Project 1 – Blocksworld Problem

Project Report

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Steps to run my program:
After downloading the zip file into a folder. All the source and header files will be present in the folder.

Requirements:

- G++/GCC compiler
- Support for C++11
- Make

Compiling the code:

- Use ‘**make’** to compile the code
- If it runs without error, then run the code with following format:
  ./ blocksworld <Number of Stacks > <Number of Blocks> e.g.

  ./Blocksworld 3 5

  It means the number of stacks will be used is 3
  And number of blocks used it 5.

  If you get an error follow use ‘make clean’ and follow the steps again.

```
./blocksworld 3 5

Number of Stacks:3 Number of Blocks: 5
Initial State
Stack 0: B
Stack 1: E A
Stack 2: D C

Iteration Number 1, Queue Size = 6, TotalCost(gCost+hCost) = 5, Depth= 0
Iteration Number 2, Queue Size = 9, TotalCost(gCost+hCost) = 8, Depth= 1
Iteration Number 3, Queue Size = 12, TotalCost(gCost+hCost) = 10, Depth= 1
Iteration Number 4, Queue Size = 13, TotalCost(gCost+hCost) = 10, Depth= 1
Iteration Number 5, Queue Size = 16, TotalCost(gCost+hCost) = 6, Depth= 2
Iteration Number 6, Queue Size = 19, TotalCost(gCost+hCost) = 6, Depth= 3
Iteration Number 7, Queue Size = 22, TotalCost(gCost+hCost) = 6, Depth= 4
Iteration Number 8, Queue Size = 23, TotalCost(gCost+hCost) = 6, Depth= 5
Iteration Number 9, Queue Size = 22, TotalCost(gCost+hCost) = 6, Depth= 6
Goal State Found
Success!! depth = 6, Total Goal Tests = 9, Maximum Queue Size= 23, Total Cost = 6
Stack 0: B
Stack 1: E A
Stack 2: D C

Stack 0:
Stack 1: E A
Stack 2: D C B

Stack 0: A
Stack 1: E
Stack 2: D C B

Stack 0: A B
Stack 1: E
Stack 2: D C

Stack 0: A B C
Stack 1: E
Stack 2: D

Stack 0: A B C D
Stack 1: E
Stack 2:

Stack 0: A B C D E
Stack 1:
Stack 2:

Done and Nailed It
```

Example Traces of my Program

Components of the Program:

1) **Node Class:**
   In the Node class I store the information about the node which consists of following member variables:
   a) currentState -> which represents the state of the blocks and stacks (Blocksworld Class)
   b) Children Nodes-> to keep the track of the children nodes
   c) Depth of the node as compared to the root node (start node)
   d) TotalCost (Path Cost) = g(n) + c(n)
   e) gCost -> number of steps to reach the node from the start node.
   f) hCost -> heuristic cost value to reach the goal node

   I made the Node class as generic as possible so that many other problems can be solved with the same code.

2) **ASearch Class:**
   ASearch is the actual implementation of the A* Search algorithm which has the following items in it:
   a) startNode
   b) goalNode
   c) frontier
   d) exploredStateSet
   e) some Flags

   ➔ **frontier**: The implementation of the frontier is typical priority queue with Node class objects as the entries ordered by the totalCost of the Node. I also implemented the overloaded function to traverse the priority queue as a vector since by default the priority queue in c++ has no traversal iterator. The functions which we needed to implement was a comparison, inserting, deleting nodes in dynamic basis.

   ➔ **exploredStateSet** : To make the traversal fast and enhanced I needed to implement the exploredStateSet as a set of nodes already explored. I used the **unordered_set** data structure to store the same. Since the operation needed to be done on this set was searching and comparison which needs to be done in O(1), I enhanced the basic structure to make the comparison as that of Java language's hash code matching. Instead of storing the Nodes, which was too much memory, I stored the states in the form of strings which were obtained by generating the hash code of the state (i.e. how the blocks are in the stacks for the current state). This was I was able to make the comparison fast enough without having to write the explicit Node comparator and iterator.

   ➔ Since the A* Search algorithm can be used in many other problem states, so I used the generic template for the ASearch so that once I need to change the problem state, I can easily do it without changing any code inside the A* Search library.

3) **Blocksworld Problem:**

Each problem can be represented in terms of the state. Since the problem we were tacking was Blocksworld, so the class for the same. This class defines how to represent the problem in the data structure which the ASeach library can use and solve.

The following information is stored inside this class:

a) currentState -- > stackHolders → which is the stacks which hold the blocks into some particular configuration.
b) All the functions for how to calculate the following:
    a. gCost
    b. heuristics for the problem
    c. printing the state
    d. goaltests
    e. Problem generator
    f. GetSuccessors

The problem generator I have used it based on the multinomial distribution of blocks and stacks once they are supplied from the user. It is a highly randomized function to create the initial state.

The main function of my code lies inside the Problem State which is Blocksworld.cpp

Heuristics Function:

I have used composite/combination of the heuristics. I got this idea while reading the Chapter 3 of AIMA by Russel and Norvig. Since the single heuristics is not enough to handle all the cases of the present problem (Blocksworld).

Since the initial intuition for the heuristics was to check how many blocks are not present in the goal state configuration, irrespective of the position. Since the goal state for our algorithm is all the blocks in the single stack (first stack), stacked over each other in ascending order.

Heuristics 1(h1):

The first heuristics I implemented was checking that how many correct number of blocks are in the first stack. This heuristic will make sure that rest of the elements needs to be moved from other stacks to the first stack. Using this heuristic, we can easily solve the simple problems with has less branching factor (or a number of stacks). But this heuristic doesn't penalize or take into the consideration the internal structure of the how blocks are arranged inside other stacks as well as in the first stack. This heuristic gives us the least number of steps to be used to make sure the other blocks from other stacks are transferred to the first stack. Thus this assumes the blocks in the other stacks are present in the best format and we just need to move them to the first stack, which is not true for majority cases.

Heuristics 2:

The second heuristic I implemented, I took into the consideration the penalty to the blocks which were not correctly in the stacks. For each block which was wrongly ordered – not in increasing order from the bottom to top in the first stack and not in decreasing order from bottom to top in other stacks (not the first stack) were penalized by two points. The first stack is the special stack as all the nodes have to end up in this stack to achieve the goal. Moreover, I will penalize if the block present in the bottom of the first stack is not what it should be in the goal state. This heuristic even though penalizing the wrong configuration did okay for a small number of stacks, but as soon the stacks starting increasing this heuristic led the solution to distribute the blocks along the stacks in decreasing order hence to reduce the penalized value but not making sure that the elements are going to first stack. One more problem with this heuristic was that it was not handling the intermediate cases where the blocks in one stack are not continuously increasing or decreasing hence resulting in more complex situations.

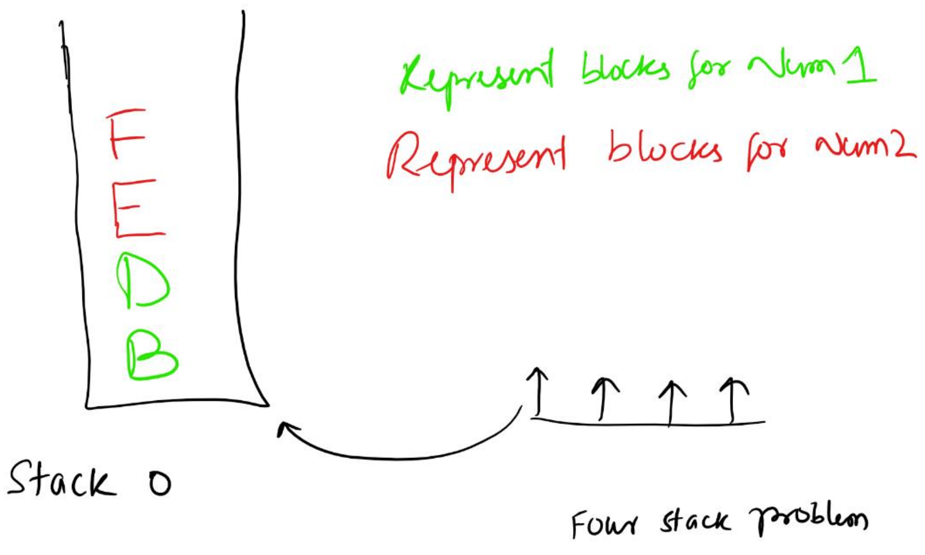
Since this heuristic was not able to converge to the solution to goal as it was settling to distribute the blocks on other stacks, it was creating a lot of nodes (around 65,000) and still not crossing the depth of 10. So the answers which were around the level 10 were easily solved.

To address the problem of complex arrangement of the blocks on the stack, I needed a different penalty for different configurations thus heuristic 3.

Heuristics 3 (h3):

This heuristic is more complicated and takes all the configurations of the blocks in calculating the heuristics. We divide the heuristic into two parts. One is for the first stack and other for stacks except the first one. For each configuration, we will store two occurrences of two types of blocks i.e. the block which should be moved at least once and blocks which needs to be moved twice from the current stack it is present in.

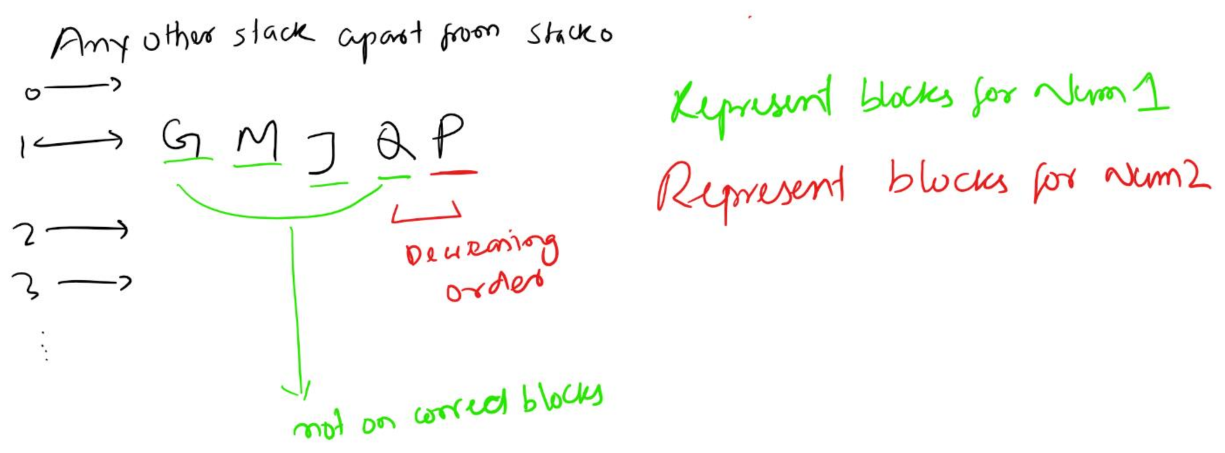
a) **For First Stack:** We will traverse from bottom to top and check if the block is not correctly placed on the block below it. If the block is not the next block in order of increasing order, then this block needs to be moved at least once to other stack and then back. So we increase the number of such blocks continuously till top and we call the number of these blocks by “Num1”. If we already met such a block, we will set a flag marking that one block is wrongly placed. Now we will also check if there is a set of blocks which are in right order but placed on the wrong stack (i.e. wrong block is below them which we will know by the flag), we count these blocks as “Num2”. So to attain the correct configurations the set of correctly placed blocks on top of the wrong block needs to be moved once out and then back to the goal state. After traversing this we get “Num1” and “Num2” for the first stack. The special treatment is given to the first stack is because we prefer the blocks in increasing order as it is needed for goal state.



So in this example,
$num1 = 2$
$num2 = 2$

b) For all other Stacks:

The penalties are similar to the blocks on other stacks but the only difference from that of the first stack is the order of checking the elements, in the first stack, we checked the increasing order but in other stacks, we would prefer the decreasing order. Thus if C, D, E are in stack number 1, then we just need to move them to stack 0 in order and need not to be moved around. The example explains it more.


Any other stack apart from stack 0
0 →
1 → G M J Q P
2 →
3 →
Decreasing order
not on correct blocks
Represent blocks for Num 1
Represent blocks for Num2

So in this example,
num 1 = 4
num2 = 1

After calculating the number of blocks represented by Num1 and Num2, then we call to calculate the number of moves to be used by each type of block to be placed into the goal state.

Num1 -> Since these blocks are out of order that means they need to move out of the stack once and then back again in case of stack 0 (first stack) and for the other stacks it needs to be moved out and then again so that the element below it can be placed correctly on the stack 0. Thus, in the best case scenario, we need move these elements twice.

Num2-> Since we have two blocks which are in order but the block below them is not in order, we need to move these blocks at least four times to get to correct stack.

Hence, the total cost generated by the heuristic is the sum of moves for “Num 1” type blocks and “Num 2” type blocks. Which is given by,

So heuristic3 = 2 * #Num1 + 4 *#Num2

Admissibility:
So by the above argument and examples, the heuristic 3 is admissible for A* Search Algorithm. As we are calculating the number of the least steps involved to move the elements from each stack without considering the inter-stack information. Thus we are only considering the lower limit of the moves needed and thus is admissible.

The problem of using single heuristics in Blocksworld Problem:
Although the heuristics 3 mentioned above is better in many terms for calculating the heuristic cost, it suffers a technical problem which I explored while going through the solution and running A* Search on examples. When the number of the stacks increase for constant blocks this leads to a problem. The program tries to settle few blocks in each stack and thus negating the heuristic 3 cost and not moving the blocks to the first stack (i.e. goal state). So when I ran the solution on 7 stacks and 10 blocks it was branching madly by reducing the heuristic 3 value by distributing the blocks into different stacks, thus it was exploring the nodes which were not promising thus in place creating new children once we explored the wrong choices. This phenomenon led to queue explosion.

This problem led me to make sure I penalize this distribution of blocks to other stacks by counting the number of pending blocks to be moved to the stack 0 (goal state).
So the total heuristic cost which I used for my A* Blocksworld Problem is given by The weighted sum of h1 and h3.
Heuristics = w1 * h1 + w2 * h3

By empirically running the algorithm over many instances I found that the optimal number of w1 and w2 is actually a function of a number of stacks. As we increase the number of the stacks, the h3 leads tend to make the blocks distributed over all stacks. I called this state as “Low h3 State” and thus to make counter this effect I increased the weight for w1, which makes these blocks to move to the stack 0 in the correct form.

Thus using these composite heuristics, I was able to solve the problem very effectively.

So w1 makes the blocks to get to the first stack and the w2 makes sure we put them in the correct order.
Hence in combination, I was able to solve even the problem with parameters as high as 15 stacks and 26 blocks.

Since I generalized my code by using the ASCII values instead of using only alphabets I can even try to make it harder.

Results:

I ran the simulations on various configurations and the corresponding results obtained by running all of them are given in the table below:

All the results are averaged over 10 iterations

Table 1:
For w1 =1 and w2 =1

Number of Stacks	Number of Blocks	Average Goal Tests	Average Maximum Queue Size	Average Actual Path Cost (Number of Steps)
3	5	11	25	9
3	6	12	28	9
3	7	23	57	16
3	8	78.49	185.47	19.39
3	9	116.56	309.73	25.32
3	10	114.88	301	28.08
4	5	16.38	53.12	9.16
4	6	46	242	11
4	7	44.75	245.39	16.74
4	8	27	162	17
4	9	37.08	238.88	18.48
4	10	43	286	23
5	5	27	172.17	9.98
5	6	9	81	8
5	7	13	141	9
5	8	30.92	300.08	16.54
5	9	21	248	16
5	10	32.93	390.63	21.54
6	5	25.89	338.88	7.11
6	6	24.5	331.9	9
6	7	29.02	440.5	12.18
6	8	26.35	428.15	14
6	9	22.07	323.62	17.09
6	10	23	321	20
7	5	60.34	670.27	8.69
7	6	38.34	636.66	9.18
7	7	38.05	724.54	12.02
7	8	30.26	640.6	15.17
7	9	34.21	564.32	16.51
7	10	26.49	464.62	15.51
8	5	58.33	808.82	7.75
8	6	22.22	471.56	7.6
8	7	14.78	251.69	9.24
8	8	32.53	702.88	12.09

Table 2:
For w1 =2 and w2 =1

Number of Stacks	Number of Blocks	Average Goal Tests	Average Maximum Queue Size	Average Actual Path Cost (Number of Steps)
3	6	48	101	17

3	7	29	59	16
3	8	40.4	106.36	16.6
3	9	52	138	22
3	10	96.78	249.79	25.93
4	5	13	65	10
4	6	13	73	12
4	7	15	80	13
4	8	39.8	223	19.96
4	9	30	187	19
4	10	19	118	18
5	5	11	94	9
5	6	9	69	8
5	7	15	127	14
5	8	25.03	253.74	15.27
5	9	22.9	255.75	17.94
5	10	24	279	20
6	5	18.68	146.93	9.97
6	6	11	140	10
6	7	13	178	11
6	8	12	135	11
6	9	20.9	339.1	16.3
6	10	31.54	538.84	18.45
7	5	13	167	9
7	6	8.89	132.67	7.05
7	7	14	222	11
7	8	19.12	382.04	15.16
7	9	18.55	340.8	16.55
7	10	16.4	329.32	13.28
8	5	12.6	189.2	7.8
8	6	7	65	6
8	7	19.4	464.16	13
8	8	17.72	368.44	14.36
8	9	25.18	713.17	15.53
8	10	22.45	564.94	18.79
9	5	6	92	5
9	6	32.84	658.29	10.11
9	7	18.5	416.25	12.75
9	8	13.08	330.46	11.3
9	9	22.23	650.13	16.38
9	10	21.27	607.13	16.68
10	5	16.49	347.03	9.07
10	6	19.84	502.4	10.54
10	7	19.54	537.78	12
10	8	20.77	666.97	13.88
10	9	28.45	937.3	16.42
10	10	21.6	633.89	17.77

Table 3:
For w1 =3 and w2 =1

Number of Stacks	Number of Blocks	Average Goal Tests	Average Maximum Queue Size	Average Actual Path Cost (Number of Steps)
3	5	8	20	6
3	6	23	55	13
3	7	36.98	83.7	17.88
3	8	109.53	276.95	17.73
3	9	51	119	25
3	10	136.68	366.65	30.7
4	5	11	54	10
4	6	19.6	103.4	11.72
4	7	13	67	12
4	8	30	166	17
4	9	37	245	18
4	10	39.07	263.52	21.99
5	5	27.6	199.26	10.92
5	6	11	91	10
5	7	19	181	14
5	8	17	133	16
5	9	36.68	420.64	20.34
5	10	27.76	313.84	20.38
6	5	11	144	8
6	6	14	172	12
6	7	12.24	142.56	11.24
6	8	18	261	14
6	9	17.62	228.34	16.62
6	10	26.64	401.54	21.16
7	5	19.05	201.59	7.51
7	6	15	177	12
7	7	17.9	312.9	13.9
7	8	26.07	387.23	12.05
7	9	10	165	9
7	10	20.28	447.33	16.2
8	5	21.99	330.08	8.33
8	6	20.24	322.78	12
8	7	18	325	14
8	8	22.76	572.7	14.35
8	9	14.16	361.82	12.58
8	10	22	517.95	19.53
9	5	8.96	167.76	6.84
9	6	16.38	435.49	11
9	7	16	436.24	11.39
9	8	28.17	869.44	14.84
9	9	19.24	661.19	14.22
9	10	19.5	508.87	17.19
10	5	9.88	199.48	6.72

10	6	12.45	332.8	8.2
10	7	20.85	688.06	12.01
10	8	20.65	722.71	12.17
10	9	27.01	976.08	15.7
10	10	22.44	628.04	18.8

Discussion or results:

As we can see from the results from the Table 1 if the penalty for the blocks not present in the first stack is less the algorithm starts exploring the less promising nodes and hence reaching the solution with many explorations.
One more important thing to keep in mind is that the problem generator function which creates the initial state is highly randomized and thus the different tables cannot be directly compared. The randomization is based on randomized multinomial distribution. So each run changes drastically. To capture the general trend even though I tried to run the algorithm for 100 random iterations, still, the general trend cannot be guaranteed.

Using the heuristics 3 alone was very slow and created a lot of the nodes in queue/frontier as the algorithm was not able to converge to the goal state. The problem and reason are already defined in the heuristics section.

Once I used the composite heuristics, the solution was easily attained and since, inside the code, I did a lot of optimizations of reducing the memory trace and keeping only necessary stuff in memory the algorithm was lightning fast. To give you a context, the heuristics 1 and heuristics 2 were taking around 2-4 seconds on the problem with 5 stacks and 10 blocks, but with the composite heuristics it took around less than one second even for bigger problems like 10 stacks and 20 blocks.
So the composite heuristics performed very well and enhanced the speed of the execution by traversing only the nodes which are highly promising to direct to the goal state.

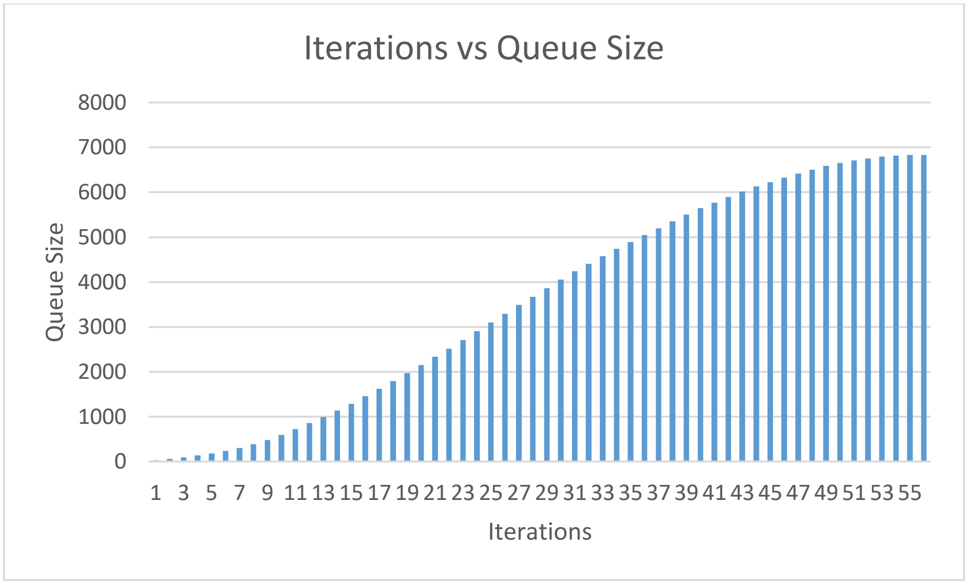


Figure 1. Plot of Queue size vs Number of Iterations for 15 stacks and 28 blocks

The largest problem I could solve within 3 seconds was 15 stacks and 28 blocks. The relationship between the iterations and queue size is depicted in the Figure 1. above. So as the number of the goal test were increasing the queue size was increasing roughly by the factor of the square of the number of the stacks(i.e. O(n^2) = n * n-1 ways). Since we were also keeping the track of the explored state so this number we were able to get down. Since the initial state is randomized the proper factor can't be predicted but it was helping.

Table 4:
For a constant number of Blocks (i.e. 10) with a variable number of stacks (3 - 10):

Number of Stacks	Number of Blocks	Average Goal Tests	Average Maximum Queue Size	Average Actual Path Cost (Number of Steps)
3	10	129.84	340.74	28.41
4	10	34.75	216.9	21.15
5	10	23	249	21
6	10	20	289.83	19
7	10	22.52	411.34	19.38
8	10	29.64	826.35	18.45
9	10	22.01	621.25	18.01
10	10	23.23	802.27	17.94

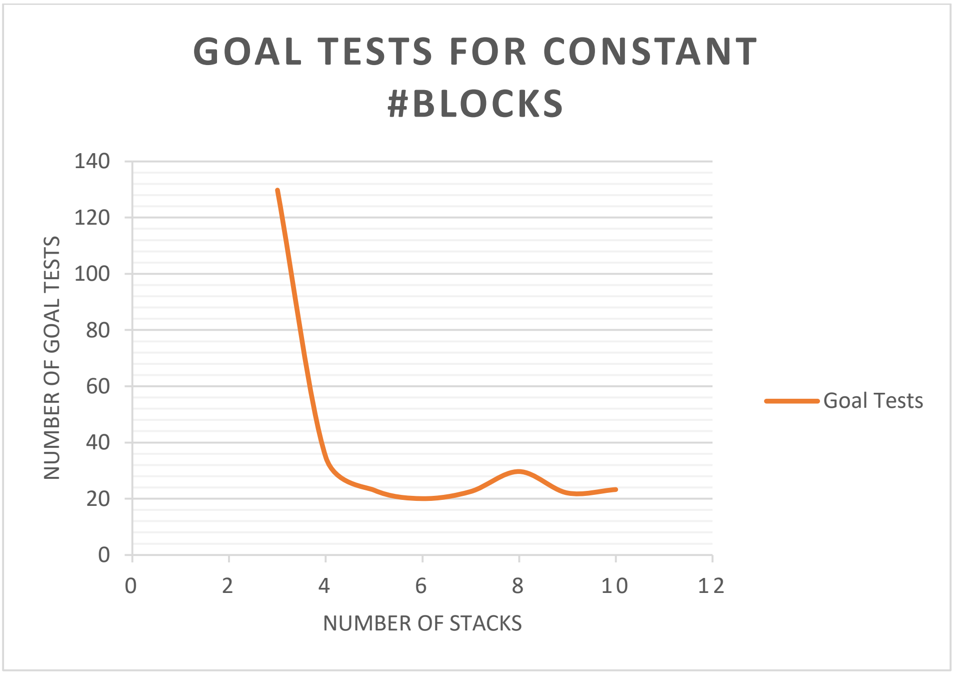


Figure – 3: Plot of Number of Goal Tests vs Number of Stacks for 10 Blocks

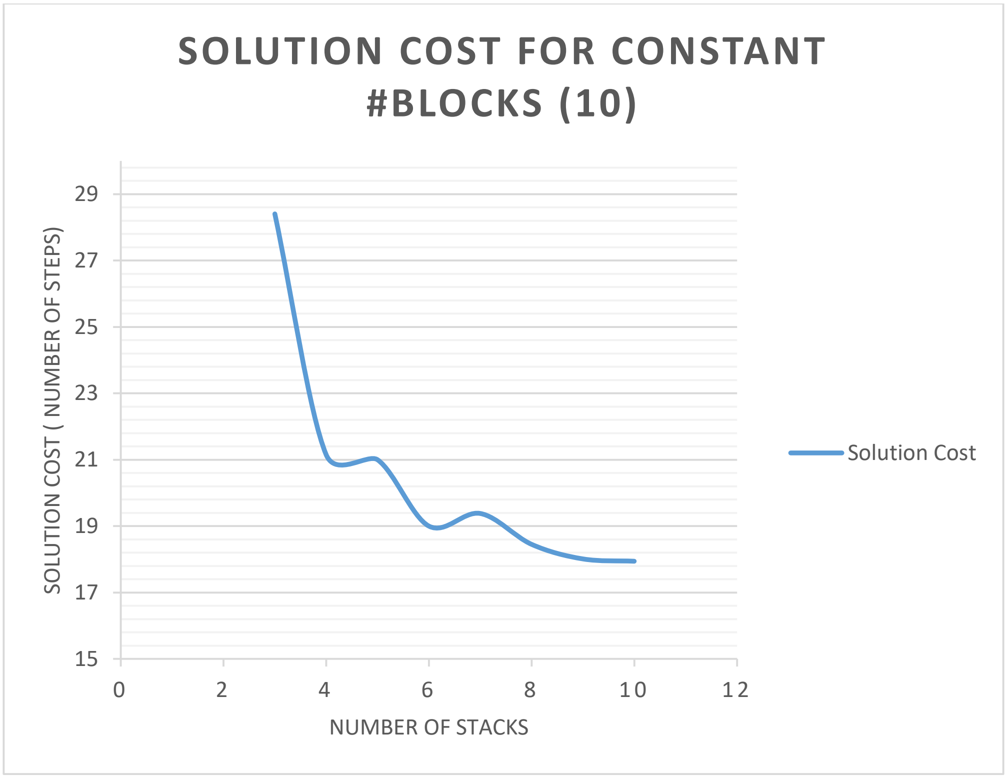


Figure – 4: Plot of Number of Solution Cost vs Number of Stacks for 10 Blocks

From Figure 3 and Figure 4 it is very evident that keeping the number of the blocks constant (10 blocks) and increasing the number of the stacks made the life easy for our algorithm. Both the number of goal tests as well as the actual number of steps to get to the solution decreased a lot. Hence making the problem quite easier. As the number of stacks provides you to spread the misplaced blocks and from there they can be moved easily to the first stack.

Table 5:

For a constant number of Stacks (i.e. 10) with a variable number of Blocks (5 - 10):

Number of Stacks	Number of Blocks	Average Goal Tests	Average Maximum Queue Size	Average Actual Path Cost (Number of Steps)
10	5	6	104	5
10	6	11	189	10
10	7	19.08	572.04	13
10	8	21.01	1063.08	13.18
10	9	22.3	699.61	16.56
10	10	25.1	791.14	18.35
10	5	6	104	5
10	6	11	189	10

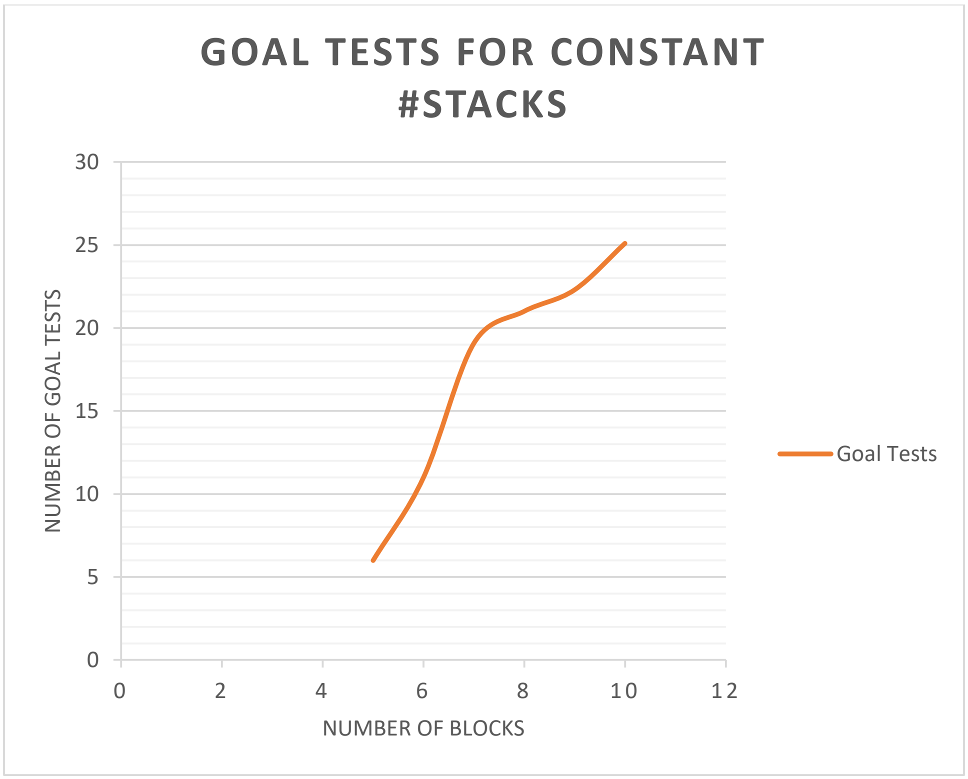


Figure – 5: Plot of Number of Goal Test vs Number of Blocks for 10 Stacks

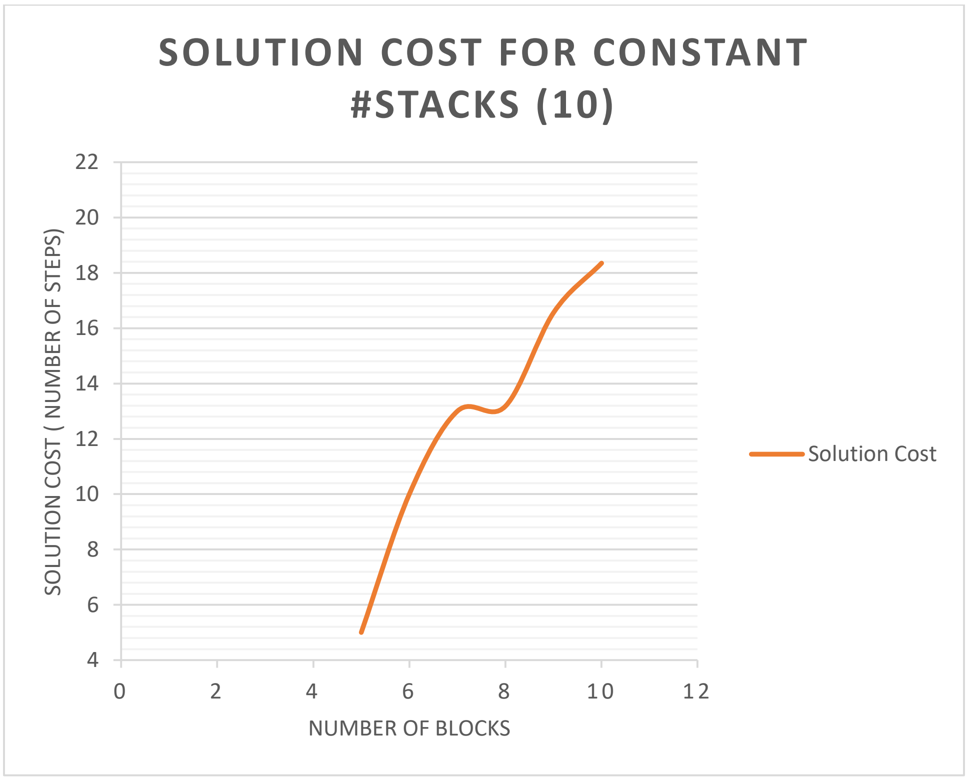


Figure – 6: Plot of Number of Goal Test vs Number of Blocks for 10 Stacks

Moreover, when we increased the number of blocks keeping the number of stacks constant (10), the problem got hard to solve as the number of places are constant to move around the stacks and this increases the goal tests as well as the actual path cost of the solution. Figure 5 and Figure 6 says the same story here.

The solutions obtained from the algorithm were typically optimal, but as we increase the number of blocks, I saw few cases which were suboptimal by 1-2 steps. The reason behind this is the way composite heuristics is working. Taking the heuristic function h1 and h3 separately are admissible and hence will make sure we have the optimal result. But as soon as we want to merge these two heuristics, the solution for some cases result in sub-optimal solutions. Maybe the way I am putting the two heuristics is making the overall heuristics not admissible and thus resulting in the sub-optimal solution.

Furthermore, there are many ways to enhance the heuristics function. One best way is to make sure the composite heuristic is formed in such a way that it is admissible and makes sure that solution obtained is optimal. Also, the next and new work can be how to make the use of information across the stacks and how it influences the heuristic cost. For now, the heuristics I have used is independent of the other stacks. Modeling this inter stack information will definitely enhance the performance both in terms of iterations, goal tests, queue size and ensure the optimality.