

PROJECT III: IMPLEMENT A PLANNING SEARCH

Written Analysis

Possible optimal plans for problems 1,2 and 3 are as follows:

Problem 1, after breadth-first, with length 6:

```
Load(C1, P1, SF0)
Load(C2, P2, JFK)
Fly(P2, JFK, SF0)
Unload(C2, P2, SF0)
Fly(P1, SF0, JFK)
Unload(C1, P1, JFK)
```

Problem 2, using uniform cost search, with length 9:

```
Load(C1, P1, SF0)
Load(C2, P2, JFK)
Load(C3, P3, ATL)
Fly(P1, SF0, JFK)
Fly(P2, JFK, SF0)
Fly(P3, ATL, SF0)
Unload(C1, P1, JFK)
Unload(C2, P2, SF0)
Unload(C3, P3, SF0)
```

Problem 3, after uniform cost search, with length 12:

```
Load(C1, P1, SF0)
Load(C2, P2, JFK)
Fly(P1, SF0, ATL)
Load(C3, P1, ATL)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, SF0)
Fly(P1, ATL, JFK)
Unload(C1, P1, JFK)
Unload(C2, P2, SF0)
Unload(C3, P1, JFK)
Unload(C4, P2, SF0)
```

We note that other paths with the same length provide also other alternative optimal solutions for each of these problems, due to the transitivity of some actions.

The metrics obtained for problem 1 are summarized in the following table:

Search	Expansions	Goal Tests	New Nodes	Duration	Plan length
Breadth-first	43	56	180	0.15	6
Depth-first	21	22	84	0.07	20
Uniform-cost	55	57	224	0.18	6
A*- ignore preconditions	41	43	170	0.16	6
A*- level-sum	11	13	50	0.76	6

We can see that among the non-heuristic searches, breadth-first is optimal. This is so, since according to Norvig and Russell's textbook "Artificial Intelligence: A Modern Approach", 3rd ed. (AIMA) "breadth-first search is optimal if the path cost is a nondecreasing function of the depth of the node" (idem, p.82), and here we use a cost function equal to 1 for all actions. Moreover, uniform-cost is also optimal, since "uniform-cost search is optimal in general." (idem, p.85). Depth-first, on the other hand, provides a non-optimal solution (see AIMA, figure 3.2.1 p.91) which can be seen by the length of the plan, even though it provides the least costly solution in terms of expansions, duration, goal tests and new nodes (the non-duration metrics).

Now, according to AIMA (p.95), letting h be the heuristic function, then A* star "graph-search version is optimal if $h(n)$ is consistent". Since for the ignore preconditions heuristic, the minimum number of actions $h(s')$ from any successor state s' is $h(s')=h(s) + 1$, since the step cost on our case is 1, consistency is verified. For the levelsum heuristic, we recall that according to AIMA, "level costs extracted from serial graphs are often quite reasonable estimates of actual costs. " (p. 382). As such, since our planning graph is serialized, it is not unreasonable to obtain optimal or close-to optimal plans, as we can see in the table. Moreover, level-sum required 4 times the duration of the search using the ignore preconditions heuristic, even though it achieved the least values for the non-duration metrics. Globally, we can see that the fast searches, in terms of elapsed time, were breadth-first and A* using "ignore preconditions.

For problem 2, we gather the following set of metrics in similar fashion to problem 1:

Search	Expansions	Goal Tests	New Nodes	Duration	Plan length
Breadth-first	3343	4609	30509	61.1	9
Depth-first	624	625	5602	12.8	619
Uniform-cost	4780	4782	43381	72.1	9
A*- ignore preconditions	1450	1452	13303	17.8	9
A*- level-sum	86	88	841	129.8	9

In this case, we can see that the increased complexity of the problem leads to a wider range of performance on both the heuristic and non-heuristic searches. Of relevance is the fact that adding one variable per category, or an increase of 50%, with respect to problem 1, makes the fastest search strategy around 100 times slower than the same strategy in problem 1.

Clearly, the solution given by depth-first search, approximately 70 times longer than that offered by breadth-first and uniform-cost searches, gives evidence of the infeasibility of depth-first to find an optimal plan. Between the remaining two non-heuristic methods, and given the similar magnitudes in expansions, goal tests, and new nodes, the breadth-first search was faster than uniform-cost, and presents the best choice among the appropriate uninformed search function used for solving problem 2. As to the informed searches, both yielded optimal solutions, as explained for problem 1. It is interesting, to see that although the magnitude of the non-duration metrics when ignore-preconditions was used is one degree higher as those by the level-sum heuristic, the duration of the former is 7 times shorter than that of the latter. Indeed, the evaluation of the level-sum function requires to search for each state, the level at which the planning graph contains each of the individual and independent sub-goals that together constitute the final goal of the planning problem. Finally, we see that A* with ignore- preconditions heuristic offers the best performance among all the 5 search strategies, taking less than 30% of the time required by the second-fastest choice, breadth-first search.

Finally, for problem 3, we have obtained the following metrics:

Search	Expansions	Goal Tests	New Nodes	Duration	Plan length
breadth-first	14663	18098	129631	339.3	12
depth-first	408	409	3364	6.8	392
uniform-cost	17882	17884	156769	309.6	12
A*- ignore preconditions	5034	5036	44886	98.2	12
A*- level-sum	314	316	2894	370.4	12

First, we observe that the current problem is of complexity degree linearly higher than problem 2. Indeed, we can see that problem 3 requires, depending on the strategy, approximately 4-6 times more expansions, goal tests and new nodes than problem 2. This increase leads to a similar magnitude of increase in duration for all strategies except depth-first search and A* level-sum. Moreover, notice that the goal is now composed of 4 independent sub-goals, one more than problem 2, which adds additional complexity to the heuristic strategies.

Now, and concerning the performance of the uninformed strategies, uniform-cost is slightly faster than breadth-first. In comparison to problem 2, we can see uniform cost giving rise to more expansions and new nodes, as expected in all problems (In fact, “uniform-cost search does strictly more work by expanding nodes at depth d unnecessarily.”) (ibidem, p.85),

and slightly fewer goal tests than breadth-first search does. Since the step costs are all one, the complexity of uniform-cost is the same as breadth-first ("When all step costs are the same, uniform-cost search is similar to breadth-first search, except that the latter stops as soon as it generates a goal, whereas uniform-cost search examines all the nodes at the goal's depth to see if one has a lower cost." (AIMA, p.85))

Any difference in performance is certainly associated to the particular characteristics of the problem, where it is faster overall selecting nodes with the smaller costs, than selecting those with the shallowest depth. Once again, depth-first search does not offer an optimal solution, although is very fast in devising a plan.

Finally, we see that while in problem 2 the ignore-preconditions heuristic provided a search strategy 7 times faster than level-sum, in the present case that speed-advantage is reduced to less than 4. Moreover, by looking also at the metrics for problem 2, the numbers seem to indicate some sub-linearity for level-sum, and some supra-linearity for the heuristic ignore-preconditions. This can be seen by comparing once again the increase in the non-duration metrics with the duration. In any case, the ignore-precondition heuristic still offers the fastest search strategy among all five tested strategies for problem 3.