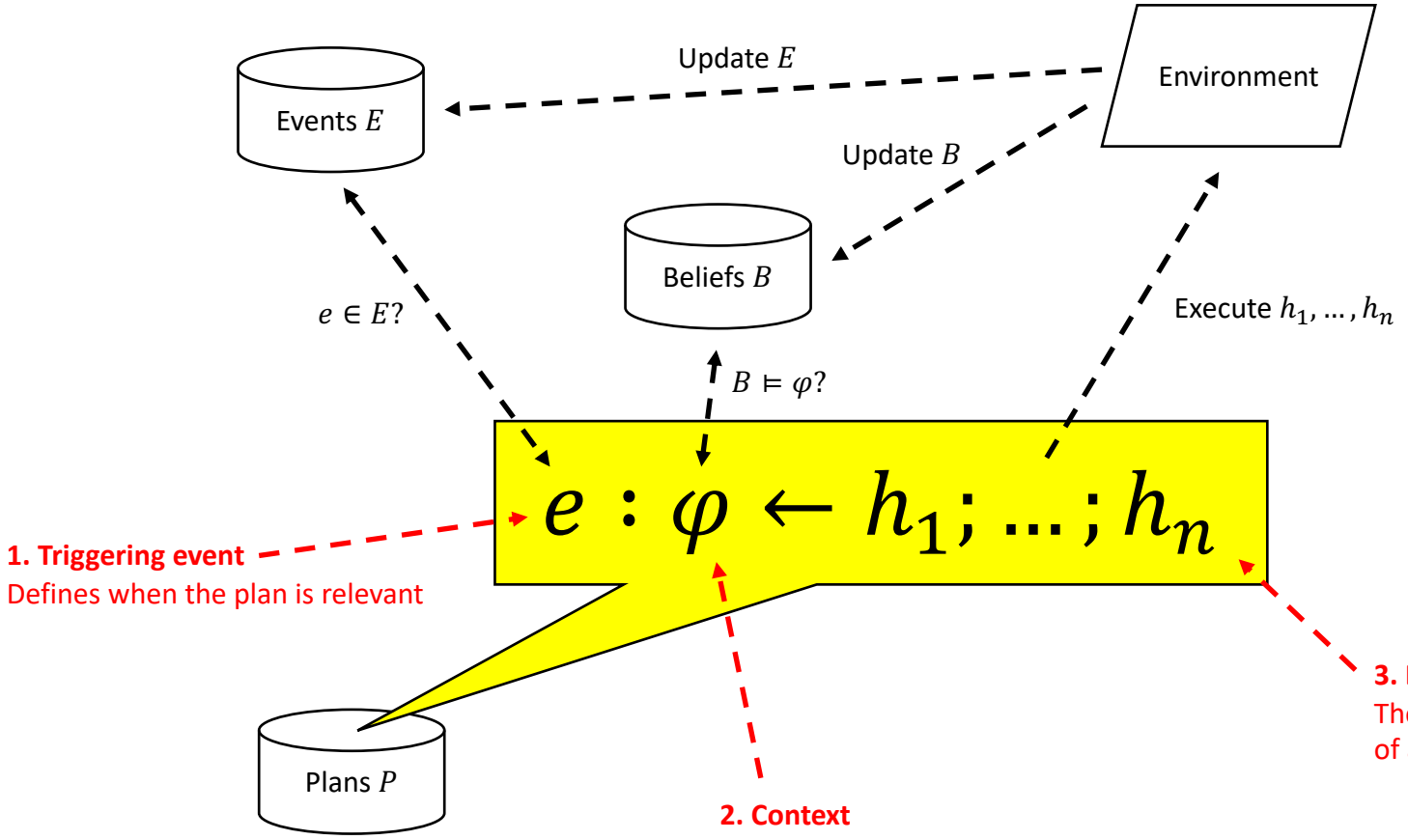
AgentSpeak

Programs & Architecture



AgentSpeak

Plan Library



Events, beliefs, plans, actions, and goals all rely on logic programming…

Logic Programming

- Long history in AI and academia
  - Prolog (1970s)
  - Constraint Logic Programming (1980s)
  - Probabilistic Logic Programming (1990s)
  - Answer Set Programming (2000s)
- Declarative programming
  - Program is comprised of facts and rules
  - Solution is answer to query (e.g. true/false, variable bindings)
- Used as basis for AgentSpeak
  - Checking if a plan is relevant to an event
  - Checking if plan is applicable given current beliefs
  - Allows plans that are lifted (i.e. that contain variables)

```
/* Facts */

female(alice).
male(bob).
female(carol).
male(dave).
female(eve).

parent(alice, carol).
parent(bob, carol).
parent(carol, eve).
parent(dave, eve).

/* Rules */

mother(X, Y) :- parent(X, Y) & female(X).
father(X, Y) :- parent(X, Y) & male(X).

grandparent(X, Z) :- parent(X, Y) & parent(Y, Z).

/* Inferences */

// |= mother(alice, carol)
// |= mother(carol, eve)
// |= father(bob, carol)
// |= father(dave, eve)

// |= grandparent(alice, eve)
// |= grandparent(bob, eve)
```

Logic Programming

Syntax (1)

Reverses FOL convention

- Variable
  - A string starting with an upper-case letter is a variable
- Constant, functor, predicate
  - A string starting with a lower-case letter may (i.e. depending on context) be a constant, functor, or predicate
- Term
  - A variable V is a term
  - A constant c is a term
  - If f is a functor and $t_1, \dots, t_n$ are terms, with $n \geq 1$, then $f(t_1, \dots, t_n)$ is a term
- Atom
  - A predicate p is an atom
  - If p is a predicate and $t_1, \dots, t_n$ are terms, with $n \geq 1$, then $p(t_1, \dots, t_n)$ is an atom
- Equation
  - An atom $= (t_1, t_2)$ is an equation, and is written simply as $t_1 = t_2$

Logic Programming

Syntax (2)

- Literal
  - If q is an atom, then q is a (positive) literal
  - If q is an atom, then $\mathbf{not}\ q$ is a (negative) literal
- (Normal) clause (or rule)
  - If h is an atom and $b_1, \ldots, b_n$ are literals, then $h \leftarrow b_1 \wedge \cdots \wedge b_n$ is a (normal) clause with h the head, $b_1 \wedge \cdots \wedge b_n$ the body, and all variables implicitly universally quantified
  - Read as "if $b_1 \wedge \cdots \wedge b_n$ then h"
- Definite clause
  - A clause $h \leftarrow b_1 \wedge \cdots \wedge b_n$ is a definite clause if each b_i a positive literal
- Fact
  - A clause $h \leftarrow \mathrm{true}$ is a fact, and is written simply as h
- Logic program
  - A logic program is a finite set of clauses

Logic Programming

Syntax – Example

Type	Examples
Variables	X, Y, Z
Constants	alice, bob, carol, dave, eve
Predicates	female, male, parent, mother, father, grandparent
Atoms	female(alice), …
Literals	female(alice), **not** female(alice) …

```
/* Facts */

female(alice).
male(bob).
female(carol).
male(dave).
female(eve).

parent(alice, carol).
parent(bob, carol).
parent(carol, eve).
parent(dave, eve).

/* Rules */

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/* Inferences */

// |= mother(alice, carol)
// |= mother(carol, eve)
// |= father(bob, carol)
// |= father(dave, eve)

// |= grandparent(alice, eve)
// |= grandparent(bob, eve)
```

Logic Programming

Unification

- Expression
  - A term, atom, clause, or logic program is an expression
- Substitution
  - If $V_1, \dots, V_n$ are distinct variables and $t_1, \dots, t_n$ are terms, then $\theta = \{V_1/t_1, \dots, V_n/t_n\}$ is a substitution
- Instantiation
  - If e is an expression and $\theta = \{V_1/t_1, \dots, V_n/t_n\}$ is a substitution, then an instantiation of e with θ is a new expression $e\theta$ found by simultaneously substituting each variable V_i in e with term t_i
- Ground expression
  - An expression is ground (or instantiated) if it does not contain any variables
- Unifier
  - A unifier for a set of equations $\{t_1 = t_1', \dots, t_n = t_n'\}$ is a substitution θ such that $t_i\theta = t_i'\theta$ for each $i = 1, \dots, n$
  - We are typically interested a special unifier called a most general unifier (MGU)

Logic Programming

Unification – Examples

#	Expression e_1	Expression e_2	Unifier θ	Result
1	alice	alice	$\emptyset$	Trivial success
2	alice	bob	$\bot$	Failure
3	X	alice	{X/alice}	Success
4	X	X	$\emptyset$	Trivial success
5	X	Y	{X/Y}	Success
6	X	father(X)	$\bot$	Failure
7	X	father(Y)	{X/father(Y)}	Success
8	father(alice)	alice	$\bot$	Failure
9	father(alice)	X	{X/father(alice)}	Success
10	father(alice)	father(alice)	$\emptyset$	Trivial success
11	father(alice)	father(X)	{X/alice}	Success
12	father(X)	alice	$\bot$	Failure
13	father(X)	Y	{Y/father(X)}	Success
14	knows(alice, Y)	knows(X, bob)	{X/alice , Y/bob}	Success
15	knows(father(X), X)	knows(Y, alice)	{X/alice , Y/father(alice)}	Success

Alias

Assuming use of occurs check

AgentSpeak
Language

- Extends syntax of LP
  - Beliefs
  - Actions
  - Goals
  - Triggering events
  - Contexts
  - Plans

- Has an operational semantics
  - Specifies how the agent can evolve
  - Can be used to design an interpreter

```
/* Initial base beliefs */

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adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

AgentSpeak
Syntax (1)

- Variable, constant, functor, predicate, term, atom, equation
  - Same as in LP
- Action symbol
  - A string starting with a lower-case letter may also (i.e. in addition to the above) be an action symbol
- Belief atom
  - If p is an LP atom, then p is a belief atom
- Belief literal
  - If b is a belief atom, then b is a (positive) belief literal
  - If b is a belief atom, then **not** b is a (negative) belief literal
- Base belief
  - If b is a ground belief atom, then b is a base belief

AgentSpeak
Syntax (2)

- Goal
  - If p is an LP atom, then $!\,p$ is an (achievement) goal
  - If p is an LP atom, then $?\,p$ is a (test) goal
- Triggering event
  - If b is a belief atom, then $+b$ is a (belief addition) triggering event
  - If b is a belief atom, then $-b$ is a (belief deletion) triggering event
  - ~~If g is a goal, then $+g$ is a (goal addition) triggering event~~
  - ~~If g is a goal, then $-g$ is a (goal deletion) triggering event~~
  - If g is an achievement goal, then $+g$ is an ([achievement] goal addition) triggering event

[Rao, 1996] includes these in the syntax, but does not account for them in the operational semantics

- Action
  - An action symbol a is an action
  - If a is an action symbol and $t_1, \ldots, t_n$ are LP terms, with $n \geq 1$, then $a(t_1, \ldots, t_n)$ is an action
- Plan
  - If e is a triggering event, $c_1, \ldots, c_n$ are belief literals, and $s_1, \ldots, s_m$ are goals or actions, then $e : c_1 \wedge \cdots \wedge c_n \leftarrow s_1; \ldots; s_m$ is a plan with $e : c_1 \wedge \cdots \wedge c_n$ the head, $s_1; \ldots; s_m$ the body, and $c_1 \wedge \cdots \wedge c_n$ the context

AgentSpeak

Syntax – Example

Type	Examples
Variables	X, Y, Z
Constants	a, b, c, d, robot, bin, waste
Predicates	adjacent, location, collect, deposit, has, go_to
Action symbols	stop, pick_up, drop, move
Belief atoms	adjacent(a, b), location(bin, Y), …
Base beliefs	adjacent(a, b), …
Goals	! collect(waste), ! collect(X), …
Triggering events	+location(waste, X), +! collect(X), …
Actions	stop, pick_up(X), …

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

AgentSpeak

Operational Semantics (1): Notation

1. Set of all possible base beliefs $\mathcal{B}$
2. Set of all possible (not necessarily ground) achievement goals $\mathcal{G}$
3. Set of all possible (not necessarily ground) triggering events $\mathcal{T}$
4. Set of all possible (not necessarily ground) plans $\mathcal{P}$

5. Set of all possible intentions $\mathcal{I}$
   - An intention $i \in \mathcal{I}$ is a stack of (partially instantiated) plans denoted as $i = [\pi_1 \mid \cdots \mid \pi_n]$ where $\pi_n \in \mathcal{P}$ is at the top of the stack
   - The empty intention [ ] is also denoted as $i_\top$

6. Set of all possible events $\mathcal{E} = \mathcal{T} \times \mathcal{I}$
   - An event $(e, i) \in \mathcal{E}$ is a tuple where e is a triggering event and i is an intention
   - An event $(e, i) \in \mathcal{E}$ is an internal event if $i \neq i_\top$, otherwise $(e, i_\top)$ is an external event

AgentSpeak

Operational Semantics (2): Inputs

1. Initial base belief set $B_1 \subseteq \mathcal{B}$
   - User-defined set of base beliefs initially believed to be true
   - Base beliefs in $\mathcal{B} \setminus B_1$ are initially believed to be false

2. Initial achievement goals $G_1 \subseteq \mathcal{G}$
   - User-defined set of initial achievement goals

3. Plan library $P \subseteq \mathcal{P}$
   - User-defined set of (not necessarily ground) plans

AgentSpeak

Operational Semantics (3): Selection Functions

1. Event selection function $\mathcal{S}_{\mathcal{E}} : 2^{\mathcal{E}} \to \mathcal{E}$
   - User-defined function that selects a single event from E
   - For example, if E is represented as a queue, then $\mathcal{S}_{\mathcal{E}}(E) = \text{dequeue}(E)$ is a first-in-first-out event selection function

2. Option selection function $\mathcal{S}_{\mathcal{O}} : 2^{\mathcal{P}} \to \mathcal{P}$
   - User-defined function that selects a single plan from the set of relevant, applicable, and partially instantiated plans $O \subseteq \mathcal{P}$
   - For example, if $\succ$ is a strict total order over $\mathcal{P}$, then $\mathcal{S}_{\mathcal{O}}(O) = \max(O, \succ)$ is a stratified option selection function

3. Intention selection function $\mathcal{S}_{\mathcal{I}} : 2^{\mathcal{I}} \to \mathcal{I}$
   - User-defined function that selects a single intention from I
   - For example, if I is represented as a queue, then $\mathcal{S}_{\mathcal{E}}(I) = \text{dequeue}(I)$ is a first-in-first-out intention selection function

AgentSpeak

Operational Semantics (4): Agent Configuration

1. Current base belief set $B \subseteq \mathcal{B}$
   - Set of base beliefs representing the agent's current beliefs about the world
   - Initially $B = B_1$

2. Current event set $E \subseteq \mathcal{E}$
   - Set of events that the agent has not yet dealt with
   - Initially $E = \{(+g, i_\top) \mid g \in G_1\}$ (i.e. initial achievement goals are treated as external achievement goal addition events)

3. Current intention set $I \subseteq \mathcal{I}$
   - Set of intentions representing the agent's current focus
   - Initially $I = \emptyset$

AgentSpeak

Interpreter (1)

Algorithm: AgentSpeak interpreter

Input: 1. Initial base belief set B_1
2. Initial event set E_1
3. Plan library P

$B \leftarrow B_1$
$E \leftarrow E_1$
$I \leftarrow \emptyset$
while *true* **do**
  $B, E \leftarrow \text{SENSE}(B, E)$
  if $E \neq \emptyset$ **then**
    $e \leftarrow \text{SELECT-EVENT}(E)$
    $\pi \leftarrow \text{SELECT-OPTION}(P, e)$
    $\text{ADOPT-INTENTION}(\pi)$
  if $I \neq \emptyset$ **then**
    $i \leftarrow \text{SELECT-INTENTION}(I)$
    $\text{PROGRESS-INTENTION}(i)$

Input: 1. Initial base belief set B_1
2. Initial achievement goals G_1
3. Plan library P
4. Event selection function $\mathcal{S}_{\mathcal{E}}$
5. Option selection function $\mathcal{S}_{\mathcal{O}}$
6. Intention selection function $\mathcal{S}_{\mathcal{I}}$

Often fixed for all agents

$B \leftarrow B_1$
$E \leftarrow \{(+g, i_\top) \mid g \in G_1\}$
$I \leftarrow \emptyset$

AgentSpeak

Interpreter (2)

Algorithm: AgentSpeak interpreter

Input: 1. Initial base belief set B_1
2. Initial event set E_1
3. Plan library P

$B \leftarrow B_1$
$E \leftarrow E_1$
$I \leftarrow \emptyset$
while *true* **do**
  $B, E \leftarrow \text{SENSE}(B, E)$
  if $E \neq \emptyset$ **then**
    $e \leftarrow \text{SELECT-EVENT}(E)$
    $\pi \leftarrow \text{SELECT-OPTION}(P, e)$
    $\text{ADOPT-INTENTION}(\pi)$
  if $I \neq \emptyset$ **then**
    $i \leftarrow \text{SELECT-INTENTION}(I)$
    $\text{PROGRESS-INTENTION}(i)$

Event = triggering event + intention

$$\textbf{if } E \neq \emptyset \textbf{ then}$$
$$(e, i) \leftarrow \mathcal{S}_{\mathcal{E}}(E)$$
$$E \leftarrow E \setminus \{(e, i)\}$$
$$P_e \leftarrow \{\pi\theta \mid \pi \in P, e\theta = \text{TRIGGERING-EVENT}(\pi)\theta\}$$
$$\textbf{if } P_e \neq \emptyset \textbf{ then}$$
$$P_B \leftarrow \{\pi\theta \mid \pi \in P_e, B \models \text{CONTEXT}(\pi)\theta\}$$
$$\textbf{if } P_B \neq \emptyset \textbf{ then}$$
$$\pi \leftarrow \mathcal{S}_{\mathcal{O}}(P_B)$$
$$i \leftarrow \text{PUSH}(\pi, i)$$
$$I \leftarrow I \cup \{i\}$$

Find relevant plans and instantiate variables

Find applicable plans and further instantiate variables

Push partially instantiated plan to intention stack, and add intention to intention set

AgentSpeak

Interpreter (3)

Algorithm: AgentSpeak interpreter

Input: 1. Initial base belief set B_1
2. Initial event set E_1
3. Plan library P

```
1  B ← B_1
2  E ← E_1
3  I ← ∅
4  while true do
5      B, E ← SENSE(B, E)
6      if E ≠ ∅ then
7          e ← SELECT-EVENT(E)
8          π ← SELECT-OPTION(P, e)
9          ADOPT-INTENTION(π)
10     if I ≠ ∅ then
11         i ← SELECT-INTENTION(I)
12         PROGRESS-INTENTION(i)
```

```
if I ≠ ∅ then
    i ← S_I(I)
    I ← I \ {i}
    switch PEEK(BODY(TOP(i))) do
        case !g do
            E ← E ∪ {(+!g, i)}                    ← Generate internal event
        case ?g do
            if B ⊨ gθ then
                π ← POP(i)
                PUSH(πθ, i)                       ← Further instantiate variables
                PROGRESS-INTENTION(i)
        case a do
            EXECUTE(a)                            ← Execute action in environment
            PROGRESS-INTENTION(i)

procedure PROGRESS-INTENTION(i)
    DEQUEUE(BODY(TOP(i)))
    while ¬EMPTY(i) ∧ EMPTY(BODY(TOP(i))) do
        π ← POP(i)                                ← Remove completed plan from stack
        if ¬EMPTY(i) then
            π′ ← POP(i)
            h ← DEQUEUE(BODY(π′))                 ← Must be an achievement goal
            TRIGGERING-EVENT(π) = hθ
            PUSH(π′θ, i)                          ← Propagate variable instantiations to next plan in stack
    if ¬EMPTY(i) then
        I ← I ∪ {i}                               ← Pause intention
```

AgentSpeak

Interpreter (4)

Algorithm: AgentSpeak interpreter

Input: 1. Initial base belief set B_1
2. Initial achievement goals G_1
3. Plan library P
4. Event selection function $\mathcal{S}_\mathcal{E}$
5. Option selection function $\mathcal{S}_\mathcal{O}$
6. Intention selection function $\mathcal{S}_\mathcal{I}$

1 $B \leftarrow B_1$
2 $E \leftarrow \{(+g, i_\top) \mid g \in G_1\}$
3 $I \leftarrow \emptyset$
4 **while** *true* **do**
5 $B, E \leftarrow \textsc{Sense}(B, E)$
6 **if** $E \neq \emptyset$ **then** `// deliberating stage`
7 $(e, i) \leftarrow \mathcal{S}_\mathcal{E}(E)$
8 $E \leftarrow E \setminus \{(e, i)\}$
9 $P_e \leftarrow \{\pi\theta \mid \pi \in P, e\theta = \textsc{Triggering-Event}(\pi)\theta\}$
10 **if** $P_e \neq \emptyset$ **then**
11 $P_B \leftarrow \{\pi\theta \mid \pi \in P_e, B \models \textsc{Context}(\pi)\theta\}$
12 **if** $P_B \neq \emptyset$ **then**
13 $\pi \leftarrow \mathcal{S}_\mathcal{O}(P_B)$
14 $i \leftarrow \textsc{Push}(\pi, i)$
15 $I \leftarrow I \cup \{i\}$
16 **if** $I \neq \emptyset$ **then** `// acting stage`
17 $i \leftarrow \mathcal{S}_\mathcal{I}(I)$
18 $I \leftarrow I \setminus \{i\}$
19 **switch** $\textsc{Peek}(\textsc{Body}(\textsc{Top}(i)))$ **do**
20 **case** $!g$ **do**
21 $E \leftarrow E \cup \{(+!g, i)\}$
22 **case** $?g$ **do**
23 **if** $B \models g\theta$ **then**
24 $\pi \leftarrow \textsc{Pop}(i)$
25 $\textsc{Push}(\pi\theta, i)$
26 $\textsc{Progress-Intention}(i)$
27 **case** a **do**
28 $\textsc{Execute}(a)$
29 $\textsc{Progress-Intention}(i)$
30 **procedure** $\textsc{Progress-Intention}(i)$
31 $\textsc{Dequeue}(\textsc{Body}(\textsc{Top}(i)))$
32 **while** $\neg\textsc{Empty}(i) \wedge \textsc{Empty}(\textsc{Body}(\textsc{Top}(i)))$ **do**
33 $\pi \leftarrow \textsc{Pop}(i)$
34 **if** $\neg\textsc{Empty}(i)$ **then**
35 $\pi' \leftarrow \textsc{Pop}(i)$
36 $h \leftarrow \textsc{Dequeue}(\textsc{Body}(\pi'))$
37 $\textsc{Triggering-Event}(\pi) = h\theta$
38 $\textsc{Push}(\pi'\theta, i)$
39 **if** $\neg\textsc{Empty}(i)$ **then**
40 $I \leftarrow I \cup \{i\}$

AgentSpeak

Intention Progression – Example

Location A	Location B	Location C	Location D
 Robot			Bin 

Waste 

```
/* Initial base beliefs */

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/* Plan library */

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      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

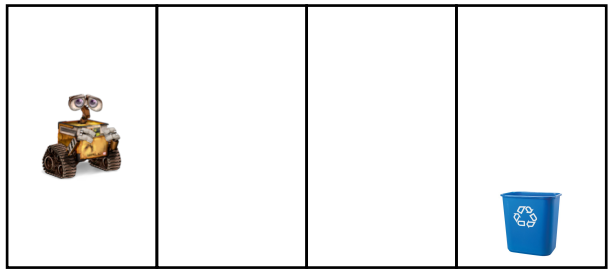
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

START



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(robot, a)}, \\ \text{location(bin, d)} \end{array} \right\}$

Current intention $i =$ N/A

History $h =$ ( )

```
/* Initial base beliefs */

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adjacent(b, c).
adjacent(c, d).
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/* Plan library */

+location(waste, X)
    : location(bin, Y)
        <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
        <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
        <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
        <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
        <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
        <- move(Y, Z); !go_to(X).
```

Event

Belief base $B =$ $\left\{\begin{array}{c}\text{adjacent(a, b)},\\ \text{adjacent(b, c)},\\ \text{adjacent(c, d)},\\ \text{location(robot, a)},\\ \text{location(bin, d)},\\ \text{location(waste, b)}\end{array}\right\}$

Current intention $i =$ N/A

History $h =$ ( )

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

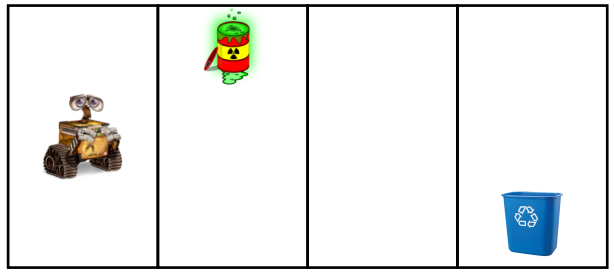
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Plan Selection



Belief base $B = \left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(robot, a)}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)} \end{array} \right\}$

Current intention $i = \left[\begin{array}{c} +\text{location(waste, b)} \\ : \text{location(bin, d)} \\ \leftarrow\ !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h = (\quad)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

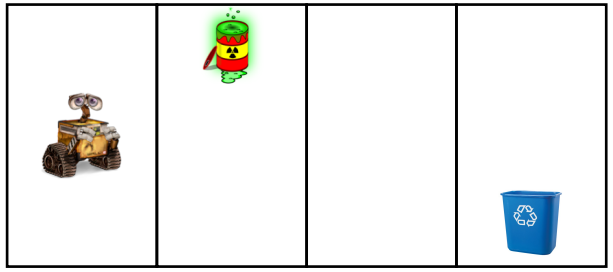
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Sub-Goal



Belief base $B =$ $\left\{\begin{array}{c}\text{adjacent(a, b)},\\ \text{adjacent(b, c)},\\ \text{adjacent(c, d)},\\ \text{location(robot, a)},\\ \text{location(bin, d)},\\ \text{location(waste, b)}\end{array}\right\}$

Current intention $i =$ $\left[\begin{array}{c}+\text{location(waste, b)}\\ :\text{location(bin, d)}\\ \leftarrow\ !\,\text{collect(waste)};\,!\,\text{deposit(waste, bin)}\end{array}\right]$

History $h =$ ( )

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

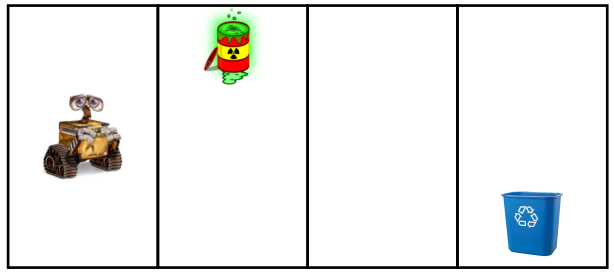
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Plan Selection



Belief base $B =$ $\left\{\begin{array}{c}\text{adjacent(a, b)},\\ \text{adjacent(b, c)},\\ \text{adjacent(c, d)},\\ \text{location(robot, a)},\\ \text{location(bin, d)},\\ \text{location(waste, b)}\end{array}\right\}$

Current intention $i =$ $\left[\begin{array}{c}+!\,\text{collect(waste)}\\ :\ \textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)}\\ \leftarrow\ !\,\text{go\_to(b)};\ \underline{\text{pick\_up(waste)}}\\ +\text{location(waste, b)}\\ :\ \text{location(bin, d)}\\ \leftarrow\ !\,\text{collect(waste)};\ !\,\text{deposit(waste, bin)}\end{array}\right]$

History $h =$ ( )

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Sub-Goal

Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(robot, a)}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{collect(waste)} \\ :\, \textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow\, !\,\text{go\_to(b)};\ \text{pick\_up(waste)} \\ \\ +\text{location(waste, b)} \\ :\, \text{location(bin, d)} \\ \leftarrow\, !\,\text{collect(waste)};\ !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ ( )

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

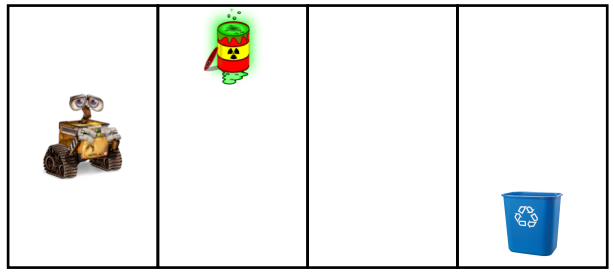
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Plan Selection



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent}(a, b), \\ \text{adjacent}(b, c), \\ \text{adjacent}(c, d), \\ \text{location}(\text{robot}, a), \\ \text{location}(\text{bin}, d), \\ \text{location}(\text{waste}, b) \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to}(b) \\ : \text{location}(\text{robot}, a) \wedge \text{adjacent}(a, b) \\ \leftarrow \text{move}(a, b); !\,\text{go\_to}(b) \\ \hline +!\,\text{collect}(\text{waste}) \\ : \textbf{not}\ \text{has}(\text{robot}, \text{waste}) \wedge \text{location}(\text{waste}, b) \\ \leftarrow !\,\text{go\_to}(b); \text{pick\_up}(\text{waste}) \\ \hline +\text{location}(\text{waste}, b) \\ : \text{location}(\text{bin}, d) \\ \leftarrow !\,\text{collect}(\text{waste}); !\,\text{deposit}(\text{waste}, \text{bin}) \end{array} \right]$

History $h =$ ( )

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

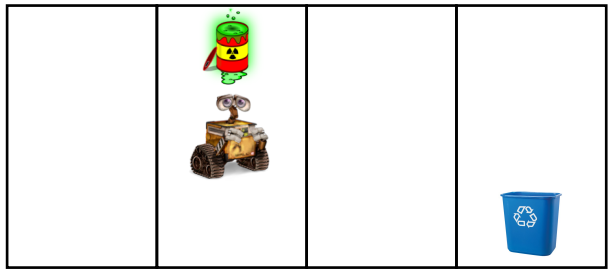
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Action



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{~~location(robot, a)~~}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)}, \\ \text{location(robot, b)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to(b)} \\ :\,\text{location(robot, a)} \wedge \text{adjacent(a, b)} \\ \leftarrow\, \underline{\text{move(a, b)}};\, !\,\text{go\_to(b)} \\ +!\,\text{collect(waste)} \\ :\,\textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow\, !\,\text{go\_to(b)};\, \underline{\text{pick\_up(waste)}} \\ +\text{location(waste, b)} \\ :\,\text{location(bin, d)} \\ \leftarrow\, !\,\text{collect(waste)};\, !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

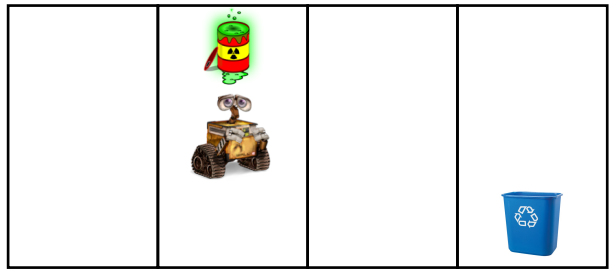
+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)}, \\ \text{location(robot, b)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to(b)} \\ :\,\text{location(robot, a)} \wedge \text{adjacent(a, b)} \\ \leftarrow \sout{\text{move(a, b)}};\,!\,\text{go\_to(b)} \\ \hline +!\,\text{collect(waste)} \\ :\,\textbf{not}\,\text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow\,!\,\text{go\_to(b)};\,\underline{\text{pick\_up(waste)}} \\ \hline +\text{location(waste, b)} \\ :\,\text{location(bin, d)} \\ \leftarrow\,!\,\text{collect(waste)};\,!\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

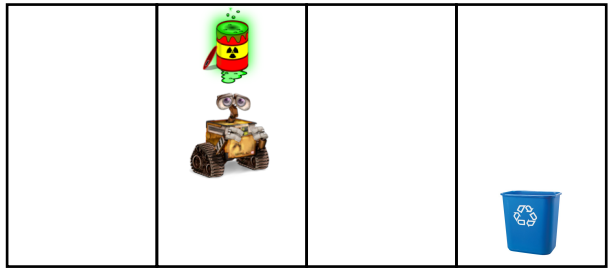
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Sub-Goal



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)}, \\ \text{location(robot, b)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to(b)} \\ :\,\text{location(robot, a)} \wedge \text{adjacent(a, b)} \\ \leftarrow\, !\,\underline{\text{go\_to(b)}} \\ \\ +!\,\text{collect(waste)} \\ :\,\textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow\, !\,\text{go\_to(b)};\, \underline{\text{pick\_up(waste)}} \\ \\ +\text{location(waste, b)} \\ :\,\text{location(bin, d)} \\ \leftarrow\, !\,\text{collect(waste)};\, !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

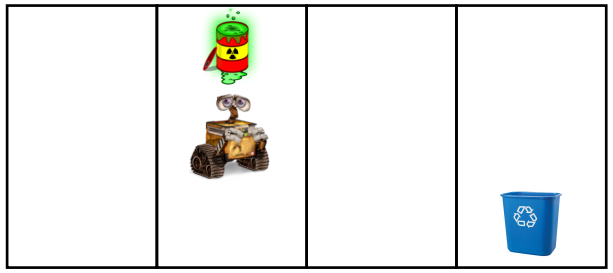
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Plan Selection



Belief base $B =$

$$\left\{\begin{array}{c}\text{adjacent(a, b)},\\ \text{adjacent(b, c)},\\ \text{adjacent(c, d)},\\ \text{location(bin, d)},\\ \text{location(waste, b)},\\ \text{location(robot, b)}\end{array}\right\}$$

Current intention $i =$

$$\left[\begin{array}{c}+!\,\text{go\_to(b)}\\ :\text{location(robot, b)}\\ \leftarrow \underline{\text{stop}}\\ +!\,\text{go\_to(b)}\\ :\text{location(robot, a)} \wedge \text{adjacent(a, b)}\\ \leftarrow !\,\underline{\text{go\_to(b)}}\\ +!\,\text{collect(waste)}\\ :\textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)}\\ \leftarrow !\,\text{go\_to(b)}; \underline{\text{pick\_up(waste)}}\\ +\text{location(waste, b)}\\ :\text{location(bin, d)}\\ \leftarrow !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)}\end{array}\right]$$

History $h =$ $\big(\text{move(a, b)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

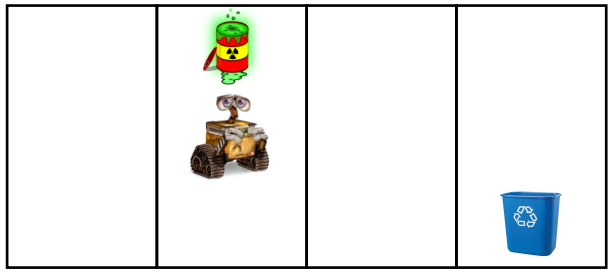
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Action



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)}, \\ \text{location(robot, b)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to(b)} \\ : \text{location(robot, b)} \\ \leftarrow \underline{\text{stop}} \\ +!\,\text{go\_to(b)} \\ : \text{location(robot, a)} \wedge \text{adjacent(a, b)} \\ \leftarrow !\,\underline{\text{go\_to(b)}} \\ +!\,\text{collect(waste)} \\ : \textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow !\,\text{go\_to(b)}; \underline{\text{pick\_up(waste)}} \\ +\text{location(waste, b)} \\ : \text{location(bin, d)} \\ \leftarrow !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $(\text{move(a, b)}, \underline{\text{stop}})$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
        <- !collect(waste); !deposit(waste, bin).

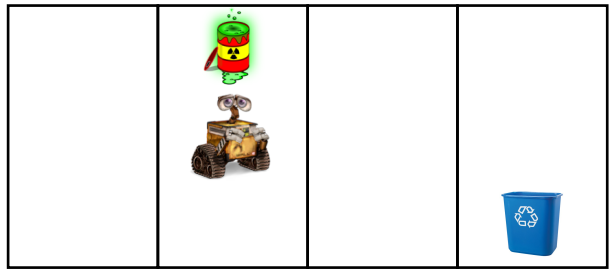
+!collect(X)
    : has(robot, X)
        <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
        <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
        <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
        <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
        <- move(Y, Z); !go_to(X).
```



Belief base $B =$

$$\left\{\begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)}, \\ \text{location(robot, b)} \end{array}\right\}$$

Current intention $i =$

$$\left[\begin{array}{c} +!\,\text{go\_to(b)} \\ :\,\text{location(robot, b)} \\ \leftarrow \underline{\text{stop}} \\ +!\,\text{go\_to(b)} \\ :\,\text{location(robot, a)} \wedge \text{adjacent(a, b)} \\ \leftarrow !\,\underline{\text{go\_to(b)}} \\ +!\,\text{collect(waste)} \\ :\,\textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow !\,\text{go\_to(b)}; \underline{\text{pick\_up(waste)}} \\ +\text{location(waste, b)} \\ :\,\text{location(bin, d)} \\ \leftarrow !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)} \end{array}\right]$$

History $h =$ (move(a, b), stop)

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

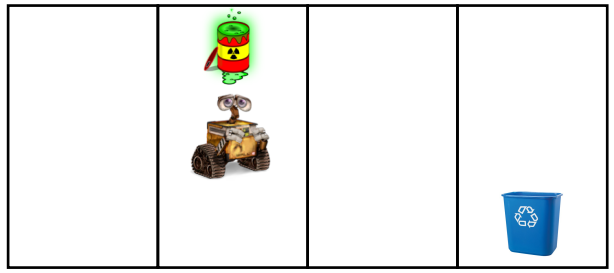
+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)}, \\ \text{location(robot, b)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} \sout{+!\text{go\_to(b)}} \\ \sout{+\text{location(robot, b)}} \\ \sout{\leftarrow \text{stop}} \\ \hline +!\,\text{go\_to(b)} \\ : \text{location(robot, a)} \wedge \text{adjacent(a, b)} \\ \leftarrow !\,\text{go\_to(b)} \\ \hline +!\,\text{collect(waste)} \\ : \textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow !\,\text{go\_to(b)}; \underline{\text{pick\_up(waste)}} \\ \hline +\text{location(waste, b)} \\ : \text{location(bin, d)} \\ \leftarrow !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $(\text{move(a, b)}, \text{stop})$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
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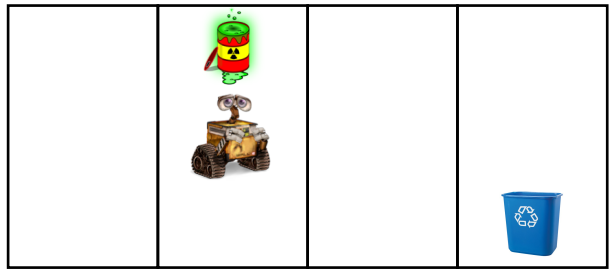

Belief base $B =$

$$\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)}, \\ \text{location(robot, b)} \end{array} \right\}$$

Current intention $i =$

$$\left[\begin{array}{c} +!\,\text{go\_to(b)} \\ : \text{location(robot, a)} \wedge \text{adjacent(a, b)} \\ \leftarrow\ !\,\underline{\text{go\_to(b)}} \\ \\ +!\,\text{collect(waste)} \\ : \textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow\ !\,\text{go\_to(b)}; \underline{\text{pick\_up(waste)}} \\ \\ +\text{location(waste, b)} \\ : \text{location(bin, d)} \\ \leftarrow\ !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)} \end{array} \right]$$

History $h =$ $(\text{move(a, b)}, \text{stop})$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

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    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

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    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
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    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
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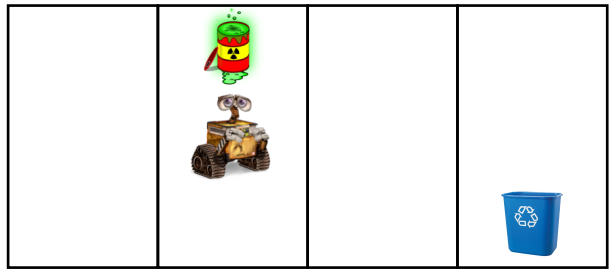

Belief base $B =$

$$\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)}, \\ \text{location(robot, b)} \end{array} \right\}$$

Current intention $i =$

$$\left[\begin{array}{c} +!\,\text{go\_to(b)} \\ :\,\text{location(robot, a)} \wedge \text{adjacent(a, b)} \\ \leftarrow \sout{!\,\text{go\_to(b)}} \\ \hline +!\,\text{collect(waste)} \\ :\,\textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow !\,\text{go\_to(b)}; \underline{\text{pick\_up(waste)}} \\ \hline +\text{location(waste, b)} \\ :\,\text{location(bin, d)} \\ \leftarrow !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)} \end{array} \right]$$

History $h =$ $(\text{move(a, b)}, \text{stop})$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
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location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
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    : has(robot, X)
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    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
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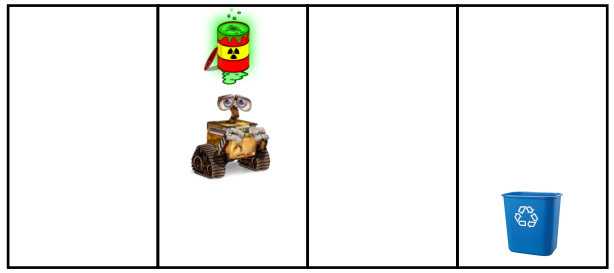

Belief base $B =$

$$\left\{\begin{array}{c}\text{adjacent(a, b)},\\ \text{adjacent(b, c)},\\ \text{adjacent(c, d)},\\ \text{location(bin, d)},\\ \text{location(waste, b)},\\ \text{location(robot, b)}\end{array}\right\}$$

Current intention $i =$

$$\left[\begin{array}{c}\sout{+!\,\text{go\_to(b)}}\\ \sout{:\,\text{location(robot, a)} \wedge \text{adjacent(a, b)}}\\ \sout{\leftarrow\,!\,\text{go\_to(b)}}\\ \hline +!\,\text{collect(waste)}\\ :\,\textbf{not}\,\text{has(robot, waste)} \wedge \text{location(waste, b)}\\ \leftarrow\,!\,\text{go\_to(b)};\,\text{pick\_up(waste)}\\ \hline +\text{location(waste, b)}\\ :\,\text{location(bin, d)}\\ \leftarrow\,!\,\text{collect(waste)};\,!\,\text{deposit(waste, bin)}\end{array}\right]$$

History $h =$ $(\text{move(a, b)}, \text{stop})$

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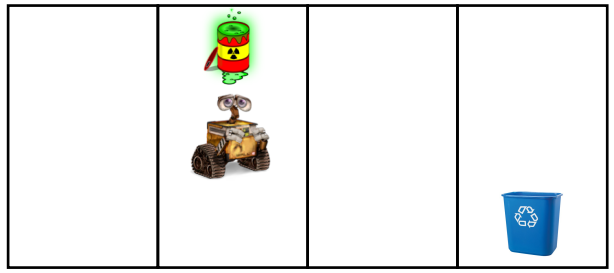
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)}, \\ \text{location(robot, b)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{collect(waste)} \\ :\, \textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow\, !\,\text{go\_to(b)};\ \underline{\text{pick\_up(waste)}} \\ \\ +\text{location(waste, b)} \\ :\, \text{location(bin, d)} \\ \leftarrow\, !\,\text{collect(waste)};\, !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $(\text{move(a, b)}, \text{stop})$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
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location(robot, a).
location(bin, d).

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    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

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    : has(robot, X)
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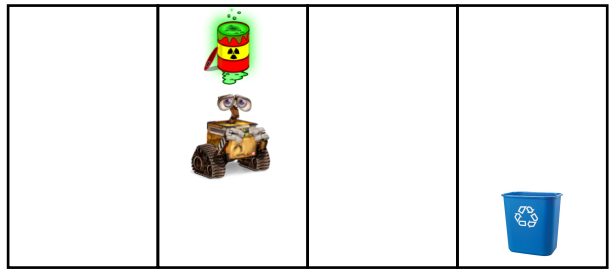

Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(waste, b)}, \\ \text{location(robot, b)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{collect(waste)} \\ :\, \textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow \sout{!\,\text{go\_to(b)}};\, \underline{\text{pick\_up(waste)}} \\ +\text{location(waste, b)} \\ :\, \text{location(bin, d)} \\ \leftarrow !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $(\text{move(a, b)}, \text{stop})$

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/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
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/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

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    : has(robot, X)
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+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Action

Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{~~location(waste, b)},~~ \\ \text{location(robot, b)}, \\ \text{has(robot, waste)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{collect(waste)} \\ :\, \textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow \text{pick\_up(waste)} \\ \hline +\text{location(waste, b)} \\ :\, \text{location(bin, d)} \\ \leftarrow\, !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}\big)$

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/* Initial base beliefs */

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adjacent(b, c).
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    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(robot, b)}, \\ \text{has(robot, waste)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{collect(waste)} \\ :\, \textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)} \\ \leftarrow \sout{\text{pick\_up(waste)}} \\ \underline{\qquad\qquad} \\ +\text{location(waste, b)} \\ :\, \text{location(bin, d)} \\ \leftarrow\, !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)} \end{array} \right]$

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```

Belief base $B = \left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(robot, b)}, \\ \text{has(robot, waste)} \end{array} \right\}$

Current intention $i = \left[\begin{array}{c} \sout{+!\,\text{collect(waste)}} \\ \sout{:\, \textbf{not}\ \text{has(robot, waste)} \wedge \text{location(waste, b)}} \\ \sout{\leftarrow\ \text{pick\_up(waste)}} \\ \hline +\text{location(waste, b)} \\ :\, \text{location(bin, d)} \\ \leftarrow\, !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h = \big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}\big)$

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    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
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Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(robot, b)}, \\ \text{has(robot, waste)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +\text{location(waste, b)} \\ : \text{location(bin, d)} \\ \leftarrow\ !\,\text{collect(waste)}; !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}\big)$

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    : location(bin, Y)
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    : not has(robot, X) & location(X, Y)
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    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Belief base $B = \left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(robot, b)}, \\ \text{has(robot, waste)} \end{array} \right\}$

Current intention $i = \left[\begin{array}{c} +\text{location(waste, b)} \\ : \text{location(bin, d)} \\ \leftarrow \sout{!\text{collect(waste)}}; !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h = \big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}\big)$

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    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

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    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Sub-Goal

Belief base $B = \left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(robot, b)}, \\ \text{has(robot, waste)} \end{array} \right\}$

Current intention $i = \left[\begin{array}{c} +\text{location(waste, b)} \\ :\text{location(bin, d)} \\ \leftarrow\ !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h = \big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}\big)$

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/* Initial base beliefs */

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adjacent(b, c).
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    : location(bin, Y)
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    : has(robot, X)
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+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Plan Selection

Belief base $B = \left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(robot, b)}, \\ \text{has(robot, waste)} \end{array} \right\}$

Current intention $i = \left[\begin{array}{c} +!\,\text{deposit(waste, bin)} \\ :\,\text{has(robot, waste)} \wedge \text{location(bin, d)} \\ \leftarrow\, !\,\text{go\_to(d)}; \underline{\text{drop(waste, bin)}} \\ +\text{location(waste, b)} \\ :\,\text{location(bin, d)} \\ \leftarrow\, !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h = \big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}\big)$

```
/* Initial base beliefs */

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adjacent(b, c).
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location(robot, a).
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/* Plan library */

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+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Sub-Goal

Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{location(robot, b)}, \\ \text{has(robot, waste)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{deposit(waste, bin)} \\ :\,\text{has(robot, waste)} \wedge \text{location(bin, d)} \\ \leftarrow\, !\,\text{go\_to(d)};\, \underline{\text{drop(waste, bin)}} \\ +\text{location(waste, b)} \\ :\,\text{location(bin, d)} \\ \leftarrow\, !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Plan Selection

Belief base $B =$

$$\left\{\begin{array}{c}\text{adjacent(a, b)},\\ \text{adjacent(b, c)},\\ \text{adjacent(c, d)},\\ \text{location(bin, d)},\\ \text{location(robot, b)},\\ \text{has(robot, waste)}\end{array}\right\}$$

Current intention $i =$

$$\left[\begin{array}{c}+!\,\text{go\_to(d)}\\ :\text{location(robot, b)} \wedge \text{adjacent(b, c)}\\ \leftarrow \text{move(b, c)}; !\,\text{go\_to(d)}\\ \hline +!\,\text{deposit(waste, bin)}\\ :\text{has(robot, waste)} \wedge \text{location(bin, d)}\\ \leftarrow !\,\text{go\_to(d)}; \text{drop(waste, bin)}\\ \hline +\text{location(waste, b)}\\ :\text{location(bin, d)}\\ \leftarrow !\,\text{deposit(waste, bin)}\end{array}\right]$$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Action

Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{~~location(robot, b),~~} \\ \text{has(robot, waste)}, \\ \text{location(robot, c)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to(d)} \\ :\text{location(robot, b)} \wedge \text{adjacent(b, c)} \\ \leftarrow \text{move(b, c)}; !\,\text{go\_to(d)} \\ \hline +!\,\text{deposit(waste, bin)} \\ :\text{has(robot, waste)} \wedge \text{location(bin, d)} \\ \leftarrow !\,\text{go\_to(d)}; \text{drop(waste, bin)} \\ \hline +\text{location(waste, b)} \\ :\text{location(bin, d)} \\ \leftarrow !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{has(robot, waste)}, \\ \text{location(robot, c)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to(d)} \\ :\, \text{location(robot, b)} \wedge \text{adjacent(b, c)} \\ \leftarrow \underline{\sout{\text{move(b, c)}}};\, !\,\text{go\_to(d)} \\ +!\,\text{deposit(waste, bin)} \\ :\, \text{has(robot, waste)} \wedge \text{location(bin, d)} \\ \leftarrow\, !\,\text{go\_to(d)}; \underline{\text{drop(waste, bin)}} \\ +\text{location(waste, b)} \\ :\, \text{location(bin, d)} \\ \leftarrow\, !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Sub-Goal

Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{has(robot, waste)}, \\ \text{location(robot, c)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to(d)} \\ :\, \text{location(robot, b)} \wedge \text{adjacent(b, c)} \\ \leftarrow\, !\,\underline{\text{go\_to(d)}} \\ +!\,\text{deposit(waste, bin)} \\ :\, \text{has(robot, waste)} \wedge \text{location(bin, d)} \\ \leftarrow\, !\,\text{go\_to(d)}; \underline{\text{drop(waste, bin)}} \\ +\text{location(waste, b)} \\ :\, \text{location(bin, d)} \\ \leftarrow\, !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Plan Selection

Belief base $B =$

$$\left\{\begin{array}{c}\text{adjacent(a, b)},\\ \text{adjacent(b, c)},\\ \text{adjacent(c, d)},\\ \text{location(bin, d)},\\ \text{has(robot, waste)},\\ \text{location(robot, c)}\end{array}\right\}$$

Current intention $i =$

$$\left[\begin{array}{c}+!\,\text{go\_to(d)}\\ :\text{location(robot, c)} \wedge \text{adjacent(c, d)}\\ \leftarrow \text{move(c, d)}; !\,\text{go\_to(d)}\\ \hline +!\,\text{go\_to(d)}\\ :\text{location(robot, b)} \wedge \text{adjacent(b, c)}\\ \leftarrow !\,\text{go\_to(d)}\\ \hline +!\,\text{deposit(waste, bin)}\\ :\text{has(robot, waste)} \wedge \text{location(bin, d)}\\ \leftarrow !\,\text{go\_to(d)}; \text{drop(waste, bin)}\\ \hline +\text{location(waste, b)}\\ :\text{location(bin, d)}\\ \leftarrow !\,\text{deposit(waste, bin)}\end{array}\right]$$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

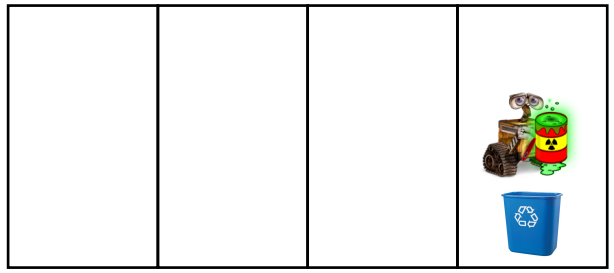
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Action



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{has(robot, waste)}, \\ \text{~~location(robot, c)~~}, \\ \text{location(robot, d)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to(d)} \\ :\, \text{location(robot, c)} \wedge \text{adjacent(c, d)} \\ \leftarrow \text{move(c, d)}; !\,\text{go\_to(d)} \\ \hline +!\,\text{go\_to(d)} \\ :\, \text{location(robot, b)} \wedge \text{adjacent(b, c)} \\ \leftarrow !\,\text{go\_to(d)} \\ \hline +!\,\text{deposit(waste, bin)} \\ :\, \text{has(robot, waste)} \wedge \text{location(bin, d)} \\ \leftarrow !\,\text{go\_to(d)}; \text{drop(waste, bin)} \\ \hline +\text{location(waste, b)} \\ :\, \text{location(bin, d)} \\ \leftarrow !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}, \text{move(c, d)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

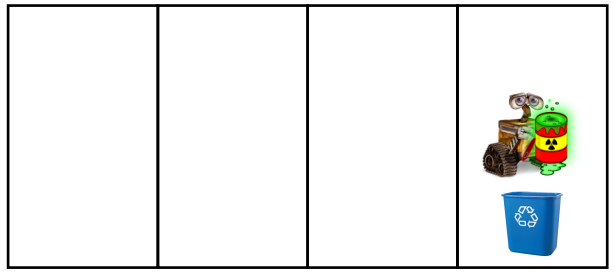
+!collect(X)
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{has(robot, waste)}, \\ \text{location(robot, d)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to(d)} \\ :\, \text{location(robot, c)} \wedge \text{adjacent(c, d)} \\ \leftarrow \underline{\sout{\text{move(c, d)}}};\, !\,\text{go\_to(d)} \\ \\ +!\,\text{go\_to(d)} \\ :\, \text{location(robot, b)} \wedge \text{adjacent(b, c)} \\ \leftarrow !\,\underline{\text{go\_to(d)}} \\ \\ +!\,\text{deposit(waste, bin)} \\ :\, \text{has(robot, waste)} \wedge \text{location(bin, d)} \\ \leftarrow !\,\text{go\_to(d)}; \underline{\text{drop(waste, bin)}} \\ \\ +\text{location(waste, b)} \\ :\, \text{location(bin, d)} \\ \leftarrow !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}, \text{move(c, d)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

+!collect(X)
    : has(robot, X)
      <- stop.

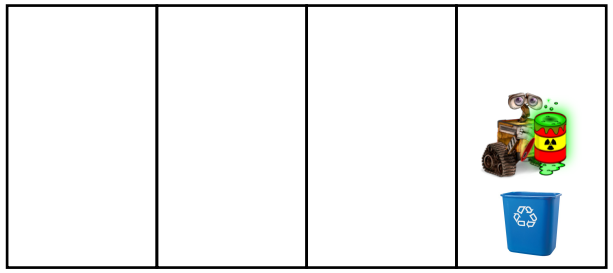
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Sub-Goal



Belief base $B =$

$$\left\{\begin{array}{c}\text{adjacent(a, b)},\\ \text{adjacent(b, c)},\\ \text{adjacent(c, d)},\\ \text{location(bin, d)},\\ \text{has(robot, waste)},\\ \text{location(robot, d)}\end{array}\right\}$$

Current intention $i =$

$$\left[\begin{array}{c}+!\,\text{go\_to(d)}\\ :\text{location(robot, c)} \wedge \text{adjacent(c, d)}\\ \leftarrow !\,\underline{\text{go\_to(d)}}\\ \\ +!\,\text{go\_to(d)}\\ :\text{location(robot, b)} \wedge \text{adjacent(b, c)}\\ \leftarrow !\,\underline{\text{go\_to(d)}}\\ \\ +!\,\text{deposit(waste, bin)}\\ :\text{has(robot, waste)} \wedge \text{location(bin, d)}\\ \leftarrow !\,\text{go\_to(d)}; \underline{\text{drop(waste, bin)}}\\ \\ +\text{location(waste, b)}\\ :\text{location(bin, d)}\\ \leftarrow !\,\text{deposit(waste, bin)}\end{array}\right]$$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}, \text{move(c, d)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

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    : has(robot, X)
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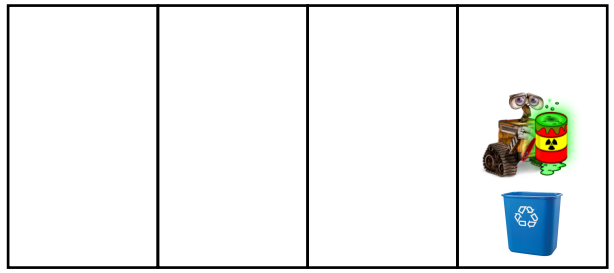
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Plan Selection



Belief base $B =$

$$\left\{\begin{array}{c}\text{adjacent(a, b)},\\ \text{adjacent(b, c)},\\ \text{adjacent(c, d)},\\ \text{location(bin, d)},\\ \text{has(robot, waste)},\\ \text{location(robot, d)}\end{array}\right\}$$

Current intention $i =$

$$\left[\begin{array}{c}+!\,\text{go\_to(d)}\\ :\text{location(robot, d)}\\ \leftarrow \underline{\text{stop}}\\ +!\,\text{go\_to(d)}\\ :\text{location(robot, c)} \wedge \text{adjacent(c, d)}\\ \leftarrow !\,\text{go\_to(d)}\\ +!\,\text{go\_to(d)}\\ :\text{location(robot, b)} \wedge \text{adjacent(b, c)}\\ \leftarrow !\,\text{go\_to(d)}\\ +!\,\text{deposit(waste, bin)}\\ :\text{has(robot, waste)} \wedge \text{location(bin, d)}\\ \leftarrow !\,\text{go\_to(d)}; \underline{\text{drop(waste, bin)}}\\ +\text{location(waste, b)}\\ :\text{location(bin, d)}\\ \leftarrow !\,\text{deposit(waste, bin)}\end{array}\right]$$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}, \text{move(c, d)}\big)$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
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location(robot, a).
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/* Plan library */

+location(waste, X)
    : location(bin, Y)
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    : has(robot, X)
      <- stop.

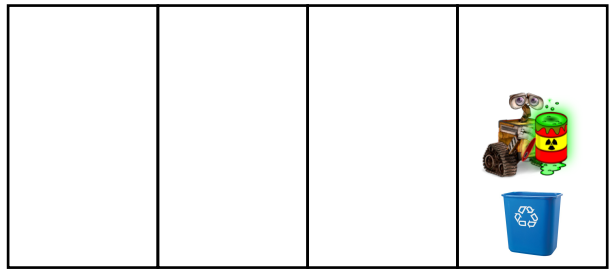
+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```

Action



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{has(robot, waste)}, \\ \text{location(robot, d)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to(d)} \\ :\,\text{location(robot, d)} \\ \leftarrow \underline{\text{stop}} \\ +!\,\text{go\_to(d)} \\ :\,\text{location(robot, c)} \wedge \text{adjacent(c, d)} \\ \leftarrow \underline{!\,\text{go\_to(d)}} \\ +!\,\text{go\_to(d)} \\ :\,\text{location(robot, b)} \wedge \text{adjacent(b, c)} \\ \leftarrow \underline{!\,\text{go\_to(d)}} \\ +!\,\text{deposit(waste, bin)} \\ :\,\text{has(robot, waste)} \wedge \text{location(bin, d)} \\ \leftarrow \underline{!\,\text{go\_to(d)}}; \text{drop(waste, bin)} \\ +\text{location(waste, b)} \\ :\,\text{location(bin, d)} \\ \leftarrow \underline{!\,\text{deposit(waste, bin)}} \end{array} \right]$

History $h =$ $(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}, \text{move(c, d)}, \text{stop})$

```
/* Initial base beliefs */

adjacent(a, b).
adjacent(b, c).
adjacent(c, d).
location(robot, a).
location(bin, d).

/* Plan library */

+location(waste, X)
    : location(bin, Y)
      <- !collect(waste); !deposit(waste, bin).

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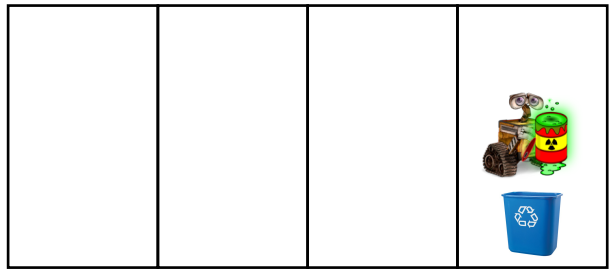
    : has(robot, X)
      <- stop.

+!collect(X)
    : not has(robot, X) & location(X, Y)
      <- !go_to(Y); pick_up(X).

+!deposit(X, Y)
    : has(robot, X) & location(Y, Z)
      <- !go_to(Z); drop(X, Y).

+!go_to(X)
    : location(robot, X)
      <- stop.

+!go_to(X)
    : location(robot, Y) & adjacent(Y, Z)
      <- move(Y, Z); !go_to(X).
```



Belief base $B =$ $\left\{ \begin{array}{c} \text{adjacent(a, b)}, \\ \text{adjacent(b, c)}, \\ \text{adjacent(c, d)}, \\ \text{location(bin, d)}, \\ \text{has(robot, waste)}, \\ \text{location(robot, d)} \end{array} \right\}$

Current intention $i =$ $\left[\begin{array}{c} +!\,\text{go\_to(d)} \\ :\,\text{location(robot, d)} \\ \leftarrow \underline{\text{stop}} \\ +!\,\text{go\_to(d)} \\ :\,\text{location(robot, c)} \wedge \text{adjacent(c, d)} \\ \leftarrow !\,\text{go\_to(d)} \\ +!\,\text{go\_to(d)} \\ :\,\text{location(robot, b)} \wedge \text{adjacent(b, c)} \\ \leftarrow !\,\text{go\_to(d)} \\ +!\,\text{deposit(waste, bin)} \\ :\,\text{has(robot, waste)} \wedge \text{location(bin, d)} \\ \leftarrow !\,\text{go\_to(d)}; \underline{\text{drop(waste, bin)}} \\ +\text{location(waste, b)} \\ :\,\text{location(bin, d)} \\ \leftarrow !\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}, \text{move(c, d)}, \text{stop})$

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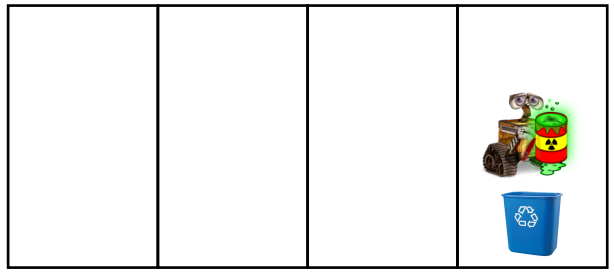

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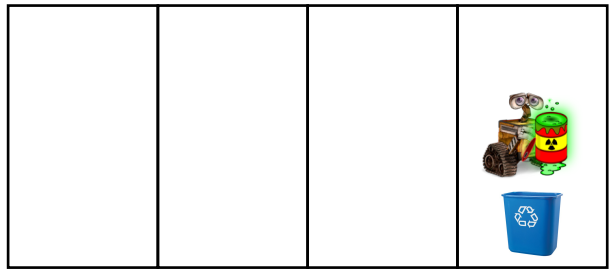

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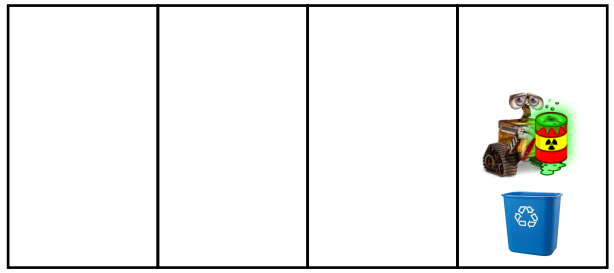

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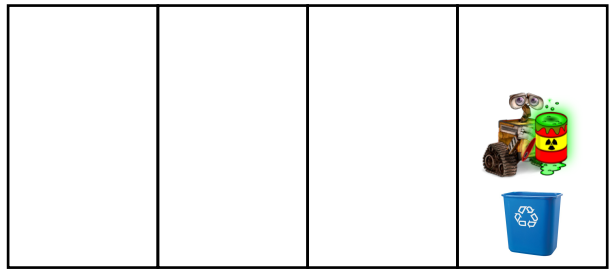

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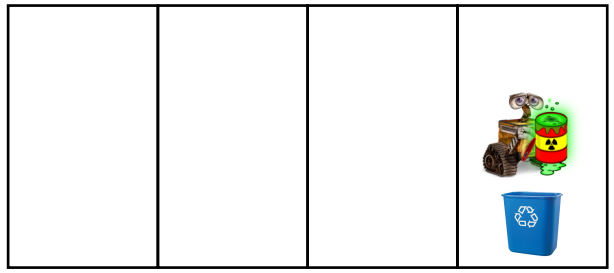

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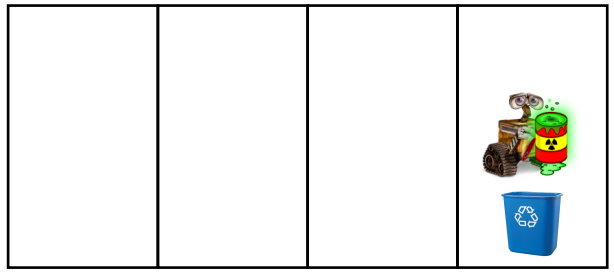

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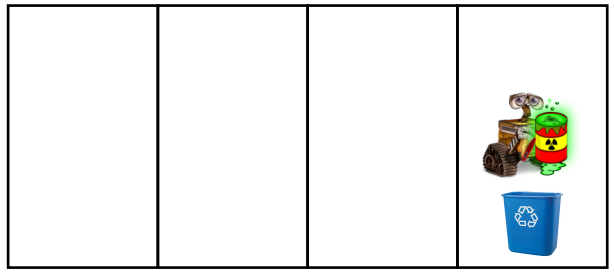

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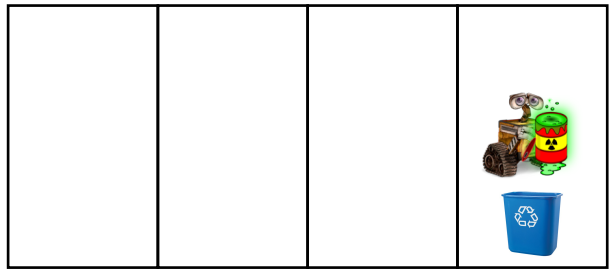

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History $h =$ (move(a, b), stop, pick_up(waste), move(b, c), move(c, d), stop)

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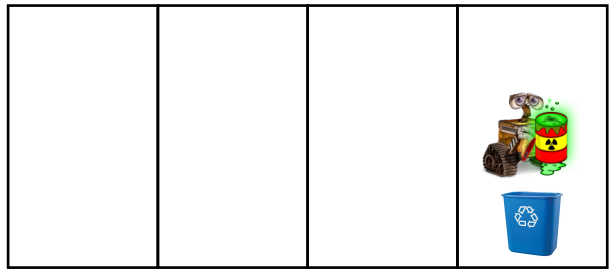

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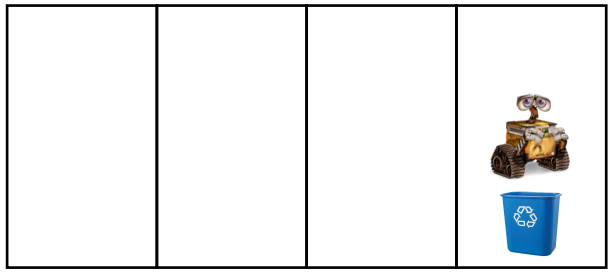
Action



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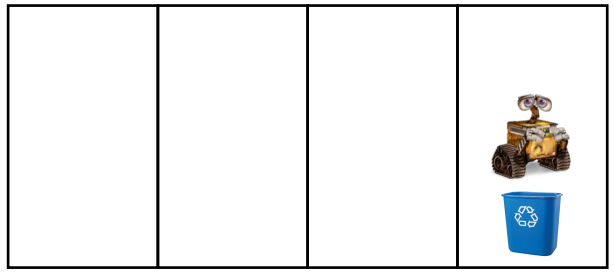

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Current intention $i =$ $\left[\begin{array}{c} +!\,\text{deposit(waste, bin)} \\ :\,\text{has(robot, waste)} \wedge \text{location(bin, d)} \\ \leftarrow \sout{\text{drop(waste, bin)}} \\ \hline - \\ +\text{location(waste, b)} \\ :\,\text{location(bin, d)} \\ \leftarrow\,!\,\text{deposit(waste, bin)} \end{array} \right]$

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}, \text{move(c, d)}, \text{stop}, \text{drop(waste, bin)}\big)$

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/* Initial base beliefs */

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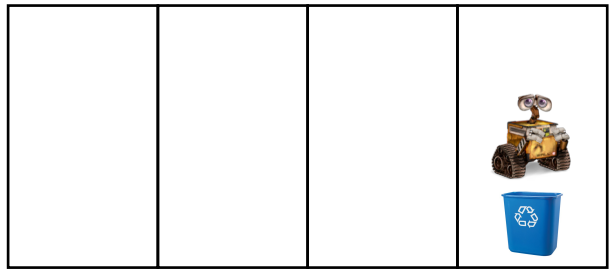

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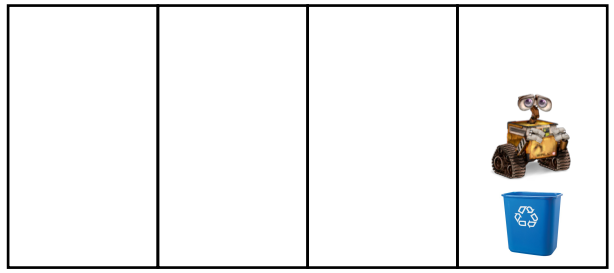

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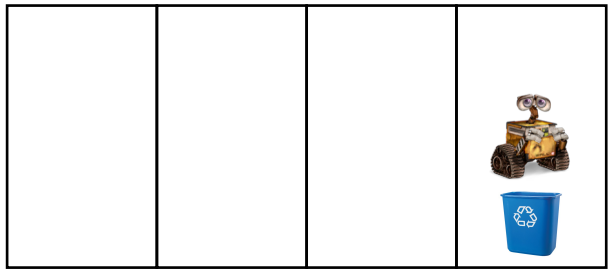

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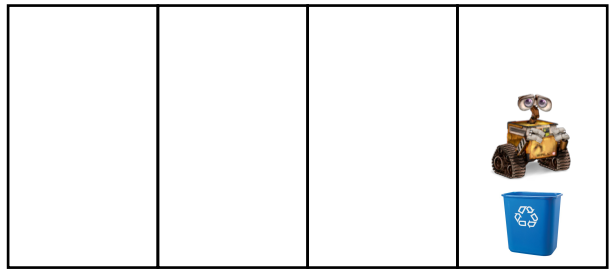

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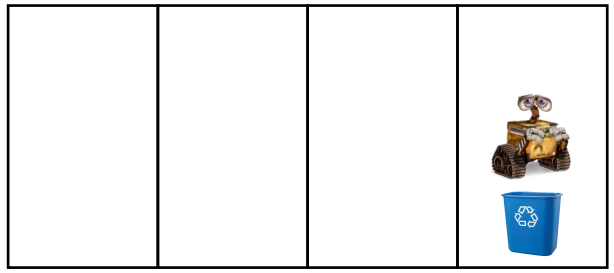

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Current intention $i =$ [ ]

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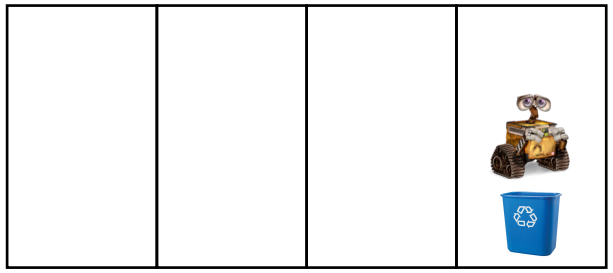

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Current intention $i =$ N/A

History $h =$ $\big(\text{move(a, b)}, \text{stop}, \text{pick\_up(waste)}, \text{move(b, c)}, \text{move(c, d)}, \text{stop}, \text{drop(waste, bin)}\big)$

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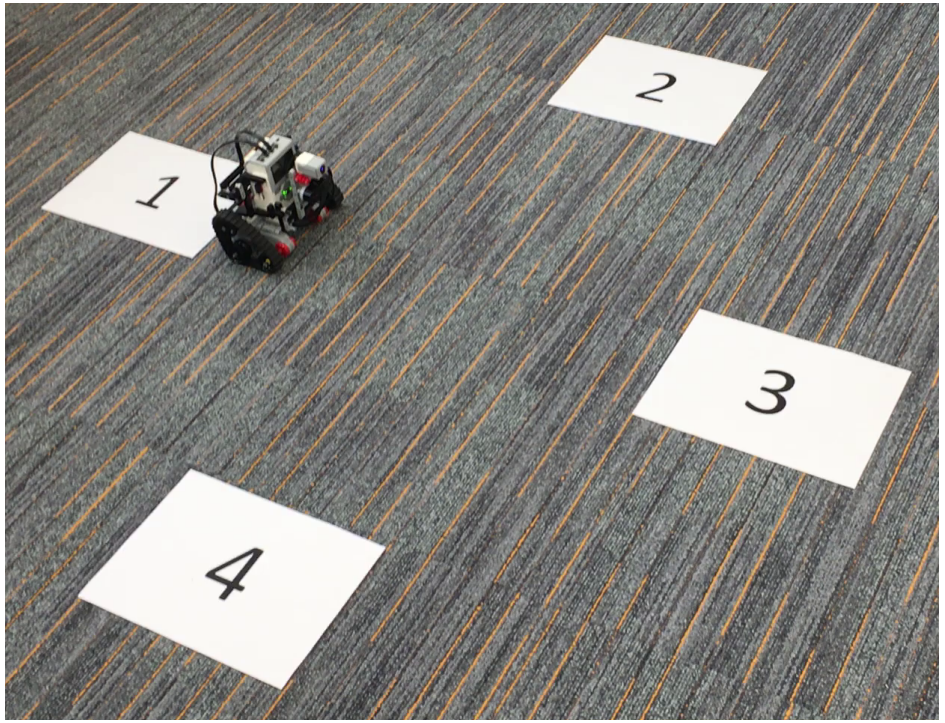
Demo

Lego Mindstorms EV3

- Consumer robot kit
  - Environment: real-world
  - Sensors: infrared (distance) sensor, colour sensor
  - Actuators: left motor, right motor, speaker
- All software is running onboard
  - Basic AgentSpeak interpreter implemented in Python
  - Additional Python API hooks for EV3 hardware
- Agent implemented as an AgentSpeak program
  - Plan library: $+!\,\mathrm{explore}$, $+!\,\mathrm{go\_to}(\mathrm{loc}(X))$, etc.
  - Action library: $\mathrm{forward}(\mathrm{Milliseconds})$, $\mathrm{right\_forward}(\mathrm{Degrees})$, $\mathrm{speak}(\mathrm{Words})$, etc.
  - Initial goal: $!\,\mathrm{explore}$



Environment
- Depot (1)
- Unexplored locations (2-4)

Objective
1. Explore all locations
2. Return to depot for collection
3. Make deliveries in order (as instructed)

Video

AgentSpeak

Some Reflections

- Pre-defined plan libraries
  - Plans in the library are not “true” plans, in that they are not necessarily ground
  - AgentSpeak performs a kind of online planning to instantiate variables
  - This is a practical, programming-based approach, but can be difficult to debug
  - In principal, an automated planner could be used to generate (fully ground) plans for the plan library
- Interleaving of multiple intentions
  - AgentSpeak may interleave the progression of multiple intentions, but this can have unexpected side-effects
  - It is up to the programmer to ensure this interleaving behaves correctly (e.g. via selection functions)
- Incomplete semantics
  - Rao only defined semantics for a subset of the syntax (e.g. no account of test goal addition or goal deletion triggering events)
  - This has been addressed by later works such as Jason
- Programming in AgentSpeak
  - Rao only proposed a language – to actually program in AgentSpeak, you need an implemented AgentSpeak interpreter
  - Examples include Jason and this basic Java implementation: https://github.com/kevinmcareavey/agentspeak

This Lecture…

1. Agent-oriented programming
   - PRS
   - AgentSpeak

2. AgentSpeak
   - Logic programming
   - Syntax
   - Semantics
   - Interpreter
   - Programming

Next Lecture…

- Jason
  - Extensions to AgentSpeak language
  - Simulation environments
  - Custom environment actions
  - Custom selection functions
  - Multiple agents
  - Agent communication

Bibliography

- Michael Wooldridge. *An Introduction to Multiagent Systems*. John Wiley & Sons, 2nd edition, 2009.
- Stuart J. Russell & Peter Norvig. *Artificial Intelligence: A Modern Approach*. Prentice Hall, 3rd edition, 2009.
- Hector Geffner & Blai Bonet. *A Concise Introduction to Models and Methods for Automated Planning*. Morgan & Claypool, 2013.

Suggested reading

- Anand S. Rao. AgentSpeak(L): BDI agents speak out in a logical computable language. In *Proceedings of the 7th European Workshop on Modelling Autonomous Agents in a Multi-Agent World (MAAMAW'96)*, pages 42-55, 1996.
- Rafael H. Bordini, Jomi Fred Hübner, & Michael Wooldridge. *Programming Multi-Agent Systems in AgentSpeak Using Jason*. John Wiley & Sons, 2007.