AUTOMATED REASONING

Agostino Dovier

Università di Udine
CLPLAB

Udine, December 2016

Action Description Languages

Formal models to represent knowledge on actions and change.

- STRIPS (STanford Research Institute Problem Solver)
  1971–Richard Fikes and Nils Nilsson
- A classification by Gelfond and Lifschitz, 1998 (e.g., $\mathcal{A}$ and $\mathcal{B}$)
- The standard de facto: PDDL

Specifications are given through declarative assertions that permit

- to describe actions and their effects on states
- to express queries on the underlying transition system

A *planning problem* can be described through an action description, which defines the notions of

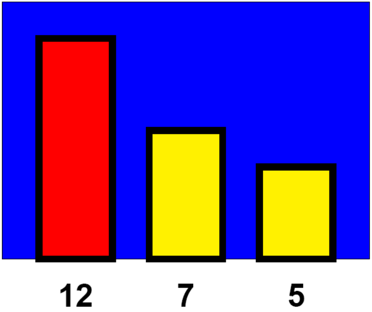
FLUENTS i.e., *variables* describing the state of the world, and whose value can change

STATES i.e., possible configurations of the domain of interest: an assignment of values to the fluents

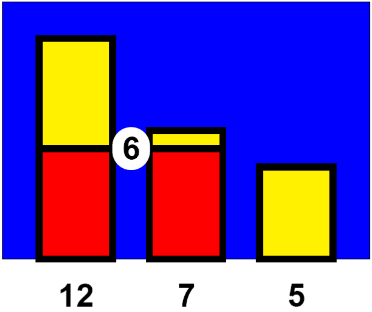
ACTIONS that affect the state of the world, and thus cause the transition from a state to another

A complete (or partial) description of the initial and final states is given in input as a query.

"There are three barrels of capacity N (even number), $N/2+1$, and $N/2-1$, resp. At the beginning the largest barrel is full of Taylor's Porto, the other two are empty. We wish to reach a state in which the two largest barrels contain the same amount of porto. The only permissible action is to pour porto from one barrel to another, until the latter is full or the former is empty."



Initial state

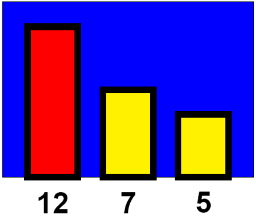


Final state

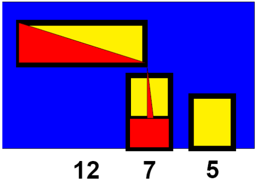
Example: the Three-barrels problem

fluents, states, and action

State 1

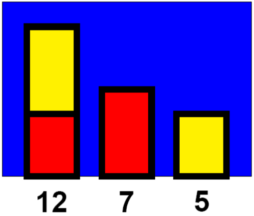


contains(12,12)
contains(7,0)
contains(5,0)
¬ contains(12,0)
...



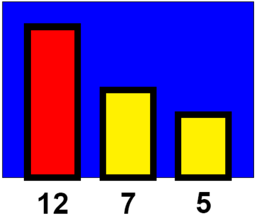
pour(12,7)

State 2

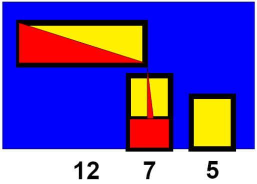


contains(12,5)
contains(7,7)
contains(5,0)
¬ contains(12,0)
...

State 1

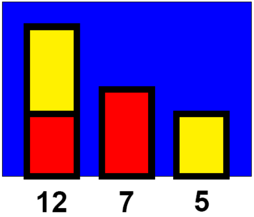


contains(12,12)
contains(7,0)
contains(5,0)
¬ contains(12,0)
...



pour(12,7)

State 2



contains(12,5)
contains(7,7)
contains(5,0)
¬ contains(12,0)
...

- An action signature consists of:
  - a set $\mathcal{A}$ of actions,
  - a set $\mathcal{F}$ of fluent names,
  - and a set $\mathcal{V}$ of values for fluents in $\mathcal{F}$ (in $\mathcal{B}$, we consider $\mathcal{V} = \{0, 1\}$)
- An action description on an action signature is a set of executability conditions, static, and dynamic laws.
- A specific planning problem is an action description $\mathcal{D}$ along with a description of the initial and the final state.

Let `a` be an action and `f` be a Boolean fluent. We have:

- Executability conditions:
  `executable(a, [list-of-preconditions])`
  asserting that the given preconditions have to be satisfied in the current state for the action `a` to be executable
- Dynamic causal laws:
  `causes(a, f, [list-of-preconditions])`
  describes the effect (the fluent literal `f`) of the execution of action `a` in a state satisfying the given preconditions
- Static causal laws:
  `caused([list-of-preconditions], f)`
  describes the fact that the fluent literal `f` is true in a state satisfying the given preconditions

```
executable(pour(X,Y),
      [contains(X,LX),contains(Y,LY)]) :-
   action(pour(X,Y)),
   fluent(contains(X,LX)),
   fluent(contains(Y,LY)),
   LX > 0, LY < Y.
caused([contains(X,LX) ],neg(contains(X,LY))):-
   fluent(contains(X,LX)),
   fluent(contains(X,LY)),
   barrel(X),liters(LX),liters(LY),
   neq(LX,LY).
```

The language $\mathcal{B}$

Barrels and Porto

```
executable(pour(X,Y),
          [contains(X,LX),contains(Y,LY)]) :-
    action(pour(X,Y)),
    fluent(contains(X,LX)),
    fluent(contains(Y,LY)),
    LX > 0, LY < Y.

caused([contains(X,LX) ],neg(contains(X,LY))):-
    fluent(contains(X,LX)),
    fluent(contains(X,LY)),
    barrel(X),liters(LX),liters(LY),
    neq(LX,LY).
```

```
causes(pour(X,Y), contains(X,0),
    [contains(X,LX),contains(Y,LY)]):-
        action(pour(X,Y)),
        fluent(contains(X,LX)),
        fluent(contains(Y,LY)),
        Y-LY >= LX.
causes(pour(X,Y), contains(Y,LYnew),
    [contains(X,LX),contains(Y,LY)]):-
        action(pour(X,Y)),
        fluent(contains(X,LX)),
        fluent(contains(Y,LY)),
        Y-LY >= LX,
        LYnew is LX + LY.
```

THE LANGUAGE $\mathcal{B}$

BARRELS AND PORTO

```
causes(pour(X,Y), contains(X,LXnew),
    [contains(X,LX),contains(Y,LY)]):-
        action(pour(X,Y)),
        fluent(contains(X,LX)),
        fluent(contains(Y,LY)),
        LX >= Y-LY,
        LXnew is LX-Y+LY.
causes(pour(X,Y), contains(Y,Y),
    [contains(X,LX),contains(Y,LY)]):-
        action(pour(X,Y)),
        fluent(contains(X,LX)),
        fluent(contains(Y,LY)),
        LX >= Y-LY.
```

THE LANGUAGE $\mathcal{B}$

GOAL

- *Initial state*

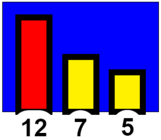
```
initially(f)
```

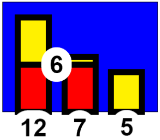
asserts that `f` holds in the initial state.

- *Goal*

```
goal(f)
```

asserts that `f` is required to hold in the final state.






```
initially(contains(12,12)).
initially(contains(7,0)).
initially(contains(5,0)).
```

```
goal(contains(12,6)).
goal(contains(7,6)).
goal(contains(5,0)).
```

- If $f \in \mathcal{F}$ is a fluent, and S is a set of fluent literals, we say that $S \models f$ iff $f \in S$ and $S \models \texttt{neg}(f)$ iff $\texttt{neg}(f) \in S$.
- Lists of literals $L = [\ell_1, \ldots, \ell_m]$ denote conjunctions of literals, hence $S \models L$ iff $S \models \ell_i$ for all $i \in \{1, \ldots, m\}$.
- We denote with $\neg S$ the set

$$\{f \in \mathcal{F} : \texttt{neg}(f) \in S\} \cup \{\texttt{neg}(f) : f \in S \cap \mathcal{F}\}.$$

- A set of fluent literals is *consistent* if there are no fluents f s.t. $S \models f$ and $S \models \texttt{neg}(f)$.
- If $S \cup \neg S \supseteq \mathcal{F}$ then S is *complete*.

- A set S of literals is *closed* under a set of static laws $\mathcal{SL} = \{\texttt{caused}(C_1, \ell_1), \ldots, \texttt{caused}(C_m, \ell_m)\}$, if for all $i \in \{1, \ldots, m\}$ it holds that $S \models C_i \Rightarrow S \models \ell_i$.
- The set $\texttt{Clo}_{\mathcal{SL}}(S)$ is defined as the smallest set of literals containing S and closed under $\mathcal{SL}$.
- It can be obtained by repeatedly applying the static laws until a fixpoint is reached
- $\texttt{Clo}_{\mathcal{SL}}(S)$ is uniquely determined and not necessarily consistent.

- The semantics of an action language on the action signature $\langle \mathcal{V}, \mathcal{F}, \mathcal{A} \rangle$ is given in terms of a transition system $\langle \mathcal{S}, v, R \rangle$
- $\langle \mathcal{S}, v, R \rangle$ consists of
  - a set $\mathcal{S}$ of states,
  - a total interpretation function $v : \mathcal{F} \times \mathcal{S} \rightarrow \mathcal{V}$, and
  - a transition relation $R \subseteq \mathcal{S} \times \mathcal{A} \times \mathcal{S}$. Given a transition system $\langle \mathcal{S}, v, R \rangle$ and a state $s \in \mathcal{S}$,
- Let (it is consistent and complete):

$$Lit(s) \quad = \quad \{f \in \mathcal{F} \ : \ v(f,s) = 1\} \cup \{\mathtt{neg}(f) \ : \ f \in \mathcal{F}, v(f,s) = 0\}.$$

- Given a set of dynamic laws $\mathcal{DL} = \{\mathtt{causes}(a, \ell_1, C_1), \ldots, \mathtt{causes}(a, \ell_m, C_m)\}$ for the action $a \in \mathcal{A}$ and a state $s \in \mathcal{S}$, we define the *effect of a in s* as follows:

$$E(a,s) = \{\ell_i : 1 \leqslant i \leqslant m, Lit(s) \models C_i\}.$$

SEMANTICS OF $\mathcal{B}$

Let $\mathcal{D}$ be an action description defined on the action signature $\langle \mathcal{V}, \mathcal{F}, \mathcal{A} \rangle$, composed of dynamic laws $\mathcal{DL}$, executability conditions $\mathcal{EL}$, and static causal laws $\mathcal{SL}$. The transition system $\langle \mathcal{S}, v, R \rangle$ *described by* $\mathcal{D}$ is a transition system such that:

- If $s \in \mathcal{S}$, then $Lit(s)$ is closed under $\mathcal{SL}$;
- R is the set of all triples $\langle s, a, s' \rangle$ such that

$$Lit(s') = \mathtt{Clo}_{\mathcal{SL}}(E(a, s) \cup (Lit(s) \cap Lit(s')))$$

  and $Lit(s) \models C$ for at least one condition $\mathtt{executable}(a, C)$ in $\mathcal{EL}$.

Let $\langle \mathcal{D}, \mathcal{O} \rangle$ be a planning problem instance, where $\{\ell \mid \mathtt{initially}(\ell) \in \mathcal{O}\}$ is a consistent and complete set of fluent literals.

A *trajectory* is a sequence $s_0 a_1 s_1 a_2 \ldots a_n s_n$ such that $\langle s_{i-1}, a_i, s_i \rangle \in R$ for all $i \in \{1, \ldots, n\}$. A sequence of actions $a_1, \ldots, a_n$ is a solution (a *plan*) to the planning problem $\langle \mathcal{D}, \mathcal{O} \rangle$ if there is a trajectory $s_0 a_1 s_1 \ldots a_n s_n$ in $\langle \mathcal{S}, v, R \rangle$ such that:

- $Lit(s_0) \models r$ for each $\texttt{initially}(r) \in \mathcal{O}$, and
- $Lit(s_n) \models \ell$ for each $\texttt{goal}(\ell) \in \mathcal{O}$.

The plans characterized in this definition are *sequential*—i.e., we disallow concurrent actions; observe also that the desired plan length n is assumed to be given.

Semantics of $\mathcal{B}$

- Without static causal laws, the semantics is deterministic. Given S and a, compute $E(a, S)$. $E(a, S)$ must be consistent for the action can be applied. Then $S' = E(a, S) \cup S \setminus (E(a, S) \cup \neg E(a, S))$.
- With static causal laws the semantics can be non-deterministic. Consider, for instance: $S = \{\mathtt{a}, \mathtt{b}, \mathtt{c}\}$, the action x that has $neg(a)$ as its effect.
  Assume there are the static laws
  `caused([neg(a),b],neg(c))` and
  `caused([neg(a),c],neg(b))`.
  Then $S' = \{\mathtt{neg(a)}, \mathtt{b}, \mathtt{neg(c)}\}$ and $S'' = \{\mathtt{neg(a)}, \mathtt{c}, \mathtt{neg(b)}\}$ are such that $\langle S, x, S' \rangle$ and $\langle S, x, S'' \rangle$ are in the transition system
- The programmer should take care of these cases.

SEMANTICS OF $\mathcal{B}$

- Without static causal laws, the semantics is deterministic. Given S and a, compute $E(a, S)$. $E(a, S)$ must be consistent for the action can be applied. Then $S' = E(a, S) \cup S \setminus (E(a, S) \cup \neg E(a, S))$.
- With static causal laws the semantics can be non-deterministic. Consider, for instance: $S = \{\mathtt{a}, \mathtt{b}, \mathtt{c}\}$, the action x that has *neg*(a) as its effect.
  Assume there are the static laws
  `caused([neg(a),b],neg(c))` and
  `caused([neg(a),c],neg(b))`.
  Then $S' = \{\mathtt{neg(a)}, \mathtt{b}, \mathtt{neg(c)}\}$ and $S'' = \{\mathtt{neg(a)}, \mathtt{c}, \mathtt{neg(b)}\}$ are such that $\langle S, x, S' \rangle$ and $\langle S, x, S'' \rangle$ are in the transition system
- The programmer should take care of these cases.

- Without static causal laws, the semantics is deterministic. Given S and a, compute $E(a, S)$. $E(a, S)$ must be consistent for the action can be applied. Then $S' = E(a, S) \cup S \setminus (E(a, S) \cup \neg E(a, S))$.
- With static causal laws the semantics can be non-deterministic. Consider, for instance: $S = \{\mathtt{a}, \mathtt{b}, \mathtt{c}\}$, the action x that has $neg(a)$ as its effect.
  Assume there are the static laws
  `caused([neg(a),b],neg(c))` and
  `caused([neg(a),c],neg(b))`.
  Then $S' = \{\mathtt{neg}(\mathtt{a}), \mathtt{b}, \mathtt{neg}(\mathtt{c})\}$ and $S'' = \{\mathtt{neg}(\mathtt{a}), \mathtt{c}, \mathtt{neg}(\mathtt{b})\}$ are such that $\langle S, x, S' \rangle$ and $\langle S, x, S'' \rangle$ are in the transition system
- The programmer should take care of these cases.

- We will see the basic encoding of B in ASP, and
- in Constraint Programming (hence, SAT)

A. Dovier, A. Formisano, E. Pontelli. Perspectives on Logic-based Approaches for Reasoning About Actions and Change. In Logic Programming, Knowledge Representation, and Nonmonotonic Reasoning, Essays Dedicated to Michael Gelfond on the Occasion of His 65th Birthday. LNCS 6565, Springer Verlag, pp. 259-279, 2011.

- We will see the basic encoding of B in ASP, and
- in Constraint Programming (hence, SAT)

A. Dovier, A. Formisano, E. Pontelli. Perspectives on Logic-based Approaches for Reasoning About Actions and Change. In Logic Programming, Knowledge Representation, and Nonmonotonic Reasoning, Essays Dedicated to Michael Gelfond on the Occasion of His 65th Birthday. LNCS 6565, Springer Verlag, pp. 259-279, 2011.

Compiling Action Theories in ASP

- `fluent` and `action` definitions are already in ASP syntax.
- We need a notion of `Time` to be associated to each state.
- A fluent literal `FL` holds or not in a state `i`. We define therefore the predicate `holds(FL,Time)`.
- An action `a` occurs or not between state `i` and `i+1`. We define the predicate `occ(Action,Time)`.
- If `initially(FL)` then `holds(FL,0)`.
- If an action `a` setting the fluent literal `FL` is executed between state `i` and `i+1` (i.e. `occ(a,i)`) then `holds(FL,i+1)`.
- Other conditions (inertia, static causal laws)

- The executability conditions

```
executable(a , [ p1, neg(r)]).
executable(a , [ q1, neg(s)]).
```

- are translated as follows:

```
exec(a,Ti) :- time(Ti),
   holds(p1,Ti),holds(neg(r),Ti).
exec(a,Ti) :- time(Ti),
   holds(q1,Ti) ,holds(neg(s),Ti).
```

Compiling Action Theories in ASP

- The Dynamic Laws:

```
causes( a , f, [ p1, neg(p2)]).
causes( a , g, [ q1, q2]).
```

- are translated as follows:

```
causes(a,f).
ok(a,f,Ti) :- time(Ti),
   hold(p1,Ti), hold(neg(p2),Ti).
causes(a,g).
ok(a,g,Ti) :- time(Ti),
   hold(q1,Ti), hold(q2,Ti).
hold(Fl,Ti+1) :- time(Ti), literal(Fl),
   occ(Act,Ti), causes(Act,Fl),
   ok(Act,Fl,Ti), exec(Act,Ti).
```

- The Static Law:

```
caused( [ p1, neg(p2)], f).
```

- is simply translated as follows:

```
hold(f,Ti) :- time(Ti),
     hold(p1,Ti), hold(neg(p2),Ti).
```

- It can be proved that stable model semantics ensures the correct semantics of state changing with static laws.

Compiling Action Theories in ASP

- At each time exactly one between `f` and `neg(f)`:

```
1{holds(F,T),holds(neg(F),T)}1 :-
    time(T), T < maxtime, fluent(F).
```

- At each time exactly one action must be executed, and its preconditions must be fulfilled:

```
1{occ(Act,Ti):action(Act)}1 :-
    time(Ti), Ti < maxtime.
:- occ(Act,Ti), action(Act),
    time(Ti), not exec(Act,Ti).
```

- If the goal state is characterized by fluents `f1,...,fk` then we define the predicate:

```
goal :- holds(f1,n),...,holds(fk,n).
:- not goal.
```

- The translator is a Prolog program available on-line.
- Answer sets of the obtained ASP program are exactly the plans for the action theory.

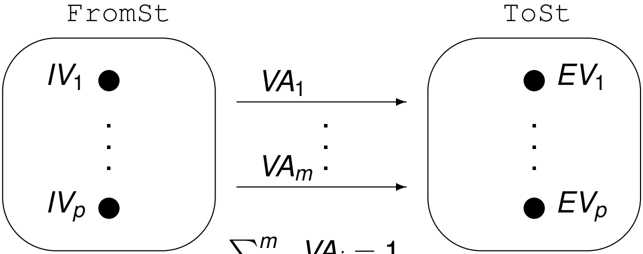
- An action theory is consulted by a constrain & generate CLP(FD) program.
- Looking for a *plan* of N states, p fluents, and m actions, $Np + (N-1)m$ Boolean variables are introduced, organized in
- A list `States`, containing N lists, each composed of p terms of the type `fluent(fluent_name, Bool_var)`, and in
- A list `ActionsOcc`, containing $N-1$ lists, each composed of m terms of the form `action(action_name,Bool_var)`.

MODELLING $\mathcal{B}$ IN CP

- Action descriptions are mapped to finite domain constraints
- Constrained variables are introduced for fluents and action occurrences
- Executability conditions and causal laws are rendered by imposing constraints
- Solutions of the constrains identify plans
- Soundness and completeness of the planner w.r.t. semantics of $\mathcal{B}$ is proved

MODELLING $\mathcal{B}$ IN CP

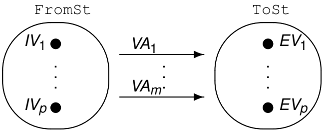
SOME CONSTRAINTS



$\sum_{i=1}^{m} VA_i = 1$

Modelling $\mathcal{B}$ in CLP(FD)

Some constraints



$$
\begin{aligned}
\mathtt{DynP}_f &\leftrightarrow \bigvee_{i=1}^{m}(\overline{\mathtt{IV}}_{\alpha_i} \wedge \mathtt{VA}_{t_i}) \qquad \mathtt{StatP}_f \leftrightarrow \bigvee_{i=1}^{h} \overline{\mathtt{EV}}_{\gamma_i} \\
\mathtt{DynN}_f &\leftrightarrow \bigvee_{i=1}^{o}(\overline{\mathtt{IV}}_{\beta_i} \wedge \mathtt{VA}_{f_i}) \qquad \mathtt{StatN}_f \leftrightarrow \bigvee_{i=1}^{k} \overline{\mathtt{EV}}_{\psi_i} \\
\mathtt{Posfired}_f &\leftrightarrow \mathtt{DynP}_f \vee \mathtt{StatP}_f \\
\mathtt{Negfired}_f &\leftrightarrow \mathtt{DynN}_f \vee \mathtt{StatN}_f \\
& \quad \neg\mathtt{Posfired}_f \vee \neg\mathtt{Negfired}_f \\
\mathtt{EV}_f &\leftrightarrow \mathtt{Posfired}_f \vee \big(\neg\mathtt{Negfired}_f \wedge \mathtt{IV}_f\big)
\end{aligned}
$$

```
main(N, Actionsocc,States):-
    setof(F, fluent(F), Lf),
    setof(A, action(A), La),
    setof(F, initially(F), Init),
    setof(F, goal(F), Goal),
    make_states(N,Lf,States),
    make_action_occurrences(N,La,Actionsocc),
    set_initial(Init,States),
    set_goal(Goal,States),
    set_transitions(Actionsocc,States),
    set_executability(Actionsocc,States),
    labelling(AllActions).
```

- The CLP(FD) interpreter of the $\mathcal{B}$ language is implemented in SICStus/B Prolog and available on-line
  `www.dimi.uniud.it/dovier/CLPASP/`
- The underlying CLP(FD) expressivity suggests immediate generalization of the action language:
  - multivalued fluents comes naturally into the scenery
  - constraints could be promoted to first-class objects: use them directly in the action theory

PDDL

Planning Domain Definition Language (PDDL) is the standard action description language introduced in 1988 by a group of top researchers in AI (Ghallab, Howe, Knoblock, Drew McDermott, Ram, Veloso, Weld, Wilkins).

The programming style is functional (declarative, but not logic programming)

There is a tradition of functional programming within the community of AI and Planning due to Mc Carthy school.

```
(define (domain DOMAIN_NAME)
  (:requirements [:strips] [:equality] [:typing] [:adl
  (:predicates
    (PREDICATE_1_NAME ?A1 ?A2 ... ?AN)
    (PREDICATE_2_NAME ?A1 ?A2 ... ?AN)
      ...
   )
  (:action ACTION_1_NAME
    [:parameters (?P1 ?P2 ... ?PN)]
    [:precondition PRECOND_FORMULA]
    [:effect EFFECT_FORMULA]
   )
  (:action ACTION_2_NAME
    ...)
)
```

For STRIPS domains, a precondition formula may be:

- an atomic formula (PREDICATE_NAME ARG1 ... ARGN) or
- a conjunction of atomic formulas: (and ATOM1 ... ATOMN)

For ADL domains, a precondition may in addition be:

- A general negation, conjunction or disjunction:
  (not CONDITION_FORMULA)
  (and CONDITION_FORMULA1 ... CONDITION_FORMULAN)
  (or CONDITION_FORMULA1 ... CONDITION_FORMULAN)
- A quantified formula: (forall (?V1 ?V2 ...) CONDITION_FORMULA)

For STRIPS domains, an effect formula may be:

- An added atom:
  (PREDICATE_NAME ARG1 ... ARGN)
  The predicate arguments must be parameters of the action (or constants declared in the domain, if the domain has constants).
- A deleted atom:
  (not (PREDICATE_NAME ARG1 ... ARGN))
  A conjunction of atomic effects: (and ATOM1 ... ATOMN)

For ADL domains an effect formula may in addition contain:

- A conditional effect:
  (when CONDITION_FORMULA EFFECT_FORMULA) or
- a universally quantified formula:
  (forall (?V1 ?V2 ...) EFFECT_FORMULA)

The problem definition contains the objects present in the problem instance, the initial state description and the goal:

```
(define (problem PROBLEM_NAME)
    (:domain DOMAIN_NAME)
    (:objects OBJ1 OBJ2 ... OBJ_N)
    (:init ATOM1 ATOM2 ... ATOM_N)
    (:goal CONDITION_FORMULA)
)
```

Other options such as action/plan cost can be set.

```
(:objects rooma roomb ball1 ball2 ball3 ball4 left right)
(:predicates (ROOM ?x) (BALL ?x) (GRIPPER ?x) (at-robby ?x)
             (at-ball ?x ?y) (free ?x) (carry ?x ?y))
(:init (ROOM rooma) (ROOM roomb) (at-robby rooma)
       (BALL ball1) (BALL ball2) (BALL ball3) (BALL ball4)
       (GRIPPER left) (GRIPPER right) (free left) (free right)
       (at-ball ball1 rooma) (at-ball ball2 rooma)
       (at-ball ball3 rooma) (at-ball ball4 rooma))
(:goal (and (at-ball ball1 roomb) (at-ball ball2 roomb)
       (at-ball ball3 roomb) (at-ball ball4 roomb)))
(:action pick-up :parameters (?x ?y ?z)
     :precondition (and (BALL ?x) (ROOM ?y) (GRIPPER ?z)
                   (at-ball ?x ?y) (at-robby ?y) (free ?z))
      :effect (and (carry ?z ?x)
                   (not (at-ball ?x ?y)) (not (free ?z))))
```

- PDDL domains can easily be transformed in B and hence in ASP programs or solved with CP as just seen
- There is the Planning competition website where you can find benchmarks/examples and the fastest solvers
- We will briefly see the logic language Picat and how it can be used to solve PDDL domains.