

# CS 4649/7649: RIP - Robot Intelligence - Planning

## PROJECT 1: CLASSICAL SOKOBAN PLANNER

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### 1 Pre-Project: Towers of Hanoi

#### Planners Used

The two classical planners which we are using for the Towers of Hanoi problem are the Blackbox planner [1] (downloaded from <http://www.cs.rochester.edu/~kautz/satplan/blackbox/blackbox-download.html>) and the FF planner [2] (downloaded from <http://fai.cs.uni-saarland.de/hoffmann/ff/FF-v2.3.tgz>). The definition of the Towers of Hanoi domain, as well as the representation of the initial state of the problem (from Figure 1) are in the corresponding PDDL files, namely *hanoi-domain.pddl* and *hanoi-3.pddl*.



Figure 1: Towers of Hanoi with 3 disks

#### 1.1 Questions

##### 1. Explain the method by which each of the two planners finds a solution

**BlackBox-** The Blackbox planning algorithm essentially represents the PDDL representation of a problem as a set of Boolean satisfiability problems (SAT), which are then solved using a variety of SAT solvers (such as satz, walksat and chaff) to produce a plan. In order to construct the SAT problem, Blackbox uses the GRAPHPLAN algorithm to construct a plan graph for the given problem representation. This plan graph is then “translated” to the SAT problem representation. This is outlined briefly below:

The GRAPHPLAN algorithm works by constructing a planning graph out of a STRIPS representation, which will propagate actions/operators across different “layers” along with their “mutex” pre-conditions. So at every stage there will be a list of actions, which have mutually exclusive pre-conditions. The plan generated by GRAPHPLAN will be a sub-graph of the plan graph such that, all the conditions of the initial and final state are incorporated without there being any “conflicting” actions. As described by Kautz et. al [3], each state in this solution graph can be encoded into propositional logic. This can be done by adding propositions of the form,

$$Precondition_i \implies Action_j$$

At each layer of the solution sub-graph, clauses/fluents can be resolved away to result in a compact propositional logic representation of the plan graph. This list of proposition corresponds to the “translation” of the plan graph into a SAT problem. Then any available SAT solver can be applied on this problem which (although NP-complete in theory) with reasonable assumptions be completed in exponential time. ( $O(n^3)$ )

**FF Planner** - The fast-forward planning algorithm utilizes GRAPHPLAN as an admissible (and informed) heuristic to solve the planning problem using a search algorithm across the set of permissible states in the state space. FF planner works as follows: it sets up a relaxed solvable sub-problem ( $S'$ ) of the original

problem ( $S$ ). Then GRAPHPLAN is applied on the relaxed sub-problem; the length of the solution plan sub-graph is then treated as a heuristic to guide the state space search algorithm for a plan to the original problem. This takes into account the positive interactions between various facts in the problem.

FF uses the enforced hill climbing algorithm to search for valid solutions. Using the length of the relaxed GRAPHPLAN solution as a heuristic, the enforced hill climbing algorithm evaluates the direct successors of a search state  $S$ . Until a state ( $S'$ ) is found with a better heuristic evaluation than  $S$ , the search goes one step further.

Thus in summary both **FF** and **Blackbox** algorithms use the GRAPHPLAN algorithm, however **Blackbox** uses it in a more direct way, to set up the SAT problem. In **FF**, GRAPHPLAN is used simply as a heuristic measure for the enforced hill climbing algorithm. Both the planners generated the same plan, which is in Figure 2.

```

step      0: MOVE-DISK D1 D2 P1
          1: MOVE-DISK D2 D3 P2
          2: MOVE-DISK D1 P1 D2
          3: MOVE-DISK D3 P3 P1
          4: MOVE-DISK D1 D2 P3
          5: MOVE-DISK D2 P2 D3
          6: MOVE-DISK D1 P3 D2

time spent: 0.00 seconds instantiating 48 easy, 0 hard action templates
           0.00 seconds reachability analysis, yielding 18 facts and 38 actions
           0.00 seconds creating final representation with 17 relevant facts
           0.00 seconds building connectivity graph
           0.00 seconds searching, evaluating 21 states, to a max depth of 1
           0.00 seconds total time

```

Figure 2: Plan for Towers of Hanoi with 3 disks

## 2. Which planner was fastest?

Both the algorithms were run on the same Linux box, and using the *time* command the time taken for them to produce plans were measure. Clearly the **FF** algorithm was the fastest among the two, with the following time measures

- FF - 0.004s
- Blackbox - 0.011s

This shows that **FF** is 2.75 times faster than **Blackbox**. This is pretty much expected from theory since the time complexity for each of the algorithms are,

$$\begin{aligned}
 O(\text{Blackbox}) &= O(\text{GRAPHPLAN}') + O(\text{SAT Solver}) \\
 O(\text{FF}) &= O(\text{GRAPHPLAN}) + O(\text{Enforced Hill Climbing}) \\
 O(\text{Enforced Hill Climbing}) &= O(\text{iterations} \times \text{successors}), \\
 O(\text{SAT Solver}) &= O(2^n)
 \end{aligned}$$

Clearly the SAT solver's exponential time complexity, as well as the time complexity of the complete GRAPHPLAN algorithm for **Blackbox** vs. that of the relaxed GRAPHPLAN as well as that of *Enforced Hill Climbing* for the **FF** make it obviously slower than FF; this has been shown by using the towers of hanoi state and domain PDDL description multiple times (to get an average measure) with Blackbox and FF.

## 3. Explain why the winning planner might be more effective on this problem

Its pretty obvious that the length of a plan in case of the Towers of Hanoi problem are a similar order of magnitude as that of the total number of states ( $2^n - 1$  steps and  $3^n$  states). In case of the **FF** planner,

GRAPHPLAN is used only as a heuristic and that too for a relaxed subset. *FF*'s major component is the local-search algorithm, which means it does not have to necessarily traverse all the states in order to obtain a solution.

*Blackbox* on the other needs to explicitly construct the mutex graph for every level until a solution is obtained. In case the state space is large (like 10 disks in the Towers of Hanoi problem), the construction of a complete plan graph is memory prohibitive and will not be effective on larger instances of this problem (it actually does not give plans for even 6 disks on my machine after 1 minute of execution). Another major issue with *Blackbox* is that several levels of the GRAPHPLAN algorithm may lead to the same set of SAT problems, which will remain unsatisfiable. *Blackbox* is bound to be less effective in similar large state problems, since it seems to perform the same computation multiple times.

## 2 Project Part I: Sokoban PDDL

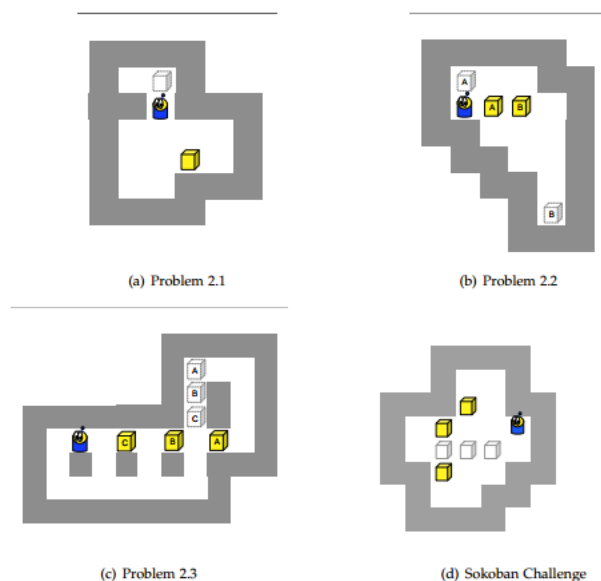


Figure 3: Sokoban Problems

**Note:** We have made the assumption that the *planner can move any box to any target square*. This assumption is carried over to Part II as well.

The Sokoban's domain definition was created with the guideline idea of keeping it simple. Then, we followed the steps:

1. Identify the constants
2. Identify the fluents
3. Identify the actions

The first step is to identify the constants we evaluate possible elements that could be part of the domain. From this, constants like *robot*, *box* and *location* appeared. However the problem only have one robot and is more natural to think about each box by its location instead of any kind of specific identification. Because of this, we moved on with only the *location* constant.

The second step is to identify fluents related to this problem. We had a lot of possible fluents, most of them were related to the idea of using the constants already eliminated. However, to keep it simple, the fluents used were:

- **in(?loc)** - true if the robot is at location loc;
- **boxAt(?loc)** - true if there is a box at location loc;
- **isLeft(?loc ?loc)** - true if loc(1) is at left of loc(2);
- **isRight(?loc ?loc)** - true if loc(1) is at right of loc(2);
- **isUp(?loc ?loc)** - true if loc(1) is at up of loc(2);
- **isDown(?loc ?loc)** - true if loc(1) is at down of loc(2).

Finally, the last step is to identify the actions. For the Sokoban domain, the robot can move or push a box in the up, down, right and left directions, provided that there is no box on the way. After defining each action in respect to its preconditions, add list and delete list we could define the following:

- **MOVE-<UP,DOWN,RIGHT or LEFT>( ?loc-to ?loc-from);**
- **PUSH-<UP,DOWN,RIGHT or LEFT>( ?box-loc ?loc ?loc-to).**

Done that, the next part of the question was to define each problem using this domain. For that, each grid position, from top to bottom, and left to right, received a nickname of a alphabet letter. Then, all the constraints of linking these grid positions were defined using the fluent *isUp*, *isDown*, *isRight*, *isLeft* and the initial and goal state using the fluents *in* and *boxAt*.

## 2.1 Questions

**1. Show successful plans from at least one planner on the three Sokoban problems in Figure 3 (1-3). The challenge problem is optional**

Using the PDDL definitions for the domain, the FF planner was able to find solutions for all the problems and to the challenge. The result plan of each problem is shown on the Figures 4, 5, 6 and 7.

```
ff: found legal plan as follows

step    0: MOVE-DOWN LOCATIONE LOCATIONC
         1: MOVE-RIGHT LOCATIONF LOCATIONE
         2: MOVE-RIGHT LOCATIONG LOCATIONF
         3: MOVE-DOWN LOCATIONK LOCATIONG
         4: PUSH-LEFT LOCATIONJ LOCATIONK LOCATIONI
         5: MOVE-UP LOCATIONF LOCATIONJ
         6: MOVE-LEFT LOCATIONE LOCATIONF
         7: MOVE-LEFT LOCATIOND LOCATIONE
         8: MOVE-DOWN LOCATIONH LOCATIOND
         9: MOVE-DOWN LOCATIONL LOCATIONH
        10: MOVE-RIGHT LOCATIONM LOCATIONL
        11: PUSH-UP LOCATIONI LOCATIONM LOCATIONE
        12: PUSH-UP LOCATIONE LOCATIONI LOCATIONC
        13: PUSH-UP LOCATIONC LOCATIONE LOCATIONB

time spent:  0.00 seconds instantiating 48 easy, 0 hard action templates
            0.00 seconds reachability analysis, yielding 38 facts and 48 actions
            0.00 seconds creating final representation with 37 relevant facts
            0.00 seconds building connectivity graph
            0.00 seconds searching, evaluating 47 states, to a max depth of 4
            0.00 seconds total time
```

Figure 4: Sokoban Problem 2.1

In order to make the solutions more readable and easier to verify, let's consider that when a robot moves for up, down, right or left direction it will be represented by a lowercase **u**, **d**, **r** or **l**, respectively. For the push actions of moving the box up, down, right or left, the capital letters **U**, **D**, **R** and **L** will be used. Thus, the solutions found can be represented as the strings shown below.

```

ff: found legal plan as follows

step    0: MOVE-UP LOCATIONA LOCATIOND
        1: MOVE-RIGHT LOCATIONB LOCATIONA
        2: MOVE-RIGHT LOCATIONC LOCATIONB
        3: PUSH-DOWN LOCATIONF LOCATIONC LOCATIONL
        4: MOVE-UP LOCATIONC LOCATIONF
        5: MOVE-LEFT LOCATIONB LOCATIONC
        6: MOVE-LEFT LOCATIONA LOCATIONB
        7: MOVE-DOWN LOCATIOND LOCATIONA
        8: PUSH-RIGHT LOCATIONE LOCATIOND LOCATIONF
        9: MOVE-DOWN LOCATIONK LOCATIONE
       10: PUSH-RIGHT LOCATIONL LOCATIONK LOCATIONM
       11: MOVE-LEFT LOCATIONK LOCATIONL
       12: MOVE-UP LOCATIONE LOCATIONK
       13: MOVE-UP LOCATIONB LOCATIONE
       14: MOVE-RIGHT LOCATIONC LOCATIONB
       15: PUSH-DOWN LOCATIONF LOCATIONC LOCATIONL
       16: MOVE-RIGHT LOCATIONG LOCATIONF
       17: PUSH-DOWN LOCATIONM LOCATIONG LOCATIONO
       18: PUSH-DOWN LOCATIONO LOCATIONM LOCATIONP
       19: PUSH-DOWN LOCATIONP LOCATIONO LOCATIONQ
       20: MOVE-UP LOCATIONO LOCATIONP
       21: MOVE-LEFT LOCATIONN LOCATIONO
       22: PUSH-UP LOCATIONL LOCATIONN LOCATIONF
       23: MOVE-RIGHT LOCATIONM LOCATIONL
       24: MOVE-UP LOCATIONG LOCATIONM
       25: PUSH-LEFT LOCATIONF LOCATIONG LOCATIONE
       26: MOVE-DOWN LOCATIONL LOCATIONF
       27: MOVE-LEFT LOCATIONK LOCATIONL
       28: PUSH-UP LOCATIONE LOCATIONK LOCATIONB
       29: MOVE-RIGHT LOCATIONF LOCATIONE
       30: MOVE-UP LOCATIONC LOCATIONF
       31: PUSH-LEFT LOCATIONB LOCATIONC LOCATIONA

time spent:  0.00 seconds instantiating 56 easy, 0 hard action templates
            0.00 seconds reachability analysis, yielding 45 facts and 56 actions
            0.00 seconds creating final representation with 42 relevant facts
            0.00 seconds building connectivity graph
            0.00 seconds searching, evaluating 135 states, to a max depth of 22
            0.00 seconds total time

```

Figure 5: Sokoban Problem 2.2

**Problem 2.1** drrdLullddrUUU

**Problem 2.2** urrDulldRdRluurDrDDDuUruLdlUru

**Problem 2.3** rddrruuLLrrddrruuLLrruuurdddLLddlluRlddrruUllddllu  
RRddrruuUUdddlluRlddrruUllddlluRRRRddrruuuddd  
lluRlddrruU

**Challenge** lldlluRRdddUruulldRrruruLLrddlluRuruulDDDlluRdrUrrd  
LdLdlUrruulDRddlUruuruulDD

**2. Compare the performance of two planners on this domain. Which one works better? Does this make sense, why?**

As an overview, the *FF*'s planner performed better than *Blackbox*. The *FF*'s planner was able to find results for all problems, including challenge, in few seconds. On the other hand, the *Blackbox* only managed to find the results from the first two problems and stopped on the others after using all the hardware resources. These results were expected since, as stated in Section 1.1, the *FF*'s planner have a lower asymptotic complexity and use an heuristic function to choose the best option of what expand next. Thus, is more likely to have better time and space complexities than the *Blackbox*.

```

ff: found legal plan as follows

step  0: MOVE-RIGHT LOCATIONJ LOCATIONI
      1: MOVE-DOWN LOCATIONR LOCATIONJ
      2: MOVE-DOWN LOCATIONW LOCATIONR
      3: MOVE-RIGHT LOCATIONX LOCATIONW
      4: MOVE-RIGHT LOCATIONY LOCATIONX
      5: MOVE-UP LOCATIONS LOCATIONY
      6: MOVE-UP LOCATIONL LOCATIONS
      7: PUSH-LEFT LOCATIONK LOCATIONL LOCATIONJ
      8: PUSH-LEFT LOCATIONJ LOCATIONK LOCATIONI
      9: MOVE-RIGHT LOCATIONK LOCATIONJ
     10: MOVE-RIGHT LOCATIONL LOCATIONK
     11: MOVE-DOWN LOCATIONS LOCATIONL
     12: MOVE-DOWN LOCATIONY LOCATIONS
     13: MOVE-RIGHT LOCATIONZ LOCATIONY
     14: MOVE-RIGHT LOCATIONA1 LOCATIONZ
     15: MOVE-UP LOCATIONT LOCATIONA1
     16: MOVE-UP LOCATIONN LOCATIONT
     17: PUSH-LEFT LOCATIONN LOCATIONNN LOCATIONL
     18: PUSH-LEFT LOCATIONL LOCATIONNN LOCATIONK
     19: MOVE-RIGHT LOCATIONNN LOCATIONL
    20: MOVE-RIGHT LOCATIONN LOCATIONM
    21: MOVE-UP LOCATIONF LOCATIONN
    22: MOVE-UP LOCATIOND LOCATIONF
    23: MOVE-UP LOCATIONA LOCATIOND
    24: MOVE-RIGHT LOCATIONB LOCATIONA
    25: MOVE-RIGHT LOCATIONC LOCATIONB
    26: MOVE-DOWN LOCATIONE LOCATIONC
    27: MOVE-DOWN LOCATIONG LOCATIONE
    28: MOVE-DOWN LOCATIONP LOCATIONG
    29: PUSH-LEFT LOCATIONO LOCATIONP LOCATIONN
    30: PUSH-LEFT LOCATIONNN LOCATIONO LOCATIONM
    31: MOVE-DOWN LOCATIONT LOCATIONNN
    32: MOVE-DOWN LOCATIONA1 LOCATIONT
    33: MOVE-LEFT LOCATIONZ LOCATIONA1
    34: MOVE-LEFT LOCATIONY LOCATIONZ
    35: MOVE-UP LOCATIONS LOCATIONY
    36: MOVE-UP LOCATIONL LOCATIONS
    37: PUSH-RIGHT LOCATIONN LOCATIONL LOCATIONNN
    38: MOVE-LEFT LOCATIONL LOCATIONM

      81: MOVE-LEFT LOCATIONK LOCATIONL
      82: MOVE-LEFT LOCATIONJ LOCATIONK
      83: MOVE-DOWN LOCATIONJ LOCATIONJ
      84: MOVE-DOWN LOCATIONW LOCATIONR
      85: MOVE-LEFT LOCATIONV LOCATIONW
      86: MOVE-LEFT LOCATIONU LOCATIONV
      87: MOVE-UP LOCATIONQ LOCATIONU
      88: MOVE-UP LOCATIONH LOCATIONQ
      89: PUSH-RIGHT LOCATIONI LOCATIONH LOCATIONJ
      90: PUSH-RIGHT LOCATIONJ LOCATIONI LOCATIONK
      91: PUSH-RIGHT LOCATIONK LOCATIONJ LOCATIONL
      92: PUSH-RIGHT LOCATIONL LOCATIONK LOCATIONM
      93: MOVE-DOWN LOCATIONS LOCATIONL
      94: MOVE-DOWN LOCATIONY LOCATIONS
      95: MOVE-RIGHT LOCATIONZ LOCATIONY
      96: MOVE-RIGHT LOCATIONA1 LOCATIONZ
      97: MOVE-UP LOCATIONT LOCATIONA1
      98: MOVE-UP LOCATIONN LOCATIONT
      99: PUSH-UP LOCATIONF LOCATIONN LOCATIOND
     100: MOVE-DOWN LOCATIONNN LOCATIONF
     101: MOVE-DOWN LOCATIONT LOCATIONN
     102: MOVE-DOWN LOCATIONA1 LOCATIONT
     103: MOVE-LEFT LOCATIONZ LOCATIONA1
     104: MOVE-LEFT LOCATIONY LOCATIONZ
     105: MOVE-UP LOCATIONS LOCATIONY
     106: MOVE-UP LOCATIONL LOCATIONS
     107: PUSH-RIGHT LOCATIONN LOCATIONL LOCATIONNN
     108: MOVE-LEFT LOCATIONL LOCATIONM
     109: MOVE-DOWN LOCATIONS LOCATIONL
     110: MOVE-DOWN LOCATIONY LOCATIONS
     111: MOVE-RIGHT LOCATIONZ LOCATIONY
     112: MOVE-RIGHT LOCATIONA1 LOCATIONZ
     113: MOVE-UP LOCATIONT LOCATIONA1
     114: PUSH-UP LOCATIONN LOCATIONT LOCATIONF

39: MOVE-DOWN LOCATIONS LOCATIONL
40: MOVE-DOWN LOCATIONY LOCATIONS
41: MOVE-RIGHT LOCATIONZ LOCATIONY
42: MOVE-RIGHT LOCATIONA1 LOCATIONZ
43: MOVE-UP LOCATIONT LOCATIONA1
44: PUSH-UP LOCATIONN LOCATIONT LOCATIONF
45: MOVE-LEFT LOCATIONN LOCATIONM
46: MOVE-LEFT LOCATIONL LOCATIONM
47: MOVE-DOWN LOCATIONS LOCATIONL
48: MOVE-DOWN LOCATIONY LOCATIONS
49: MOVE-LEFT LOCATIONK LOCATIONY
50: MOVE-LEFT LOCATIONN LOCATIONX
51: MOVE-UP LOCATIONR LOCATIONW
52: MOVE-UP LOCATIONJ LOCATIONR
53: PUSH-RIGHT LOCATIONK LOCATIONJ LOCATIONL
54: PUSH-RIGHT LOCATIONL LOCATIONK LOCATIONM
55: MOVE-DOWN LOCATIONS LOCATIONL
56: MOVE-DOWN LOCATIONY LOCATIONS
57: MOVE-RIGHT LOCATIONZ LOCATIONY
58: MOVE-RIGHT LOCATIONA1 LOCATIONZ
59: MOVE-UP LOCATIONT LOCATIONA1
60: MOVE-UP LOCATIONN LOCATIONT
61: PUSH-UP LOCATIONF LOCATIONN LOCATIOND
62: PUSH-UP LOCATIOND LOCATIONF LOCATIONA
63: MOVE-DOWN LOCATIONF LOCATIOND
64: MOVE-DOWN LOCATIONN LOCATIONF
65: MOVE-DOWN LOCATIONT LOCATIONN
66: MOVE-DOWN LOCATIONA1 LOCATIONT
67: MOVE-LEFT LOCATIONZ LOCATIONA1
68: MOVE-LEFT LOCATIONY LOCATIONZ
69: MOVE-UP LOCATIONS LOCATIONY
70: MOVE-UP LOCATIONL LOCATIONS
71: PUSH-RIGHT LOCATIONM LOCATIONL LOCATIONN
72: MOVE-LEFT LOCATIONL LOCATIONM
73: MOVE-DOWN LOCATIONS LOCATIONL
74: MOVE-DOWN LOCATIONY LOCATIONS
75: MOVE-RIGHT LOCATIONZ LOCATIONY
76: MOVE-RIGHT LOCATIONA1 LOCATIONZ
77: MOVE-UP LOCATIONT LOCATIONA1
78: PUSH-UP LOCATIONN LOCATIONT LOCATIONF
79: MOVE-LEFT LOCATIONM LOCATIONN
80: MOVE-LEFT LOCATIONL LOCATIONM

time spent:  0.00 seconds instantiating 104 easy, 0 hard action templates
            0.00 seconds reachability analysis, yielding 68 facts and 82 actions
            0.00 seconds creating final representation with 55 relevant facts
            0.00 seconds building connectivity graph
            0.00 seconds searching, evaluating 2104 states, to a max depth of 9
            0.00 seconds total time

```

Figure 6: Sokoban Problem 2.3

### 3. Clearly PDDL was not intended for this sort of application. Discuss the challenges in expressing geometric constraints in semantic planning

While solving this problem is possible to notice that there are two approaches. The first one requires a previous knowledge of a solution, and the developer states that a specific box goes to a specific location. The second approach, there is no kind of identification for the boxes, and this is the one we used as a solution. Independently of the approach, the domain contains a grid on which the robot should move. Thus, it is necessary to come up with a way to express when the robot can, or cannot, move between two locations if there is a wall or a box in between. Also, it is necessary to express when the robot is allowed to do something, like moving between two empty adjacent squares. Thus, all these logic expressions were used to represent geometric constraints like collisions between the robot and the walls or boxes.

```

ff: found legal plan as follows

step  0: MOVE-LEFT LOCATIONH LOCATIONI
      1: MOVE-LEFT LOCATIONG LOCATIONH
      2: MOVE-DOWN LOCATIONL LOCATIONG
      3: MOVE-LEFT LOCATIONK LOCATIONL
      4: MOVE-LEFT LOCATIONJ LOCATIONK
      5: MOVE-UP LOCATIONE LOCATIONJ
      6: PUSH-RIGHT LOCATIONF LOCATIONE LOCATIONG
      7: PUSH-RIGHT LOCATIONG LOCATIONF LOCATIONH
      8: MOVE-DOWN LOCATIONL LOCATIONG
      9: MOVE-DOWN LOCATIONP LOCATIONL
     10: MOVE-DOWN LOCATIONS LOCATIONP
     11: MOVE-LEFT LOCATIONR LOCATIONS
     12: PUSH-UP LOCATIONO LOCATIONR LOCATIONK
     13: MOVE-RIGHT LOCATIONP LOCATIONO
     14: MOVE-UP LOCATIONL LOCATIONP
     15: MOVE-UP LOCATIONG LOCATIONL
     16: MOVE-LEFT LOCATIONF LOCATIONG
     17: MOVE-LEFT LOCATIONE LOCATIONF
     18: MOVE-DOWN LOCATIONJ LOCATIONE
     19: PUSH-RIGHT LOCATIONK LOCATIONJ LOCATIONL
     20: MOVE-DOWN LOCATIONO LOCATIONK
     21: MOVE-RIGHT LOCATIONP LOCATIONO
     22: MOVE-RIGHT LOCATIONQ LOCATIONP
     23: MOVE-UP LOCATIONM LOCATIONQ
     24: MOVE-RIGHT LOCATIONN LOCATIONM
     25: MOVE-UP LOCATIONI LOCATIONN
     26: PUSH-LEFT LOCATIONH LOCATIONI LOCATIONG
     27: PUSH-LEFT LOCATIONG LOCATIONH LOCATIONF
     28: MOVE-RIGHT LOCATIONH LOCATIONG
     29: MOVE-DOWN LOCATIONM LOCATIONH
     30: MOVE-DOWN LOCATIONQ LOCATIONM
     31: MOVE-LEFT LOCATIONP LOCATIONQ
     32: MOVE-LEFT LOCATIONO LOCATIONP
     33: MOVE-UP LOCATIONK LOCATIONO
     34: PUSH-RIGHT LOCATIONL LOCATIONK LOCATIONM
     35: MOVE-UP LOCATIONG LOCATIONL
     36: MOVE-RIGHT LOCATIONH LOCATIONG
     37: MOVE-UP LOCATIOND LOCATIONH
     38: MOVE-UP LOCATIONB LOCATIOND
     39: MOVE-LEFT LOCATIONA LOCATIONB
     40: PUSH-DOWN LOCATIONC LOCATIONA LOCATIONG
     41: PUSH-DOWN LOCATIONG LOCATIONC LOCATIONL
     42: PUSH-DOWN LOCATIONL LOCATIONG LOCATIONP
     43: MOVE-LEFT LOCATIONK LOCATIONL
     44: MOVE-LEFT LOCATIONJ LOCATIONK
     45: MOVE-UP LOCATIONE LOCATIONJ
     46: PUSH-RIGHT LOCATIONF LOCATIONE LOCATIONG
     47: MOVE-DOWN LOCATIONK LOCATIONF
     48: MOVE-RIGHT LOCATIONL LOCATIONK
     49: PUSH-UP LOCATIONG LOCATIONL LOCATIONC
     50: MOVE-RIGHT LOCATIONH LOCATIONG
     51: MOVE-RIGHT LOCATIONI LOCATIONH
     52: MOVE-DOWN LOCATIONN LOCATIONI
     53: PUSH-LEFT LOCATIONM LOCATIONN LOCATIONL
     54: MOVE-DOWN LOCATIONQ LOCATIONM
     55: PUSH-LEFT LOCATIONP LOCATIONQ LOCATIONO
     56: MOVE-DOWN LOCATIONS LOCATIONP
     57: MOVE-LEFT LOCATIONR LOCATIONS
     58: PUSH-UP LOCATIONO LOCATIONR LOCATIONK
     59: MOVE-RIGHT LOCATIONP LOCATIONO
     60: MOVE-RIGHT LOCATIONQ LOCATIONP
     61: MOVE-UP LOCATIONM LOCATIONQ
     62: MOVE-UP LOCATIONH LOCATIONM
     63: MOVE-LEFT LOCATIONG LOCATIONH
     64: MOVE-LEFT LOCATIONF LOCATIONG
     65: PUSH-DOWN LOCATIONK LOCATIONF LOCATIONO
     66: PUSH-RIGHT LOCATIONL LOCATIONK LOCATIONM
     67: MOVE-DOWN LOCATIONP LOCATIONL
     68: MOVE-DOWN LOCATIONS LOCATIONP
     69: MOVE-LEFT LOCATIONR LOCATIONS
     70: PUSH-UP LOCATIONO LOCATIONR LOCATIONK
     71: MOVE-RIGHT LOCATIONP LOCATIONO
     72: MOVE-UP LOCATIONL LOCATIONP
     73: MOVE-UP LOCATIONG LOCATIONL
     74: MOVE-RIGHT LOCATIONH LOCATIONG
     75: MOVE-UP LOCATIOND LOCATIONH
     76: MOVE-UP LOCATIONB LOCATIOND
     77: MOVE-LEFT LOCATIONA LOCATIONB
     78: PUSH-DOWN LOCATIONC LOCATIONA LOCATIONG
     79: PUSH-DOWN LOCATIONG LOCATIONC LOCATIONL

time spent:  0.00 seconds instantiating 86 easy, 0 hard action templates
            0.00 seconds reachability analysis, yielding 58 facts and 86 actions
            0.00 seconds creating final representation with 57 relevant facts
            0.00 seconds building connectivity graph
            0.04 seconds searching, evaluating 10010 states, to a max depth of 8
            0.04 seconds total time

```

Figure 7: Sokoban Challenge

**4. In many cases, geometric and dynamic planning are insufficient to describe a domain. Give an example of a problem that is best suited for semantic (classical) planning. Explain why a semantic representation would be desirable**

The classical planners have a variety of best suited problems, like in logistics, manufacturing, and management. One example is the DART system used for military logistics. Logistics are better expressed by a set of logical expressions to specify complex operations not related to the kinect motion.

## 3 Project Part II: Sokoban Planner

### 3.1 Questions

1. Give successful plans from your planner on the Sokoban problems in Figure 3 and any others
2. Compare the performance of your planner to the PDDL planners you used in the previous problem. Which was faster? Why?
3. Prove that your planner was complete. Your instructor has a math background: a proof “is a convincing argument.” Make sure you address each aspect of completeness and why your planner satisfies it. Pictures are always welcome.
4. What methods did you use to speed up the planning? Give a short description of each method and explain why it did or didn’t help on each relevant problem

## 4 Post-Project: Towers of Hanoi Revisited

Constructing a PDDL representation for the N-disk towers of hanoi is pretty simple by utilizing the following simple structures, for initializing the problem state

1. Each disk labeled  $D_i$  is smaller than a disk labeled  $D_{i+1}$ . That is (smaller  $d_i$   $d_{i+1}$ ).



2. Every disk is smaller than each of the three poles (by definition).
3. The smallest disk (i.e., D1), and the two other poles (P1 and P2) are clear.
4. Every disk  $D_i$  is *on* the disk  $D_{i+1}$ . The largest disk D10, is *on* the pole P3.
5. Every element  $D_i$  is a disk

The goal state is simply a conjunction (AND-ing) of all the states mentioned in Step 4 above, except that the largest disk D10, is *on* the pole P1.

The corresponding PDDL representations for the 6 disk and 10 disk towers of hanoi problem are present in the files “hanoi-6.pddl” and “hanoi-10.pddl”.

Both **FF** and **Blackbox** planners were applied onto the PDDL representations, however only *FF* was able to produce valid plans for the 6 disk and 10 disk problem. *Blackbox* was unable to produce any results, due to relatively large nature of the state-space (I halted execution after 1 minute since the blackbox executable started running).

## 4.1 Questions

### 1. Give successful plans from at least one planner with 6 and 10 disks

The plan for the towers of hanoi problem with 6 disks, generated by *FF* is shown in Figure 8.

step	0: MOVE-DISK D1 D2 P2	
	1: MOVE-DISK D2 D3 P1	
	2: MOVE-DISK D1 P2 D2	
	3: MOVE-DISK D3 D4 P2	
	4: MOVE-DISK D1 D2 D4	
	5: MOVE-DISK D2 P1 D3	
	6: MOVE-DISK D1 D4 D2	42: MOVE-DISK D1 D4 D2
	7: MOVE-DISK D4 D5 P1	43: MOVE-DISK D3 D6 D4
	8: MOVE-DISK D1 D2 D4	44: MOVE-DISK D1 D2 D6
	9: MOVE-DISK D2 D3 D5	45: MOVE-DISK D2 D5 D3
	10: MOVE-DISK D1 D4 D2	46: MOVE-DISK D1 D6 D2
	11: MOVE-DISK D3 P2 D4	47: MOVE-DISK D5 P2 D6
	12: MOVE-DISK D1 D2 P2	48: MOVE-DISK D1 D2 P2
	13: MOVE-DISK D2 D5 D3	49: MOVE-DISK D2 D3 D5
	14: MOVE-DISK D1 P2 D2	50: MOVE-DISK D1 P2 D2
	15: MOVE-DISK D5 D6 P2	51: MOVE-DISK D3 D4 P2
	16: MOVE-DISK D1 D2 D6	52: MOVE-DISK D1 D2 D4
	17: MOVE-DISK D2 D3 D5	53: MOVE-DISK D2 D5 D3
	18: MOVE-DISK D1 D6 D2	54: MOVE-DISK D1 D4 D2
	19: MOVE-DISK D3 D4 D6	55: MOVE-DISK D4 P3 D5
	20: MOVE-DISK D1 D2 D4	56: MOVE-DISK D1 D2 D4
	21: MOVE-DISK D2 D5 D3	57: MOVE-DISK D2 D3 P3
	22: MOVE-DISK D1 D4 D2	58: MOVE-DISK D1 D4 D2
	23: MOVE-DISK D4 P1 D5	59: MOVE-DISK D3 P2 D4
	24: MOVE-DISK D1 D2 D4	60: MOVE-DISK D1 D2 P2
	25: MOVE-DISK D2 D3 P1	61: MOVE-DISK D2 P3 D3
	26: MOVE-DISK D1 D4 D2	62: MOVE-DISK D1 P2 D2
	27: MOVE-DISK D3 D6 D4	
	28: MOVE-DISK D1 D2 D6	
	29: MOVE-DISK D2 P1 D3	
	30: MOVE-DISK D1 D6 D2	
	31: MOVE-DISK D6 P3 P1	
	32: MOVE-DISK D1 D2 D6	
	33: MOVE-DISK D2 D3 P3	
	34: MOVE-DISK D1 D6 D2	
	35: MOVE-DISK D3 D4 D6	
	36: MOVE-DISK D1 D2 D4	
	37: MOVE-DISK D2 P3 D3	
	38: MOVE-DISK D1 D4 D2	
	39: MOVE-DISK D4 D5 P3	
	40: MOVE-DISK D1 D2 D4	
	41: MOVE-DISK D2 D3 D5	

time spent:	0.00 seconds instantiating 231 easy, 0 hard action templates
	0.00 seconds reachability analysis, yielding 42 facts and 166 actions
	0.00 seconds creating final representation with 41 relevant facts
	0.00 seconds building connectivity graph
	0.00 seconds searching, evaluating 334 states, to a max depth of 4
	0.00 seconds total time

Figure 8: Plan for Towers of Hanoi with 6 disks

Clearly it has  $2^6 - 1 = 63$  steps in the plan. Now the problem with 10 disks will have a plan of  $2^{10} - 1 = 1023$  steps. The *FF* planner produces a valid plan with 1023 steps, but for the lack of space it is not produced here. The plan is present under the resources directory as “hanoi-10-solutions”.

### 2. Do you notice anything about the structure of the plans? Can you use this to increase the efficiency of planning for Towers of Hanoi? Explain

One observation from the three plans generated (3, 6 and 10 disks) is that whenever there are odd number of initial disks, then the top most disk is moved onto the “destination” pole, and when there are even number of initial disks, then the top most disk is moved onto the “middle” pole.

Another noticeable aspect of the problem is that the towers of hanoi can be viewed as a simple recursive problem of moving the smaller  $n - 1$  disks from  $P3$  to  $P2$  then moving the largest disk from  $P3$  to  $P1$



followed by moving the  $n - 1$  disks from  $P2$  to  $P1$ . This can be empirically verified - at every  $(2^N - 1)^{th}$  step, if the initial number of disks  $n$  are odd, then there will be  $N - 1$  disks on  $P2$  and largest disk will be on  $P1$ . If the initial number of disks  $n$  are even, then there will be  $N - 1$  disks on  $P3$  and the largest will be on  $P2$ . Of course here,  $0 < N \leq n$ .

Thus the entire plan can be represented recursively (and efficiently) as:

---

**Algorithm 1** Towers of Hanoi recursive definition

---

```

1: function HANOI-SOLVER( $N, P3, P2, P1$ )    ▷ Move N disks from P3 to P1 (using P2 as intermediate)
2:   HANOI-SOLVER( $N - 1, P3, P1, P2$ )
3:   MOVE( $1, P3, P1$ )                      ▷ Move the largest disk from P3 to P1
4:   HANOI-SOLVER( $N - 1, P2, P3, P1$ )

```

---

Thus this is a bottom-up approach in constructing a plan. All one needs to define are the “macro” propositions HANOI-SOLVER and MOVE (which is applied when there is just the largest disk remaining on  $P3$ ). The planner can then use this base condition (a.k.a “macro” proposition) and basically “un-wind” the call stack to generate sub-plans. The correct plan is then obtained by simply reversing the “popped” elements of the call stack.

**3. In a paragraph or two, explain a general planning strategy that would take advantage of problem structure. Make sure your strategy applies to problems other than Towers of Hanoi. Would such a planner still be complete?**

A general recursive algorithm takes advantage of whenever there is a possibility of breaking down a problem into multiple smaller, but similarly structured problems, each if solved (and possibly in parallel if there is sufficient independence) can be “combined” to get the solution to the original problem. The generic recursive algorithm is:

---

**Algorithm 2** Recursive Planner

---

```

1: function RECURSIVE-PLANNER( $Prob_N$ )                      ▷ Solve a sub-problem
2:   if Some Terminal Condition then
3:     TERMINAL-OPERATION( $Prob_1$ )                          ▷ Some constant terminal operation
4:   RECURSIVE-PLANNER( $Subset(Prob_N)$ )

```

---

There are a whole class of problems to which a recursive planner can be applied. For instance, this algorithm can be used in large scale map navigation problems, where loading an entire terrain in one go may be memory prohibitive.

There are two conditions for a planner to be complete,

1. **Produces a plan if there is one:** The recursive planner relies on all the sub-goals to complete their execution (or the recursion stack to be empty). So in case all the sub-goals reach their respective terminating condition, then all of them will reach completion (this is from an execution standpoint - different from the notion of completeness). If all the individual problems finish, then the top-level problem, which is basically a composition of these sub-problems will also produce a valid plan.

However, it is possible that even though the entire problem has a solution, one of the sub-problems may never reach completion – this would cause the original problem to not produce a plan. Hence it cannot always be guaranteed that the planner produces a plan if there is a valid one.

2. **Reports that there is no plan if there is none:** The same sub-problem non-termination issue exists here as well. In case one of the sub-problems gets “stuck”, there is no way for the original problem to terminate reporting that there is no plan.

However, if some sort of a terminating “*parameter*” can be used to force the sub-problems to halt/report no solution. In such a case the “stack overflow” issue will be resolved and both the conditions of completeness will be met. Basically, we need to ensure that the sub-problems will be forcibly terminated which will ensure that the main problem will always terminate as well!

## References

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- [3] Henry Kautz, David McAllester, and Bart Selman. Encoding plans in propositional logic. *KR*, 96:374–384, 1996.