

# *HEURISTIC ANALYSIS*

For deterministic logistics planning problems in an Air Cargo transport system.

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## Introduction

This project gives a group of problems to solve using classical PDDL (Planning Domain Definition Language) for an Air Cargo Transport System. The project defines a schema and has 3 problems to solve which are set up below.

## Schema

```
Action(Load(c, p, a),
  PRECOND: At(c, a) ∧ At(p, a) ∧ Cargo(c) ∧ Plane(p) ∧ Airport(a)
  EFFECT: ¬ At(c, a) ∧ In(c, p))
Action(Unload(c, p, a),
  PRECOND: In(c, p) ∧ At(p, a) ∧ Cargo(c) ∧ Plane(p) ∧ Airport(a)
  EFFECT: At(c, a) ∧ ¬ In(c, p))
Action(Fly(p, from, to),
  PRECOND: At(p, from) ∧ Plane(p) ∧ Airport(from) ∧ Airport(to)
  EFFECT: ¬ At(p, from) ∧ At(p, to))
```

## Problem 1

```
Init(At(C1, SF0) ∧ At(C2, JFK)
  ∧ At(P1, SF0) ∧ At(P2, JFK)
  ∧ Cargo(C1) ∧ Cargo(C2)
  ∧ Plane(P1) ∧ Plane(P2)
  ∧ Airport(JFK) ∧ Airport(SF0))
Goal(At(C1, JFK) ∧ At(C2, SF0))
```

## Problem 2

```
Init(At(C1, SF0) ∧ At(C2, JFK) ∧ At(C3, ATL)
  ∧ At(P1, SF0) ∧ At(P2, JFK) ∧ At(P3, ATL)
  ∧ Cargo(C1) ∧ Cargo(C2) ∧ Cargo(C3)
  ∧ Plane(P1) ∧ Plane(P2) ∧ Plane(P3)
  ∧ Airport(JFK) ∧ Airport(SF0) ∧ Airport(ATL))
Goal(At(C1, JFK) ∧ At(C2, SF0) ∧ At(C3, SF0))
```

## Problem 3

```
Init(At(C1, SF0) ∧ At(C2, JFK) ∧ At(C3, ATL) ∧ At(C4, ORD)
  ∧ At(P1, SF0) ∧ At(P2, JFK)
  ∧ Cargo(C1) ∧ Cargo(C2) ∧ Cargo(C3) ∧ Cargo(C4)
  ∧ Plane(P1) ∧ Plane(P2)
  ∧ Airport(JFK) ∧ Airport(SF0) ∧ Airport(ATL) ∧ Airport(ORD))
Goal(At(C1, JFK) ∧ At(C3, JFK) ∧ At(C2, SF0) ∧ At(C4, SF0))
```

## Uniform Non-Heuristic Search

For the Uniform Non-Heuristic Search experiments I used Breadth First Search (BF), Depth First Search (DF) and Uniform Cost Search (UC). The result of these experiments are shown in the table below.

Problem	Search	Length	Time (s)	Nodes Expanded	Goal Tests	Optimal?
1	BF	6	0.030	43	56	Yes
1	DF	12	0.009	12	13	No
1	UC	6	0.032	55	57	Yes
2	BF	9	7.681	3343	4609	Yes
2	DF	575	2.757	582	583	No
2	UC	9	10.114	4605	4607	Yes
3	BF	12	39.400	14663	18098	Yes
3	DF	596	3.493	627	628	No
3	UC	12	54.340	16961	16963	Yes

## Results Analysis

Of the 3 search methods used, Breadth First search and Uniform Cost search produced an optimal result at the end of their testing. Depth First search, although much faster to produce a result, did not find the optimal length plan for any of the problems (12 vs 6 for problem 1, 575 vs 9 for problem 2 and 596 vs 12 for problem 3). If optimality was necessary in our result, then Depth First search would not be used.

The memory required to produce a result can be represented by the number of nodes each search algorithm expanded. From the results, we can see that Depth First search wins this round by a long shot in all 3 problems. Breadth First search comes in second place with Uniform Cost search coming a close 3<sup>rd</sup>. This means that if memory was a limiting factor in gaining a result, then Depth First search should be used.

From the results, we can also determine that Depth First search is the fastest algorithm to produce a result. Second is Breadth First, followed by Uniform Cost. If time was the limiting factor in gaining a result, then Depth First search should be used to produce the quickest result.

In conclusion, we can see that if we are looking for the most optimal path then either Breadth First search or Uniform Cost search should be used. But if time or memory are a constraint on the system, then Depth First search should be used, although it is very unlikely that it will produce an optimal solution.

## Heuristic Search

For the heuristic search, I experimented with:

- h\_1: Similar to Uniform Cost search.
- h\_ignore\_preconditions (h\_ip): An approach explained in “Artificial Intelligence: A Modern Approach”.
- h\_pg\_level\_sum (h\_pls): Planning graph.

The searches were performed using the A\* algorithm and the results are shown in the table below.

Problem	Heuristic	Length	Time (s)	Nodes Expanded	Goal Tests	Optimal?
1	h_1	6	0.034	55	57	Yes
1	h_ip	6	0.036	41	43	Yes
1	h_pls	6	0.718	11	13	Yes
2	h_1	9	10.122	4605	4607	Yes
2	h_ip	9	3.602	1311	1313	Yes
2	h_pls	9	117.268	74	76	Yes
3	h_1	12	43.457	16961	16963	Yes
3	h_ip	12	12.635	4444	4446	Yes
3	h_pls	13	593.163	229	231	No

## Results Analysis

From the results, we can see that overall h\_ignore\_preconditions produced a result the quickest. H\_1, which is similar to Uniform Cost search came second and h\_pg\_level\_sum came in third place. In all 3 problems, h\_pg\_level\_sum took significantly longer to produce a result than the other 2.

From the Expanded Nodes results we can see that h\_pg\_level\_sum uses significantly less memory than the other heuristics with h\_ignore\_preconditions coming in second place and h\_1 using the most memory.

In all but one case, the tests produced an optimal result. Each of the heuristics produced the same minimum number of actions except for the h\_pg\_level\_sum heuristic on problem 3. This test took significantly longer than the others and did not produce an optimal plan.

In conclusion, if the limiting factor is memory, and time is not an issue, then h\_pg\_level\_sum should be used to find the result. This produced a result using less node expansions than any other heuristic or non-heuristic search. If however, the solution is time critical, then h\_ignore\_preconditions will produce an optimal result in the quickest time, and in some cases, quicker than the non-heuristic searches.

## Best Heuristic

From the results, we can say that h\_ignore\_preconditions is the best heuristic to use as it is a good balance between time and memory usage and has always produced an optimal

result. It has been proven that Depth First search will produce a solution faster with less memory usage but we can say that this has never produced an optimal result and therefore should be discounted.

## Appendix A

Below are the raw results for each experiment.

Problem: 1

Searches: Breadth first, depth first, uniform cost

Solving Air Cargo Problem 1 using breadth\_first\_search...

Expansions	Goal Tests	New Nodes
43	56	180

Plan length: 6 Time elapsed in seconds: 0.029864649986848235

```
Load(C2, P2, JFK)
Load(C1, P1, SF0)
Fly(P2, JFK, SF0)
Unload(C2, P2, SF0)
Fly(P1, SF0, 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: 0.008633717196062207

```
Fly(P1, SF0, JFK)
Fly(P2, JFK, SF0)
Load(C1, P2, SF0)
Fly(P2, SF0, JFK)
Fly(P1, JFK, SF0)
Unload(C1, P2, JFK)
Fly(P2, JFK, SF0)
Fly(P1, SF0, JFK)
Load(C2, P1, JFK)
Fly(P2, SF0, JFK)
Fly(P1, JFK, SF0)
Unload(C2, P1, SF0)
```

Solving Air Cargo Problem 1 using uniform\_cost\_search...

Expansions	Goal Tests	New Nodes
55	57	224

Plan length: 6 Time elapsed in seconds: 0.031943968031555414

```
Load(C1, P1, SF0)
Load(C2, P2, JFK)
Fly(P1, SF0, JFK)
Fly(P2, JFK, SF0)
Unload(C1, P1, JFK)
Unload(C2, P2, SF0)
```

Problem: 2

Searches: Breadth first, depth first, uniform cost

Solving Air Cargo Problem 2 using breadth\_first\_search...

Expansions	Goal Tests	New Nodes
3343	4609	30509

Plan length: 9 Time elapsed in seconds: 7.680813051993027

```
Load(C2, P2, JFK)
Load(C1, P1, SF0)
Load(C3, P3, ATL)
Fly(P2, JFK, SF0)
Unload(C2, P2, SF0)
Fly(P1, SF0, JFK)
Unload(C1, P1, JFK)
Fly(P3, ATL, SF0)
Unload(C3, P3, SF0)
```

Solving Air Cargo Problem 2 using depth\_first\_graph\_search...

Expansions	Goal Tests	New Nodes
582	583	5211

Plan length: 575 Time elapsed in seconds: 2.756572267971933

```
Fly(P3, ATL, SF0)
Fly(P1, SF0, ATL)
Fly(P3, SF0, JFK)
Fly(P1, ATL, JFK)
Fly(P2, JFK, ATL)
Fly(P3, JFK, ATL)
Fly(P2, ATL, SF0)
Fly(P3, ATL, SF0)
Load(C1, P3, SF0)
Fly(P3, SF0, ATL)
Fly(P2, SF0, ATL)
Fly(P3, ATL, JFK)
Fly(P2, ATL, JFK)
Fly(P1, JFK, ATL)
Fly(P3, JFK, ATL)
Fly(P1, ATL, SF0)
Unload(C1, P3, ATL)
Fly(P3, ATL, SF0)
Fly(P1, SF0, ATL)
Fly(P3, SF0, JFK)
Fly(P1, ATL, JFK)
Fly(P2, JFK, ATL)
Fly(P3, JFK, SF0)
Fly(P2, ATL, SF0)
Load(C2, P1, JFK)
Fly(P3, SF0, ATL)
Fly(P2, SF0, ATL)
Fly(P1, JFK, ATL)
Fly(P3, ATL, SF0)
Fly(P1, ATL, SF0)
Fly(P2, ATL, JFK)
Fly(P3, SF0, ATL)
Unload(C2, P1, SF0)
Fly(P3, ATL, JFK)
Fly(P1, SF0, ATL)
Fly(P2, JFK, ATL)
Fly(P1, ATL, JFK)
Fly(P2, ATL, SF0)
Fly(P3, JFK, ATL)
Fly(P1, JFK, ATL)
Fly(P3, ATL, SF0)
Fly(P1, ATL, SF0)
Load(C2, P3, SF0)
Fly(P3, SF0, ATL)
Fly(P2, SF0, ATL)
Fly(P3, ATL, JFK)
Fly(P1, SF0, ATL)
Fly(P2, ATL, SF0)
```



Load(C3, P1, ATL)  
Fly(P1, ATL, SF0)  
Fly(P2, SF0, ATL)  
Fly(P1, SF0, JFK)  
Fly(P2, ATL, JFK)  
Fly(P3, JFK, ATL)  
Fly(P1, JFK, ATL)  
Fly(P3, ATL, SF0)  
Fly(P1, ATL, SF0)  
Unload(C2, P3, SF0)  
Fly(P3, SF0, ATL)  
Fly(P1, SF0, ATL)  
Fly(P2, JFK, ATL)  
Fly(P3, ATL, SF0)  
Fly(P1, ATL, JFK)  
Fly(P2, ATL, SF0)  
Fly(P3, SF0, ATL)  
Unload(C3, P1, JFK)  
Fly(P3, ATL, JFK)  
Fly(P2, SF0, ATL)  
Fly(P1, JFK, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Fly(P3, JFK, ATL)  
Fly(P2, JFK, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, ATL, SF0)  
Fly(P1, SF0, ATL)  
Load(C1, P1, ATL)  
Fly(P1, ATL, SF0)  
Fly(P3, SF0, ATL)  
Fly(P2, SF0, ATL)  
Fly(P3, ATL, JFK)  
Fly(P2, ATL, JFK)  
Fly(P1, SF0, JFK)  
Fly(P3, JFK, ATL)  
Fly(P1, JFK, ATL)  
Load(C3, P2, JFK)  
Fly(P3, ATL, SF0)  
Fly(P1, ATL, SF0)  
Fly(P2, JFK, ATL)  
Fly(P3, SF0, ATL)  
Fly(P2, ATL, SF0)  
Fly(P3, ATL, JFK)  
Fly(P1, SF0, ATL)  
Fly(P2, SF0, ATL)  
Fly(P1, ATL, JFK)  
Unload(C3, P2, ATL)  
Fly(P2, ATL, SF0)  
Fly(P3, JFK, ATL)  
Fly(P2, SF0, JFK)  
Fly(P3, ATL, SF0)  
Fly(P1, JFK, ATL)  
Fly(P2, JFK, ATL)  
Fly(P3, SF0, ATL)  
Load(C3, P3, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, ATL, SF0)  
Fly(P1, ATL, SF0)  
Fly(P3, SF0, ATL)  
Fly(P2, SF0, JFK)  
Unload(C1, P1, SF0)  
Fly(P3, ATL, SF0)  
Fly(P1, SF0, ATL)  
Fly(P3, SF0, JFK)  
Fly(P1, ATL, JFK)  
Fly(P2, JFK, ATL)  
Fly(P3, JFK, ATL)  
Fly(P2, ATL, SF0)  
Fly(P3, ATL, SF0)

Unload(C3, P3, SF0)  
Fly(P3, SF0, ATL)  
Fly(P2, SF0, ATL)  
Fly(P3, ATL, JFK)  
Fly(P2, ATL, JFK)  
Fly(P1, JFK, ATL)  
Fly(P3, JFK, ATL)  
Fly(P1, ATL, SF0)  
Load(C3, P1, SF0)  
Fly(P3, ATL, SF0)  
Fly(P1, SF0, ATL)  
Fly(P3, SF0, JFK)  
Fly(P1, ATL, JFK)  
Fly(P2, JFK, ATL)  
Fly(P3, JFK, ATL)  
Fly(P2, ATL, SF0)  
Fly(P3, ATL, SF0)  
Unload(C3, P1, JFK)  
Fly(P2, SF0, ATL)  
Fly(P1, JFK, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Fly(P3, SF0, ATL)  
Fly(P1, SF0, JFK)  
Load(C3, P2, JFK)  
Fly(P3, ATL, SF0)  
Fly(P2, JFK, ATL)  
Fly(P3, SF0, JFK)  
Fly(P2, ATL, SF0)  
Fly(P1, JFK, ATL)  
Fly(P2, SF0, JFK)  
Fly(P1, ATL, SF0)  
Load(C2, P1, SF0)  
Fly(P1, SF0, ATL)  
Fly(P3, JFK, ATL)  
Fly(P1, ATL, JFK)  
Fly(P3, ATL, SF0)  
Fly(P2, JFK, ATL)  
Fly(P3, SF0, JFK)  
Fly(P2, ATL, SF0)  
Unload(C3, P2, SF0)  
Fly(P2, SF0, ATL)  
Fly(P3, JFK, ATL)  
Fly(P2, ATL, JFK)  
Fly(P3, ATL, SF0)  
Fly(P1, JFK, ATL)  
Fly(P3, SF0, JFK)  
Fly(P1, ATL, SF0)  
Load(C3, P1, SF0)  
Fly(P1, SF0, ATL)  
Fly(P3, JFK, ATL)  
Fly(P1, ATL, JFK)  
Fly(P3, ATL, SF0)  
Fly(P2, JFK, ATL)  
Fly(P3, SF0, JFK)  
Fly(P2, ATL, SF0)  
Unload(C3, P1, JFK)  
Fly(P2, SF0, JFK)  
Unload(C2, P1, JFK)  
Fly(P3, JFK, ATL)  
Fly(P2, JFK, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, ATL, SF0)  
Fly(P1, JFK, ATL)  
Fly(P3, SF0, ATL)  
Fly(P1, ATL, SF0)  
Fly(P3, ATL, JFK)  
Fly(P2, SF0, ATL)  
Fly(P1, SF0, ATL)  
Load(C3, P3, JFK)

Fly(P2, ATL, SF0)  
Fly(P1, ATL, JFK)  
Fly(P3, JFK, SF0)  
Fly(P2, SF0, ATL)  
Fly(P1, JFK, SF0)  
Fly(P2, ATL, JFK)  
Fly(P1, SF0, ATL)  
Fly(P3, SF0, ATL)  
Fly(P1, ATL, JFK)  
Load(C2, P2, JFK)  
Fly(P3, ATL, SF0)  
Fly(P2, JFK, ATL)  
Fly(P3, SF0, JFK)  
Fly(P2, ATL, SF0)  
Fly(P1, JFK, ATL)  
Fly(P2, SF0, JFK)  
Fly(P1, ATL, SF0)  
Unload(C3, P3, JFK)  
Fly(P3, JFK, ATL)  
Fly(P1, SF0, ATL)  
Fly(P3, ATL, SF0)  
Fly(P1, ATL, JFK)  
Fly(P2, JFK, ATL)  
Fly(P3, SF0, ATL)  
Fly(P2, ATL, SF0)  
Load(C1, P2, SF0)  
Fly(P3, ATL, SF0)  
Fly(P2, SF0, ATL)  
Fly(P3, SF0, JFK)  
Fly(P2, ATL, JFK)  
Fly(P1, JFK, ATL)  
Fly(P3, JFK, ATL)  
Fly(P1, ATL, SF0)  
Fly(P3, ATL, SF0)  
Unload(C2, P2, JFK)  
Fly(P1, SF0, ATL)  
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Fly(P3, ATL, JFK)  
Fly(P1, JFK, ATL)  
Load(C2, P3, JFK)  
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Fly(P3, ATL, SF0)  
Fly(P1, ATL, SF0)  
Unload(C2, P3, SF0)  
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Fly(P1, SF0, ATL)  
Fly(P3, ATL, JFK)  
Fly(P1, ATL, JFK)  
Fly(P2, JFK, SF0)  
Fly(P1, JFK, SF0)  
Fly(P2, SF0, ATL)  
Load(C2, P1, SF0)  
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Fly(P1, SF0, ATL)  
Fly(P3, JFK, ATL)  
Fly(P1, ATL, JFK)  
Fly(P3, ATL, SF0)  
Fly(P2, JFK, SF0)  
Fly(P1, JFK, ATL)  
Fly(P2, SF0, ATL)  
Unload(C1, P2, ATL)  
Fly(P2, ATL, SF0)

Fly(P1, ATL, JFK)  
Fly(P3, SF0, ATL)  
Fly(P2, SF0, ATL)  
Fly(P3, ATL, JFK)  
Fly(P2, ATL, JFK)  
Fly(P1, JFK, ATL)  
Fly(P3, JFK, ATL)  
Unload(C2, P1, ATL)  
Fly(P3, ATL, SF0)  
Fly(P1, ATL, SF0)  
Fly(P3, SF0, JFK)  
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Fly(P2, ATL, JFK)  
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Fly(P1, SF0, ATL)  
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Fly(P2, JFK, SF0)  
Load(C1, P1, ATL)  
Fly(P1, ATL, SF0)  
Fly(P2, SF0, ATL)  
Fly(P1, SF0, JFK)  
Fly(P2, ATL, JFK)  
Fly(P3, JFK, ATL)  
Fly(P1, JFK, ATL)  
Fly(P3, ATL, SF0)  
Fly(P1, ATL, SF0)  
Unload(C1, P1, SF0)  
Fly(P3, SF0, ATL)  
Fly(P2, JFK, ATL)  
Fly(P1, SF0, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, ATL, SF0)  
Fly(P3, SF0, JFK)  
Fly(P1, ATL, JFK)  
Load(C1, P2, SF0)  
Fly(P2, SF0, ATL)  
Fly(P1, JFK, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Fly(P3, JFK, ATL)  
Fly(P1, SF0, JFK)  
Fly(P3, ATL, SF0)  
Unload(C1, P2, JFK)  
Fly(P2, JFK, ATL)  
Fly(P3, SF0, ATL)  
Fly(P2, ATL, SF0)  
Fly(P3, ATL, JFK)  
Fly(P1, JFK, ATL)  
Fly(P2, SF0, ATL)  
Fly(P1, ATL, SF0)  
Unload(C2, P1, SF0)

Fly(P2, ATL, SF0)  
Fly(P1, SF0, ATL)  
Fly(P2, SF0, JFK)  
Fly(P1, ATL, JFK)  
Load(C1, P3, JFK)  
Fly(P3, JFK, ATL)  
Fly(P2, JFK, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, ATL, SF0)  
Fly(P1, JFK, ATL)  
Fly(P2, SF0, JFK)  
Fly(P1, ATL, SF0)  
Load(C2, P3, SF0)  
Fly(P3, SF0, ATL)  
Fly(P1, SF0, ATL)  
Fly(P2, JFK, ATL)  
Fly(P3, ATL, SF0)  
Unload(C1, P3, SF0)  
Fly(P2, ATL, SF0)  
Fly(P1, ATL, SF0)  
Fly(P3, SF0, ATL)  
Fly(P2, SF0, ATL)  
Fly(P3, ATL, JFK)  
Fly(P2, ATL, JFK)  
Load(C1, P1, SF0)  
Fly(P1, SF0, ATL)  
Fly(P3, JFK, ATL)  
Fly(P1, ATL, JFK)  
Fly(P2, JFK, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, ATL, SF0)  
Fly(P3, SF0, JFK)  
Unload(C2, P3, JFK)  
Fly(P3, JFK, ATL)  
Fly(P2, SF0, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, ATL, JFK)  
Load(C2, P2, JFK)  
Fly(P3, SF0, ATL)  
Fly(P2, JFK, ATL)  
Fly(P3, ATL, JFK)  
Fly(P1, JFK, ATL)  
Fly(P2, ATL, SF0)  
Fly(P1, ATL, SF0)  
Fly(P2, SF0, JFK)  
Unload(C1, P1, SF0)  
Fly(P2, JFK, ATL)  
Fly(P1, SF0, ATL)  
Fly(P2, ATL, SF0)  
Fly(P1, ATL, JFK)  
Fly(P3, JFK, ATL)  
Fly(P2, SF0, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, ATL, JFK)  
Load(C1, P3, SF0)  
Fly(P3, SF0, ATL)  
Fly(P2, JFK, ATL)  
Fly(P3, ATL, JFK)  
Fly(P2, ATL, SF0)  
Fly(P1, JFK, ATL)  
Fly(P3, JFK, ATL)  
Fly(P1, ATL, SF0)  
Fly(P3, ATL, SF0)  
Fly(P2, SF0, ATL)  
Fly(P1, SF0, ATL)  
Unload(C2, P2, ATL)  
Fly(P2, ATL, SF0)  
Fly(P1, ATL, SF0)  
Fly(P3, SF0, ATL)  
Fly(P2, SF0, ATL)

Fly(P3, ATL, JFK)  
Fly(P2, ATL, JFK)  
Fly(P1, SF0, ATL)  
Unload(C1, P3, JFK)  
Fly(P1, ATL, JFK)  
Fly(P3, JFK, ATL)  
Fly(P2, JFK, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, ATL, SF0)  
Fly(P1, JFK, ATL)  
Fly(P3, SF0, ATL)  
Fly(P1, ATL, SF0)  
Load(C3, P3, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, SF0, ATL)  
Fly(P1, SF0, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, JFK)  
Fly(P3, SF0, JFK)  
Fly(P2, JFK, ATL)  
Unload(C3, P3, JFK)  
Fly(P2, ATL, SF0)  
Fly(P3, JFK, ATL)  
Fly(P2, SF0, JFK)  
Fly(P3, ATL, SF0)  
Fly(P1, JFK, ATL)  
Fly(P3, SF0, JFK)  
Fly(P1, ATL, SF0)  
Load(C1, P3, JFK)  
Fly(P1, SF0, JFK)  
Fly(P3, JFK, ATL)  
Load(C2, P3, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, JFK, ATL)  
Fly(P3, SF0, JFK)  
Fly(P2, ATL, SF0)  
Fly(P1, JFK, ATL)  
Fly(P2, SF0, JFK)  
Fly(P1, ATL, SF0)  
Unload(C2, P3, JFK)  
Fly(P1, SF0, JFK)  
Fly(P3, JFK, ATL)  
Fly(P2, JFK, ATL)  
Fly(P1, JFK, ATL)  
Fly(P3, ATL, SF0)  
Fly(P1, ATL, SF0)  
Fly(P2, ATL, SF0)  
Fly(P3, SF0, ATL)  
Unload(C1, P3, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, SF0, ATL)  
Fly(P3, SF0, JFK)  
Fly(P2, ATL, JFK)  
Fly(P1, SF0, ATL)  
Fly(P3, JFK, ATL)  
Load(C1, P1, ATL)  
Fly(P3, ATL, SF0)  
Fly(P1, ATL, SF0)  
Fly(P3, SF0, JFK)  
Fly(P1, SF0, JFK)  
Fly(P2, JFK, ATL)  
Fly(P3, JFK, ATL)  
Fly(P2, ATL, SF0)  
Fly(P3, ATL, SF0)  
Unload(C1, P1, JFK)  
Fly(P2, SF0, ATL)  
Fly(P1, JFK, ATL)  
Fly(P3, SF0, ATL)  
Fly(P2, ATL, SF0)  
Fly(P1, ATL, SF0)

Fly(P3, ATL, JFK)  
Fly(P2, SF0, ATL)  
Load(C3, P3, JFK)  
Fly(P2, ATL, JFK)  
Fly(P1, SF0, ATL)  
Fly(P3, JFK, ATL)  
Fly(P1, ATL, JFK)  
Fly(P3, ATL, SF0)  
Fly(P2, JFK, ATL)  
Fly(P1, JFK, ATL)  
Fly(P2, ATL, SF0)  
Fly(P1, ATL, SF0)  
Fly(P3, SF0, ATL)  
Unload(C3, P3, ATL)  
Fly(P3, ATL, SF0)  
Fly(P2, SF0, ATL)  
Fly(P1, SF0, ATL)  
Fly(P2, ATL, JFK)  
Load(C3, P1, ATL)  
Fly(P1, ATL, SF0)  
Fly(P3, SF0, ATL)  
Fly(P1, SF0, JFK)  
Fly(P3, ATL, JFK)  
Fly(P2, JFK, ATL)  
Fly(P1, JFK, ATL)  
Fly(P2, ATL, SF0)  
Fly(P1, ATL, SF0)  
Unload(C3, P1, SF0)  
Fly(P2, SF0, ATL)  
Fly(P1, SF0, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, JFK)  
Fly(P3, JFK, ATL)  
Fly(P2, JFK, ATL)  
Load(C2, P1, JFK)  
Fly(P3, ATL, SF0)  
Fly(P2, ATL, SF0)  
Fly(P3, SF0, JFK)  
Fly(P1, JFK, ATL)  
Fly(P2, SF0, ATL)  
Fly(P1, ATL, SF0)  
Fly(P2, ATL, JFK)  
Fly(P3, JFK, ATL)  
Fly(P1, SF0, ATL)  
Fly(P3, ATL, SF0)  
Load(C1, P2, JFK)  
Fly(P1, ATL, SF0)  
Fly(P2, JFK, ATL)  
Fly(P3, SF0, ATL)  
Fly(P2, ATL, SF0)  
Fly(P3, ATL, JFK)  
Fly(P1, SF0, ATL)  
Fly(P2, SF0, ATL)  
Fly(P1, ATL, JFK)  
Unload(C1, P2, ATL)  
Fly(P2, ATL, SF0)  
Fly(P3, JFK, ATL)  
Fly(P2, SF0, JFK)  
Fly(P3, ATL, SF0)  
Fly(P1, JFK, ATL)  
Fly(P3, SF0, JFK)  
Fly(P1, ATL, SF0)  
Unload(C2, P1, SF0)  
Fly(P1, SF0, ATL)  
Fly(P3, JFK, ATL)  
Fly(P1, ATL, JFK)  
Fly(P3, ATL, SF0)  
Fly(P2, JFK, ATL)  
Fly(P3, SF0, JFK)  
Fly(P2, ATL, SF0)

```

Load(C3, P2, SF0)
Fly(P2, SF0, JFK)
Fly(P3, JFK, ATL)
Fly(P2, JFK, ATL)
Fly(P3, ATL, SF0)
Fly(P1, JFK, ATL)
Fly(P2, ATL, SF0)
Fly(P1, ATL, SF0)
Fly(P3, SF0, ATL)
Unload(C3, P2, SF0)
Fly(P2, SF0, ATL)
Load(C1, P3, ATL)
Fly(P3, ATL, SF0)
Fly(P2, ATL, SF0)
Fly(P1, SF0, ATL)
Fly(P3, SF0, ATL)
Fly(P1, ATL, JFK)
Fly(P3, ATL, JFK)
Fly(P2, SF0, ATL)
Fly(P1, JFK, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SF0)
Load(C3, P1, SF0)
Fly(P1, SF0, ATL)
Fly(P2, JFK, ATL)
Fly(P1, ATL, JFK)
Fly(P2, ATL, SF0)
Unload(C1, P3, JFK)
Fly(P2, SF0, JFK)
Fly(P3, JFK, ATL)
Fly(P2, JFK, ATL)
Fly(P3, ATL, SF0)
Fly(P1, JFK, ATL)
Fly(P2, ATL, SF0)
Fly(P1, ATL, SF0)
Fly(P3, SF0, ATL)
Unload(C3, P1, SF0)

```

Solving Air Cargo Problem 2 using uniform\_cost\_search...

Expansions	Goal Tests	New Nodes
4605	4607	41839

Plan length: 9 Time elapsed in seconds: 10.11354769510217

```

Load(C1, P1, SF0)
Load(C2, P2, JFK)
Load(C3, P3, ATL)
Fly(P1, SF0, JFK)
Fly(P2, JFK, SF0)
Fly(P3, ATL, SF0)
Unload(C1, P1, JFK)
Unload(C2, P2, SF0)
Unload(C3, P3, SF0)

```

### Problem: 3

Searches: Breadth first, depth first, uniform cost

Solving Air Cargo Problem 3 using breadth\_first\_search...

Expansions	Goal Tests	New Nodes
14663	18098	129631

Plan length: 12 Time elapsed in seconds: 39.396542366128415



```

Load(C2, P2, JFK)
Load(C1, P1, SF0)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P1, SF0, ATL)
Load(C3, P1, ATL)
Fly(P1, ATL, JFK)
Unload(C1, P1, JFK)
Unload(C3, P1, JFK)
Fly(P2, ORD, SF0)
Unload(C2, P2, SF0)
Unload(C4, P2, SF0)

```

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: 3.4934276069980115

```

Fly(P1, SF0, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, ATL)
Fly(P2, ORD, ATL)
Fly(P1, ATL, JFK)
Fly(P2, ATL, SF0)
Load(C1, P2, SF0)
Fly(P2, SF0, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SF0)
Unload(C1, P2, JFK)
Fly(P1, SF0, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, ATL)
Fly(P2, ORD, ATL)
Fly(P1, ATL, JFK)
Fly(P2, ATL, SF0)
Load(C2, P1, JFK)
Fly(P2, SF0, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, ATL)
Fly(P1, ORD, ATL)
Fly(P2, ATL, JFK)
Fly(P1, ATL, SF0)
Unload(C2, P1, SF0)
Fly(P1, SF0, ORD)
Fly(P2, JFK, ORD)
Fly(P1, ORD, ATL)
Fly(P2, ORD, ATL)
Fly(P1, ATL, JFK)
Fly(P2, ATL, SF0)
Load(C2, P2, SF0)
Fly(P2, SF0, 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, SF0)
Fly(P2, ORD, ATL)
Fly(P1, SF0, JFK)
Fly(P2, ATL, SF0)
Unload(C2, P2, SF0)
Fly(P2, SF0, ORD)
Fly(P1, JFK, ORD)

```

Fly(P2, ORD, ATL)  
Fly(P1, ORD, SF0)  
Fly(P2, ATL, JFK)  
Fly(P1, SF0, ATL)  
Load(C1, P2, JFK)  
Fly(P1, ATL, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, SF0)  
Fly(P2, ORD, ATL)  
Fly(P1, SF0, JFK)  
Fly(P2, ATL, SF0)  
Unload(C1, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Unload(C3, P1, SF0)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, JFK)  
Fly(P2, ATL, SF0)  
Load(C3, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Unload(C3, P2, JFK)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, SF0)  
Load(C2, P2, SF0)  
Fly(P1, ATL, ORD)  
Fly(P2, SF0, ORD)  
Fly(P1, ORD, SF0)  
Fly(P2, ORD, ATL)  
Fly(P1, SF0, 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, SF0)  
Fly(P1, ATL, SF0)  
Load(C1, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, SF0, 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, SF0)  
Fly(P2, ORD, SF0)  
Fly(P1, SF0, JFK)  
Fly(P2, SF0, JFK)  
Unload(C4, P1, JFK)

Fly(P2, JFK, ORD)  
Load(C3, P1, JFK)  
Fly(P2, ORD, ATL)  
Fly(P1, JFK, ORD)  
Fly(P2, ATL, SF0)  
Fly(P1, ORD, ATL)  
Fly(P2, SF0, JFK)  
Fly(P1, ATL, SF0)  
Unload(C3, P1, SF0)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, JFK)  
Fly(P2, ATL, SF0)  
Load(C3, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Load(C4, P2, JFK)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, JFK)  
Fly(P2, ATL, SF0)  
Unload(C4, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Unload(C3, P2, JFK)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, JFK)  
Fly(P2, ATL, SF0)  
Load(C4, P2, SF0)  
Fly(P2, SF0, ATL)  
Fly(P1, JFK, ORD)  
Unload(C4, P2, ATL)  
Fly(P1, ORD, SF0)  
Fly(P2, ATL, ORD)  
Fly(P1, SF0, JFK)  
Fly(P2, ORD, SF0)  
Fly(P1, JFK, ATL)  
Fly(P2, SF0, JFK)  
Load(C3, P2, JFK)  
Fly(P1, ATL, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, SF0)  
Fly(P2, ORD, ATL)  
Unload(C3, P2, ATL)  
Fly(P2, ATL, ORD)  
Fly(P1, SF0, ORD)  
Fly(P2, ORD, SF0)  
Fly(P1, ORD, ATL)  
Fly(P2, SF0, 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, SF0)  
Fly(P1, ATL, SF0)  
Unload(C2, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, SF0, 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, SF0)  
Fly(P1, ATL, SF0)  
Unload(C1, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, SF0, 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, SF0)  
Fly(P2, ORD, ATL)  
Fly(P1, SF0, JFK)  
Fly(P2, ATL, SF0)  
Unload(C4, P1, JFK)  
Fly(P2, SF0, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Load(C2, P1, SF0)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, JFK)  
Fly(P2, ATL, SF0)  
Unload(C2, P1, JFK)  
Fly(P2, SF0, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Load(C1, P1, SF0)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, JFK)  
Fly(P2, ATL, SF0)  
Unload(C1, P1, JFK)  
Fly(P2, SF0, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, JFK)  
Fly(P1, ORD, SF0)  
Load(C4, P2, JFK)  
Fly(P1, SF0, ATL)  
Fly(P2, JFK, SF0)  
Fly(P1, ATL, ORD)  
Unload(C4, P2, SF0)  
Fly(P1, ORD, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, SF0, 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, SF0, JFK)  
Fly(P2, ORD, ATL)  
Fly(P1, JFK, ORD)  
Fly(P2, ATL, SF0)  
Load(C3, P2, SF0)  
Fly(P1, ORD, ATL)  
Fly(P2, SF0, ORD)  
Fly(P1, ATL, SF0)  
Fly(P2, ORD, JFK)  
Fly(P1, SF0, JFK)  
Unload(C3, P2, JFK)  
Fly(P2, JFK, ORD)  
Fly(P1, JFK, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, ORD)  
Fly(P2, ATL, SF0)  
Fly(P1, ORD, SF0)  
Unload(C4, P1, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, SF0, 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, SF0)  
Fly(P1, ATL, SF0)  
Unload(C3, P2, SF0)  
Fly(P1, SF0, ORD)  
Load(C4, P2, SF0)  
Fly(P1, ORD, ATL)  
Fly(P2, SF0, JFK)  
Fly(P1, ATL, SF0)  
Fly(P2, JFK, ORD)  
Load(C3, P1, SF0)  
Fly(P2, ORD, ATL)  
Fly(P1, SF0, ORD)  
Fly(P2, ATL, SF0)  
Fly(P1, ORD, ATL)  
Fly(P2, SF0, JFK)  
Fly(P1, ATL, JFK)  
Unload(C4, P2, JFK)  
Fly(P2, JFK, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, SF0)  
Fly(P2, ATL, SF0)  
Fly(P1, SF0, ATL)  
Load(C2, P2, SF0)  
Fly(P1, ATL, ORD)  
Fly(P2, SF0, ORD)  
Fly(P1, ORD, SF0)  
Fly(P2, ORD, ATL)  
Fly(P1, SF0, JFK)  
Fly(P2, ATL, JFK)  
Unload(C2, P2, JFK)  
Fly(P2, JFK, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, SF0)  
Fly(P2, ATL, SF0)  
Fly(P1, SF0, ATL)  
Load(C1, P2, SF0)  
Fly(P1, ATL, ORD)  
Fly(P2, SF0, ORD)  
Fly(P1, ORD, SF0)

Fly(P2, ORD, ATL)  
Fly(P1, SF0, 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, SF0)  
Fly(P1, ATL, SF0)  
Unload(C4, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, SF0, 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, SF0)  
Fly(P1, ATL, SF0)  
Unload(C3, P1, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, SF0, 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, SF0)  
Fly(P1, ATL, SF0)  
Unload(C2, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, SF0, 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, SF0)  
Load(C2, P2, SF0)  
Fly(P1, ATL, ORD)  
Fly(P2, SF0, ORD)  
Fly(P1, ORD, SF0)  
Fly(P2, ORD, ATL)  
Fly(P1, SF0, JFK)  
Unload(C2, P2, ATL)  
Fly(P2, ATL, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, SF0)  
Fly(P1, ORD, ATL)  
Fly(P2, SF0, JFK)  
Fly(P1, ATL, SF0)  
Unload(C1, P2, JFK)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, SF0)  
Fly(P1, ATL, JFK)

Fly(P2, SF0, ATL)  
Load(C1, P1, JFK)  
Fly(P2, ATL, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, SF0)  
Fly(P1, ORD, ATL)  
Fly(P2, SF0, JFK)  
Fly(P1, ATL, SF0)  
Unload(C1, P1, SF0)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, JFK)  
Fly(P2, ATL, SF0)  
Load(C4, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Unload(C4, P2, JFK)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, JFK)  
Fly(P2, ATL, SF0)  
Load(C3, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Unload(C3, P2, JFK)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, JFK)  
Fly(P2, ATL, SF0)  
Load(C1, P2, SF0)  
Fly(P2, SF0, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Unload(C1, P2, JFK)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, JFK)  
Fly(P2, ATL, SF0)  
Load(C4, P1, JFK)  
Fly(P2, SF0, ORD)  
Fly(P1, JFK, ORD)  
Fly(P2, ORD, ATL)  
Fly(P1, ORD, ATL)  
Fly(P2, ATL, JFK)  
Fly(P1, ATL, SF0)  
Unload(C4, P1, SF0)  
Fly(P1, SF0, ORD)  
Fly(P2, JFK, ORD)  
Fly(P1, ORD, ATL)  
Fly(P2, ORD, ATL)  
Fly(P1, ATL, JFK)



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Fly(P2, ATL, SF0)
Load(C4, P2, SF0)
Fly(P2, SF0, 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, SF0)
Fly(P2, ORD, ATL)
Unload(C4, P2, ATL)
Fly(P2, ATL, ORD)
Fly(P1, SF0, ORD)
Fly(P2, ORD, SF0)
Fly(P1, ORD, ATL)
Fly(P2, SF0, 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, SF0)
Unload(C2, P1, ATL)
Fly(P1, ATL, ORD)
Fly(P2, SF0, ORD)
Fly(P1, ORD, SF0)
Fly(P2, ORD, ATL)
Fly(P1, SF0, JFK)
Fly(P2, ATL, JFK)
Unload(C3, P2, JFK)
Fly(P2, JFK, ORD)
Fly(P1, JFK, ORD)
Fly(P2, ORD, SF0)
Fly(P1, ORD, SF0)
Fly(P2, SF0, ATL)
Load(C2, P2, ATL)
Fly(P2, ATL, ORD)
Fly(P1, SF0, ORD)
Fly(P2, ORD, SF0)
Fly(P1, ORD, ATL)
Unload(C2, P2, SF0)
Fly(P1, ATL, SF0)
Fly(P2, SF0, JFK)
Fly(P1, SF0, 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, SF0)
Fly(P1, ORD, ATL)
Unload(C4, P2, SF0)

```

Solving Air Cargo Problem 3 using uniform\_cost\_search...

Expansions	Goal Tests	New Nodes
16961	16963	149117

Plan length: 12 Time elapsed in seconds: 54.33968257904053

```

Load(C1, P1, SF0)
Load(C2, P2, JFK)
Fly(P1, SF0, ATL)
Load(C3, P1, ATL)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)

```

Fly(P1, ATL, JFK)  
Unload(C1, P1, JFK)  
Fly(P2, ORD, SF0)  
Unload(C2, P2, SF0)  
Unload(C3, P1, JFK)  
Unload(C4, P2, SF0)

## Problem: 1

Searches: h\_1, h\_ignore\_preconditions, h\_pg\_level\_sum

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: 0.034243029076606035

Load(C1, P1, SF0)  
Load(C2, P2, JFK)  
Fly(P1, SF0, JFK)  
Fly(P2, JFK, SF0)  
Unload(C1, P1, JFK)  
Unload(C2, P2, SF0)

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: 0.03645280795171857

Load(C1, P1, SF0)  
Fly(P1, SF0, JFK)  
Unload(C1, P1, JFK)  
Load(C2, P2, JFK)  
Fly(P2, JFK, SF0)  
Unload(C2, P2, SF0)

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: 0.7183507580775768

Load(C1, P1, SF0)  
Fly(P1, SF0, JFK)  
Load(C2, P2, JFK)  
Fly(P2, JFK, SF0)  
Unload(C1, P1, JFK)  
Unload(C2, P2, SF0)

## Problem: 2

Searches: h\_1, h\_ignore\_preconditions, h\_pg\_level\_sum

Solving Air Cargo Problem 2 using astar\_search with h\_1...

Expansions	Goal Tests	New Nodes
4605	4607	41839

Plan length: 9 Time elapsed in seconds: 10.121870519826189  
Load(C1, P1, SF0)  
Load(C2, P2, JFK)  
Load(C3, P3, ATL)  
Fly(P1, SF0, JFK)  
Fly(P2, JFK, SF0)  
Fly(P3, ATL, SF0)  
Unload(C1, P1, JFK)  
Unload(C2, P2, SF0)  
Unload(C3, P3, SF0)

Solving Air Cargo Problem 2 using astar\_search with h\_ignore\_preconditions...

Expansions	Goal Tests	New Nodes
1311	1313	11989

Plan length: 9 Time elapsed in seconds: 3.6023131718393415  
Load(C1, P1, SF0)  
Fly(P1, SF0, JFK)  
Unload(C1, P1, JFK)  
Load(C2, P2, JFK)  
Fly(P2, JFK, SF0)  
Unload(C2, P2, SF0)  
Load(C3, P3, ATL)  
Fly(P3, ATL, SF0)  
Unload(C3, P3, SF0)

Solving Air Cargo Problem 2 using astar\_search with h\_pg\_levelsum...

Expansions	Goal Tests	New Nodes
74	76	720

Plan length: 9 Time elapsed in seconds: 117.26753376796842  
Load(C1, P1, SF0)  
Fly(P1, SF0, JFK)  
Unload(C1, P1, JFK)  
Load(C2, P2, JFK)  
Fly(P2, JFK, SF0)  
Unload(C2, P2, SF0)  
Load(C3, P3, ATL)  
Fly(P3, ATL, SF0)  
Unload(C3, P3, SF0)

### Problem: 3

Searches: h\_1, h\_ignore\_preconditions, h\_pg\_level\_sum

Solving Air Cargo Problem 3 using astar\_search with h\_1...

Expansions	Goal Tests	New Nodes
16961	16963	149117

Plan length: 12 Time elapsed in seconds: 43.456858785124496  
Load(C1, P1, SF0)  
Load(C2, P2, JFK)  
Fly(P1, SF0, ATL)  
Load(C3, P1, ATL)  
Fly(P2, JFK, ORD)  
Load(C4, P2, ORD)  
Fly(P1, ATL, JFK)  
Unload(C1, P1, JFK)  
Fly(P2, ORD, SF0)  
Unload(C2, P2, SF0)  
Unload(C3, P1, JFK)

Unload(C4, P2, SF0)

Solving Air Cargo Problem 3 using astar\_search with h\_ignore\_preconditions...

Expansions	Goal Tests	New Nodes
4444	4446	39227

Plan length: 12 Time elapsed in seconds: 12.634809517068788

Load(C1, P1, SF0)  
Fly(P1, SF0, ATL)  
Load(C3, P1, ATL)  
Fly(P1, ATL, JFK)  
Unload(C3, P1, JFK)  
Unload(C1, P1, JFK)  
Load(C2, P2, JFK)  
Fly(P2, JFK, ORD)  
Load(C4, P2, ORD)  
Fly(P2, ORD, SF0)  
Unload(C4, P2, SF0)  
Unload(C2, P2, SF0)

Solving Air Cargo Problem 3 using astar\_search with h\_pg\_levelsum...

Expansions	Goal Tests	New Nodes
229	231	2081

Plan length: 13 Time elapsed in seconds: 593.6134534038138

Load(C1, P1, SF0)  
Fly(P1, SF0, ATL)  
Load(C3, P1, ATL)  
Fly(P1, ATL, JFK)  
Load(C2, P2, JFK)  
Fly(P2, JFK, SF0)  
Unload(C2, P2, SF0)  
Unload(C1, P1, JFK)  
Unload(C3, P1, JFK)  
Fly(P2, SF0, ORD)  
Load(C4, P2, ORD)  
Fly(P2, ORD, SF0)  
Unload(C4, P2, SF0)