

Search methods analysis by Yevgen Nerush

This analysis contains brief overview of the different search methods including non-heuristic and heuristic ones, their performance metrics along with benefits and limitations. Each search method is researched on the Air Cargo Problem of small (1), medium (2) and large sizes (3).

There are five performance metrics in each search method evaluation:

- Expansions: the number of times the frontier is expanded by calling `PlanningProblem's actions` function
- Goal Tests: the number of nodes verified for the goal match by calling `PlanningProblem's goal_test` function
- New Nodes: the number of nodes added to the graph during the search by calling `PlanningProblem's result` function
- Plan length: size of a list of the actions consecutive execution of which leads to an optimal solution (a solution with all sub-goals being satisfied)
- Execution time: the number of seconds a search algorithm takes to search for an optimal solution

After analysing all 10 search methods listed in this paper, the following optimal plans have been found for Problems 1, 2 and 3.

Air Cargo Problem 1

TODO:

	Expansions	Goal Tests	New Nodes	Plan length	Execution time in seconds
1. Breadth first search	43	56	180	6	0.035
2. Breadth first tree search	1458	1459	5960	6	6.019
3. Depth first graph search	21	22	84	20	0.098
4. Depth limited search	101	271	414	50	0.480
5. Uniform cost search	55	57	224	6	0.241
6. Recursive best first search with h1	4229	4230	17023	6	17.971
7. Greedy best first graph search with h1	7	9	28	6	0.027
8. A* search with h1 heuristic	55	57	224	6	0.251
9. A* search with h_ignore_preconditions heuristic	41	43	170	6	0.042
10. A* search with levelsum heuristic	7	9	28	6	0.900

The optimal solution for the problem.

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

Air Cargo Problem 2

TODO:

	Expansions	Goal Tests	New Nodes	Plan length	Execution time in seconds
1. Breadth first search	3346	4612	30534	9	81.659
2. Breadth first tree search	?	?	?	?	> 600
3. Depth first graph search	107	108	959	105	2.255
4. Depth limited search	?	?	?	?	> 600
5. Uniform cost search	4853	4855	44041	9	140.891
6. Recursive best first search with h1	?	?	?	?	> 600
7. Greedy best first graph search with h1	998	1000	8982	21	26.120
8. A* search with h1 heuristic	4853	4855	44041	9	162.157
9. A* search with h_ignore_preconditions heuristic	1506	1508	13820	9	13.943
10. A* search with levelsum heuristic	77	79	760	9	129.232

The optimal solution for the problem.

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

```

Air Cargo Problem 3

TODO:

	Expansions	Goal Tests	New Nodes	Plan length	Execution time in seconds
1. Breadth first search	14663	18098	129631	12	457.617
2. Breadth first tree search	?	?	?	?	> 600
3. Depth first graph search	408	409	3364	392	11.076
4. Depth limited search	?	?	?	?	> 600
5. Uniform cost search	?	?	?	?	> 600
6. Recursive best first search with h1	?	?	?	?	> 600
7. Greedy best first graph search with h1	5614	5616	49429	22	259.745
8. A* search with h1 heuristic	?	?	?	?	> 600
9. A* search with h_ignore_preconditions heuristic	5118	5120	45650	12	93.625
10. A* search with levelsum heuristic	403	405	3708	12	950.926

The optimal solution for the problem.

```

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)
```

1. Breadth first search

Air Cargo Problem 1

- Expansions: 43
- Goal Tests: 56
- New Nodes: 180
- Plan length: 6
- Execution time: 0.03547631500987336 seconds

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

Air Cargo Problem 2

- Expansions: 3346
- Goal Tests: 4612
- New Nodes: 30534
- Plan length: 9
- Execution time: 81.65928123100002 seconds

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

Air Cargo Problem 3

- Expansions: 14663
- Goal Tests: 18098
- New Nodes: 129631
- Plan length: 12
- Execution time: 457.6173511959996 seconds

```
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)
```

2. Breadth first tree search

Air Cargo Problem 1

- Expansions: 1458
- Goal Tests: 1459
- New Nodes: 5960
- Plan length: 6
- Execution time: 6.019270433000202 seconds

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

Air Cargo Problem 2

Does not terminate in 10 minutes.

Air Cargo Problem 3

Does not terminate in 10 minutes.

3. Depth first graph search

Air Cargo Problem 1

- Expansions: 21
- Goal Tests: 22
- New Nodes: 84

- Plan length: 20
- Execution time: 0.09816352300003928 seconds

```

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)

```

Air Cargo Problem 2

- Expansions: 107
- Goal Tests: 108
- New Nodes: 959
- Plan length: 105
- Execution time: 2.255084823999823 seconds

```

Fly(P3, ATL, JFK)
Fly(P2, JFK, ATL)
Fly(P3, JFK, SFO)
Fly(P2, ATL, SFO)
Fly(P1, SFO, ATL)
Fly(P3, SFO, ATL)
Fly(P1, ATL, JFK)
Fly(P3, ATL, JFK)
...
Unload(C2, P3, SFO)

```

Air Cargo Problem 3

- Expansions: 408
- Goal Tests: 409
- New Nodes: 3364

- Plan length: 392
- Execution time: 11.076630202999695 seconds

```
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(C3, P1, JFK)
```

4. Depth limited search

Air Cargo Problem 1

- Expansions: 101
- Goal Tests: 271
- New Nodes: 414
- Plan length: 50
- Execution time: 0.48083225499794935 seconds

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

Air Cargo Problem 2

Does not terminate in 10 minutes.

Air Cargo Problem 3

Does not terminate in 10 minutes.

5. Uniform cost search

Air Cargo Problem 1

- Expansions: 55

- Goal Tests: 57
- New Nodes: 224
- Plan length: 6
- Execution time: 0.2418411139951786 seconds

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

Air Cargo Problem 2

- Expansions: 4853
- Goal Tests: 4855
- New Nodes: 44041
- Plan length: 9
- Execution time: 140.8912663539959 seconds

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

Air Cargo Problem 3

Does not terminate in 10 minutes.

6. Recursive best first search with h1 heuristic function

Air Cargo Problem 1

- Expansions: 4229
- Goal Tests: 4230
- New Nodes: 17023
- Plan length: 6
- Execution time: 17.971775871999853 seconds

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



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

Air Cargo Problem 2

Does not terminate in 10 minutes.

Air Cargo Problem 3

Does not terminate in 10 minutes.

7. Greedy best first graph search with h1

Air Cargo Problem 1

- Expansions: 7
- Goal Tests: 9
- New Nodes: 28
- Plan length: 6
- Execution time: 0.02786448599999858 seconds

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

Air Cargo Problem 2

- Expansions: 998
- Goal Tests: 1000
- New Nodes: 8982
- Plan length: 21
- Execution time: 26.12001982899983 seconds

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

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

Air Cargo Problem 3

- Expansions: 5614
- Goal Tests: 5616
- New Nodes: 49429
- Plan length: 22
- Execution time: 259.74592149100044 seconds

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

8. A* search with h1 heuristic function

Air Cargo Problem 1

- Expansions: 55
- Goal Tests: 57
- New Nodes: 224
- Plan length: 6
- Execution time: 0.25108054200245533 seconds

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

Air Cargo Problem 2

- Expansions: 4853
- Goal Tests: 4855
- New Nodes: 44041
- Plan length: 9
- Execution time: 162.15786768100224 seconds

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

Air Cargo Problem 3

Does not terminate in 10 minutes.

9. A* search with h_ignore_preconditions

Air Cargo Problem 1

- Expansions: 41
- Goal Tests: 43
- New Nodes: 170
- Plan length: 6
- Execution time: 0.042065354995429516 seconds

```
Load(C1, P1, SFO)
Fly(P1, SFO, JFK)
```

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

Air Cargo Problem 2

- Expansions: 1506
- Goal Tests: 1508
- New Nodes: 13820
- Plan length: 9
- Execution time: 13.943244863010477 seconds

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

Air Cargo Problem 3

- Expansions: 5118
- Goal Tests: 5120
- New Nodes: 45650
- Plan length: 12
- Execution time: 93.62522890602122 seconds

```
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)
```

10. A* search with levelsum heuristic function

Air Cargo Problem 1

- Expansions: 7
- Goal Tests: 9
- New Nodes: 28
- Plan length: 6
- Execution time: 0.9002755659894319 seconds

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

Air Cargo Problem 2

- Expansions: 77
- Goal Tests: 79
- New Nodes: 760
- Plan length: 9
- Execution time: 129.23260724698775 seconds

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

Air Cargo Problem 3

- Expansions: 403
- Goal Tests: 405
- New Nodes: 3708
- Plan length: 12
- Execution time: 950.9264681539935 seconds

```
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)
```