

# Martin Přílučík – Artificial Intelligence nanodegree

## Planning Search - Heuristic analysis

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### Purpose

Purpose of this document is to present and analyze results of planning search project. Three air cargo problems were defined and heuristics implemented as part of this project. P1, P2 and P3 definitions in PDDL can be found here:

<https://github.com/udacity/AIND-Planning#given-classical-pddl-problems>

### Experiment 1

During this experiment uninformed planning searches were run to find solution for each problem. Following three searches were used: breadth\_first\_search (BFS), depth\_first\_graph\_search (DFGS) and uniform\_cost\_search (UCS). Results with the required metrics are in the below tables.

#### P1

P1	BFS	DFGS	UCS
Expansions	43	21	55
Goal Tests	56	22	57
New Nodes	180	84	224
Plan Length	6	20	6
Time (s)	0.039058	0.01842	0.0468

#### P2

P2	BFS	DFGS	UCS
Expansions	3343	624	4852

<b>Goal Tests</b>	4609	625	4854
<b>New Nodes</b>	30509	5602	44030
<b>Plan Length</b>	9	619	9
<b>Time (s)</b>	17.02444	4.18725	14.9314

## P3

<b>P3</b>	<b>BFS</b>	<b>DFGS</b>	<b>UCS</b>
<b>Expansions</b>	14663	408	18223
<b>Goal Tests</b>	18098	409	18225
<b>New Nodes</b>	129631	3364	159618
<b>Plan Length</b>	12	392	12
<b>Time (s)</b>	516.878	9.6085	247.298

## Experiment 2

During this experiment A\* searches were run to find solutions for P1, P2 and P3. Heuristics “h\_1”, “ignore preconditions” and “level sum” implemented as part of this project were used. Results are in the below tables.

## P1

<b>P1</b>	<b>h_1</b>	<b>ignore-precond</b>	<b>level-sum</b>
<b>Expansions</b>	55	41	11
<b>Goal Tests</b>	57	43	13
<b>New Nodes</b>	224	170	50
<b>Plan Length</b>	6	6	6
<b>Time (s)</b>	0.04699	0.03617	0.5475

## P2

P2	h_1	ignore-precond	level-sum
Expansions	4852	1450	86
Goal Tests	4854	1452	88
New Nodes	44030	13303	841
Plan Length	9	9	9
Time (s)	15.06935	4.62173	43.3695

## P3

P3	h_1	ignore-precond	level-sum
Expansions	18223	5040	325
Goal Tests	18225	5042	327
New Nodes	159618	44944	3002
Plan Length	12	12	12
Time (s)	247.8534	73.0712	870.6878

## Optimal plans

For this simple problems it is easy to manually verify that optimal solution/plan was found.  
For P3 the possibility that plane can be loaded with more than one cargo was used.

## P1

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

## P2

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

## P3

```
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)
```

## Non-heuristic search results comparison

Breadth\_first\_search (BFS), depth\_first\_graph\_search (DFGS) and uniform\_cost\_search (UCS) were used as non-heuristic searches. The numbers for Expansions, Goal Tests, New Nodes, Plan length and Time elapsed can be found in the tables [here](#)

**DFGS** did not found optimal solution. Even though it used the least number of expansions, goal tests and new nodes, the plan length was much longer (in the hundreds) than optimal plan. It was much faster (in the hundreds) than the other searches but this cannot weight out that fact that the solution found would be useless.

**BFS** and **UCS**, both were able to find optimal solutions for all three problems. BFS needed less Expansions, Goal Tests and New Nodes (about 23% for P3) but UCS was faster (about 50% for P3). As the difference in space needed is not so big **UCS** seems to be the best search among the three.

## Heuristic search results comparison

A\* searches with heuristics “h\_1”, “ignore preconditions” and “level sum” were used to find solution for planning search problems P1, P2 and P3. The numbers for Expansions, Goal Tests, New Nodes, Plan length and Time elapsed can be found in the tables [here](#).

**H\_1** is not really heuristic (it always return one) and therefore the result were the same as for UCS.

**Ignore-preconditions** and **level-sum** both of them were able to find optimal solution. For P3, ignore-preconditions was about hundred times faster but level-sum needed more than a thousand times less Expansions, Goal Tests and New Nodes. So **level-sum** was more efficient in terms of required space/memory. So if we made assumption based on P3 results **level-sum** could be better for larger problems where the time of finding solution is not critical.

## Conclusion

We have measured and compared planning searches with and without heuristics. **UCS** was selected as the best non-heuristic search. For **P3** it is about three times faster than **level-sum** but level-sum required more than thousand times less Expansions, Goal Tests and New Nodes. This is caused by the fact that with each call for the heuristic the new planning graph is created for the actual node. So the heuristic is more accurate but it takes more time to compute it. Also the time of level-sum could be improved by better implementation of planning graph operations and the heuristic itself in terms of performance.

## Appendix - search outputs

### P1

#### BFS(breadth\_first\_search - 1)

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

Expansions	Goal Tests	New Nodes
43	56	180

Plan length: 6 Time elapsed in seconds: 0.039058

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P2, JFK, SFO)

Unload(C2, P2, SFO)

Fly(P1, SFO, JFK)

Unload(C1, P1, JFK)

#### DFGS (depth\_first\_graph\_search - 3)

Solving Air Cargo Problem 1 using depth\_first\_graph\_search...

Expansions	Goal Tests	New Nodes
21	22	84

```

Plan length: 20   Time elapsed in seconds: 0.018420199999999998
Fly(P1, SFO, JFK)
Fly(P2, JFK, SFO)
Load(C2, P1, JFK)
Fly(P1, JFK, SFO)
Fly(P2, SFO, JFK)
Unload(C2, P1, SFO)
Fly(P1, SFO, JFK)
Fly(P2, JFK, SFO)
Load(C2, P2, SFO)
Fly(P1, JFK, SFO)
Load(C1, P2, SFO)
Fly(P2, SFO, JFK)
Fly(P1, SFO, JFK)
Unload(C2, P2, JFK)
Unload(C1, P2, JFK)
Fly(P2, JFK, SFO)
Load(C2, P1, JFK)
Fly(P1, JFK, SFO)
Fly(P2, SFO, JFK)
Unload(C2, P1, SFO)

```

## UCS (uniform\_cost\_search - 5)

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

Expansions	Goal Tests	New Nodes
55	57	224

Plan length: 6 Time elapsed in seconds: 0.0468037

```

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

```

## P2

## BFS(breadth\_first\_search - 1)

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

Expansions	Goal Tests	New Nodes
3343	4609	30509

Plan length: 9 Time elapsed in seconds: 17.0244477

```

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)
```

## DFGS (depth\_first\_graph\_search - 3)

```
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: 4.1872502
[plan is too long hence not included]
```

## UCS (uniform\_cost\_search - 5)

```
Solving Air Cargo Problem 2 using uniform_cost_search...
Expansions   Goal Tests   New Nodes
      4852           4854       44030
Plan length: 9   Time elapsed in seconds: 14.9314096
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(C1, P1, JFK)
Unload(C2, P2, SFO)
```

## P3

## BFS(breadth\_first\_search - 1)

```
Solving Air Cargo Problem 3 using breadth_first_search...
Expansions   Goal Tests   New Nodes
      14663           18098       129631
Plan length: 12   Time elapsed in seconds: 516.8780197
Load(C1, P1, SFO)
Load(C2, P2, JFK)
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)
```

## DFGS (depth\_first\_graph\_search - 3)

Solving Air Cargo Problem 3 using depth\_first\_graph\_search...

Expansions	Goal Tests	New Nodes
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408	409	3364
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Plan length: 392 Time elapsed in seconds: 9.608561199999999

[plan is too long hence not included]

## UCS (uniform\_cost\_search - 5)

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

Expansions	Goal Tests	New Nodes
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18223	18225	159618
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Plan length: 12 Time elapsed in seconds: 247.2986251

```
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)
```

## Experiment 2

### P1

#### astar\_search h\_1

*Solving Air Cargo Problem 1 using astar\_search with h\_1...*

<i>Expansions</i>	<i>Goal Tests</i>	<i>New Nodes</i>
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<i>55</i>	<i>57</i>	<i>224</i>
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*Plan length: 6 Time elapsed in seconds: 0.0469932*

*Load(C1, P1, SFO)*



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

## astar\_search h\_ignore\_preconditions

*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: 0.036171600000000005*

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

## astar\_search h\_pg\_levelsum

*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: 0.5475185*

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

## P2

## astar\_search h\_1

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

Expansions	Goal Tests	New Nodes
4852	4854	44030

*Plan length: 9 Time elapsed in seconds: 15.069351*

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

### astar\_search h\_ignore\_preconditions

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

<i>Expansions</i>	<i>Goal Tests</i>	<i>New Nodes</i>
1450	1452	13303

*Plan length: 9 Time elapsed in seconds: 4.6217326000000005*

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

### astar\_search h\_pg\_levelsum

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

<i>Expansions</i>	<i>Goal Tests</i>	<i>New Nodes</i>
86	88	841

*Plan length: 9 Time elapsed in seconds: 43.3695094*

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

## P3

### astar\_search h\_1

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

<i>Expansions</i>	<i>Goal Tests</i>	<i>New Nodes</i>
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<i>18223</i>	<i>18225</i>	<i>159618</i>
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*Plan length: 12 Time elapsed in seconds: 247.8534043*

*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)*

### astar\_search h\_ignore\_preconditions

*Solving Air Cargo Problem 3 using astar\_search with*

*h\_ignore\_preconditions...*

<i>Expansions</i>	<i>Goal Tests</i>	<i>New Nodes</i>
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<i>5040</i>	<i>5042</i>	<i>44944</i>
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*Plan length: 12 Time elapsed in seconds: 73.0712492*

*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)*

## astar\_search h\_pg\_levelsum

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

<i>Expansions</i>	<i>Goal Tests</i>	<i>New Nodes</i>
<i>325</i>	<i>327</i>	<i>3002</i>

*Plan length: 12 Time elapsed in seconds: 870.6878017*

*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)*