1. Introduction

In this AIND assignment I have evaluated **three different uninformed and informed (6 overall)** search algorithms using PDDL (Planning Domain Definition Language) to solve three different air cargo shipping problems. The goal was to find an optimal solution for all problems. This document provides a brief summary and discussion of the achieved results for each problem and each class of search algorithm.

2. Air Cargo Shipping Problems using PDDL

2.1 Problem1

First problem was defined in PDDL as follows:

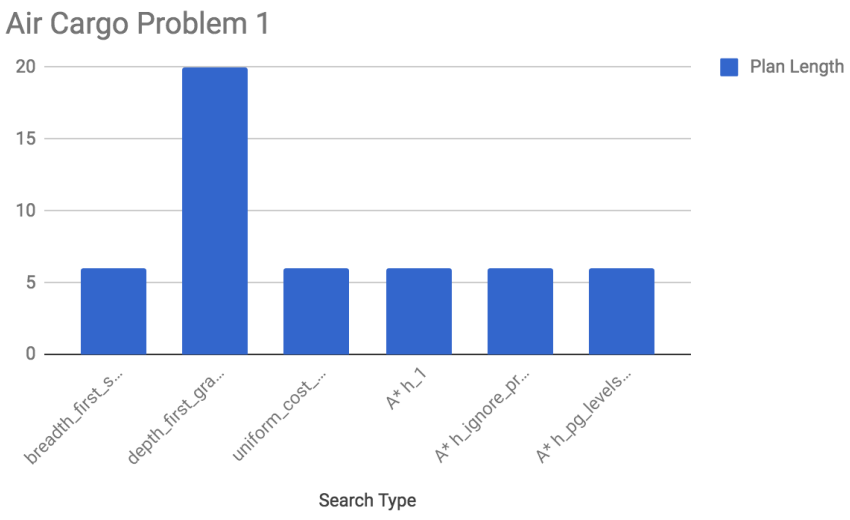
```
Init(At(C1, SFO) ∧ At(C2, JFK)
    ∧ At(P1, SFO) ∧ At(P2, JFK)
    ∧ Cargo(C1) ∧ Cargo(C2)
    ∧ Plane(P1) ∧ Plane(P2)
    ∧ Airport(JFK) ∧ Airport(SFO))
Goal(At(C1, JFK) ∧ At(C2, SFO))
```

This problem was the easiest of the three, so I expected the fastest results. You can find the breakdown of the results in the table below:

Air Cargo Problem 1						
Search Type	**Expansions**	**Goal Tests**	**New Nodes**	**Plan Length**	**Time Elapsed**	**Optimality**
breadth_first_search	43	56	180	6	0.036714033	TRUE
depth_first_graph_search	21	22	84	20	0.017907941	FALSE
uniform_cost_search	55	57	224	6	0.044758609	TRUE
A* h_1	55	57	224	6	0.0354644	TRUE
A* h_ignore_preconditions	41	43	170	6	0.0409764	TRUE
A* h_pg_levelsum	58	60	234	6	1.8038796	TRUE

You can find the problem 1 program run log in GitHub repo [1] in *p1_uninformed.txt* and *p1_informed.txt* files or see the console screenshots attached in Appendix 1.

Plan length found by each tested algorithm for Problem 1 is illustrated in the chart below:



2.2 Problem 2

Second problem was defined in PDDL as follows:

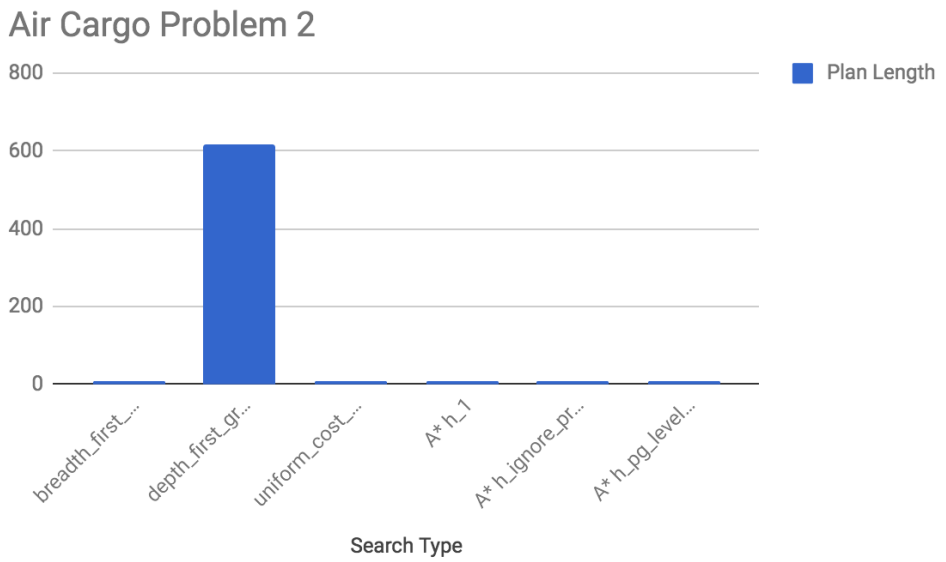
```
Init(At(C1, SFO) ∧ At(C2, JFK) ∧ At(C3, ATL)
    ∧ At(P1, SFO) ∧ At(P2, JFK) ∧ At(P3, ATL)
    ∧ Cargo(C1) ∧ Cargo(C2) ∧ Cargo(C3)
    ∧ Plane(P1) ∧ Plane(P2) ∧ Plane(P3)
    ∧ Airport(JFK) ∧ Airport(SFO) ∧ Airport(ATL))
Goal(At(C1, JFK) ∧ At(C2, SFO) ∧ At(C3, SFO))
```

Second problem was visibly slightly more complex. The resulting state space was bigger and the search for the result was expected to take longer than in the case of the first problem. The breakdown of the results confirm this:

Air Cargo Problem 2						
Search Type	**Expansions**	**Goal Tests**	**New Nodes**	**Plan Length**	**Time Elapsed**	**Optimality**
breadth_first_search	3343	4609	30509	9	14.28175125	TRUE
depth_first_graph_search	624	625	5602	619	3.615272659	FALSE
uniform_cost_search	4853	4855	44041	9	12.36563489	TRUE
A* h_1	4853	4855	44041	9	12.70595564	TRUE
A* h_ignore_preconditions	1450	1452	13303	9	4.281149854	TRUE
A* h_pg_levelsum	4853	4855	44041	9	1779.856773	TRUE

You can find the problem 2 program run log in GitHub repo [1] in *p2_uninformed.txt* and *p2_informed.txt* files or see the console screenshots attached in Appendix 1.

Plan length found by each tested algorithm for Problem 2 is illustrated in the chart below:



2.3 Problem 2

The third problem was defined in PDDL as follows:

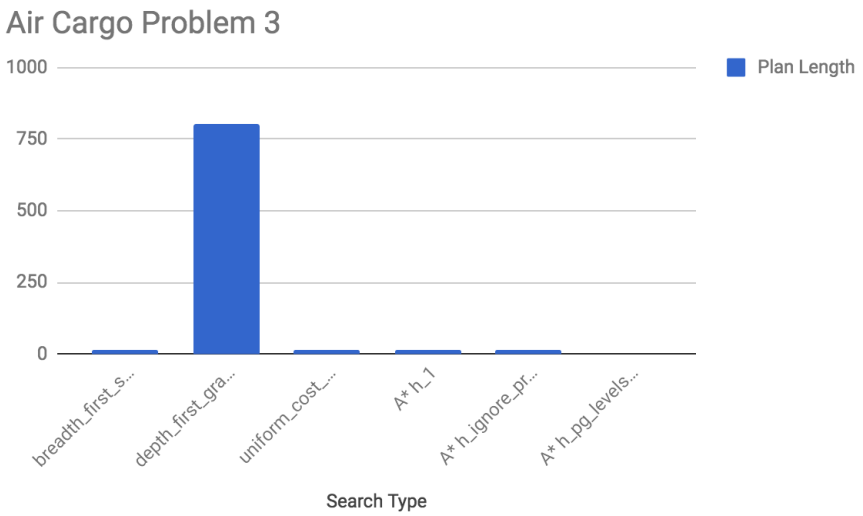
```
Init(At(C1, SFO) ∧ At(C2, JFK) ∧ At(C3, ATL) ∧ At(C4, ORD)
    ∧ At(P1, SFO) ∧ At(P2, JFK)
    ∧ Cargo(C1) ∧ Cargo(C2) ∧ Cargo(C3) ∧ Cargo(C4)
    ∧ Plane(P1) ∧ Plane(P2)
    ∧ Airport(JFK) ∧ Airport(SFO) ∧ Airport(ATL) ∧
Airport(ORD))
Goal(At(C1, JFK) ∧ At(C3, JFK) ∧ At(C2, SFO) ∧ At(C4,
SFO))
```

Third problem was visibly the hardest of the three to solve with most constraints and thus biggest state space of the three problems. The breakdown of the results confirm this:

Air Cargo Problem 3						
Search Type	**Expansions**	**Goal Tests**	**New Nodes**	**Plan Length**	**Time Elapsed**	**Optimality**
breadth_first_search	14415	17516	112865	12	93.36730828	TRUE
depth_first_graph_search	1119	1120	4974	805	3.029434124	FALSE
uniform_cost_search	17263	17265	134008	12	56.97802723	TRUE
A* h_1	17263	17265	134008	12	46.17499095	TRUE
A* h_ignore_preconditions	7593	7595	60971	13	23.58171814	TRUE
A* h_pg_levelsum	-	-	-	-	> 10 min	-

You can find the problem 3 program run log in GitHub repo [1] in *p3_uninformed.txt* and *p3_informed.txt* files or see the console screenshots attached in Appendix 1. Please note that *p3_informed.txt* is missing the results of *A* h_pg_levelsum* algorithm as it took a long time to compute and thus was terminated before it finished.

Plan length found by each tested algorithm for Problem 3 is illustrated in the chart below:



3. Experimental results

All the experiments were performed on Google Container Engine (GKE) [2] running in Docker containers using custom built Docker image publicly available on the Docker Hub [3] which packages my source code in it. The source code is also available on Github [1]. The Github repository also contains a Kubernetes job definition [4] which was used to run the *run_search.py* jobs on GKE. All of this allows for an easy experiment reproduction. Furthermore, you can find all the results and chart in the Google spreadsheet [5]. Hardware spec used for these experiments was: 2.4 GHz Intel Core i7, 16 GB 1867 MHz LPDDR3.

3.1 Uninformed search

All uninformed search algorithms find the solution to all three cargo shipping problems.

BFS (Breadth First Search) is guaranteed to find a solution if it exists [6]. Furthermore BFS finds optimal solution [6]. This is nicely demonstrated in the provided results where we can see that BFS finds the optimal results for each cargo shipping problem. However, BFS time complexity is exponential in depth, so the bigger the state space the longer it might take to find a solution, alas the solution will always be optimal if it exists. The time complexity of BFS is nicely illustrated in the BFS run for the third, the most complex problem.

DFS (Depth First Search) finds the "leftmost" solution regardless of depth or cost [6] as it searches the nodes that go as deep as possible in the state space without considering the nodes at same depths during the search. This has a nice property of low memory footprint as we need to keep the track of only the explored branch, however the solution found by DFS is not optimal. This is nicely demonstrated in the experimental results provided in this report. The paths to solution found by DFS for each of the problems is the longest one of all three uninformed search algorithms.

Finally I have also tested UCS (Uniformed Cost Search). UCS finds an optimal solution [6]. I would expect the UCS to perform about the same as BFS which becomes a UCS for path costs of 1.

3.2 Informed search

Informed search algorithms performed for more complex problems where uninformed search algorithm struggle due to a large size of the problem state space.

A h_1* performed about the same as uniformed searches for first two problem whilst finding the optimal solution for each problem. The most visible improvement of using this algorithm is in the third problem where the *A* h_1* performed over

50% faster than BFS and almost 20% faster than UCS whilst still finding an optimal solution to the problem.

A h_ignore_precondition* improves the search performance of finding the solution for complex problems (2 and 3) further still, up to 3x faster than uninformed search algorithms.

It's worth noting that *A* h_pg_levelsum* didn't find the solution for the third problem in reasonable amount of time (>15 minutes) whilst it also took it a long time to find the solution for the second problem. This is most likely due to heuristic being rather complex to calculate (note that this heuristic traverses the graph to accumulate the cost of partial goal presence at each graph level!).

4. Conclusion

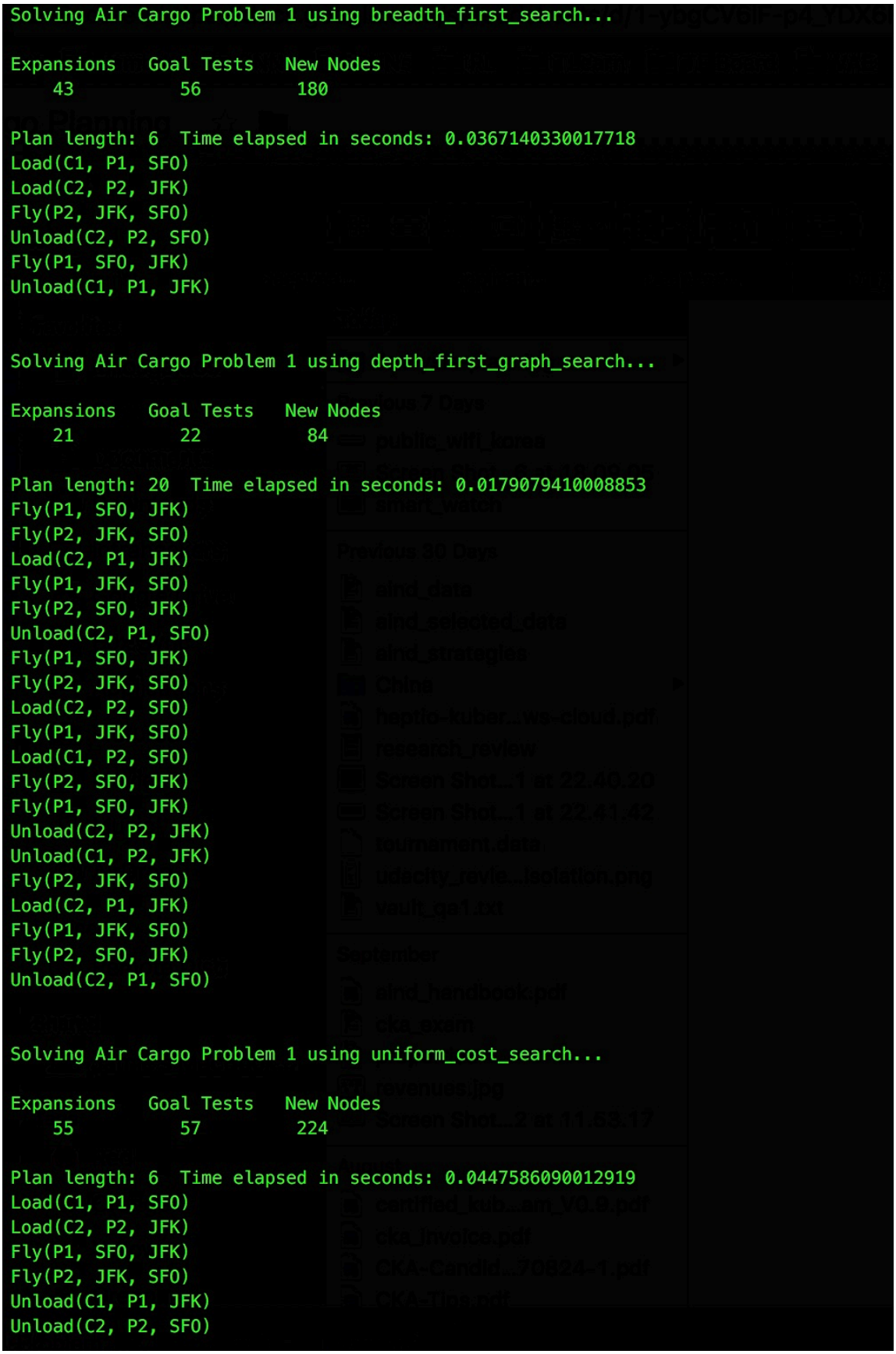
From the provided results we can see that of the uninformed search algorithms only BFS and UCS arrived at the optimal result. DFS failed to find the optimal solution, although it found a solution faster than the other two uninformed searches. Furthermore it appears that the most optimal uninformed search algorithm for Problem1 is BFS, whilst the best uninformed search algorithm for Problem 2 and 3 is UCS. Whilst both BFS and UCS find the optimal plans, UCS runs faster for Problem 2 and 3 and thus was chosen as the best one for these two problems.

With regards to informed search algorithms we can see that the best algorithm is A* with h_ignore_preconditions heuristic. This heuristics greatly relaxes the problem and takes short time to compute. This algorithm finds the optimal solution and clearly outperforms the remaining two informed search algorithms. In the more complex problems 2 and 3. As for the problem 1, A* with h_1 does the best in terms of finding the optimal solution in the shortest time and thus was chosen as the best algorithm for this problem.

References:

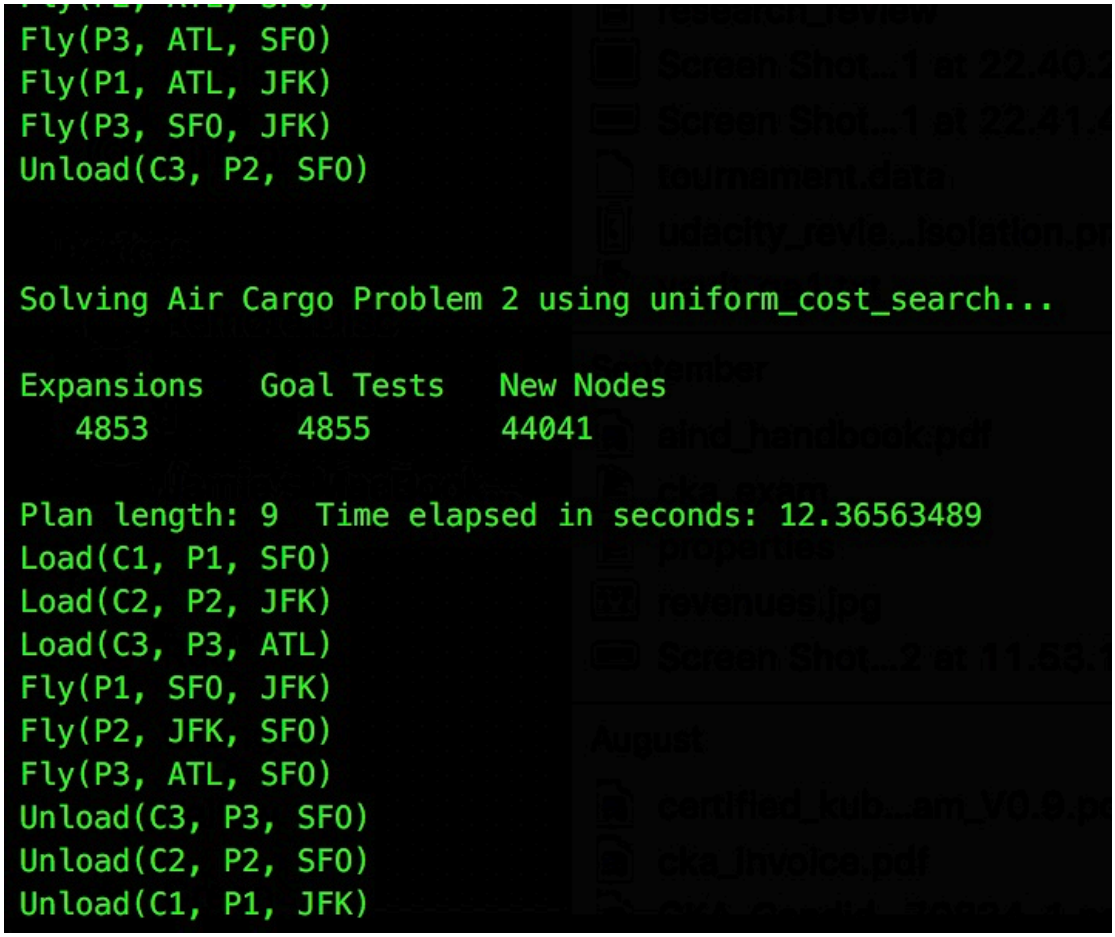
[1] https://github.com/milosgajdos83/udacity-aind/tree/master/planning-ai
[2] https://cloud.google.com/container-engine/
[3] https://hub.docker.com/r/gyre007/planning/
[4] https://kubernetes.io/docs/concepts/workloads/controllers/jobs-run-to-completion/
[5] https://docs.google.com/spreadsheets/d/1-ybgCV6lF-p4_YDX6F6AVGnWBhU6GA1ZT-3KarLPejY/edit#gid=0
[6] Russell, S. J., Norvig, P. (2010), Artificial intelligence: A modern approach.

APPENDIX Result Screenshots



```
Solving Air Cargo Problem 1 using astar_search with h_1...

Expansions   Goal Tests   New Nodes
    55          57         224

Plan length: 6  Time elapsed in seconds: 0.0354643999962718
Load(C1, P1, SFO)
Load(C2, P2, JFK)
Fly(P1, SFO, JFK)
Fly(P2, JFK, SFO)
Unload(C1, P1, JFK)
Unload(C2, P2, SFO)


Solving Air Cargo Problem 1 using astar_search with h_ignore_preconditions...

Expansions   Goal Tests   New Nodes
    41          43         170

Plan length: 6  Time elapsed in seconds: 0.0409763999996357
Load(C1, P1, SFO)
Fly(P1, SFO, JFK)
Unload(C1, P1, JFK)
Load(C2, P2, JFK)
Fly(P2, JFK, SFO)
Unload(C2, P2, SFO)


Solving Air Cargo Problem 1 using astar_search with h_pg_levelsum...

Expansions   Goal Tests   New Nodes
    55          57         224

Plan length: 6  Time elapsed in seconds: 1.80387959999643
Load(C1, P1, SFO)
Load(C2, P2, JFK)
Fly(P1, SFO, JFK)
Fly(P2, JFK, SFO)
Unload(C1, P1, JFK)
Unload(C2, P2, SFO)
```

```
Solving Air Cargo Problem 2 using breadth_first_search...

Expansions   Goal Tests   New Nodes
   3343        4609       30509

Plan length: 9  Time elapsed in seconds: 14.28175125
Load(C1, P1, SFO)
Load(C2, P2, JFK)
Load(C3, P3, ATL)
Fly(P2, JFK, SFO)
Unload(C2, P2, SFO)
Fly(P1, SFO, JFK)
Unload(C1, P1, JFK)
Fly(P3, ATL, SFO)
Unload(C3, P3, SFO)


Solving Air Cargo Problem 2 using depth_first_graph_search...

Expansions   Goal Tests   New Nodes
   624         625         5602

Plan length: 619  Time elapsed in seconds: 3.615272659
Fly(P3, ATL, SFO)
Fly(P1, SFO, ATL)
Fly(P3, SFO, JFK)
Fly(P1, ATL, JFK)
Fly(P2, JFK, ATL)
Fly(P3, JFK, ATL)
Fly(P2, ATL, SFO)
Fly(P3, ATL, SFO)
Load(C2, P1, JFK)
Fly(P2, SFO, ATL)
Fly(P1, JFK, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Fly(P3, SFO, ATL)
Fly(P1, SFO, JFK)
Load(C3, P3, ATL)
Fly(P3, ATL, SFO)
Fly(P2, JFK, ATL)
Fly(P3, SFO, JFK)
Fly(P2, ATL, SFO)
Fly(P1, JFK, ATL)
Fly(P2, SFO, JFK)
Fly(P1, ATL, SFO)
Unload(C3, P3, JFK)
Fly(P1, SFO, JFK)
Fly(P3, JFK, ATL)
Fly(P2, JFK, ATL)
Fly(P3, ATL, SFO)
Fly(P2, ATL, SFO)
```


Fly(P3, ATL, SFO)
Fly(P1, ATL, JFK)
Fly(P3, SFO, JFK)
Unload(C3, P2, SFO)
Solving Air Cargo Problem 2 using uniform_cost_search...
Expansions Goal Tests New Nodes
4853 4855 44041
Plan length: 9 Time elapsed in seconds: 12.36563489
Load(C1, P1, SFO)
Load(C2, P2, JFK)
Load(C3, P3, ATL)
Fly(P1, SFO, JFK)
Fly(P2, JFK, SFO)
Fly(P3, ATL, SFO)
Unload(C3, P3, SFO)
Unload(C2, P2, SFO)
Unload(C1, P1, JFK)

```
Solving Air Cargo Problem 2 using astar_search with h_1...

Expansions   Goal Tests   New Nodes
   4853         4855        44041

Plan length: 9  Time elapsed in seconds: 12.70595564
Load(C1, P1, SFO)
Load(C2, P2, JFK)
Load(C3, P3, ATL)
Fly(P1, SFO, JFK)
Fly(P2, JFK, SFO)
Fly(P3, ATL, SFO)
Unload(C3, P3, SFO)
Unload(C2, P2, SFO)
Unload(C1, P1, JFK)


Solving Air Cargo Problem 2 using astar_search with h_ignore_preconditions...

Expansions   Goal Tests   New Nodes
   1450         1452        13303

Plan length: 9  Time elapsed in seconds: 4.281149854
Load(C3, P3, ATL)
Fly(P3, ATL, SFO)
Unload(C3, P3, SFO)
Load(C2, P2, JFK)
Fly(P2, JFK, SFO)
Unload(C2, P2, SFO)
Load(C1, P1, SFO)
Fly(P1, SFO, JFK)
Unload(C1, P1, JFK)


Solving Air Cargo Problem 2 using astar_search with h_pg_levelsum...

Expansions   Goal Tests   New Nodes
   4853         4855        44041

Plan length: 9  Time elapsed in seconds: 1779.856773
Load(C1, P1, SFO)
Load(C2, P2, JFK)
Load(C3, P3, ATL)
Fly(P1, SFO, JFK)
Fly(P2, JFK, SFO)
Fly(P3, ATL, SFO)
Unload(C3, P3, SFO)
Unload(C2, P2, SFO)
Unload(C1, P1, JFK)
```

```
Solving Air Cargo Problem 3 using breadth_first_search...

Expansions   Goal Tests   New Nodes
  14415       17516       112865

Plan length: 12  Time elapsed in seconds: 93.36730828
Load(C2, P2, JFK)
Fly(P2, JFK, ATL)
Load(C3, P2, ATL)
Fly(P2, ATL, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, SFO)
Load(C1, P2, SFO)
Unload(C2, P2, SFO)
Unload(C4, P2, SFO)
Fly(P2, SFO, JFK)
Unload(C1, P2, JFK)
Unload(C3, P2, JFK)


Solving Air Cargo Problem 3 using depth_first_graph_search...

Expansions   Goal Tests   New Nodes
   1119        1120        4974

Plan length: 805  Time elapsed in seconds: 3.029434124
Fly(P1, SFO, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, ATL)
Fly(P2, ORD, ATL)
Fly(P1, ATL, JFK)
Fly(P2, ATL, SFO)
Load(C1, P2, SFO)
Fly(P2, SFO, ORD)
Unload(C1, P2, ORD)
Fly(P2, ORD, ATL)
Load(C3, P2, ATL)
Fly(P2, ATL, ORD)
Unload(C3, P2, ORD)
Fly(P2, ORD, JFK)
Load(C2, P2, JFK)
Fly(P2, JFK, ORD)
Unload(C2, P2, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, ATL)
Unload(C4, P2, ATL)
Fly(P2, ATL, ORD)
Load(C3, P2, ORD)
Fly(P2, ORD, ATL)
```

```
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, SFO)
Unload(C4, P2, SFO)


Solving Air Cargo Problem 3 using uniform_cost_search...

Expansions   Goal Tests   New Nodes
  17263       17265       134008

Plan length: 12  Time elapsed in seconds: 56.97802723
Load(C2, P2, JFK)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, SFO)
Load(C1, P2, SFO)
Unload(C4, P2, SFO)
Unload(C2, P2, SFO)
Fly(P2, SFO, ATL)
Load(C3, P2, ATL)
Fly(P2, ATL, JFK)
Unload(C3, P2, JFK)
Unload(C1, P2, JFK)
```

```
Solving Air Cargo Problem 3 using astar_search with h_1...

Expansions   Goal Tests   New Nodes
  17263       17265       134008

Plan length: 12  Time elapsed in seconds: 47.32398976299737
Load(C2, P2, JFK)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, SFO)
Load(C1, P2, SFO)
Unload(C4, P2, SFO)
Unload(C2, P2, SFO)
Fly(P2, SFO, ATL)
Load(C3, P2, ATL)
Fly(P2, ATL, JFK)
Unload(C3, P2, JFK)
Unload(C1, P2, JFK)


Solving Air Cargo Problem 3 using astar_search with h_ignore_preconditions...

Expansions   Goal Tests   New Nodes
   7593        7595       60971

Plan length: 13  Time elapsed in seconds: 23.581718139997975
Fly(P2, JFK, ATL)
Load(C3, P2, ATL)
Fly(P2, ATL, JFK)
Unload(C3, P2, JFK)
Load(C2, P2, JFK)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, SFO)
Unload(C4, P2, SFO)
Unload(C2, P2, SFO)
Load(C1, P2, SFO)
Fly(P2, SFO, JFK)
Unload(C1, P2, JFK)
```