

Udacity AIND December 2017 cohort

Planning Search

Written Analysis

Rohit Jain

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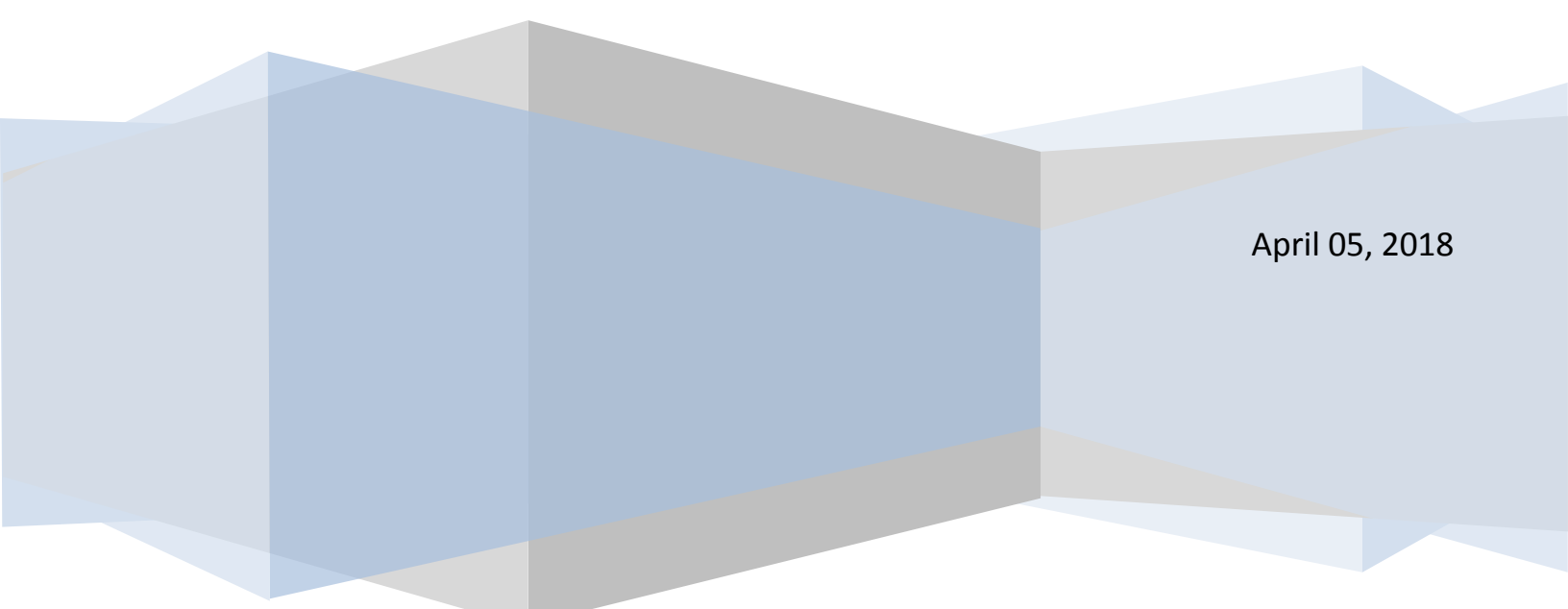


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Optimal Plan for Problems

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. All the given optimal paths are provided through Breadth First Search execution.

Problem1

Initial State and Goal

```
Init (At (C1, SFO)  $\wedge$  At (C2, JFK)
 $\wedge$  At (P1, SFO)  $\wedge$  At (P2, JFK)
 $\wedge$  Cargo (C1)  $\wedge$  Cargo (C2)
 $\wedge$  Plane (P1)  $\wedge$  Plane (P2)
 $\wedge$  Airport (JFK)  $\wedge$  Airport (SFO))
Goal (At (C1, JFK)  $\wedge$  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)  $\wedge$  At (C2, JFK)  $\wedge$  At (C3, ATL)
 $\wedge$  At (P1, SFO)  $\wedge$  At (P2, JFK)  $\wedge$  At (P3, ATL)
 $\wedge$  Cargo (C1)  $\wedge$  Cargo (C2)  $\wedge$  Cargo (C3)
 $\wedge$  Plane (P1)  $\wedge$  Plane (P2)  $\wedge$  Plane (P3)
 $\wedge$  Airport (JFK)  $\wedge$  Airport (SFO)  $\wedge$  Airport (ATL))
Goal (At (C1, JFK)  $\wedge$  At (C2, SFO)  $\wedge$  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)  $\wedge$  At(C2, JFK)  $\wedge$  At(C3, ATL)  $\wedge$  At(C4, ORD)
 $\wedge$  At(P1, SFO)  $\wedge$  At(P2, JFK)
 $\wedge$  Cargo(C1)  $\wedge$  Cargo(C2)  $\wedge$  Cargo(C3)  $\wedge$  Cargo(C4)
 $\wedge$  Plane(P1)  $\wedge$  Plane(P2)
 $\wedge$  Airport(JFK)  $\wedge$  Airport(SFO)  $\wedge$  Airport(ATL)  $\wedge$ 
Airport(ORD))
Goal(At(C1, JFK)  $\wedge$  At(C3, JFK)  $\wedge$  At(C2, SFO)  $\wedge$  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 (h₁), 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 (h₁)

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

h₁ > 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)
```