Planning Search

Written Analysis

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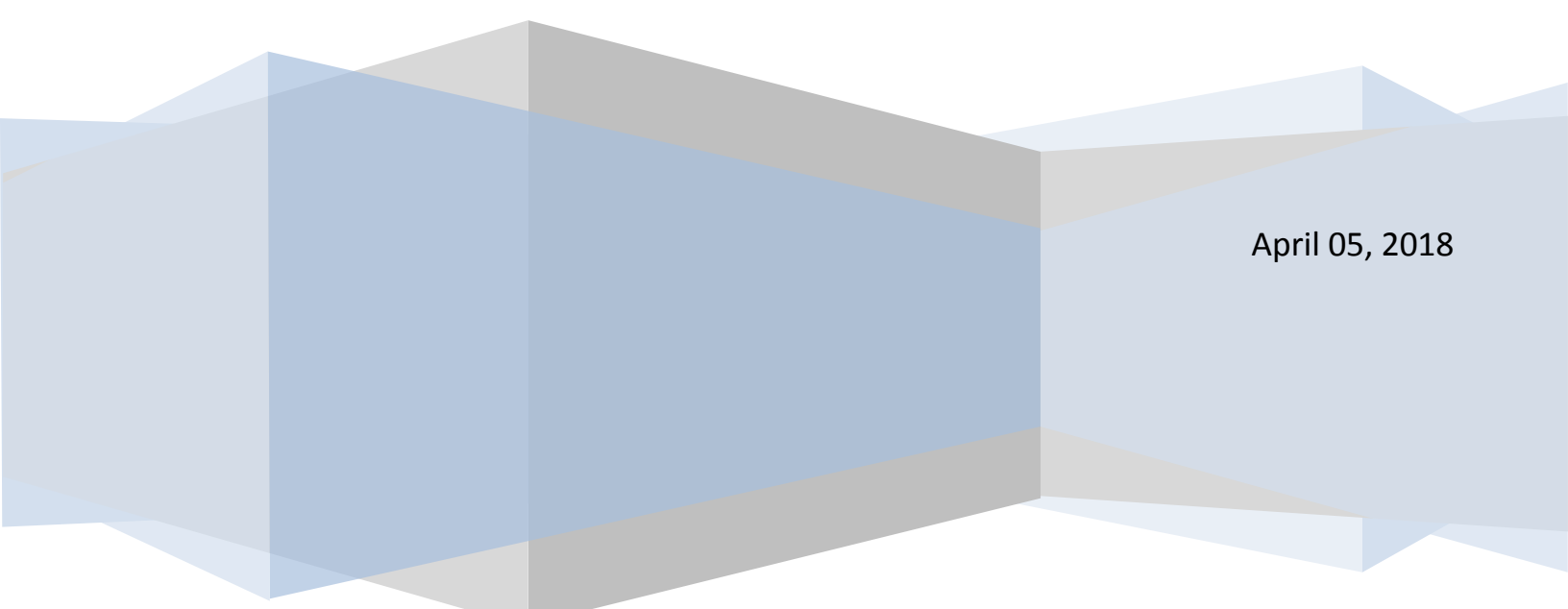
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Optimal Plan for Problems

Breadth-first search is optimal if the path cost is a non-decreasing function of the depth of the node. The most common such scenario is that all actions have the same cost. BFS finds an optimal solution as explained in AIMA book, Stuart Russell and Peter Norvig, 3rd edition, pp 82. Also we can assure that BFS will return the optimal plan for any problem because there is a mathematical proof about that. (Refer - https://cs.stackexchange.com/questions/16758/artificial-intelligence-condition-for-bfs-being-optimal)
All the given optimal paths are provided through Breadth First Search execution.

Problem1

Initial State and Goal

```
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))
```

Optimal Plan

```
Plan length: 6

Load(C2, P2, JFK)
Load(C1, P1, SFO)
Fly(P2, JFK, SFO)
Unload(C2, P2, SFO)
Fly(P1, SFO, JFK)
Unload(C1, P1, JFK)
```

Problem2

Initial State and Goal

```
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))
```

Optimal Plan

Plan length: 9

```
Load(C2, P2, JFK)
Load(C1, P1, SFO)
Fly(P2, JFK, ATL)
Load(C3, P2, ATL)
Fly(P1, SFO, JFK)
Unload(C1, P1, JFK)
Fly(P2, ATL, SFO)
Unload(C2, P2, SFO)
Unload(C3, P2, SFO)
```

Problem3

Initial State and Goal

```
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))
```

Optimal Plan

Plan length: 12

```
Load(C2, P2, JFK)
Load(C1, P1, SFO)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P1, SFO, ATL)
Load(C3, P1, ATL)
Fly(P1, ATL, JFK)
Unload(C1, P1, JFK)
Unload(C3, P1, JFK)
Fly(P2, ORD, SFO)
Unload(C2, P2, SFO)
Unload(C4, P2, SFO)
```

Uninformed Non-Heuristic Search

Search Result Summary

Uninformed Non-Heuristic search executed with Breadth First Search (BFS), Depth First Graph Search (DFS) and Uniform Cost Search (UCS). Summary of search execution result is given in the Table-1 below

Uninformed Non Heuristic Search	air_cargo_p1					
	Expansions	Goal Tests	New Nodes	Path Length	Time elapsed	Optimal
Breadth First Search	43	56	180	6	0.074898982	Yes
Depth First Graph Search	12	13	48	12	0.039374683	No
Uniform Cost Search	55	57	224	6	0.179323843	Yes
	air_cargo_p2					
	Expansions	Goal Tests	New Nodes	Path Length	Time elapsed	Optimal
Breadth First Search	1923	2672	15352	9	12.6776324	Yes
Depth First Graph Search	42	43	260	37	0.39658179	No
Uniform Cost Search	2724	2726	21377	9	15.2247564	Yes
	air_cargo_p3					
	Expansions	Goal Tests	New Nodes	Path Length	Time elapsed	Optimal
Breadth First Search	14663	18098	129631	12	98.42668082	Yes
Depth First Graph Search	627	628	5176	596	7.044076239	No
Uniform Cost Search	18222	18224	159608	12	119.5666757	Yes

Table-1 – Uninformed Non-Heuristic Search Result Summary

Nodes Expansion Analysis

Required memory/space and execution time increases with increasing number of expanded nodes. Least number of nodes are expanded by DFS then by BFS and then by UCS

For all the given problems - **Number of nodes expanded** is in the order

UCS > BFS > DFS

Time Elapsed Analysis

Required processing/execution time is directly impacted by the number of nodes expanded. Least time is taken by DFS then by BFS and then by UCS

For all the given problems – **Time elapsed** is in the order

UCS > BFS > DFS

Optimality Analysis

DFS is faster and expands fewer nodes than UCS, BFS but it does not provide optimal path, whereas both UCS and BFS provide optimal paths with best/least possible path length.

Optimality for Uninformed non-heuristic search methods is given below –

BFS   :   Optimal

DFS   :   Not Optimal

UCS   :   Optimal

Heuristic Search

Search Result Summary

A-star search executed with - null heuristic (h_1), ignore precondition heuristic (h_ignore_preconditions) and levelsum heuristic (h_pg_level_sum). Summary of search execution result is given in the Table-2 below.

A-Star Search	air_cargo_p1					
	Expansions	Goal Tests	New Nodes	Path Length	Time elapsed	Optimal
null heuristic	55	57	224	6	0.178929908	Yes
ignore preconditions heuristic	41	43	170	6	0.159391843	Yes
levelsum heuristic	11	13	50	6	2.509168079	Yes
	air_cargo_p2					
	Expansions	Goal Tests	New Nodes	Path Length	Time elapsed	Optimal
null heuristic	2724	2726	21377	9	12.25930121	Yes
ignore preconditions heuristic	876	878	7199	9	6.041756257	Yes
levelsum heuristic	238	240	1911	9	176.3866594	Yes
	air_cargo_p3					
	Expansions	Goal Tests	New Nodes	Path Length	Time elapsed	Optimal
null heuristic	18222	18224	159608	12	120.7371119	Yes
ignore preconditions heuristic	5040	5042	44944	12	36.6310467	Yes
levelsum heuristic	325	327	3002	12	761.411805	Yes

Table-2 – Heuristic Search Result Summary

Nodes Expansion Analysis

Required memory/space and execution time increases with increasing number of expanded nodes. While executing A* search least number of nodes are expanded through levelsum heuristic (h_pg_level_sum) then by ignore precondition heuristic (h_ignore_preconditions) and then by null heuristic (h_1)

For all the given problems - **Number of nodes expanded** in A* search through different heuristics is in the order -

h_1 > h_ignore_preconditions > h_pg_level_sum

Time Elapsed Analysis

Required processing/execution time is directly impacted by computation complexity of heuristic method and the number of nodes expanded. A* search execution with ignore precondition heuristic (h_ignore_preconditions) is the fastest as it takes the least time followed by null heuristic (h_1) followed by levelsum heuristic (h_pg_level_sum)

For all the given problems – **Time elapsed** in A* search through different heuristics is in the order -

h_pg_level_sum > h_1 > h_ignore_preconditions

Optimality Analysis

Executing A* search with all the given heuristic methods provides optimal paths with best/least possible path length.

Optimality for heuristic search methods is given below –

null heuristic   :   **Optimal**

ignore precondition heuristic   :   **Optimal**

levelsum heuristic   :   **Optimal**

Best heuristic

Among all the given heuristic methods **ignore precondition heuristic (h_ignore_preconditions) is the best heuristic.**

Ignore precondition heuristic **provides the optimal path and is the fastest** among all the given heuristic methods. If we compare with uninformed non-heuristic search methods then DFS is faster than h_ignore_preconditions but DFS is not optimal.

Level sum heuristic is also optimal and expands fewer nodes than h_ignore_preconditions but level sum heuristic has higher computational complexity which makes it slower than h_ignore_preconditions

Console Output

Uninformed Non-Heuristic Search Output

```
Solving Air Cargo Problem 1 using
breadth_first_search...

Expansions    Goal Tests    New Nodes
    43            56           180

Plan length: 6  Time elapsed in seconds:
0.07489898197094974
Load(C2, P2, JFK)
Load(C1, P1, SFO)
Fly(P2, JFK, SFO)
Unload(C2, P2, SFO)
Fly(P1, SFO, JFK)
Unload(C1, P1, JFK)



Solving Air Cargo Problem 1 using
depth_first_graph_search...

Expansions    Goal Tests    New Nodes
    12            13            48

Plan length: 12  Time elapsed in seconds:
0.0393746826812732
Fly(P1, SFO, JFK)
Fly(P2, JFK, SFO)
Load(C1, P2, SFO)
Fly(P2, SFO, JFK)
Fly(P1, JFK, SFO)
Unload(C1, P2, JFK)
Fly(P2, JFK, SFO)
Fly(P1, SFO, JFK)
Load(C2, P1, JFK)
Fly(P2, SFO, JFK)
```

```
Fly(P1, JFK, SFO)
Unload(C2, P1, SFO)
```

Solving Air Cargo Problem 1 using
uniform_cost_search...

Expansions	Goal Tests	New Nodes
55	57	224

Plan length: 6 Time elapsed in seconds:
0.17932384324893316
```
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
1923	2672	15352

Plan length: 9 Time elapsed in seconds:
12.677632403444216
```
Load(C2, P2, JFK)
Load(C1, P1, SFO)
Fly(P2, JFK, ATL)
Load(C3, P2, ATL)
Fly(P1, SFO, JFK)
Unload(C1, P1, JFK)
Fly(P2, ATL, SFO)
Unload(C2, P2, SFO)
Unload(C3, P2, SFO)
```

Solving Air Cargo Problem 2 using
depth_first_graph_search...

```
Expansions    Goal Tests    New Nodes
   42            43            260


Plan length: 37  Time elapsed in seconds:
0.3965817902785732
Fly(P3, ATL, JFK)
Fly(P1, SFO, ATL)
Fly(P2, JFK, ATL)
Fly(P1, ATL, JFK)
Fly(P2, ATL, SFO)
Load(C1, P2, SFO)
Fly(P2, SFO, ATL)
Fly(P1, JFK, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Unload(C1, P2, JFK)
Fly(P1, SFO, JFK)
Fly(P2, JFK, ATL)
Fly(P1, JFK, ATL)
Fly(P2, ATL, SFO)
Load(C3, P1, ATL)
Fly(P1, ATL, SFO)
Fly(P2, SFO, ATL)
Fly(P1, SFO, JFK)
Fly(P2, ATL, JFK)
Unload(C3, P1, JFK)
Fly(P1, JFK, ATL)
Load(C3, P2, JFK)
Fly(P1, ATL, SFO)
Fly(P2, JFK, SFO)
Fly(P1, SFO, JFK)
Unload(C3, P2, SFO)
Fly(P2, SFO, ATL)
Fly(P1, JFK, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Load(C2, P2, JFK)
Fly(P1, SFO, JFK)
Fly(P2, JFK, ATL)
Fly(P1, JFK, ATL)
```

```
Fly(P2, ATL, SFO)
Unload(C2, P2, SFO)


Solving Air Cargo Problem 2 using
uniform_cost_search...

Expansions    Goal Tests    New Nodes
   2724          2726         21377

Plan length: 9  Time elapsed in seconds:
15.22475639973327
Load(C1, P1, SFO)
Load(C2, P2, JFK)
Fly(P2, JFK, ATL)
Load(C3, P2, ATL)
Fly(P1, SFO, JFK)
Fly(P2, ATL, SFO)
Unload(C3, P2, SFO)
Unload(C2, P2, SFO)
Unload(C1, P1, JFK)


Solving Air Cargo Problem 3 using
breadth_first_search...

Expansions    Goal Tests    New Nodes
  14663         18098        129631

Plan length: 12  Time elapsed in seconds:
98.42668082152348
Load(C2, P2, JFK)
Load(C1, P1, SFO)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P1, SFO, ATL)
Load(C3, P1, ATL)
Fly(P1, ATL, JFK)
Unload(C1, P1, JFK)
Unload(C3, P1, JFK)
Fly(P2, ORD, SFO)
```

```
Unload(C2, P2, SFO)
Unload(C4, P2, SFO)


Solving Air Cargo Problem 3 using
depth_first_graph_search...

Expansions    Goal Tests    New Nodes
   627           628           5176

Plan length: 596  Time elapsed in seconds:
7.044076239473145
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)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Unload(C1, P2, JFK)
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(C2, P1, JFK)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Unload(C2, P1, SFO)
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(C2, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Load(C3, P1, ATL)
Fly(P1, ATL, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, SFO)
Fly(P2, ORD, ATL)
Fly(P1, SFO, JFK)
Fly(P2, ATL, SFO)
Unload(C2, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, SFO)
Fly(P2, ATL, JFK)
Fly(P1, SFO, ATL)
Load(C1, P2, JFK)
Fly(P1, ATL, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, SFO)
Fly(P2, ORD, ATL)
Fly(P1, SFO, JFK)
Fly(P2, ATL, SFO)
Unload(C1, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Unload(C3, P1, SFO)
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(C3, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Unload(C3, P2, JFK)
Fly(P1, SFO, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, ATL)
Fly(P2, ORD, SFO)
Load(C2, P2, SFO)
Fly(P1, ATL, ORD)
Fly(P2, SFO, ORD)
Fly(P1, ORD, SFO)
Fly(P2, ORD, ATL)
Fly(P1, SFO, JFK)
Fly(P2, ATL, JFK)
Unload(C2, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, SFO)
Fly(P1, ATL, SFO)
Load(C1, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, JFK)
Unload(C1, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
```

```
Fly(P2, ORD, ATL)
Load(C4, P1, ORD)
Fly(P1, ORD, ATL)
Fly(P2, ATL, ORD)
Fly(P1, ATL, SFO)
Fly(P2, ORD, SFO)
Fly(P1, SFO, JFK)
Fly(P2, SFO, JFK)
Unload(C4, P1, JFK)
Fly(P2, JFK, ORD)
Load(C3, P1, JFK)
Fly(P2, ORD, ATL)
Fly(P1, JFK, ORD)
Fly(P2, ATL, SFO)
Fly(P1, ORD, ATL)
Fly(P2, SFO, JFK)
Fly(P1, ATL, SFO)
Unload(C3, P1, SFO)
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(C3, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Load(C4, P2, JFK)
Fly(P1, SFO, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, ATL)
Fly(P2, ORD, ATL)
Fly(P1, ATL, JFK)
Fly(P2, ATL, SFO)
Unload(C4, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
```

```
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Unload(C3, P2, JFK)
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(C4, P2, SFO)
Fly(P2, SFO, ATL)
Fly(P1, JFK, ORD)
Unload(C4, P2, ATL)
Fly(P1, ORD, SFO)
Fly(P2, ATL, ORD)
Fly(P1, SFO, JFK)
Fly(P2, ORD, SFO)
Fly(P1, JFK, ATL)
Fly(P2, SFO, JFK)
Load(C3, P2, JFK)
Fly(P1, ATL, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, SFO)
Fly(P2, ORD, ATL)
Unload(C3, P2, ATL)
Fly(P2, ATL, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ORD, ATL)
Fly(P2, SFO, JFK)
Fly(P1, ATL, JFK)
Load(C2, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, SFO)
Fly(P1, ATL, SFO)
Unload(C2, P2, SFO)
```

```
Fly(P2, SFO, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, JFK)
Load(C1, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, SFO)
Fly(P1, ATL, SFO)
Unload(C1, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Load(C4, P1, ATL)
Fly(P1, ATL, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, SFO)
Fly(P2, ORD, ATL)
Fly(P1, SFO, JFK)
Fly(P2, ATL, SFO)
Unload(C4, P1, JFK)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Load(C2, P1, SFO)
Fly(P1, SFO, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, ATL)
Fly(P2, ORD, ATL)
Fly(P1, ATL, JFK)
Fly(P2, ATL, SFO)
Unload(C2, P1, JFK)
```

```
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Load(C1, P1, SFO)
Fly(P1, SFO, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, ATL)
Fly(P2, ORD, ATL)
Fly(P1, ATL, JFK)
Fly(P2, ATL, SFO)
Unload(C1, P1, JFK)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, JFK)
Fly(P1, ORD, SFO)
Load(C4, P2, JFK)
Fly(P1, SFO, ATL)
Fly(P2, JFK, SFO)
Fly(P1, ATL, ORD)
Unload(C4, P2, SFO)
Fly(P1, ORD, SFO)
Fly(P2, SFO, ORD)
Fly(P1, SFO, ATL)
Fly(P2, ORD, JFK)
Fly(P1, ATL, JFK)
Fly(P2, JFK, ATL)
Load(C2, P1, JFK)
Fly(P2, ATL, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ORD, ATL)
Fly(P2, SFO, JFK)
Fly(P1, ATL, SFO)
Unload(C2, P1, SFO)
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(C4, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, JFK, SFO)
Fly(P2, ORD, ATL)
Load(C3, P2, ATL)
Fly(P2, ATL, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ORD, ATL)
Fly(P2, SFO, JFK)
Fly(P1, ATL, JFK)
Unload(C4, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, SFO)
Fly(P1, ATL, SFO)
Unload(C3, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, JFK)
Load(C4, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Unload(C4, P2, ATL)
Fly(P2, ATL, ORD)
Fly(P1, ATL, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ORD, SFO)
Fly(P2, SFO, JFK)
Fly(P1, SFO, JFK)
Load(C1, P2, JFK)
Fly(P2, JFK, ORD)
```

```
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, SFO)
Fly(P1, ATL, SFO)
Unload(C1, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Load(C4, P1, ATL)
Fly(P1, ATL, SFO)
Fly(P2, JFK, ORD)
Fly(P1, SFO, JFK)
Fly(P2, ORD, ATL)
Fly(P1, JFK, ORD)
Fly(P2, ATL, SFO)
Load(C3, P2, SFO)
Fly(P1, ORD, ATL)
Fly(P2, SFO, ORD)
Fly(P1, ATL, SFO)
Fly(P2, ORD, JFK)
Fly(P1, SFO, JFK)
Unload(C3, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ATL)
Fly(P2, ORD, ATL)
Fly(P1, ATL, ORD)
Fly(P2, ATL, SFO)
Fly(P1, ORD, SFO)
Unload(C4, P1, SFO)
Fly(P2, SFO, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, JFK)
Load(C3, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
```

```
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, SFO)
Fly(P1, ATL, SFO)
Unload(C3, P2, SFO)
Fly(P1, SFO, ORD)
Load(C4, P2, SFO)
Fly(P1, ORD, ATL)
Fly(P2, SFO, JFK)
Fly(P1, ATL, SFO)
Fly(P2, JFK, ORD)
Load(C3, P1, SFO)
Fly(P2, ORD, ATL)
Fly(P1, SFO, ORD)
Fly(P2, ATL, SFO)
Fly(P1, ORD, ATL)
Fly(P2, SFO, JFK)
Fly(P1, ATL, JFK)
Unload(C4, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, SFO)
Fly(P2, ATL, SFO)
Fly(P1, SFO, ATL)
Load(C2, P2, SFO)
Fly(P1, ATL, ORD)
Fly(P2, SFO, ORD)
Fly(P1, ORD, SFO)
Fly(P2, ORD, ATL)
Fly(P1, SFO, JFK)
Fly(P2, ATL, JFK)
Unload(C2, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, SFO)
Fly(P2, ATL, SFO)
Fly(P1, SFO, ATL)
Load(C1, P2, SFO)
Fly(P1, ATL, ORD)
```

```
Fly(P2, SFO, ORD)
Fly(P1, ORD, SFO)
Fly(P2, ORD, ATL)
Fly(P1, SFO, JFK)
Fly(P2, ATL, JFK)
Load(C4, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, SFO)
Fly(P1, ATL, SFO)
Unload(C4, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, JFK)
Unload(C1, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, SFO)
Fly(P1, ATL, SFO)
Unload(C3, P1, SFO)
Fly(P2, SFO, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, JFK)
Load(C2, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, SFO)
Fly(P1, ATL, SFO)
Unload(C2, P2, SFO)
```

```
Fly(P2, SFO, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, JFK)
Load(C1, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, SFO)
Load(C2, P2, SFO)
Fly(P1, ATL, ORD)
Fly(P2, SFO, ORD)
Fly(P1, ORD, SFO)
Fly(P2, ORD, ATL)
Fly(P1, SFO, JFK)
Unload(C2, P2, ATL)
Fly(P2, ATL, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ORD, ATL)
Fly(P2, SFO, JFK)
Fly(P1, ATL, SFO)
Unload(C1, P2, JFK)
Fly(P1, SFO, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, ATL)
Fly(P2, ORD, SFO)
Fly(P1, ATL, JFK)
Fly(P2, SFO, ATL)
Load(C1, P1, JFK)
Fly(P2, ATL, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ORD, ATL)
Fly(P2, SFO, JFK)
Fly(P1, ATL, SFO)
Unload(C1, P1, SFO)
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(C4, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Unload(C4, P2, JFK)
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(C3, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Unload(C3, P2, JFK)
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)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Unload(C1, P2, JFK)
```

```
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(C4, P1, JFK)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SFO)
Unload(C4, P1, SFO)
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(C4, P2, SFO)
Fly(P2, SFO, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Load(C2, P1, ATL)
Fly(P1, ATL, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, SFO)
Fly(P2, ORD, ATL)
Unload(C4, P2, ATL)
Fly(P2, ATL, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ORD, ATL)
Fly(P2, SFO, JFK)
Fly(P1, ATL, JFK)
Load(C3, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
```

```
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, SFO)
Unload(C2, P1, ATL)
Fly(P1, ATL, ORD)
Fly(P2, SFO, ORD)
Fly(P1, ORD, SFO)
Fly(P2, ORD, ATL)
Fly(P1, SFO, JFK)
Fly(P2, ATL, JFK)
Unload(C3, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ORD, SFO)
Fly(P2, SFO, ATL)
Load(C2, P2, ATL)
Fly(P2, ATL, ORD)
Fly(P1, SFO, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ORD, ATL)
Unload(C2, P2, SFO)
Fly(P1, ATL, SFO)
Fly(P2, SFO, JFK)
Fly(P1, SFO, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, JFK)
Fly(P2, ORD, ATL)
Load(C4, P2, ATL)
Fly(P2, ATL, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ORD, ATL)
Unload(C4, P2, SFO)
```

Solving Air Cargo Problem 3 using
uniform_cost_search...

Expansions	Goal Tests	New Nodes
18222	18224	159608

```
Plan length: 12   Time elapsed in seconds:
119.5666757487011
Load(C1, P1, SFO)
Load(C2, P2, JFK)
Fly(P1, SFO, ATL)
Load(C3, P1, ATL)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ATL, JFK)
Unload(C4, P2, SFO)
Unload(C3, P1, JFK)
Unload(C2, P2, SFO)
Unload(C1, P1, JFK)
```

Heuristic Search Output

```
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:
0.17892990822297664
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:
0.15939184302138326
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
    11            13            50

Plan length: 6   Time elapsed in seconds:
2.5091680785166828
Load(C1, P1, SFO)
Fly(P1, SFO, JFK)
Load(C2, P2, JFK)
Fly(P2, JFK, SFO)
Unload(C1, P1, JFK)
Unload(C2, P2, SFO)


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

Expansions    Goal Tests    New Nodes
   2724          2726          21377

Plan length: 9   Time elapsed in seconds:
12.259301208024642
Load(C1, P1, SFO)
Load(C2, P2, JFK)
Fly(P2, JFK, ATL)
Load(C3, P2, ATL)
Fly(P1, SFO, JFK)
Fly(P2, ATL, SFO)
```

```
Unload(C3, P2, 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
   876           878          7199
```

Plan length: 9 Time elapsed in seconds:
6.041756257300737

```
Load(C2, P2, JFK)
Fly(P2, JFK, ATL)
Load(C3, P2, ATL)
Fly(P2, ATL, SFO)
Unload(C3, P2, 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
   238           240          1911
```

Plan length: 9 Time elapsed in seconds:
176.38665941814813

```
Load(C2, P2, JFK)
Fly(P2, JFK, ATL)
Load(C3, P2, ATL)
Fly(P2, ATL, SFO)
Load(C1, P1, SFO)
Fly(P1, SFO, JFK)
Unload(C3, P2, SFO)
Unload(C2, P2, SFO)
Unload(C1, P1, JFK)
```

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

Expansions    Goal Tests    New Nodes
  18222         18224        159608

Plan length: 12  Time elapsed in seconds:
120.73711188738505
Load(C1, P1, SFO)
Load(C2, P2, JFK)
Fly(P1, SFO, ATL)
Load(C3, P1, ATL)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, SFO)
Fly(P1, ATL, JFK)
Unload(C4, P2, SFO)
Unload(C3, P1, JFK)
Unload(C2, P2, SFO)
Unload(C1, P1, JFK)


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

Expansions    Goal Tests    New Nodes
   5040          5042         44944

Plan length: 12  Time elapsed in seconds:
36.6310466994789
Load(C2, P2, JFK)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, SFO)
Unload(C4, P2, SFO)
Load(C1, P1, SFO)
Fly(P1, SFO, ATL)
Load(C3, P1, ATL)
Fly(P1, ATL, JFK)
```

```
Unload(C3, P1, JFK)
Unload(C2, P2, SFO)
Unload(C1, P1, JFK)


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

Expansions    Goal Tests    New Nodes
   325           327          3002

Plan length: 12  Time elapsed in seconds:
761.4118049623837
Load(C2, P2, JFK)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, SFO)
Load(C1, P1, SFO)
Fly(P1, SFO, ATL)
Load(C3, P1, ATL)
Fly(P1, ATL, JFK)
Unload(C4, P2, SFO)
Unload(C3, P1, JFK)
Unload(C2, P2, SFO)
Unload(C1, P1, JFK)
```