**Udacity AI Nanodegree**

**Project 2 – Forward Planning Agent**

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1. Analyze the search complexity as a function of domain size, search algorithm, and heuristic.



Figure - Actions vs Expanded Nodes

Figure 1 shows the number of expanded nodes for each number of actions for each search algorithm. I have colored the cells green for the lowest number of nodes expanded for each number of actions and red for the highest number expanded. It is easy to see that the Greedy Best First Search algorithms all expand the fewest nodes for the four heuristics tested. Breadth First Search and Uniform Cost Search expand the most nodes. This table makes it easy to see which algorithms and heuristics will expand the fewest and the most nodes as the number of actions in the domain continues to increase.

1. Analyze search time as a function of domain size, search algorithm, and heuristic.



Figure - Actions vs Elapsed Time

Figure 2 shows the time elapsed for each number of actions for each search algorithm. The cells in green are the shortest elapsed time for each number of actions and the cells in red are the longest elapsed time for each number of actions. Greedy Best First Search with unmet goals heuristic is consistently the fastest algorithm and heuristic. The unmet goals heuristic estimates the minimum number of actions that must be carried out from the current state to satisfy all goal conditions by ignoring the preconditions for an action to be executed. Ignoring the preconditions allows for quicker runtime. Using this heuristic with Greedy Best First Search and with A\* results in the top runtimes for the number of actions defined above.

1. Analyze the optimality of solution as a function of domain size, search algorithm, and heuristic.



Figure - Actions vs Plan Length

Figure 3 shows the plan length for each number of actions for each search algorithm. The cells in green are the shortest plans for each number of actions and the cells in red are the longest plans. Depth First Graph Search consistently produces the longest plans, producing a plan that is more than 24,000 steps longer than the optimal plan for 104 domain actions. This table makes it easy to see that Breadth First Search, Uniform Cost Search, A\* Search with unmet goals heuristic, A\* Search with max level heuristic, and A\* search with set level heuristic consistently produce optimal plans. The Greedy Best First Search algorithm is faster but does not always produce optimal plans.

1. Which algorithm or algorithms would be most appropriate for planning in a very restricted domain (i.e., one that has only a few actions) and needs to operate in real time?

Greedy Best First Search with unmet goals heuristic is the most appropriate for real-time scenarios. It consistently had the fastest time elapsed across all 4 problems. For Problem 4, Greedy Best First Search with unmet goals heuristic completed in 0.034 seconds and performed 884 times faster than the second fastest algorithm (which took over 30 seconds).

1. Which algorithm or algorithms would be most appropriate for planning in very large domains (e.g., planning delivery routes for all UPS drivers in the U.S. on a given day)?

For large domains, speed is essential. Greedy Best First Search with unmet goals heuristic would be the most appropriate because it could arrive at a solution in the least amount of time. The plan may not be optimal, but it will find a plan for large domains in a reasonable amount of time.

1. Which algorithm or algorithms would be most appropriate for planning problems where it is important to find only optimal plans?

A\* Search with unmet goals, Breadth First Search, and Uniform Cost Search will find the optimal plan and are also relatively fast. A\* search with pg\_maxlevel, and A\* search with pg\_setlevel also find the optimal plan but are extremely slow in large domains.

# Appendix – Full Data Tables

## Air Cargo Problem 1

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Search** | **Actions** | **Expansions** | **Goal Tests** | **New Nodes** | **Plan Length** | **Time Elapsed** |
| **Breadth First Search** | 20 | 43 | 56 | 178 | 6 | 0.003566 |
| **Depth First Graph Search** | 20 | 21 | 22 | 84 | 20 | 0.001954 |
| **Uniform Cost Search** | 20 | 60 | 62 | 240 | 6 | 0.005625 |
| **Greedy Best First Search with h\_unmet\_goals** | 20 | 7 | 9 | 29 | 6 | 0.000962 |
| **Greedy Best First Search with h\_pg\_levelsum** | 20 | 6 | 8 | 28 | 6 | 0.3115 |
| **Greedy Best First Search with h\_pg\_maxlevel** | 20 | 6 | 8 | 24 | 6 | 0.228897 |
| **Greedy Best First Search with h\_pg\_setlevel** | 20 | 6 | 8 | 28 | 6 | 0.793634 |
| **A\* Search with h\_unmet\_goals** | 20 | 50 | 52 | 206 | 6 | 0.005005 |
| **A\* Search with h\_pg\_levelsum** | 20 | 28 | 30 | 122 | 6 | 0.780065 |
| **A\* Search with h\_pg\_maxlevel** | 20 | 43 | 45 | 180 | 6 | 0.787484 |
| **A\* Search with h\_pg\_setlevel** | 20 | 33 | 35 | 138 | 6 | 2.075342 |

## Air Cargo Problem 2

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Search** | **Actions** | **Expansions** | **Goal Tests** | **New Nodes** | **Plan Length** | **Time Elapsed** |
| **Breadth First Search** | 72 | 3343 | 4609 | 30503 | 9 | 1.106208 |
| **Depth First Graph Search** | 72 | 624 | 625 | 5602 | 619 | 1.625992 |
| **Uniform Cost Search** | 72 | 5154 | 5156 | 46618 | 9 | 1.871376 |
| **Greedy Best First Search with h\_unmet\_goals** | 72 | 17 | 19 | 170 | 9 | 0.010953 |
| **Greedy Best First Search with h\_pg\_levelsum** | 72 | 9 | 11 | 86 | 9 | 7.040004 |
| **Greedy Best First Search with h\_pg\_maxlevel** | 72 | 27 | 29 | 249 | 9 | 14.14175 |
| **Greedy Best First Search with h\_pg\_setlevel** | 72 | 9 | 11 | 84 | 9 | 17.62334 |
| **A\* Search with h\_unmet\_goals** | 72 | 2467 | 2469 | 22522 | 9 | 1.227088 |
| **A\* Search with h\_pg\_levelsum** | 72 | 357 | 359 | 3426 | 9 | 178.374 |
| **A\* Search with h\_pg\_maxlevel** | 72 | 2887 | 2889 | 26594 | 9 | 1025.968 |
| **A\* Search with h\_pg\_setlevel** | 72 | 1037 | 1039 | 9605 | 9 | 1346.402 |

## Air Cargo Problem 3

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Search** | **Actions** | **Expansions** | **Goal Tests** | **New Nodes** | **Plan Length** | **Time Elapsed** |
| **Breadth First Search** | 88 | 14663 | 18098 | 129625 | 12 | 5.990785 |
| **Depth First Graph Search** | 88 | 408 | 409 | 3364 | 392 | 0.642064 |
| **Uniform Cost Search** | 88 | 18510 | 18512 | 161936 | 12 | 8.000985 |
| **Greedy Best First Search with h\_unmet\_goals** | 88 | 25 | 27 | 230 | 15 | 0.020434 |
| **Greedy Best First Search with h\_pg\_levelsum** | 88 | 14 | 16 | 126 | 14 | 15.8088 |
| **Greedy Best First Search with h\_pg\_maxlevel** | 88 | 21 | 23 | 195 | 13 | 19.08094 |
| **Greedy Best First Search with h\_pg\_setlevel** | 88 | 35 | 37 | 345 | 17 | 85.83039 |
| **A\* Search with h\_unmet\_goals** | 88 | 7388 | 7390 | 65711 | 12 | 4.636046 |
| **A\* Search with h\_pg\_levelsum** | 88 | 369 | 371 | 3403 | 12 | 287.3965 |
| **A\* Search with h\_pg\_maxlevel** | 88 | 9580 | 9582 | 86312 | 12 | 5142.155 |
| **A\* Search with h\_pg\_setlevel** | 88 | 3423 | 3425 | 31596 | 12 | 6513.484 |

## Air Cargo Problem 4

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Search** | **Actions** | **Expansions** | **Goal Tests** | **New Nodes** | **Plan Length** | **Time Elapsed** |
| **Breadth First Search** | 104 | 99736 | 114953 | 944130 | 14 | 55.22623 |
| **Depth First Graph Search** | 104 | 25174 | 25175 | 228849 | 24132 | 2276.519 |
| **Uniform Cost Search** | 104 | 113339 | 113341 | 1066413 | 14 | 67.02948 |
| **Greedy Best First Search with h\_unmet\_goals** | 104 | 29 | 31 | 280 | 18 | 0.034245 |
| **Greedy Best First Search with h\_pg\_levelsum** | 104 | 17 | 19 | 165 | 17 | 30.30131 |
| **Greedy Best First Search with h\_pg\_maxlevel** | 104 | 56 | 58 | 580 | 17 | 73.67826 |
| **Greedy Best First Search with h\_pg\_setlevel** | 104 | 107 | 109 | 1164 | 23 | 413.2171 |
| **A\* Search with h\_unmet\_goals** | 104 | 34330 | 34332 | 328509 | 14 | 31.90939 |
| **A\* Search with h\_pg\_levelsum** | 104 | 1208 | 1210 | 12210 | 15 | 1723.163 |
| **A\* Search with h\_pg\_maxlevel** | 104 | 62077 | 62079 | 599376 | 14 | 51875.21 |
| **A\* Search with h\_pg\_setlevel** | 104 | 22606 | 22608 | 224229 | 14 | 62613.47 |