Q1: Provide an optimal plan for Problems 1, 2, and 3.

P1	P2	P3
Load(C1, P1, SFO) Fly(P1, SFO, JFK) UnLoad(C1, P1, JFK) Load(C2, P2, JFK) Fly(P2, JFK, SFO) UnLoad(C2, P2, SFO)	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)	Load(C1, P1, SFO) Fly(P1, SFO, ATL) Load(C3, P1, ATL) Fly(P1, ATL, JFK) UnLoad(C3, P1, JFK) Load(C2, P2, JFK) Fly(P2, JFK, ORD) Load(C4, P2, ORD) Fly(P2, ORD, SFO) UnLoad(C4, P2, SFO) UnLoad(C1, P1, JFK) UnLoad(C2, P2, SFO)

Q2: Compare and contrast non-heuristic search result metrics (optimality, time elapsed, number of node expansions) for Problems 1,2, and 3. Include breadth-first, depth-first, and at least one other uninformed non-heuristic search in your comparison; Your third choice of non-heuristic search may be skipped for Problem 3 if it takes longer than 10 minutes to run, but a note in this case should be included.

Non-heuristic search

	P1	P2	P3
depth-first	21 | 22 | 84 | 20 | 0.04s	624 | 625 | 5602 | 619 | 6.0s	408 | 409 | 3364 | 392 | 3.3s
breadth-first	43 | 56 | 180 | 6 | 0.09s	3343 | 4609 | 30509 | 9 | 28.7s	14663 | 18098 | 129631 | 12 | 163.6s
depth-limit	101 | 271 | 414 | 50 | 0.2s	222719 | 2053741 | 2054119 | 50 | 2065.0s	Takes too long to run

Data presented in the format of "expansions | goal tests | new nodes | plan length | time elapsed

Q3: Compare and contrast heuristic search result metrics using A* with the "ignore preconditions" and "level-sum" heuristics for Problems 1, 2, and 3.

Heuristic search

	P1	P2	P3
A* - h1	55 | 57 | 224 | 6 | 0.1s	4841 | 4843 | 43929 | 9 | 32.4s	18181 | 18183 | 159281 | 12 | 122.6s
A* - ignore preconditions	41 | 43 | 170 | 6 | 0.1s	1438 | 1440 | 13188 | 9 | 10.0s	4931 | 4933 | 43869 | 12 | 37.7s
A* - level-sum	11 | 13 | 50 | 6 | 0.9s	85 | 87 | 831 | 9 | 70.4s	250 | 252 | 2286 | 12 | 259.0s

Data presented in the format of "expansions | goal tests | new nodes | plan length | time elapsed

Q4: What was the best heuristic used in these problems? Was it better than non-heuristic search planning methods for all problems? Why or why not?

Q: What was the best heuristic used in these problems?
A: First of all, we need to define what does "best" mean for a planning solution. Obviously a must-have criteria is that the plan has to take the minimal step possible to reach the goal, this means the fewer steps a solution takes the better it is. In this case, there are several solutions produce the optimal number of steps, so additional criterias are needed.

How to find the next best criteria in our metric space (expansions, goal tests, new nodes, time elapsed)? Answer is that it depends. If we assume computer resources are infinite, time elapsed is the best pick because time complexity is usually how people judge the performance of an algorithm. But in the old days, computer resources is very limited, so space complexity is sometimes a higher priority. In A* search, every node expansion needs to put all its children on the stack which takes memory, in a problem with high branching factor, it can be very big. So when we have limited memory that's less than enough to hold the entire graph, we should favor solutions that visit least amount of nodes while solving the problem.

In this particular case, computer memory are way sufficient to hold the entire graph for all three problems, so I pick time elapsed + number steps as the criteria to judge the solutions.

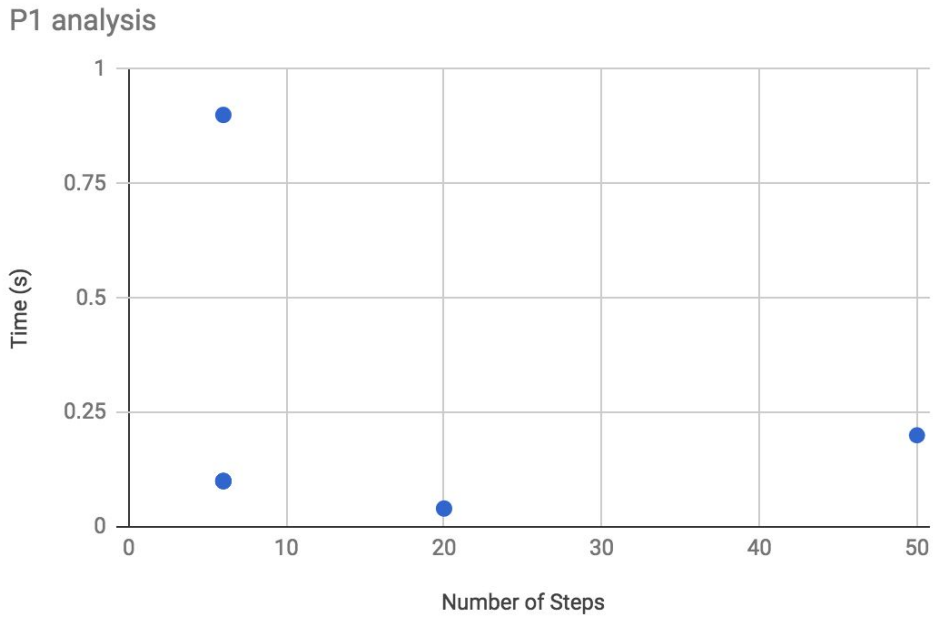
The optimal solution is more obvious once we visualize all search results onto a 2-d space (show below). The x-axis represents the number of steps to the plan and y-axis represents the

duration in second the algorithm takes to reach a result. The solution that is closest to (0,0) is the optimal. Here's the result:

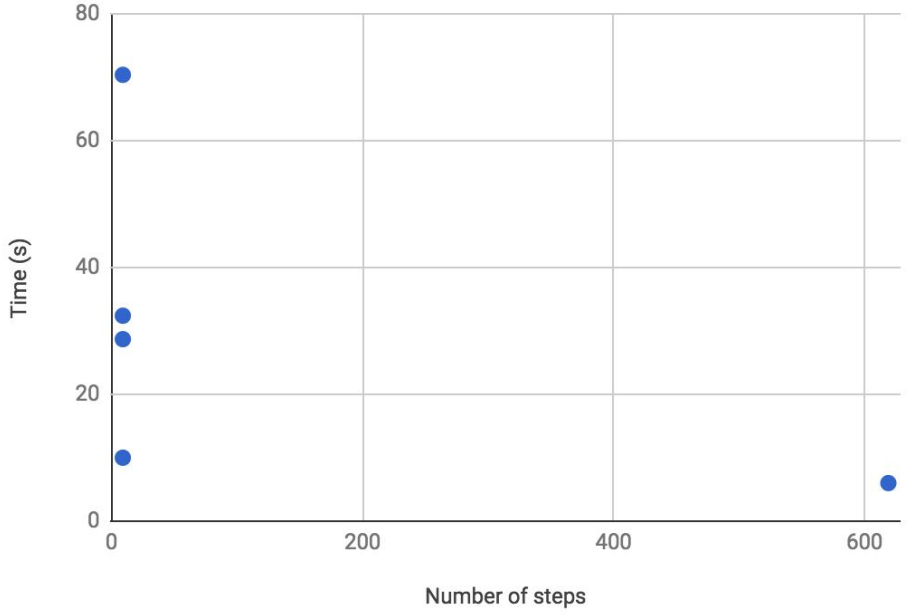
P1: breadth-first search
P2: A* - ignore precondition
P3: A* - ignore precondition

Q: Was it better than non-heuristic search planning methods for all problems? Why or why not?
A: As P1's result shown above, breadth-first search wins over heuristic search for time-complexity, this indicates that non-heuristic search is not always better than heuristic search. In general, A* is efficient when the branching factor is large, so it can efficiently filter out redundant branches. However, A* search needs to run through the heuristic function for each state visited, it slows down the algorithm. Thus, **for problem with relatively smaller expansions factor, a simple non-heuristic is better.**

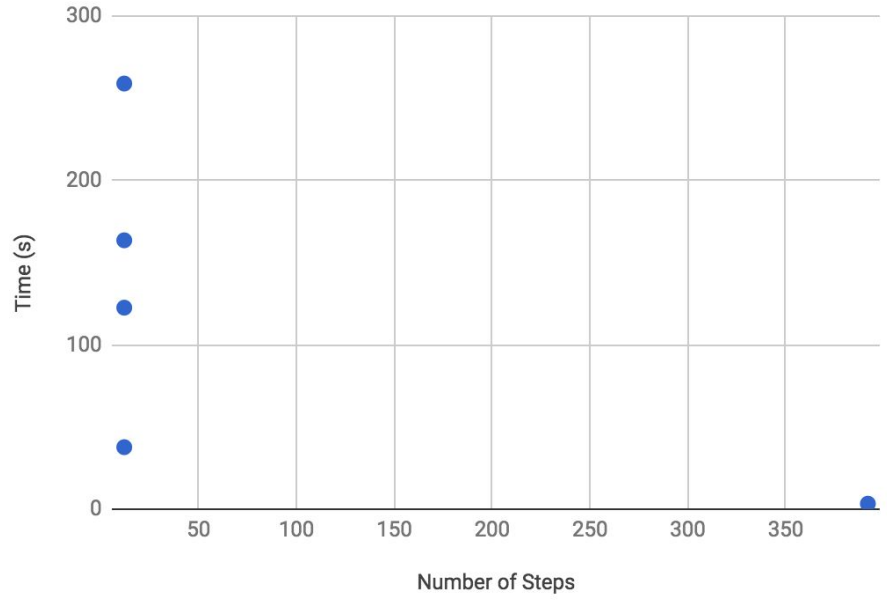
P1:



P2:


80
60
40
20
0
Time (s)
0
200
400
600
Number of steps

P3:


300
200
100
0
Time (s)
50
100
150
200
250
300
350
Number of Steps