Introduction

Experiment with different search algorithms and heuristics for a agent that performs progression search to solve planning problems. Use the results to answer questions about designing planning systems

Setting up notebook to use the provided code

- Create a data class to contain our experiment data
- Modify main method from run_search.py to be able to execute from this notebook
- Modify run_search method from _utils.py to be able to execute from this notebook

In [21]:

```
from dataclasses import make_dataclass
from timeit import default_timer as timer
import run_search as rs
import _utils as utils


Experiment = make_dataclass("Experiment", [("Problem_Name", str), ("Search_Algo", str), ("Heuristic", str),
                                           ("Actions", int), ("Expansions", int), ("Goal_Tests", int), ("New_Nodes", int),
                                           ("Plan_Length", int), ("Elapsed_Time", float)])

def main_modified(p_choices, s_choices):
    problems = [rs.PROBLEMS[i-1] for i in map(int, p_choices)]
    searches = [rs.SEARCHES[i-1] for i in map(int, s_choices)]

    results = [] # list of experiments
    for pname, problem_fn in problems:
        for sname, search_fn, heuristic in searches:
            problem_instance = problem_fn()
            heuristic_fn = None if not heuristic else getattr(problem_instance, heuristic)
            result = run_search_modified(problem_instance, search_fn, heuristic_fn)
            results.append(Experiment(pname, sname, heuristic, len(result[0].actions_list),
                                      result[0].succs, result[0].goal_tests, result[0].states, result[1], result[2]))
    return results

def run_search_modified(problem, search_function, parameter=None):
    ip = utils.PrintableProblem(problem)
    start = timer()
    if parameter is not None:
        node = search_function(ip, parameter)
```

```
    else:
        node = search_function(ip)
    end = timer()
    return (ip, len(node.solution()), (end - start))
```

Run searches on Cargo problems

In [12]:

```
all_searches = [x for x in range(1, 12)] # Used for Cargo problem 1 and 2
cargo_3_searches = [x for x in range(1, 11)] # Used for Cargo problem 3
cargo_4_searches = [x for x in range(1, 10)] # Used for Cargo problem 4
```

```
[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]
```

In [16]:

```
# Ran 1 search per cargo problem to get aa bit more feedback from the computations

# Cargo 1 problem
search_results_c1  = main_modified([1], all_searches)
df_c1 = pd.DataFrame(search_results_c1)
```

In [18]:

```
# Cargo 2 problem
search_results_c2  = main_modified([2], all_searches)
df_c2 = pd.DataFrame(search_results_c2)
```

In [20]:

```
search_results_c3  = main_modified([3], cargo_3_searches)
df_c3 = pd.DataFrame(search_results_c3)
```

In [27]:

```
search_results_c4  = main_modified([4], cargo_4_searches)
df_c4 = pd.DataFrame(search_results_c4)
```

Combine the dataframe

In [54]:

```
df_combined = pd.concat([df_c1, df_c2, df_c3, df_c4])
```

In [55]:

```
df_combined = df_combined.set_index(["Problem_Name", "Search_Algo"])
df_combined
```

Out[55]:

Problem_Name	Search_Algo	Heuristic	Actions	Expansions	Goal_Tests	New_Nodes	Plan_Length	Elapsed_Time
Air Cargo Problem 1	**breadth_first_search**		20	43	56	178	6	0.007711
	depth_first_graph_search		20	21	22	84	20	0.004123
	uniform_cost_search		20	60	62	240	6	0.011405
	greedy_best_first_graph_search	h_unmet_goals	20	7	9	29	6	0.001880
	greedy_best_first_graph_search	h_pg_levelsum	20	6	8	28	6	0.475017
	greedy_best_first_graph_search	h_pg_maxlevel	20	6	8	24	6	0.346950
	greedy_best_first_graph_search	h_pg_setlevel	20	6	8	28	6	1.990053
	astar_search	h_unmet_goals	20	50	52	206	6	0.010775
	astar_search	h_pg_levelsum	20	28	30	122	6	1.153056
	astar_search	h_pg_maxlevel	20	43	45	180	6	1.276995
	astar_search	h_pg_setlevel	20	33	35	138	6	5.150055
Air Cargo Problem 2	**breadth_first_search**		72	3343	4609	30503	9	2.313699
	depth_first_graph_search		72	624	625	5602	619	2.903870
	uniform_cost_search		72	5154	5156	46618	9	3.825029
	greedy_best_first_graph_search	h_unmet_goals	72	17	19	170	9	0.028149
	greedy_best_first_graph_search	h_pg_levelsum	72	9	11	86	9	10.795064
	greedy_best_first_graph_search	h_pg_maxlevel	72	27	29	249	9	21.246409
	greedy_best_first_graph_search	h_pg_setlevel	72	9	11	84	9	46.505007
	astar_search	h_unmet_goals	72	2467	2469	22522	9	2.508096
	astar_search	h_pg_levelsum	72	357	359	3426	9	266.773466
	astar_search	h_pg_maxlevel	72	2887	2889	26594	9	1570.773955
	astar_search	h_pg_setlevel	72	1037	1039	9605	9	3616.764546
Air Cargo Problem 3	**breadth_first_search**		88	14663	18098	129625	12	11.392577

Problem_Name	Search_Algo	Heuristic	Actions	Expansions	Goal_Tests	New_Nodes	Plan_Length	Elapsed_Time
	depth_first_graph_search		88	408	409	3364	392	1.170486
	uniform_cost_search		88	18510	18512	161936	12	15.210399
	greedy_best_first_graph_search	h_unmet_goals	88	25	27	230	15	0.047403
	greedy_best_first_graph_search	h_pg_levelsum	88	14	16	126	14	22.725623
	greedy_best_first_graph_search	h_pg_maxlevel	88	21	23	195	13	27.618326
	greedy_best_first_graph_search	h_pg_setlevel	88	35	37	345	17	220.472328
	astar_search	h_unmet_goals	88	7388	7390	65711	12	8.966065
	astar_search	h_pg_levelsum	88	369	371	3403	12	422.298002
	astar_search	h_pg_maxlevel	88	9580	9582	86312	12	7346.606979
Air Cargo Problem 4	**breadth_first_search**		104	99736	114953	944130	14	101.328007
	depth_first_graph_search		104	25174	25175	228849	24132	3372.150481
	uniform_cost_search		104	113339	113341	1066413	14	120.116413
	greedy_best_first_graph_search	h_unmet_goals	104	29	31	280	18	0.063102
	greedy_best_first_graph_search	h_pg_levelsum	104	17	19	165	17	41.053186
	greedy_best_first_graph_search	h_pg_maxlevel	104	56	58	580	17	99.347298
	greedy_best_first_graph_search	h_pg_setlevel	104	107	109	1164	23	995.940341
	astar_search	h_unmet_goals	104	34330	34332	328509	14	58.310369
	astar_search	h_pg_levelsum	104	1208	1210	12210	15	2299.479587

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

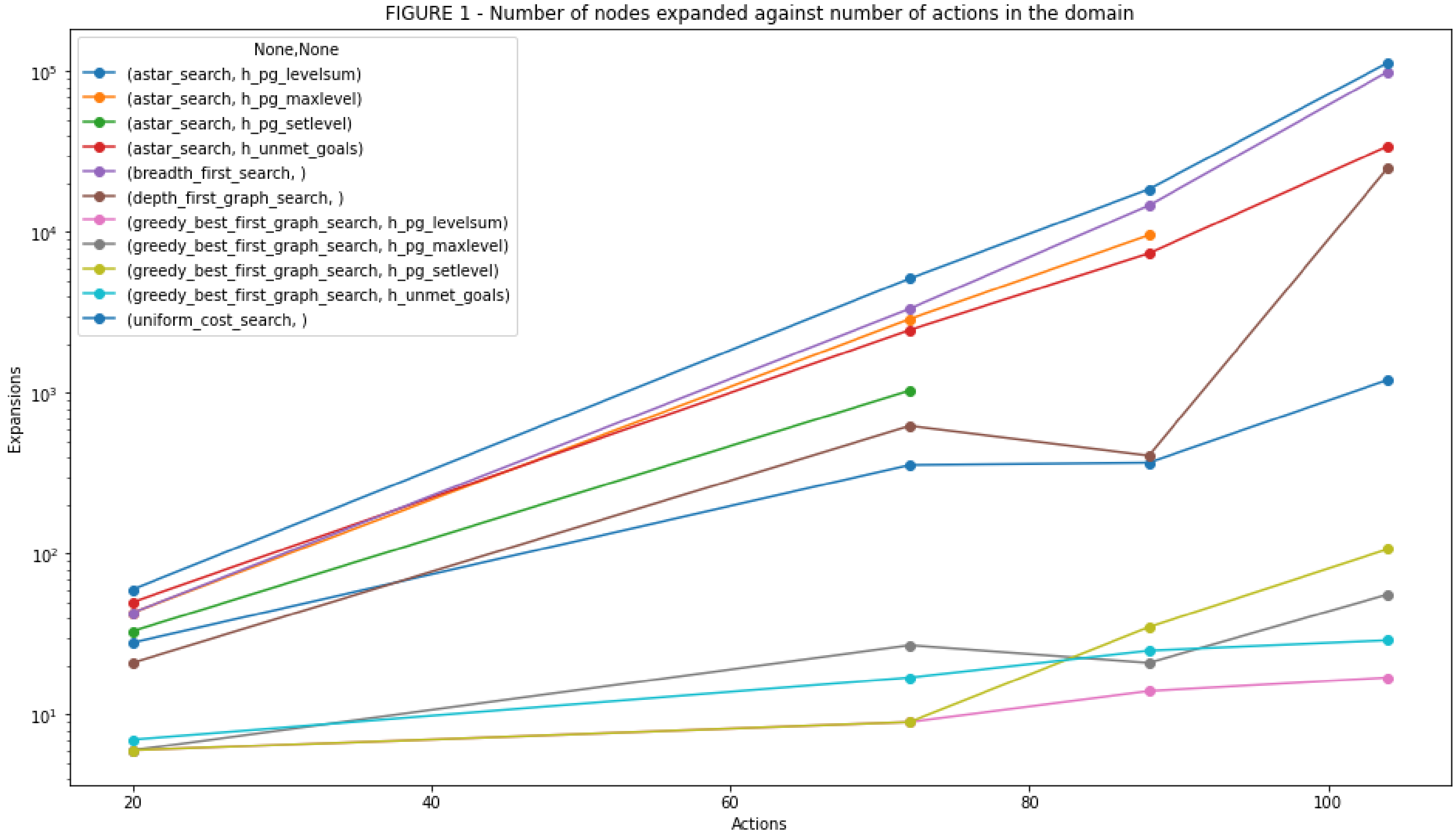
- Analyze the number of nodes expanded against number of actions in the domain.

In [160…

```
import matplotlib.pyplot as plt

df_plot = df_combined.reset_index()
df_plot = df_plot.set_index('Actions', inplace=False)
df_plot.groupby(['Search_Algo', 'Heuristic'])['Expansions'].plot(ylabel='Expansions', legend=True, marker='o',
                                                                  figsize=(16,9), logy=True,
                                                                  title='FIGURE 1 - Number of nodes expanded against number of acti

plt.show()
```



Discussion of results:

All the graph searching algorithms show exponential behavior as the domain size increases. This behavior is illustrated by the nearly straight lines in the log-plot shown above in Figure 1.

Regarding the 3 groups of search algorithms: uninformed, greedy BFS and A*:

- Uninformed search algorithms expands most nodes as expected. In Figure 1 UCS and BFS are at the top of the plot. This is a consequence of having no goal direction, they consider every successor step, in any direction, equally important.
- At the bottom of Figure 1 we see the 4 greedy BFS searches. With this algorithm the frontier is directed towards the goal, it first expands the node whose estimated distance to the goal is the smallest, resulting in a smaller footprint when it comes to nodes visited.
- Finally we have A* in the middle. This algorithm uses both the knowledge acquired so far while exploring the search space, as well as a heuristic function to point it toward the goal(s). In fact UCS can be viewed as a special case of A* where *h(x) = 0* for all x. Not surprisingly the results end up between uninformed and greedy BFS.

Regarding heuristic functions:

- A more accurate heuristic function is expected to expand less nodes that a less accurate heuristic. Intuitively _unmet*goals* and *maxlevel* are expected to be less accurate and result in more expansions. This is partly supported by the data in Figure 1, here *levelsum* performs the best indicating that the problems are largely decomposable. Interesting to see that *setlevel* starts getting in 'trouble' for larger problems Cargo 3 + 4. Maybe it is a lack of interaction between subplans or maybe it pays the price for ignoring interactions among three or more literals.

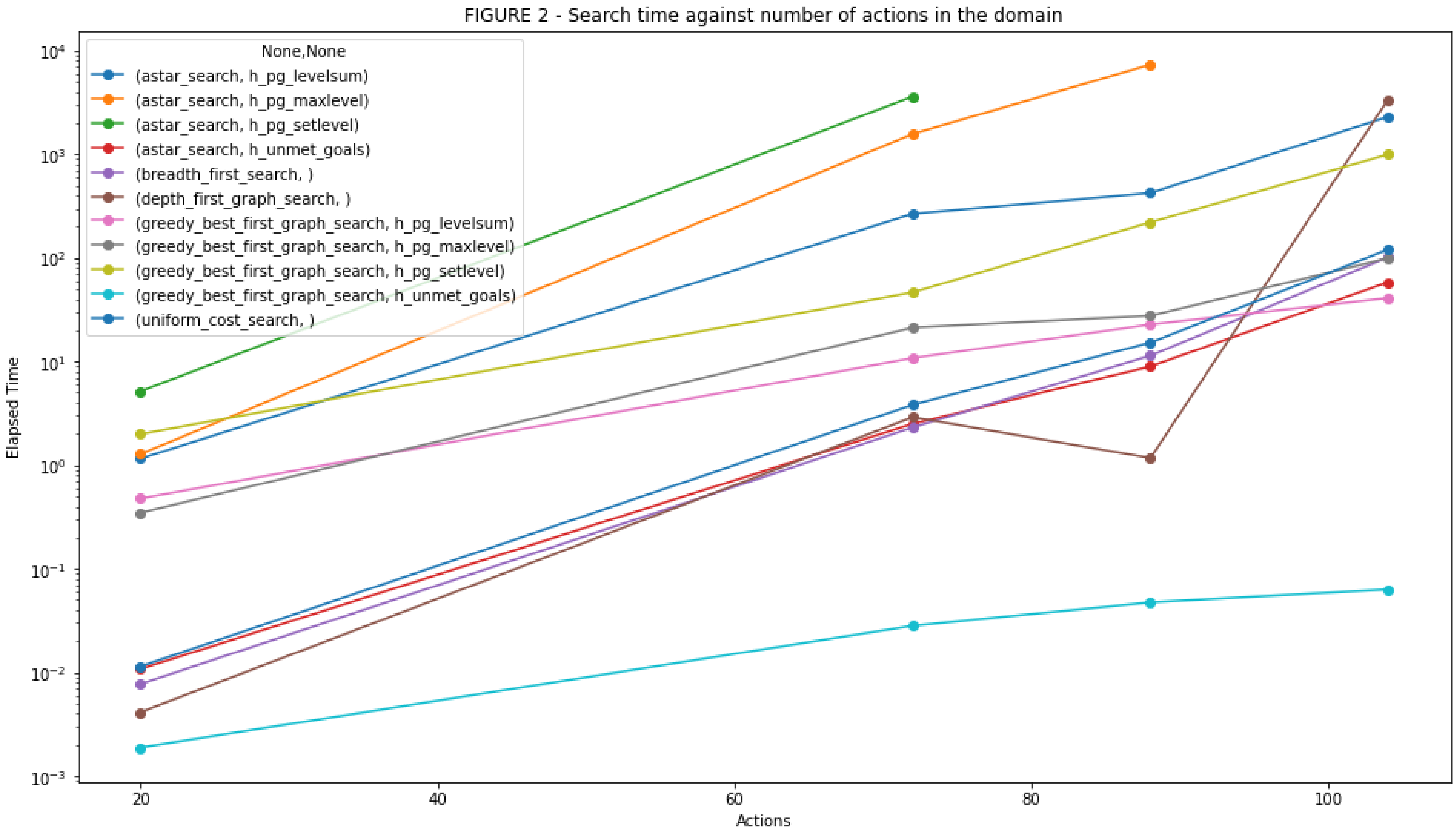
Analyze search time as a function of domain size, search algorithm, and heuristic.

- Analyze the search time against the number of actions in the domain.

In [162…

```
df_plot = df_combined.reset_index()
df_plot = df_plot.set_index('Actions', inplace=False)
df_plot.groupby(['Search_Algo', 'Heuristic'])['Elapsed_Time'].plot(ylabel='Elapsed Time', legend=True, marker='o',
                                                                   figsize=(16,9), logy=True,
                                                                   title='FIGURE 2 - Search time against number of actions in the do

plt.show()
```



Discussion of results:

Generally all the algorithms follow a time complexity looking like O(*b^(d+1)*) (worst case) where the tree has a depth d and an average branching factor b; so again the time complexity grows exponentially with the domain size, also illustrated by the nearly straight lines in the log-plot shown above in Figure 2.

Regarding the 3 groups of search algorithms: uninformed, greedy BFS and A*:

- The A* algorithms are the most computational expensive in terms of time. This is no surprise as A* essentially performs an "exhaustive search" using both the knowledge acquired so far while exploring the search space and a heuristic function.
- Uninformed search algorithms perform very well for small domain sizes, that is, are most time efficient. However, they are being overtaken by the greedy BFS as the domain size increases (Cargo 4).

Regarding heuristic functions:

- What was said in the 'Search Complexity' section also applies here. The order of time complexity found in Figure 2 are as expected from a purely functional level (high to low):
  - *setlevel*
  - *maxlevel*
  - *levelsum*
  - *unmet_goals*

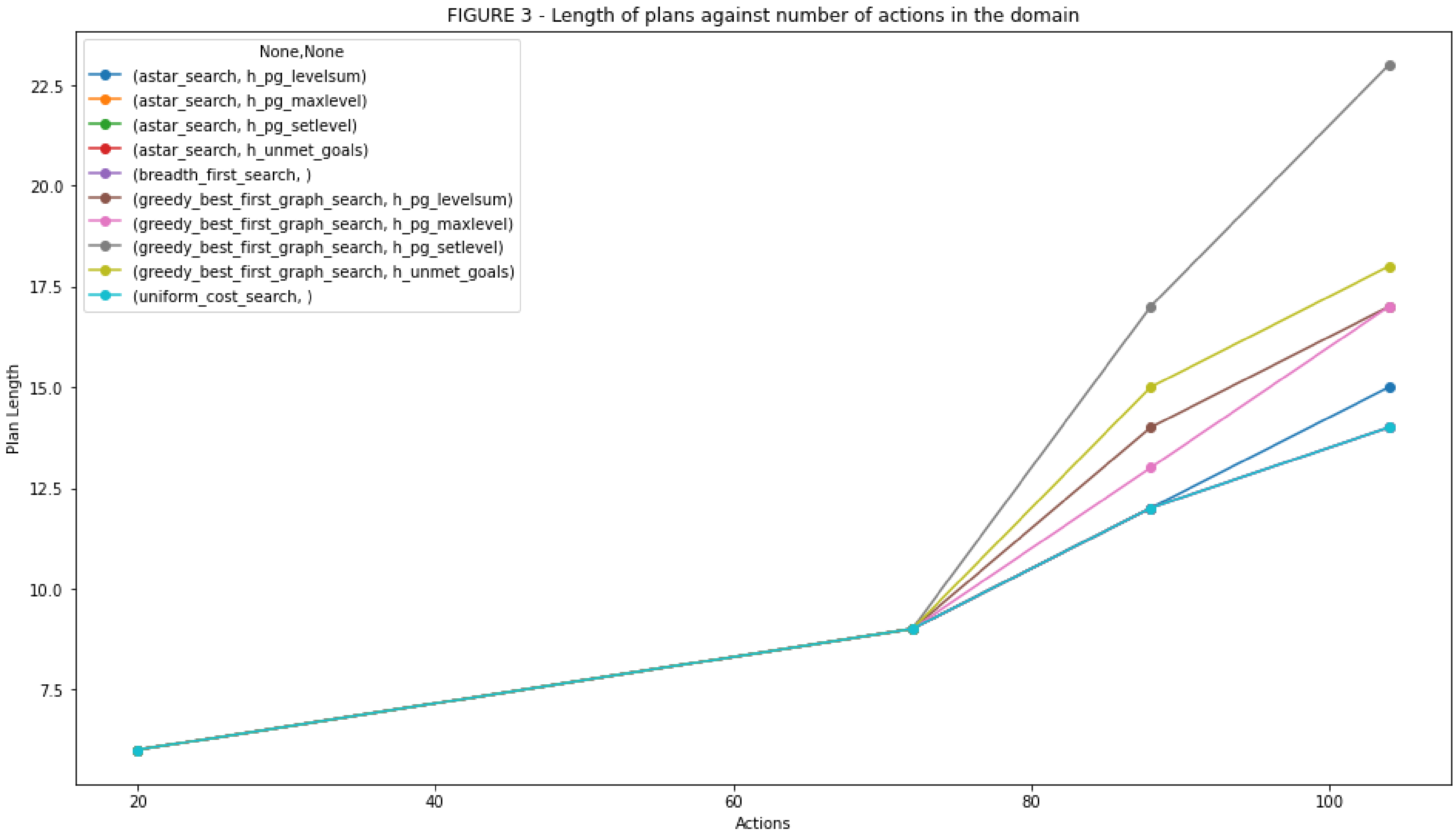
Analyze the optimality of solution as a function of domain size, search algorithm, and heuristic.

- Analyze the length of the plans returned by each algorithm on all search problems.

In [163…

```
df_plot = df_combined.reset_index()
df_plot = df_plot[df_plot.Search_Algo != 'depth_first_graph_search'] # remove depth_first_graph_search as plan length is 'noise'
df_plot = df_plot.set_index('Actions', inplace=False)
df_plot.groupby(['Search_Algo', 'Heuristic'])['Plan_Length'].plot(ylabel='Plan Length', legend=True, marker='o',
                                                                   figsize=(16,9), logy=False,
                                                                   title='FIGURE 3 - Length of plans against number of actions in th

plt.show()
```



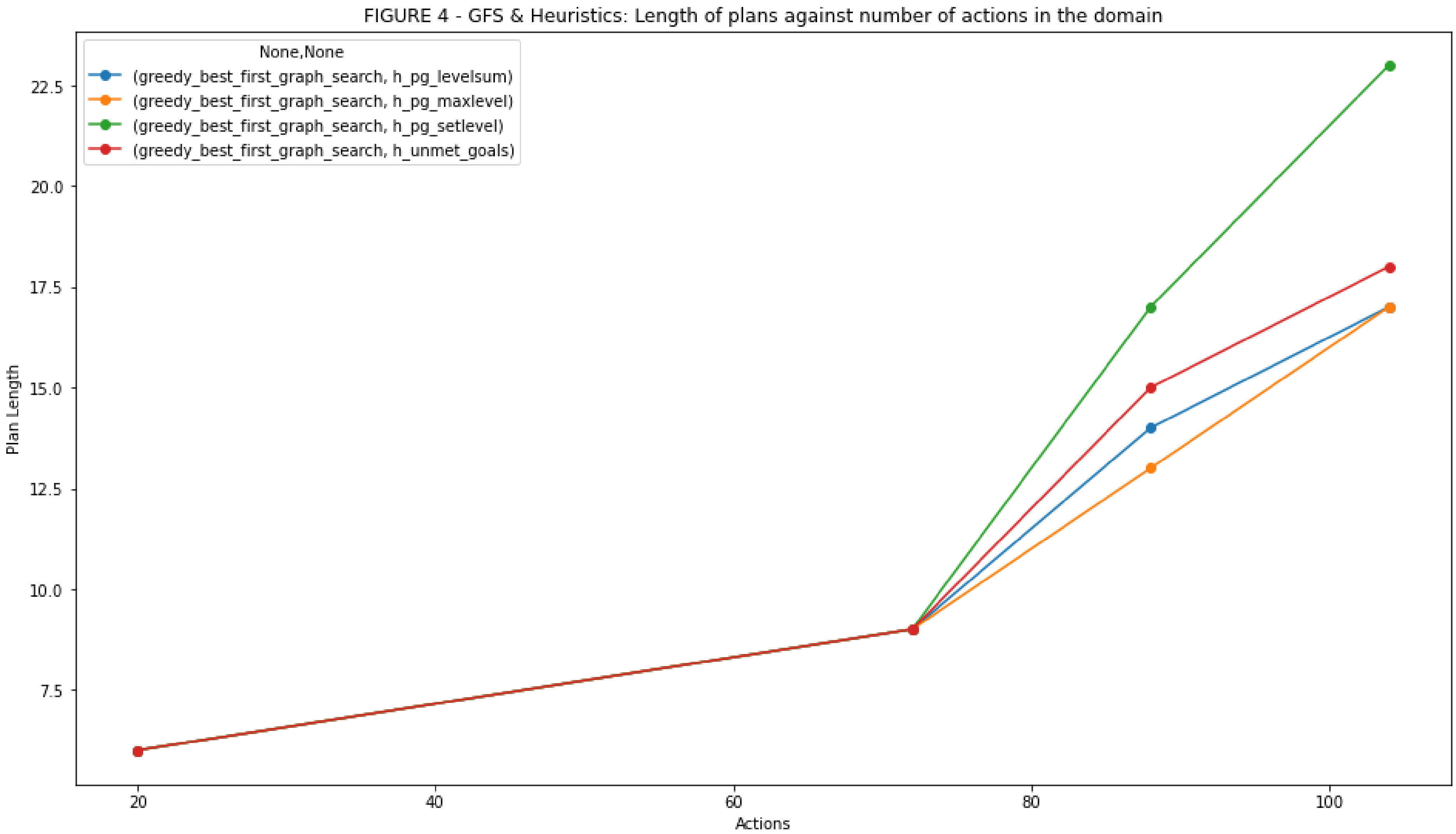
Note to Figure 3:

1. DFS has beeen removed from the plot as it is not designed for arrriving at optimal plans.
2. All uninformed and A* searches are overlapping in the bottom blue lines

In [164…

```
df_plot = df_combined.reset_index()
df_plot = df_plot[df_plot.Search_Algo == 'greedy_best_first_graph_search'] # remove depth_first_graph_search as plan length is 'no
df_plot = df_plot.set_index('Actions', inplace=False)
```

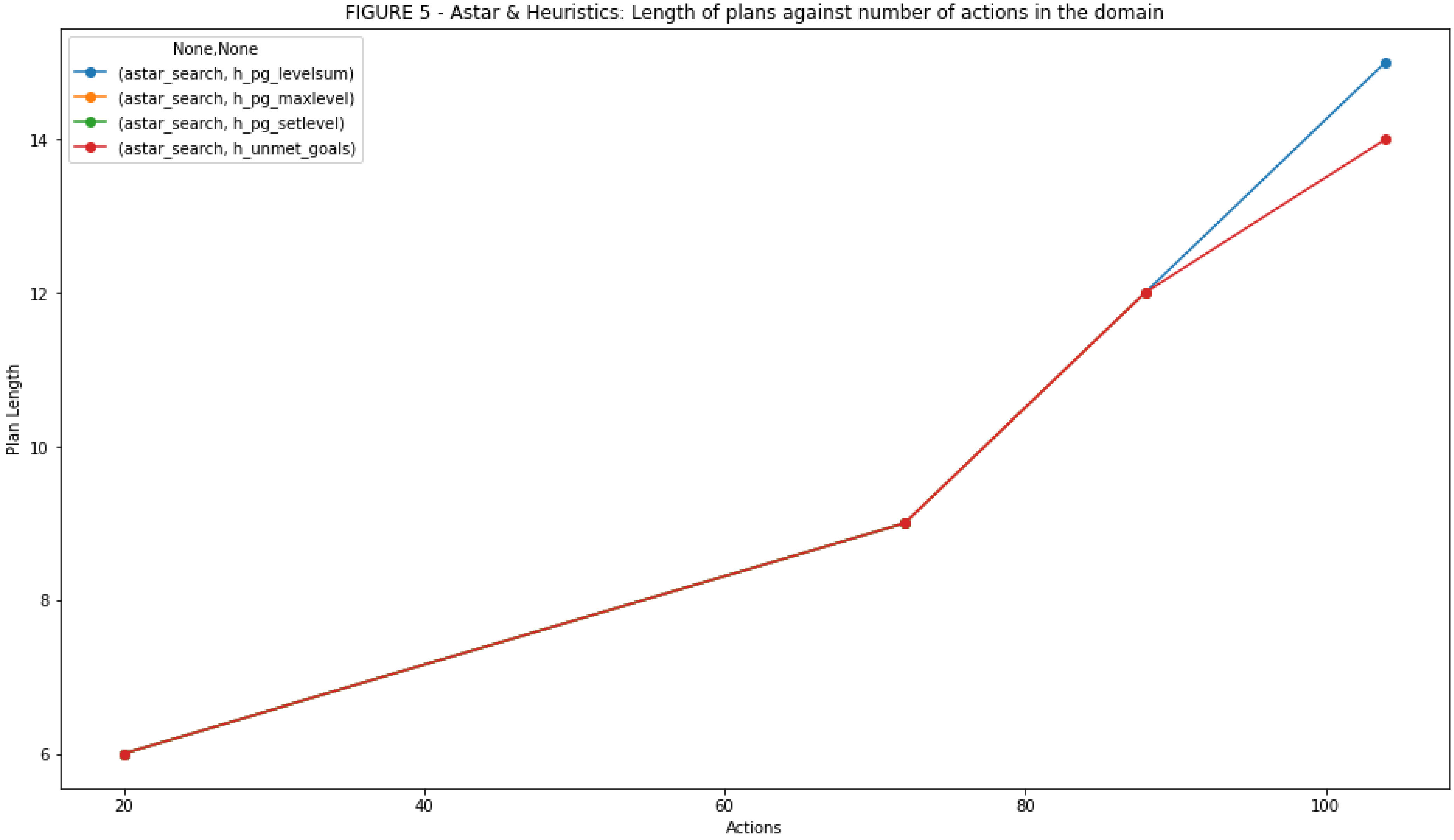
```
df_plot.groupby(['Search_Algo', 'Heuristic'])['Plan_Length'].plot(ylabel='Plan Length', legend=True, marker='o',
                                                                  figsize=(16,9), logy=False,
                                                                  title='FIGURE 4 - GFS & Heuristics: Length of plans against numbe
plt.show()
```



In [165…

```
df_plot = df_combined.reset_index()
df_plot = df_plot[df_plot.Search_Algo == 'astar_search'] # remove depth_first_graph_search as plan length is 'noise'
df_plot = df_plot.set_index('Actions', inplace=False)
```

```
df_plot.groupby(['Search_Algo', 'Heuristic'])['Plan_Length'].plot(ylabel='Plan Length', legend=True, marker='o',
                                                                   figsize=(16,9), logy=False,
                                                                   title='FIGURE 5 - Astar & Heuristics: Length of plans against num
plt.show()
```



Discussion of results

Generally all the algorithms comes up with the ideal plan length for small domain problems (Cargo 1 + 2). For larger problems we see the greedy BFS algorithms move away from optimal plan lengths, that is, getting longer than the optimal solution. This is visualized in Figure 3 + 4. Even A* starts showing differences in plan length for more complex problems, see Figure 5.

Regarding the 3 groups of search algorithms: uninformed, greedy BFS and A*:

- In general, the greedy BFS is not optimal, that is, the path found may not be the optimal one as illustrated in Figure 4.
- Given that A* uses an admissible heuristic function, then A* is optimal as illustrated in figure 5 (discussed below under heuristic functions)
- Uninformed search algorithms in form of Breadth-First-Search and Uniform-Cost-Search are optimal and guaranteed to find the shortest path, shown by the light-blue line in Figure 3.

Regarding heuristic functions:

- For the A* searches if the heuristic function is admissible then A* will find the optimal path:
  - *setlevel* is admissible
  - *maxlevel* is admissible
  - *levelsum* NOT admissible in our case
  - *unmet_goals* is admisssible (basically UCS)

So A* with a heuristic of *setlevel* or *maxlevel* should arrive at a plan-length of 14 for Cargo 4 problem.

Q&A

- **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?**
  The 3 groups of search algorithms: uninformed, greedy BFS and A* will all arrive at optimal plans in very restricted domains. Nothing has been mentioned around space complexity so will be ignored, instead we focus on a real time solution, meaning fast response times, and that points to the following choices (ordered):
  1. Greedy BFS with simple heuristic like _unmet*goals*
  2. Uninformed BFS or UCS

- **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)?**

A* becomes impractical when the search space is huge both in terms of time and space complexity. Greedy BFS is the better choice compared to the uninformed searches (BSF and UCS) as it consumes less memory and compute time. This assumes we are prepared to accept a potential none optimal solution, but a solution good enough.

- **Which algorithm or algorithms would be most appropriate for planning problems where it is important to find only optimal plans?**
  Uninformed BFS or UCS would be first choice based on the data shown, A* with admissible heuristic function would be second choice.

NOTE: It may be possible that A* with optimised admissible heuristic function may change the answer to questions 1 and 3.