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Planning Search - Heuristic analysis

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

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

P3

P3	BFS	DFGS	UCS
Expansions	14663	408	18223
Goal Tests	18098	409	18225
New Nodes	129631	3364	159618
Plan Length	12	392	12
Time (s)	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

P1	h_1	ignore-precond	level-sum
Expansions	55	41	11
Goal Tests	57	43	13
New Nodes	224	170	50
Plan Length	6	6	6
Time (s)	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.
The reason is that depth first search always expand the deepest node (Russell, Norvig, 85) and is not optimal i.e. returns the first solution found even though there might be better one (Russell, Norvig, 86).

BFS and **UCS,** both were able to find optimal solutions for all three problems. BFS needed less Expansions, Goal Tests and New Nodes (abou 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.
The results confirms that both algorithms are optimal (Russell, Norvig, 82, 83). USC is modification of BFS in a way the instead of expanding the shallowest node it expands the node with the *lowest path cost g(n)* (Russell, Norvig, 83). This is the reason why it's able to find the optimal solution faster.

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.

All the searches found optimal solution because A* is enhanced version of BFS which is optional (Russell, Norvig, 82).

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.
The reason is that ignore-precondition is easier to compute but is less accurate (also more on this topic is mentioned in the conclusion).
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.
UCS and A* search are identical except the heuristic function $f(n) = g(n) + h(n)$. (Russell, Norvig, 93).
The fact that with each call for the heuristic function new planning graph is created for the actual node is the reason why UCS is faster. So the heuristic is more accurate but it takes more time to compute it. The reason why $h(n)$= ***level-sum*** required significantly less space is that $h(n)$ express the estimated cost of the **cheapest** path to the goal (Russell, Norvig, 93).
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
   408         409         3364
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
  18223       18225       159618
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...
Expansions   Goal Tests   New Nodes
    55          57         224
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...
Expansions   Goal Tests   New Nodes
   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...
Expansions   Goal Tests   New Nodes
    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...
Expansions   Goal Tests   New Nodes
  18223       18225       159618
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...
Expansions   Goal Tests   New Nodes
   5040        5042       44944
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...
Expansions   Goal Tests   New Nodes
325 327 3002
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)

References

[1] Russell, S. and Norvig, P. (2010). *Artificial intelligence*. New Jersey: Pearson.