CSC2542 Representations for (Classical) Planning

Sheila McIlraith
Department of Computer Science
University of Toronto
Summer 2014

Acknowledgements

Some the slides used in this course are modifications of Dana Nau's lecture slides for the textbook *Automated Planning,* licensed under the Creative Commons Attribution-NonCommercial-ShareAlike License: http://creativecommons.org/licenses/by-nc-sa/2.0/

Other slides are modifications of slides developed by Malte Helmert, Bernhard Nebel, and Jussi Rintanen.

I have also used some material prepared by P@trick Haslum and Rao Kambhampati.

I would like to gratefully acknowledge the contributions of these researchers, and thank them for generously permitting me to use aspects of their presentation material.

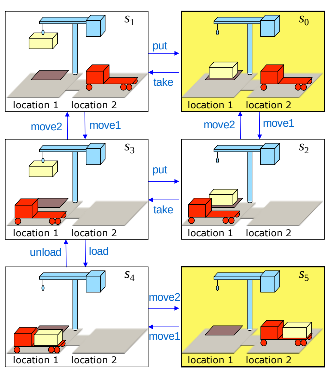
Recall: Planning Problem

$P = (\Sigma, s_0, G)$

Σ: System Description

s_0: Initial state(s)
E.g., Initial state = s_0

G: Objective
Goal state,
Set of goal states,
Set of tasks,
"trajectory" of states,
Objective function, …
E.g., Goal state = s_5



The Dock Worker Robots (DWR) domain

Further Recall: System Description (as a state transition system)

$\Sigma = (S, A, E, \gamma)$

- S = {states}
- A = {actions}
- E = {exogenous events}
- State-transition function $\gamma : S \times (A \cup E) \to 2^S$

Example: Dock Workers Robots from previous slide

- $S = \{s_0, \ldots, s_5\}$
- A = {move1, move2, put, take, load, unload}
- E = {}
- γ: as captured by the arrows mapping states and actions to successor states

Representational Challenge

- How do we represent our planning problem is a way that supports exploration of the principles and practice of automated planning?

Approach:

- There isn't one answer.
- The [GNT04] proposes representations that are suitable for ***generating classical*** plans.

[GNT04] = Ghallab, Nau, Traverso, **Automated Planning: Theory and Practice**, 2004

Broad Perspective on Plan Representation

The right representation for the right objective.
Distinguish representation schemes for:

1. **studying the principles of planning** and related tasks.
2. **specifying planning domains**
3. **direct use within (classical) planners**

Summary: Broad Perspective

1. Studying the formal principles of planning and other related task
- (First-order) logical languages
  (e.g., situation calculus, *A* languages, event calculus, fluent calculus, PDL)

Properties:
- well-defined semantics, representational issues must be addressed in the language (not in the algorithm that interprets and manipulates them)
- excellent for study and proving properties. Not ideal for 3 below.

2. Specifying planning domains
- PDDL-n (PDDL2.1, PDDL2.2, PDDL3, ….)

Properties:
- (reasonably) well-defined semantics
- designed for input to planners – translate to an internal representation for specific planners. Translators exist for most state-of-the-art planners

3. Direct use within (classical) planners
- Classical representation (e.g., STRIPS)
- Set-theoretic representation (basis for rep'ns used w/ SAT solvers)
- State-variable representation (aka "*Finite Domain Repn' (FDR)*"*)(e.g., SAS, SAS+)

Variants of these exist for particular planners (e.g., SAT solvers, model checkers, etc.)

* [Helmert, AIJ 2009]

This Lecture:

1. Studying the formal principles of planning and other related task
- (First-order) logical languages
  (calculus, PDL)

Pro
- v dressed in the
  l es them)
- e elow.

2. Spec

WILL COVER LATER

- PDDL-n (PDDL2.1, PDDL2.2, PDDL3, ….)

Properties:
- (reasonably) well-defined semantics
- designed for input to planners – translate to an internal representation for specific planners. Translators exist for most state-of-the-art planners

3. Direct use within (classical) planners (what's in the text)
- Classical representation (e.g., STRIPS)
- Set-theoretic representation (basis for rep'ns used w/ SAT solvers)
- State-variable representation (aka "FDR") (e.g., SAS, SAS+)

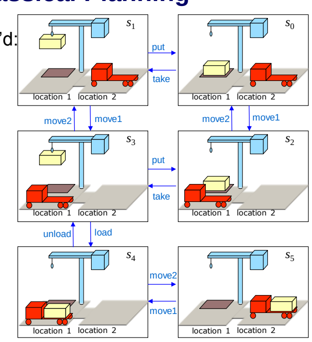
Variants of these exist for particular planners (e.g., SAT solvers, model checkers, etc.)

Outline

- Representation schemes for classical planning
  1. Classical representation
  2. Set-theoretic representation
  3. State-variable representation
- Examples: DWR and the Blocks World
- Comparisons

Quick Review of Classical Planning

8 restrictive assumptions req'd:
- A0: Finite
- A1: Fully observable
- A2: Deterministic
- A3: Static
- A4: Attainment goals
- A5: Sequential plans
- A6: Implicit time
- A7: Offline planning



Representation: Motivation for Approach

Default view:
- represent state explicitly
- represent actions as a transition system (e.g., as an incidence matrix)

Problem:
- explicit graph corresponding to transition system is huge
- direct manipulation of transition system is cumbersome

Solution:

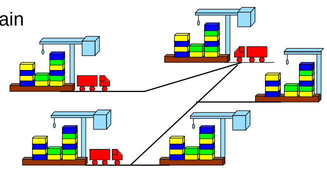
Provide **compact representation** of transition system & induced graph
1. Explicate the structure of the "states"
   - e.g., states specified in terms of state variables
2. Represent actions not as transition system/incidence matrices but as functions (e.g., operators) specified in terms of the state variables
   - An action is applicable to a state when some state variables have certain values. When applicable, it will change the values of certain (other) state variables
3. To plan,
   - Just give the initial state
   - Use the operators to generate the other states as needed

Why is this more compact?

Why is this more compact than an explicit transition system?
- In an explicit transition system, actions are represented as state-to-state transitions. Each action will be represented by an incidence matrix of size |S|x|S|
- In the proposed model, actions are represented only in terms of state variables whose values they care about, and whose value they affect. *(It exploits the structure of the problem!)*
- Consider a state space of 1024 states. It can be represented by $\log_2 1024$=10 state variables. If an action needs variable v1 to be true and makes v7 to be false, it can be represented by just 2 bits (instead of a 1024x1024 matrix)
  - Of course, if the action has a complicated mapping from states to states, in the worst case the action rep will be just as large
  - <u>The assumption being made here is that the actions will have effects on a small number of state variables.</u>

1. Classical Representation

- Start with a *function-free* first-order language
  - Finitely many predicate symbols and constant symbols, but *no* function symbols
- Example: the DWR domain
  - Locations: l1, l2, …
  - Containers: c1, c2, …
  - Piles: p1, p2, …
  - Robot carts: r1, r2, …
  - Cranes: k1, k2, …



Quick review of terminology

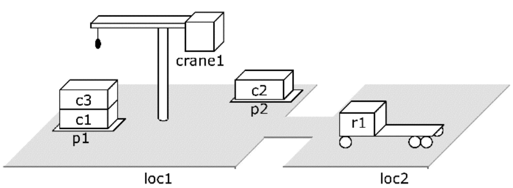
- **Atom:** predicate symbol and args
  - Use these to represent both fixed and dynamic (“fluent”) relations

adjacent(*l*,*l'*)	attached(*p*,*l*)	belong(*k*,*l*)
occupied(*l*)	at(*r*,*l*)	
loaded(*r*,*c*)	unloaded(*r*)	
holding(*k*,*c*)	empty(*k*)	
in(*c*,*p*)	on(*c*,*c'*)	
top(*c*,*p*)	top(pallet,*p*)	

- **Ground** expression: contains no variable symbols - e.g., in(c1,p3)
- **Unground** expression: at least one variable symbol - e.g., in(c1,*x*)
- **Substitution:** $\theta = \{x_1 \leftarrow t_1,\ x_2 \leftarrow t_2,\ \ldots,\ x_n \leftarrow t_n\}$
  - Each x_i is a variable symbol; each t_i is a term
- **Instance** of *e*: result of applying a substitution θ to *e*
  - Replace variables of *e* simultaneously, not sequentially

States

- **State:** a **set** *s* of ground atoms
  - The atoms represent the things that are **true** in one of Σ's states
  - Only finitely many ground atoms, so only finitely many possible states



{attached(p1,loc1), in(c1,p1), in(c3,p1), top(c3,p1), on(c3,c1), on(c1,pallet), attached(p2,loc1), in(c2,p2), top(c2,p2), on(c2,pallet), belong(crane1,loc1), empty(crane1), adjacent(loc1,loc2), adjacent(loc2,loc1), at(r1,loc2), occupied(loc2), unloaded(r1)}.

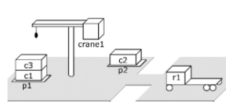
Operators

- **Operator:** a triple *o*=(name(*o*), precond(*o*), effects(*o*))
  - name(*o*) is a syntactic expression of the form $n(x_1,\ldots,x_k)$
    - *n*: *operator symbol* - must be unique for each operator
    - $x_1,\ldots,x_k$: variable symbols (parameters)
      - must include every variable symbol in *o*
  - precond(*o*): *preconditions*
    - literals that must be true in order to use the operator
  - effects(*o*): *effects*
    - literals the operator will make true

take(k, l, c, d, p)
;; crane k at location l takes c off of d in pile p
precond: belong(k,l), attached(p,l), empty(k), top(c,p), on(c,d)
effects: holding(k,c), $\neg$empty(k), $\neg$in(c,p), $\neg$top(c,p), $\neg$on(c,d), top(d,p)

Actions

- **Action:** ground instance (via substitution) of an operator



take(k, l, c, d, p)
;; crane k at location l takes c off of d in pile p
precond: belong(k,l), attached(p,l), empty(k), top(c,p), on(c,d)
effects: holding(k,c), $\neg$empty(k), $\neg$in(c,p), $\neg$top(c,p), $\neg$on(c,d), top(d,p)

take(crane1,loc1,c3,c1,p1)
;; crane crane1 at location loc1 takes c3 off c1 in pile p1
precond: belong(crane1,loc1), attached(p1,loc1), empty(crane1), top(c3,p1), on(c3,c1)
effects: holding(crane1,c3), ¬empty(crane1), ¬in(c3,p1), ¬top(c3,p1), ¬on(c3,c1), top(c1,p1)

Notation

- Let *a* be an operator or action. Then
  - precond$^+$(*a*) = {atoms that appear positively in *a*'s preconditions}
  - precond$^-$(*a*) = {atoms that appear negatively in *a*'s preconditions}
  - effects$^+$(*a*) = {atoms that appear positively in *a*'s effects}
  - effects$^-$(*a*) = {atoms that appear negatively in *a*'s effects}

E.g.,

take(k, l, c, d, p)
;; crane k at location l takes c off of d in pile p
precond: belong(k,l), attached(p,l), empty(k), top(c,p), on(c,d)
effects: holding(k,c), $\neg$empty(k), $\neg$in(c,p), $\neg$top(c,p), $\neg$on(c,d), top(d,p)

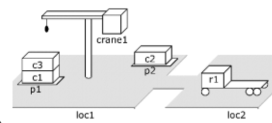
- effects$^+$(take(*k*,*l*,*c*,*d*,*p*) = {holding(*k*,*c*), top(*d*,*p*)}
- effects$^-$(take(*k*,*l*,*c*,*d*,*p*) = {empty(*k*), in(*c*,*p*), top(*c*,*p*), on(*c*,*d*)}

Aside: Some things to note

- The state only explicitly represents what is **true**. The semantics of this representation is that any fluent not included in the state is **false** – just like a database. *(Recall that one of the assumptions of classical planning is complete initial (and subsequent) state. The problem would be a lot harder w/o this assumption!!)*
- **Terminology:** an action is a ground operator. In the Knowledge Representation (KR) literature the concept of an "operator" is not used. Actions may be ground or unground.
- Classical planners generally operate over ground actions.

Applicability

- An action *a* is ***applicable*** to a state *s* if *s* satisfies precond(*a*),
  - i.e., if $\text{precond}^+(a) \subseteq s$ and $\text{precond}^-(a) \cap s = \varnothing$
- Here are an action and a state that it's applicable to:



take(crane1,loc1,c3,c1,p1)
;; crane crane1 at location loc1 takes c3 off c1 in pile p1
precond: belong(crane1,loc1), attached(p1,loc1), empty(crane1), top(c3,p1), on(c3,c1)
effects: holding(crane1,c3), ¬empty(crane1), ¬in(c3,p1), ¬top(c3,p1), ¬on(c3,c1), top(c1,p1)

Result of Performing an Action

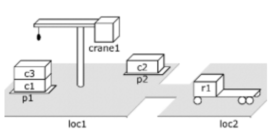
- If *a* is applicable to *s*, the **result of performing** it is

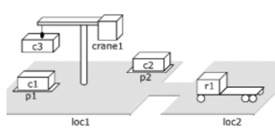
$$\gamma(s,a) = (s - \text{effects}^-(a)) \cup \text{effects}^+(a)$$

Set of things that are true. (if not in set then false)

  - Delete negative effects, and add positive ones

take(crane1,loc1,c3,c1,p1)
;; crane crane1 at location loc1 takes c3 off c1 in pile p1
precond: belong(crane1,loc1), attached(p1,loc1), empty(crane1), top(c3,p1), on(c3,c1)
effects: holding(crane1,c3), ¬empty(crane1), ¬in(c3,p1), ¬top(c3,p1), ¬on(c3,c1), top(c1,p1)





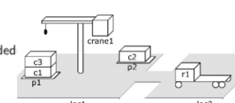
Operators for the DWR Domain

- Planning domain: language & operators
- Operators corresponds to a set of state-transition systems

$\text{move}(r,l,m)$
;; robot r moves from location l to location m
precond: adjacent(l,m), at(r,l), ¬occupied(m)
effects: at(r,m), occupied(m), ¬occupied(l), ¬at(r,l)

$\text{load}(k,l,c,r)$
;; crane k at location l loads container c onto robot r
precond: belong(k,l), holding(k,c), at(r,l), unloaded(r)
effects: empty(k), ¬holding(k,c), loaded(r,c), ¬unloaded(r)

$\text{unload}(k,l,c,r)$
;; crane k at location l takes container c from robot r
precond: belong(k,l), at(r,l), loaded(r,c), empty(k)
effects: ¬empty(k), holding(k,c), unloaded(r), ¬loaded



$\text{put}(k,l,c,d,p)$
;; crane k at location l puts c onto d in pile p
precond: belong(k,l), attached(p,l), holding(k,c), top(d,p)
effects: ¬holding(k,c), empty(k), in(c,p), top(c,p), on(c,d), ¬top(d,p)

$\text{take}(k,l,c,d,p)$
;; crane k at location l takes c off of d in pile p
precond: belong(k,l), attached(p,l), empty(k), top(c,p), on(c,d)
effects: holding(k,c), ¬empty(k), ¬in(c,p), ¬top(c,p), ¬on(c,d), top(d,p)

Planning Problems

Given a planning domain (language *L*, operators *O*)

- ***Encoding*** of a planning problem: a triple $P=(O,s_0,g)$
  - *O* is the collection of operators
  - s_0 is a state (the initial state)
  - *g* is a set of literals (the goal formula)
- The ***actual planning problem***: $\mathcal{P} = (\Sigma, s_0, g)$
  - s_0 and *g* are as above
  - $\Sigma = (S,A,\gamma)$ is a state-transition system
  - *S* = {all sets of ground atoms in *L*}
  - *A* = {all ground instances of operators in *O*}
  - γ = state-transition function determined by the operators

Plans and Solutions

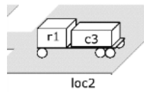
- **Plan*:** any sequence of actions $\sigma = \langle a_1, a_2, \ldots, a_n \rangle$ such that each a_i is a ground instance of an operator in *O*
- The plan is a ***solution*** for $P=(O,s_0,g)$ if it is executable and achieves *g*
  - i.e., if there are states $s_0, s_1, \ldots, s_n$ such that
    - $\gamma(s_0,a_1) = s_1$
    - $\gamma(s_1,a_2) = s_2$
    - …
    - $\gamma(s_{n-1},a_n) = s_n$
    - s_n satisfies *g*

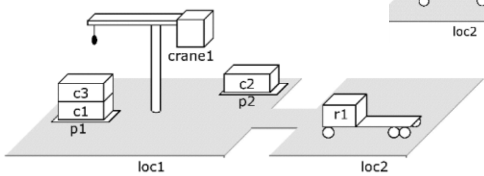
* *Recall that we are restricting our attention to "Classical Planning"*

Example

- Let $P_1 = (O, s_1, g_1)$, where
  - O is the set of operators given earlier

g_1 = {loaded(r1,c3), at(r1,loc2)}



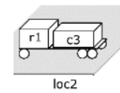


s_1={attached(p1,loc1), in(c1,p1), in(c3,p1), top(c3,p1), on(c3,c1), on(c1,pallet), attached(p2,loc1), in(c2,p2), top(c2,p2), on(c2,pallet), belong(crane1,loc1), empty(crane1), adjacent(loc1,loc2), adjacent(loc2,loc1), at(r1,loc2), occupied(loc2), unloaded(r1)}.

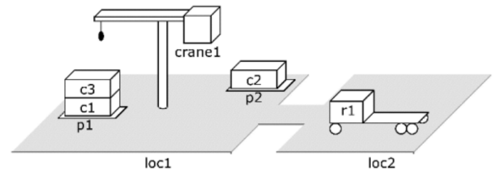
Example

GOAL STATE:

g_1 = {loaded(r1,c3),at(r1,loc2)}

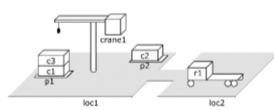


INITIAL STATE:

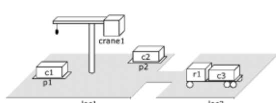


The DWR state s_1={attached(p1,loc1), in(c1,p1), in(c3,p1), top(c3,p1), on(c3,c1), on(c1,pallet), attached(p2,loc1), in(c2,p2), top(c2,p2), on(c2,pallet), belong(crane1,loc1), empty(crane1), adjacent(loc1,loc2), adjacent(loc2,loc1), at(r1,loc2), occupied(loc2), unloaded(r1)}.

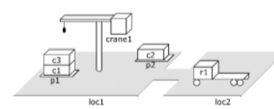
Example (cont.)



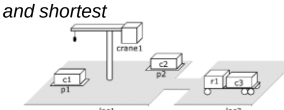
- Here are three solutions for P_1:
  - ⟨take(crane1,loc1,c3,c1,p1), move(r1,loc2,loc1), move(r1,loc1,loc2), move(r1,loc2,loc1), load(crane1,loc1,c3,r1), move(r1,loc1,loc2)⟩
  - ⟨take(crane1,loc1,c3,c1,p1), move(r1,loc2,loc1), load(crane1,loc1,c3,r1), move(r1,loc1,loc2)⟩
  - ⟨move(r1,loc2,loc1), take(crane1,loc1,c3,c1,p1), load(crane1,loc1,c3,r1), move(r1,loc1,loc2)⟩
- Each produces:



Example (cont.)

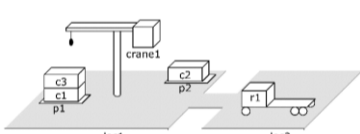


- First is *redundant*: can remove actions and still have a solution
  1. ⟨take(crane1,loc1,c3,c1,p1), move(r1,loc2,loc1), move(r1,loc1,loc2), move(r1,loc2,loc1), load(crane1,loc1,c3,r1), move(r1,loc1,loc2)⟩
  2. ⟨take(crane1,loc1,c3,c1,p1), move(r1,loc2,loc1), load(crane1,loc1,c3,r1), move(r1,loc1,loc2)⟩
  3. ⟨move(r1,loc2,loc1), take(crane1,loc1,c3,c1,p1), load(crane1,loc1,c3,r1), move(r1,loc1,loc2)⟩
- 2nd and 3rd are *irredundant and shortest*



2. Set-Theoretic Representation

Like classical rep'n, but restricted to **propositional logic.**



- States:
  - Instead of a collection of ground atoms …

    {on(c1,pallet), on(c1,r1), on(c1,c2), …, at(r1,l1), at(r1,l2), …}

  … use a collection of propositions (boolean variables):

    {on-c1-pallet, on-c1-r1, on-c1-c2, …, at-r1-l1, at-r1-l2, …}

Instead of operators like this one,

take(k, l, c, d, p)
;; crane k at location l takes c off of d in pile p
precond: belong(k, l), attached(p, l), empty(k), top(c, p), on(c, d)
effects: holding(k, c), $\neg$ empty(k), $\neg$ in(c, p), $\neg$ top(c, p), $\neg$ on(c, d), top(d, p)

Take all of the operator **instances**, E.g.:

take(crane1,loc1,c3,c1,p1)
;; crane crane1 at location loc1 takes c3 off c1 in pile p1
precond: belong(crane1,loc1), attached(p1,loc1), empty(crane1), top(c3,p1), on(c3,c1)
effects: holding(crane1,c3), ¬empty(crane1), ¬in(c3,p1), ¬top(c3,p1), ¬on(c3,c1), top(c1,p1)

And rewrite ground atoms as **propositions**, E.g.:

take-crane1-loc1-c3-c1-p1
precond: belong-crane1-loc1, attached-p1-loc1,empty-crane1, top-c3-p1, on-c3-c1
delete: empty-crane1, in-c3-p1, top-c3-p1, on-c3-p1
add: holding-crane1-c3, top-c1-p1

Comparison

A set-theoretic representation is equivalent to a classical representation in which all of the atoms are ground

Problem: Exponential blowup

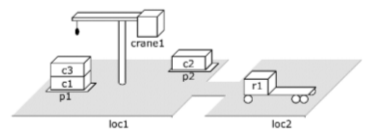
- If a classical operator contains n atoms and each atom has arity k, then it corresponds to c^{nk} actions where c = |{constant symbols}|

3. State-Variable Representation (aka FDR)

- Non-fluents (properties that don't change) are ground relations:
  - e.g., adjacent(loc1,loc2)
- Fluents are functions:
  i.e., for properties that can change, assign values to *state variables*
- Classical and state-variable rep'ns take similar amounts of space
  each can be translated into the other in low-order polynomial time

move(r, l, m)
;; robot r at location l moves to an adjacent location m
precond: rloc(r) $= l$, adjacent(l, m)
effects: rloc(r) $\leftarrow m$

{top(p1)=c3,
cpos(c3)=c1,
cpos(c1)=pallet,
holding(crane1)=nil,
rloc(r1)=loc2,
loaded(r1)=nil, ...}



State-Variable Representation (cont.)

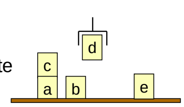
- Captures further information about the state. E.g., that state variables can only take on one of the values in the domain. This helps reduce the search space.
- Basis for the SAS and SAS+ formalisms (used most recently in the FastDownward Planner (FD) and its descendents (e.g., LAMA, etc)
- Basis for encodings further plan properties such as domain transition graphs (DTGs) and causal graphs (CG)

Example: The Blocks World (Review on your own)

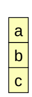
Example: The Blocks World

- Infinitely wide table, finite number of children's blocks
- Ignore where a block is located on the table
- A block can sit on the table or on another block
- Want to move blocks from one configuration to another
  - e.g.,

initial state



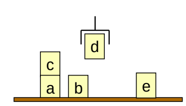
goal



- Classical, set-theoretic, and state-variable formulations for the case of FIVE BLOCKS follow.

1. Example Classical Representation

- Constant symbols:
  - The blocks: a, b, c, d, e
- Predicates:
  - ontable(x) - block x is on the table
  - on(x,y) - block x is on block y
  - clear(x) - block x has nothing on it
  - holding(x) - the robot hand is holding block x
  - handempty - the robot hand isn't holding anything



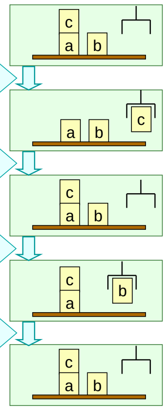
Classical Operators

unstack(x,y)
Precond: on(x,y), clear(x), handempty
Effects: ~on(x,y), ~clear(x), ~handempty, holding(x), clear(y)

stack(x,y)
Precond: holding(x), clear(y)
Effects: ~holding(x), ~clear(y), on(x,y), clear(x), handempty

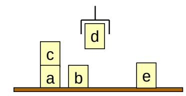
pickup(x)
Precond: ontable(x), clear(x), handempty
Effects: ~ontable(x), ~clear(x), ~handempty, holding(x)

putdown(x)
Precond: holding(x)
Effects: ~holding(x), ontable(x), clear(x), handempty



2. Example Set-Theoretic Representation

For five blocks, **36 propositions, 50 actions**



E.g.,

ontable-a	- block a is on the table
on-c-a	- block c is on block a
clear-c	- block c has nothing on it
holding-d	- the robot hand is holding block d
handempty	- the robot hand isn't holding anything
… (31 more)	

Set-Theoretic Actions

E.g.,

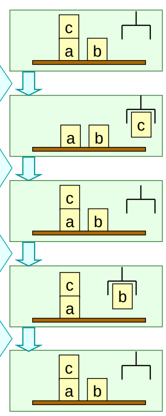
unstack-c-a
Pre: on-c,a, clear-c, handempty
Del: on-c,a, clear-c, handempty
Add: holding-c, clear-a

stack-c-a
Pre: holding-c, clear-a
Del: holding-c, clear-a
Add: on-c-a, clear-c, handempty

pickup-c
Pre: ontable-c, clear-c, handempty
Del: ontable-c, clear-c, handempty
Add: holding-c

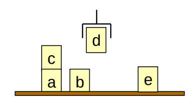
putdown-c
Pre: holding-c
Del: holding-c
Add: ontable-c, clear-c, handempty

. . . (46 more)



3. Example State-Variable Representation

- Constant symbols:
  - a, b, c, d, e of type block
  - 0, 1, table, nil of type other
- State variables:
  - pos(x) = y if block x is on block y
  - pos(x) = table if block x is on the table
  - pos(x) = nil if block x is being held
  - clear(x) = 1 if block x has nothing on it
  - clear(x) = 0 if block x is being held or has a block on it
  - holding = x if the robot hand is holding block x
  - holding = nil if the robot hand is holding nothing



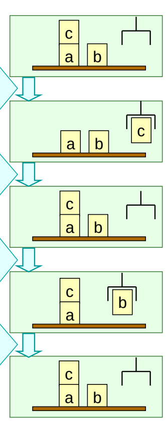
State-Variable Operators

unstack(x : block, y : block)
Precond: pos(x)=y, clear(y)=0, clear(x)=1, holding=nil
Effects: pos(x)=nil, clear(x)=0, holding=x, clear(y)=1

stack(x : block, y : block)
Precond: holding=x, clear(x)=0, clear(y)=1
Effects: holding=nil, clear(y)=0, pos(x)=y, clear(x)=1

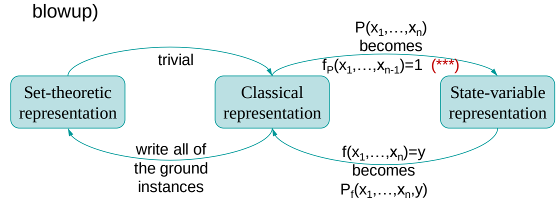
pickup(x : block)
Precond: pos(x)=table, clear(x)=1, holding=nil
Effects: pos(x)=nil, clear(x)=0, holding=x

putdown(x : block)
Precond: holding=x
Effects: holding=nil, pos(x)=table, clear(x)=1



Representational Equivalence

- Any problem that can be represented in one representation can also be represented in the other two
- Can convert in linear time and space, except when converting to set-theoretic (where we get an exponential blowup)



(***) trivially, or there can be a more parsimonious problem-specific encoding that ignores irrelevant variables

Comparison

- Classical representation
  - Most popular for classical planning, basis of PDDL
- Set-theoretic representation
  - Can take much more space than classical representation
  - Useful in algorithms that manipulate ground atoms directly
    - e.g., planning graphs, SAT
  - Useful for certain kinds of theoretical studies
- State-variable representation (e.g., SAS, SAS+,"FDR")
  - Equivalent to classical representation in expressive power
  - Arguably less natural to conceive
  - Clever problem-specific encodings can be much more compact and embed critical info (e.g., one-of constraints)
  - Leveraged in many of the state-of-the-art heuristic search classical planners (e.g., FD, LAMA, etc)
  - Useful in non-classical planning problems as a way to handle numbers, functions, time

Extending Expressivity: ADL*

- Previous representations were so-called "STRIPS" rep'ns. These have useful properties for automatically generating classical plans, but are not always sufficient to express the behaviour of more complex domains.
- ADL is a richer, and thus more compact, representation language that allows for
  - Disjunction and Quantification in *preconditions* and *goals*
  - *Effects* that are Quantified, and/or Conditional (effect is conditioned on state)
- PDDL supports STRIPS and ADL, but not all planners support ADL, and not all planners even support a so-called Classical Representation
- In the KR community ADL or greater is common.

* ADL = "Action Description Language", [Pednault, KR89]

Pros/Cons: Compiling to Canonical Action Rep'n

Possible to compile down ADL actions into STRIPS actions

- Quantification -> conjunctions/disjunctions over finite universes
- Actions with conditional effects -> multiple (exponentially more) actions without conditional effects
- Actions with disjunctive effects -> multiple actions, each of which take one of the disjuncts as their preconditions (*called "determinization")*
- Domain axioms (ramifications) -> the individual effects of the actions; so all actions satisfy STRIPS assumption

Compilation is not always a win-win.

- By compiling down to canonical form, we can concentrate on highly efficient planning for canonical actions
  - However, often compilation leads to an exponential blowup and makes it harder to exploit the structure of the domain
- By leaving actions in non-canonical form, we can often do more compact encoding of the domains <u>as well as more efficient search</u>
  - However, we will have to continually extend planning algorithms to handle these representations