

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 (generated from FF planner)

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

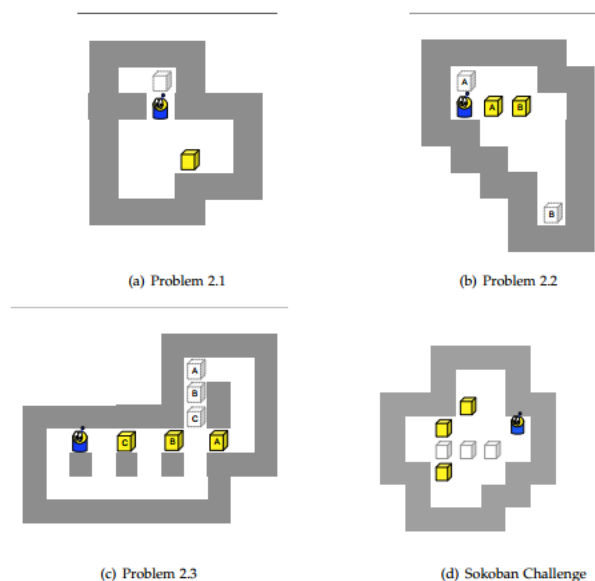


Figure 3: Sokoban Problems

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 rddrruuLLrrddrruuLLrruuurddddLLddlluuRlddrruUllddllu
RRddrruuUUddddlluRlddrruUlllddlluRRRRddrruuuddd
lluRlddrruU

Challenge lldlluRRdddlUruulldRdruruLLrddlluRuruulDDDlluRdrUrrd
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 LOCATIONM LOCATIONL
     18: PUSH-LEFT LOCATIONL LOCATIONM LOCATIONK
     19: MOVE-RIGHT LOCATIONM 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 LOCATIONN LOCATIONO LOCATIONM
    31: MOVE-DOWN LOCATIONT LOCATIONN
    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 LOCATIONM
    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 LOCATIONN 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 LOCATIONM LOCATIONL LOCATIONN
     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 LOCATIONM 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 LOCATIONM LOCATIONN
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 LOCATIONM LOCATIONF
65: MOVE-DOWN LOCATIONT LOCATIONM
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 LOCATIONN
     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

In this part of the project, we came up with our own representation of the Sokoban domain. The domain has the following specifications:

- **Geometry/Grid:** A world represented as a $M \times N$ grid. The Sokoban domain's geometry is defined by M rows and N columns, where each "cell" in the map has the same dimensions as the box.
- **Walls:** A wall is any of the grey boundary of the world, as well as a logical extension of the wall to fit the map. For instance, looking at the first problem in Figure 3, the top most row is entirely made up of walls (although there is some white space in the top right, that cannot be logically reached by the man and hence is a "wall". In our representation a wall is defined by the constant W .
- **Boxes:** In the grid for each problem, we define a constant B which corresponds to whether the box is present in that particular cell of the grid. We have assumed again that any box can be moved to any target square.
- **Target:** This is the target square where any box can be moved. Represented as D .
- **Man:** This represents the starting square in which the man is present. Represented in the grid as M .
- **Empty Squares:** These correspond to squares which are within the boundaries of the "walls" and can be occupied by a man or a box. Represented by $*$.

Note: In our plans, we do not explicitly show the man. Instead we show one or more boxes changing their position with respect to the previous step. Since the man will be in one of the adjacent spaces of the box (left, right, top or bottom) we have effectively treated the man and the box as one “logical” unit. This can be verified in the plans as well by tracing the location change of the various boxes.

In other words, we don’t have actions such as PUSH, since we treat the box to be able to MOVE automatically based on the available white space. However we do respect the geometric constraints of the presence of the man (i.e., the box will not move to a location where a man should have been standing).

Representation of the Domain

Now that we have defined the components of the representation, we have defined the Sokoban domain for each of the 4 problems. Each problem has a “*input*” map file which has the following header:

```
{Rows} {Columns} {Number of boxes}
```

Below the header is the grid based representation of the domain. The grid is a *Row* x *Column* matrix, where each element is a single character as defined previously. The 4 Sokoban problems (including the challenge problem) and their corresponding state representation as per our domain definition are presented in Figures 8, 9, 10, 11 respectively.



Figure 8: Sokoban Problem 2.1 and its corresponding representation

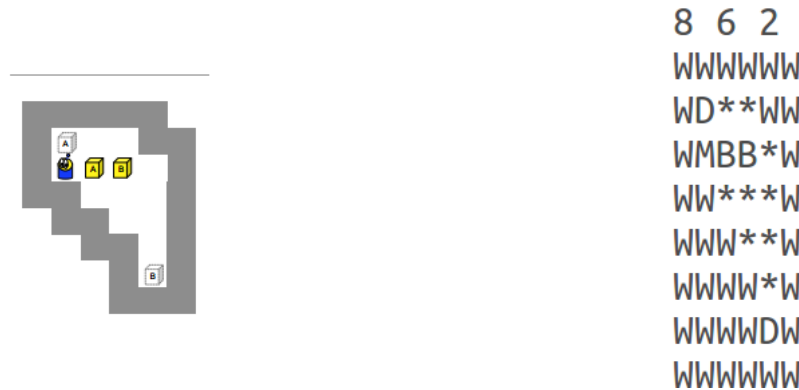


Figure 9: Sokoban Problem 2.2 and its corresponding representation

Brief Outline of the Algorithm

The algorithm is a simple implementation of the breadth-first search algorithm. The state is represented by the position of all the boxes and the position of the man (as per the representation). These arguments are integrated into a single *long* integer.



Figure 10: Sokoban Problem 2.3 and its corresponding representation



Figure 11: Sokoban Challenge and its corresponding representation

At the beginning of search, there is only one element in the search queue which is the initial state. Every time we look at a state, we first check if it is the final state (target configuration, where boxes (B) are in the places where target squares (D) are placed initially). If it is the final state, the program terminates with the solution. If not, we see if we can make any of the boxes move. If one of the boxes can be moved one step away in any direction, we take that move and add the new state into the queue.

Also, every time we add a new state into the queue we check if the state is already explored (already in the queue). This is done by using a hash map. After adding all possible states that can be derived from the state we are dealing with right now, we move on to the next state in the queue.

The program also terminates if the queue is empty, which indicates that there is no solution to the puzzle (and we report that).

Completeness, Speed and Efficiency

We believe that our planner is complete as well as fast. We discuss more about this in the questions sections (Questions 3 and 4). The state representation is pretty compact and really small in size. The processing on the input is also pretty fast since we cache the entire world state into a hash map. The maximum space complexity for the problem is $O(MXN)$ with M rows and N columns. However, this representation is pretty specific to the Sokoban domain. The only “strong” action in this domain is the PUSH action which we have incorporated into the state-space search. Our domain has nicely captured fluents such as LOCATION, BOX-AT and so on within the grid representation.

Miscellaneous Pieces of Information

We were able to capture most of the necessary pieces of information. We used a breadth-first search to explore the states, but we have not logged the explored states. So we are unable to report the number of states explored.

1. **Language Used:** C++
2. **Number of steps in plan:** We calculate the number of steps, assuming the man is adjacent to the box (which we have reported below). So we might have to add the steps it takes for the man to move near the box.
 - Problem 1: 4
 - Problem 2: 11
 - Problem 3: 21
 - Challenge Problem: 18
3. **Computation Time:** We have compared our planner against FF (which was only able to produce the solution for all the 4 problems). Both planners were executed on the same system and the computation time is shown in Table 1.

Table 1: Comparison of Computation Times

Problem	FF Time (in s)	Our Planner Time (in s)
1	0.005	0.004
2	0.007	0.008
3	0.021	0.022
Sokoban Challenge	0.043	0.070

This might not be a totally fair comparison, since we do not take into account the man moving adjacent to the box.

4. **Machine Vitals:** The input representation for each of the problems was very small (of the order of 50-60 bytes), and the output was also suitably compact. Our program can compile and run on any C++ compiler conforming to ANSI standard, and does not require too much of memory to run. The only memory constraints are the fact that we are loading the entire world onto a hash map, but again this is not very significant for the Sokoban domain as well as the BFS which explores every possible reachable state.

3.1 Questions

1. **Give successful plans from your planner on the Sokoban problems in Figure 3 and any others**

The plans as per our domain representation, for the 4 Sokoban problems (including the challenge) is presented in Figures 12, 13, 14 and 15 respectively.

2. **Compare the performance of your planner to the PDDL planners you used in the previous problem. Which was faster? Why?**

As mentioned earlier, our planner was able to be almost as fast as the FF planner. Especially in the case of the Sokoban Challenge problem, our planner was clearly faster. However, this is not strictly a fair comparison, since our planner assumes that man starts adjacent to one of the boxes. FF is clearly going to be fast, since it uses enforced hill climbing optimized with GRAPHPLAN's heuristics, whereas our algorithm is a simple Breadth-First Search.


```

Total Step : 21
Step : 0
WWWWWWWWWW
WWWWWWWD**W
WWWWWWWD**W
WWWWWWWD**W
W*W*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 1
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 2
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 3
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 4
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 5
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 6
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 7
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 8
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 9
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 10
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 11
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 12
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 13
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 14
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 15
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 16
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 17
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 17
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 18
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 19
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 20
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW
Step : 21
WWWWWWWWWW
WWWWWW**W
WWWWWW**W
WWWWWW**W
W*B*B*B*B*W
W*W*W*W*W*W
W*****W*W
WWWWWWWWWW

```

Figure 14: Sokoban Problem 2.3's Plan

C++ to set and get a specific argument (For example, the position of the person), which saves a lot of space. Our algorithm searches for every possible move of the box, that is, as long as we can make a box move from the current state, we add this new state with the box moved to the new position. (And of course we assert that this new state is a state that we have not discovered yet. This is one of the branch optimizations) We keep on doing this until we hit the final state or we run out of states. If we hit the final state (with all boxes in designated positions), our algorithm ends and it prints out the plan we are looking for. If the set of states is empty and we still don't find a solution, the algorithm also terminates with no solution. Since BFS

<pre> Total Step : 18 Step : 0 WWWWWWW WWW**WW WWNB*WW W*B**WW W*DDD*W WWB**WW WW**WWW WWWWWWW Step : 1 WWWWWWW WWW**WW WWNB*WW W**B**W W****W WWB**WW WW**WWW WWWWWWW Step : 2 WWWWWWW WWW**WW WWNB*WW W**B*W W****W WWB**WW WW**WWW WWWWWWW Step : 3 WWWWWWW WWW**WW WWNB*WW W**B*W W*B***W WW**WWW WWWWWWW Step : 4 WWWWWWW WWW**WW WWNB*WW W**B*W W**B**W WW**WWW WWWWWWW </pre>	<pre> Step : 5 WWWWWWW WWW**WW WWNB*WW W**B**W W**B**W WW**WWW WW**WWW WWWWWWW Step : 6 WWWWWWW WWW**WW WWNB*WW W*B***W W**B**W WW**WWW WW**WWW WWWWWWW Step : 7 WWWWWWW WWW**WW WWNB*WW W*B***W W**B*W WW**WWW WW**WWW WWWWWWW Step : 8 WWWWWWW WWW**WW WWW**WW W*B*B**W W**B*W WW**WWW WW**WWW WWWWWWW Step : 9 WWWWWWW WWW**WW WWW**WW W*B***W W**B**W WW**WWW WW**WWW WWWWWWW Step : 15 WWWWWWW WWW**WW WWNB*WW W****W W**B*W WWB**WW WW**WWW WWWWWWW Step : 16 WWWWWWW WWW**WW WWNB*WW W****W W*B*B*W WW**WWW WW**WWW WWWWWWW Step : 17 WWWWWWW WWW**WW WWW**WW W**B**W W*B*B*W WW**WWW WW**WWW WWWWWWW Step : 18 WWWWWWW WWW**WW WWW**WW W****W W*BBB*W WW**WWW WW**WWW WWWWWWW </pre>	<pre> Step : 10 WWWWWWW WWW**WW WWW**WW W*B***W W**B*W WW*B*WW WW**WWW WWWWWWW Step : 11 WWWWWWW WWW**WW WWW**WW W**B*W W**B*W WW*B*WW WW**WWW WWWWWWW Step : 12 WWWWWWW WWW**WW WWW**WW W****W W**B*W WW*B*WW WW**WWW WWWWWWW Step : 13 WWWWWWW WWW**WW WWNB*WW W****W W**B*W WW*B*WW WW**WWW WWWWWWW Step : 14 WWWWWWW WWW**WW WWNB*WW W****W W**B*W WWB**WW WW**WWW WWWWWWW </pre>
--	--	---

Figure 15: Sokoban Challenge Problem's Plan

searches for every possible state that is reachable from the original state, if there exists a solution, we can always find it. If there is no solution, since our algorithm only search for possible states, it will terminate with no solution.

Also our algorithm is optimal in terms of box moves. This is because every time we add a new state, it is a state that is one box-move away from the previous state. Since we are using Breadth First Search, we can gaurantee that our solution uses the least box moves.

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

First of all we discard the new state that has already been explored. This branch optimization cuts out a lot of useless branches, and it asserts that our algorithm terminates when there is no solution.

Also when checking if the state has been explored, we use hash map. Specifically, we use a large integer to represent the state, and throw the explored states into the hash. So this saves the time needed for checking duplicate states.

Another branch optimization is that when we are in a state where one of the boxes has two adjacent sides facing the wall and this box is not in the designated position. This box cannot be moved anyway because we need the man on one side of the box and we need the opposite side of the wall to be clear so that we can move. (In this case at least one side of these two is wall) Therefore this state is itself a dead state. We will never make it to the final state in this case.

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 16.

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

```

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
        7: MOVE-DISK D4 D5 P1
        8: MOVE-DISK D1 D2 D4
        9: MOVE-DISK D2 D3 D5
       10: MOVE-DISK D1 D4 D2
       11: MOVE-DISK D3 P2 D4
       12: MOVE-DISK D1 D2 P2
       13: MOVE-DISK D2 D5 D3
       14: MOVE-DISK D1 P2 D2
       15: MOVE-DISK D5 D6 P2
       16: MOVE-DISK D1 D2 D6
       17: MOVE-DISK D2 D3 D5
       18: MOVE-DISK D1 D6 D2
       19: MOVE-DISK D3 D4 D6
       20: MOVE-DISK D1 D2 D4
       21: MOVE-DISK D2 D5 D3
       22: MOVE-DISK D1 D4 D2
       23: MOVE-DISK D4 P1 D5
       24: MOVE-DISK D1 D2 D4
       25: MOVE-DISK D2 D3 P1
       26: MOVE-DISK D1 D4 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
       42: MOVE-DISK D1 D4 D2
       43: MOVE-DISK D3 D6 D4
       44: MOVE-DISK D1 D2 D6
       45: MOVE-DISK D2 D5 D3
       46: MOVE-DISK D1 D6 D2
       47: MOVE-DISK D5 P2 D6
       48: MOVE-DISK D1 D2 P2
       49: MOVE-DISK D2 D3 D5
       50: MOVE-DISK D1 P2 D2
       51: MOVE-DISK D3 D4 P2
       52: MOVE-DISK D1 D2 D4
       53: MOVE-DISK D2 D5 D3
       54: MOVE-DISK D1 D4 D2
       55: MOVE-DISK D4 P3 D5
       56: MOVE-DISK D1 D2 D4
       57: MOVE-DISK D2 D3 P3
       58: MOVE-DISK D1 D4 D2
       59: MOVE-DISK D3 P2 D4
       60: MOVE-DISK D1 D2 P2
       61: MOVE-DISK D2 P3 D3
       62: MOVE-DISK D1 P2 D2

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 16: Plan for Towers of Hanoi with 6 disks

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

- [1] Henry Kautz and Bart Selman. Blackbox: A new approach to the application of theorem proving to problem solving. In *AIPS98 Workshop on Planning as Combinatorial Search*, volume 58260, pages 58–60, 1998.
- [2] J. Hoffmann. The fast-forward planning system. *AI magazine*, 22(3), 2001.
- [3] Henry Kautz, David McAllester, and Bart Selman. Encoding plans in propositional logic. *KR*, 96:374–384, 1996.