Heuristic analysis

for planning problems for an Air Cargo transport

Introduction

The project is a part of Udacity Artificial Intelligence Nanodegree Program and consists of deterministic logistics planning problems for an Air Cargo transport system using a planning search agent. It includes skeletons for the classes and functions needed to solve those problems.

Problem definitions

All problems are classical PDDL problems and defined in the Air Cargo domain. They have the same action schema defined, but different initial states and goals.

- Air Cargo Action Schema

```
Action(Load(c, p, a),
    PRECOND: At(c, a) ∧ At(p, a) ∧ Cargo(c) ∧ Plane(p) ∧ Airport(a)
    EFFECT: ¬ At(c, a) ∧ In(c, p))
Action(Unload(c, p, a),
    PRECOND: In(c, p) ∧ At(p, a) ∧ Cargo(c) ∧ Plane(p) ∧ Airport(a)
    EFFECT: At(c, a) ∧ ¬ In(c, p))
Action(Fly(p, from, to),
    PRECOND: At(p, from) ∧ Plane(p) ∧ Airport(from) ∧ Airport(to)
    EFFECT: ¬ At(p, from) ∧ At(p, to))
```

- Problem 1 initial state and goal

```
Init(At(C1, SFO) ∧ At(C2, JFK)
    ∧ At(P1, SFO) ∧ At(P2, JFK)
    ∧ Cargo(C1) ∧ Cargo(C2)
    ∧ Plane(P1) ∧ Plane(P2)
    ∧ Airport(JFK) ∧ Airport(SFO))
Goal(At(C1, JFK) ∧ At(C2, SFO))
```

- Problem 2 initial state and goal

```
Init(At(C1, SFO) ∧ At(C2, JFK) ∧ At(C3, ATL)
     ∧ At(P1, SFO) ∧ At(P2, JFK) ∧ At(P3, ATL)
     ∧ Cargo(C1) ∧ Cargo(C2) ∧ Cargo(C3)
     ∧ Plane(P1) ∧ Plane(P2) ∧ Plane(P3)
     ∧ Airport(JFK) ∧ Airport(SFO) ∧ Airport(ATL))
Goal(At(C1, JFK) ∧ At(C2, SFO) ∧ At(C3, SFO))
```

- Problem 3 initial state and goal

```
Init(At(C1, SFO) ∧ At(C2, JFK) ∧ At(C3, ATL) ∧ At(C4, ORD)
     ∧ At(P1, SFO) ∧ At(P2, JFK)
```

```
        ∧ Cargo(C1) ∧ Cargo(C2) ∧ Cargo(C3) ∧ Cargo(C4)
        ∧ Plane(P1) ∧ Plane(P2)
        ∧ Airport(JFK) ∧ Airport(SFO) ∧ Airport(ATL) ∧ Airport(ORD))
    Goal(At(C1, JFK) ∧ At(C3, JFK) ∧ At(C2, SFO) ∧ At(C4, SFO))
```

Uniformed non-heuristic search

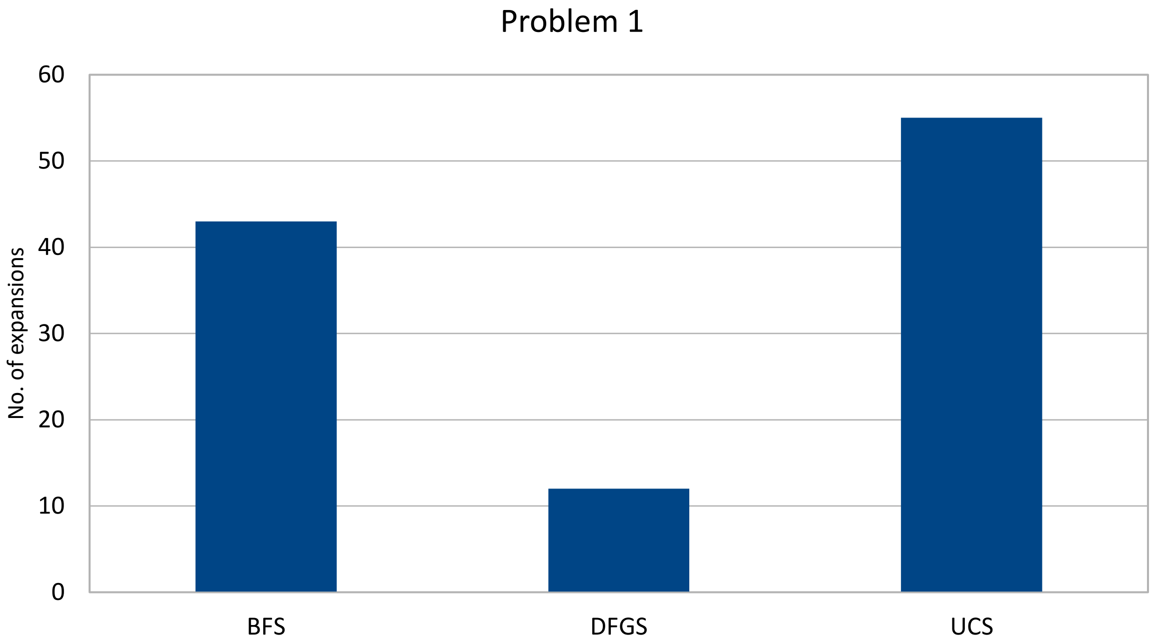
I experimented with the following searches:

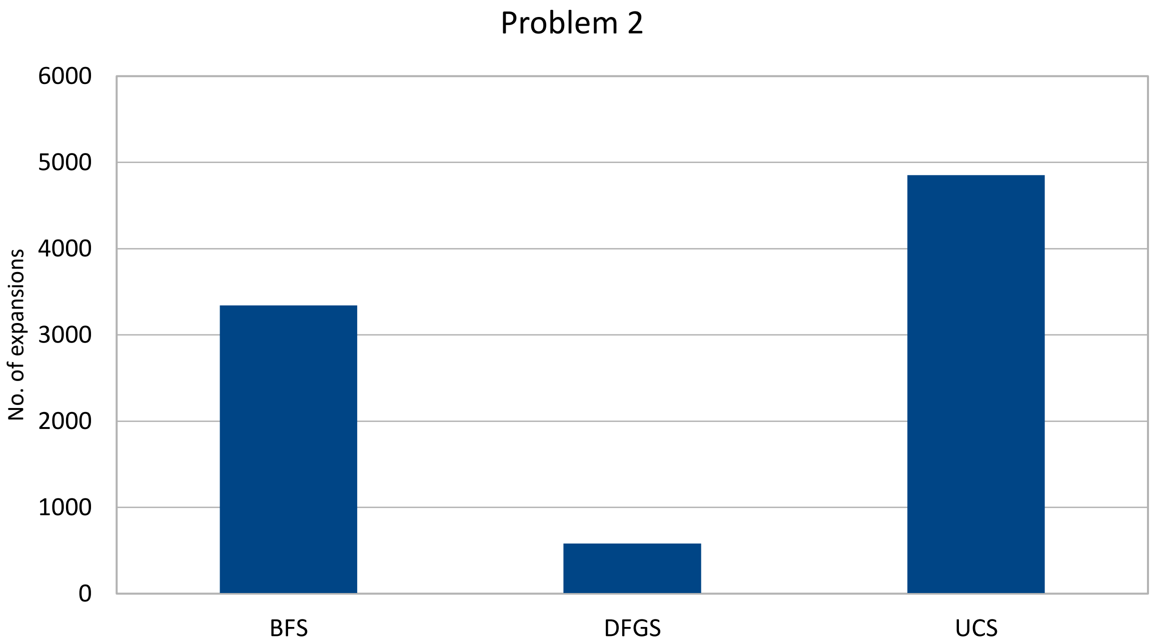
- **BFS** – Breadth First Search.
- **DFGS** – Depth First Graph Search.
- **UCS** – Uniform Cost Search.

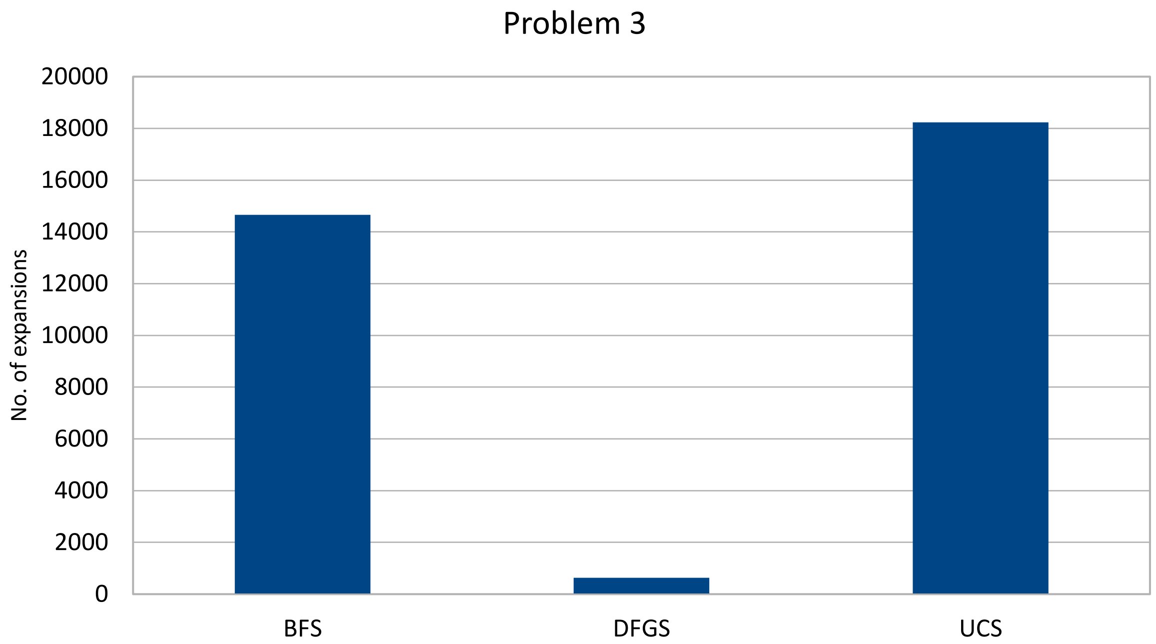
The first two are obligatory according to the task description and the last one I selected, since it works at best for a non-heuristic search and I wanted to compare obligatory searches to it.

Problem	Search type	No. of expansions	No. of goal tests	Plan length	Time elapsed (sec.)	Is optimal
P1	**BFS**	43	56	6	0.028	Yes
P1	**DFGS**	12	13	12	0.008	No
P1	**UCS**	55	57	6	0.035	Yes
P2	**BFS**	3343	4609	9	11.769	Yes
P2	**DFGS**	582	583	575	2.704	No
P2	**UCS**	4852	4854	9	9.672	Yes
P3	**BFS**	14663	18098	12	87.707	Yes
P3	**DFGS**	627	628	596	2.763	No
P3	**UCS**	18235	18237	12	42.841	Yes

Memory consumption charts

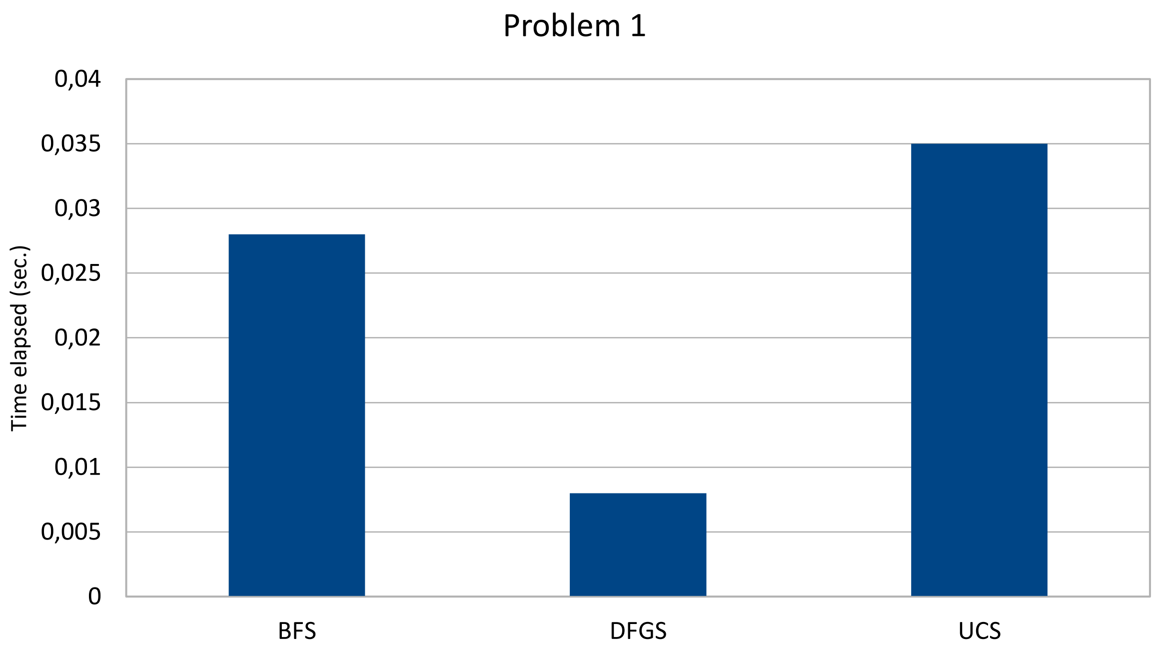


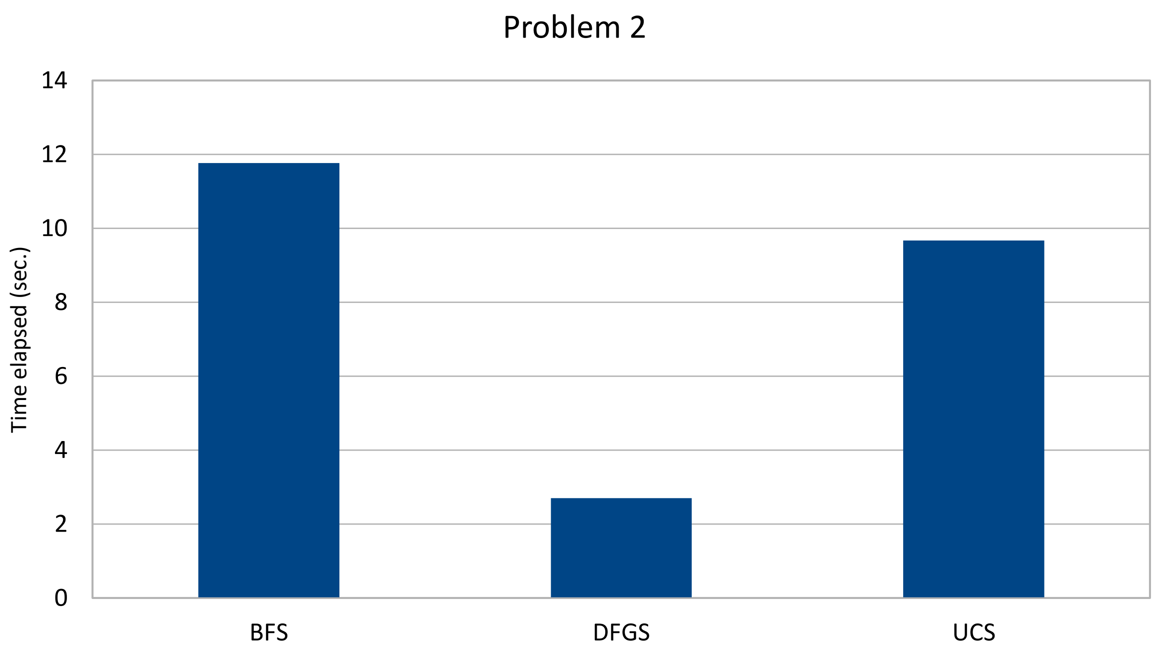


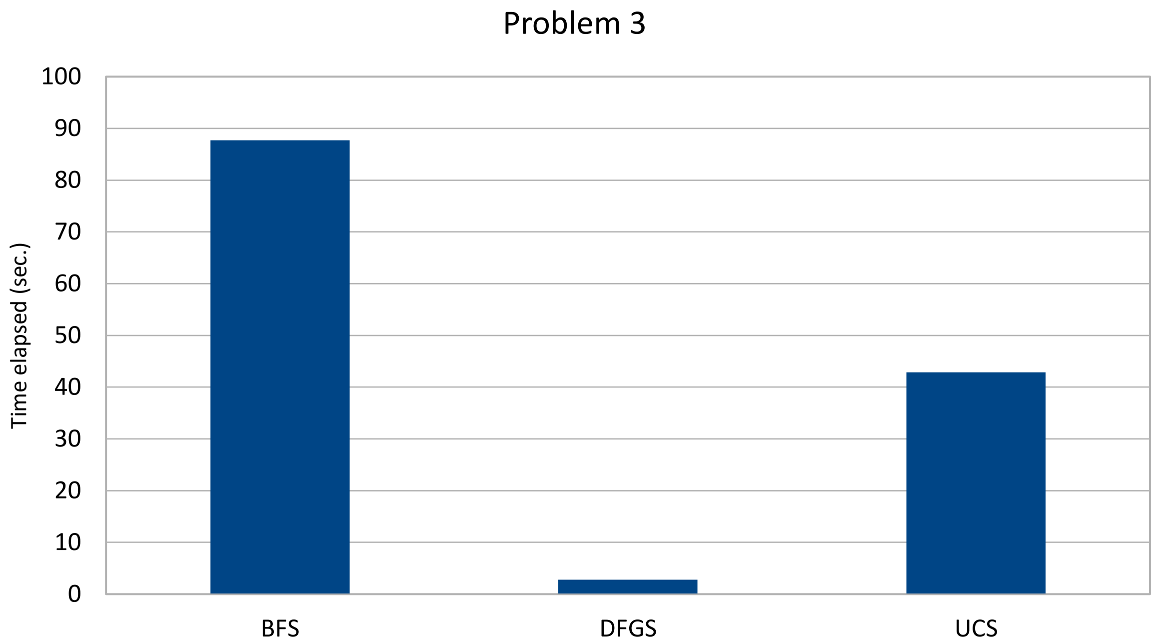


Problem 3
No. of expansions
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
BFS
DFGS
UCS

Execution time charts







Analysis

Columns explanation

"**Time elapsed**" column indicates the speed of the search – the less is better. "**No. of expansions**" indicates the memory consumption – how often a search node was expanded, the less is better. "**Plan length**" indicates optimality – the optimal plan allows a goal achieving in minimal number of steps.

Optimal plan

Optimal plans for the problem are following:

- Problem 1. The plan has a length of 6:

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

- Problem 2. The plan has a length of 9:

```
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)
```

- Problem 3. The plan has a length of 12:

```
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(C1, P1, JFK)
Unload(C2, P2, SFO)
```

Searches analysis

All applied searches do not use any heuristic for a next search node selection.

Depth First Graph Search is a fastest search and uses much less memory comparing to other searches. While Breadth First Search and Uniformed Cost Search produced an optimal solution, DFGS never achieved it.

Breadth First Search and **Uniformed Cost Search** both produced optimal solutions for the problems. For all problems **BFS** required less memory but was slower than **UCS** on more complex problems. That was a surprise, because according to a table from AIMA Book [1], Chapter 3.4.7

Criterion	Breadth-First	Uniform-Cost	Depth-First	Depth-Limited	Iterative Deepening	Bidirectional (if applicable)
Complete?	Yes^a	Yes^{a,b}	No	No	Yes^a	Yes^{a,d}
Time	$O(b^d)$	$O(b^{1+\lfloor C^*/\epsilon \rfloor})$	$O(b^m)$	$O(b^\ell)$	$O(b^d)$	$O(b^{d/2})$
Space	$O(b^d)$	$O(b^{1+\lfloor C^*/\epsilon \rfloor})$	$O(bm)$	$O(b\ell)$	$O(bd)$	$O(b^{d/2})$
Optimal?	Yes^c	Yes	No	No	Yes^c	Yes^{c,d}

Figure 3.21 Evaluation of tree-search strategies. b is the branching factor; d is the depth of the shallowest solution; m is the maximum depth of the search tree; l is the depth limit. Superscript caveats are as follows: ^{a} complete if b is finite; ^{b} complete if step costs $\geq \epsilon$ for positive ϵ; ^{c} optimal if step costs are all identical; ^{d} if both directions use breadth-first search.

and from common sense, BFS must be faster than UCS since it expands less nodes. The reason of that strange behavior is that BFS uses FIFOQueue, but UCS – PriorityQueue. Both queues are implemented in provided utils and with some changes in the FIFOQueue, the BFS must be faster than UCS. Please see [2] for more details.

I did check that and, indeed, after mentioned changes BFS was, as expected, **20-30%** faster than UCS. I did not include new times here, since it was not my intention to change provided code.

Recommendation

I do not recommend using of **Depth First Graph Search** since it didn't produce an optimal result. To me it is a KO criteria for a search.

I recommend using of **Breadth First Search** because it produced optimal solution, was **20-30%** faster than **Uniformed Cost Search** after correct implementation of underlying FIFO queue and consumed **20-30%** less memory.

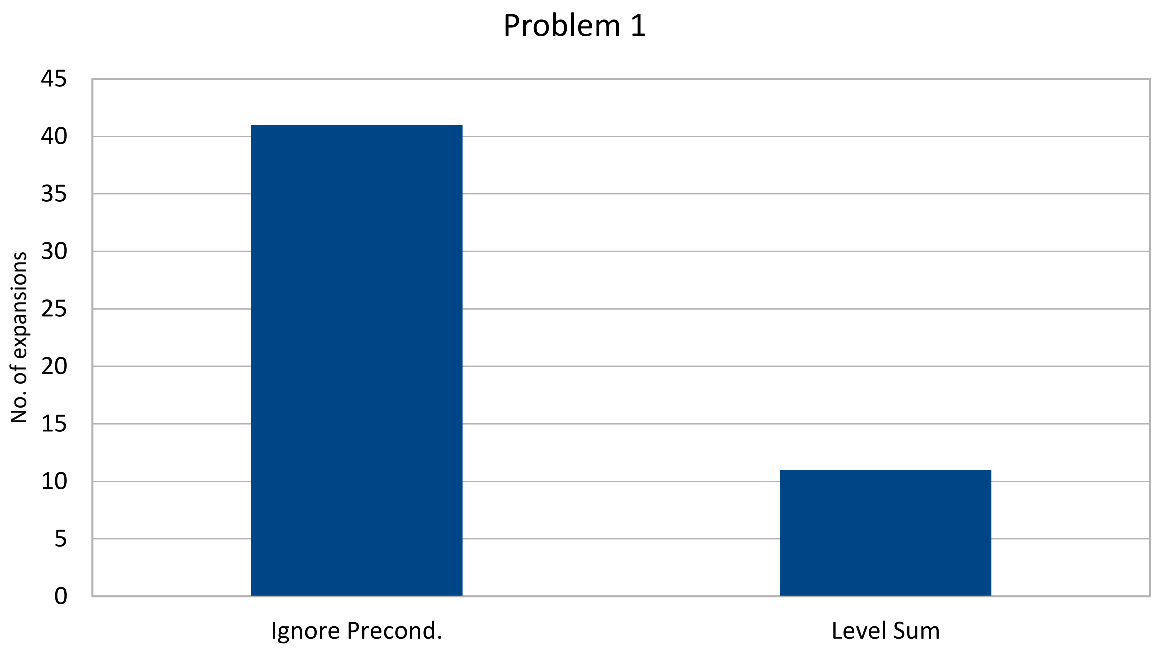
A* heuristic search

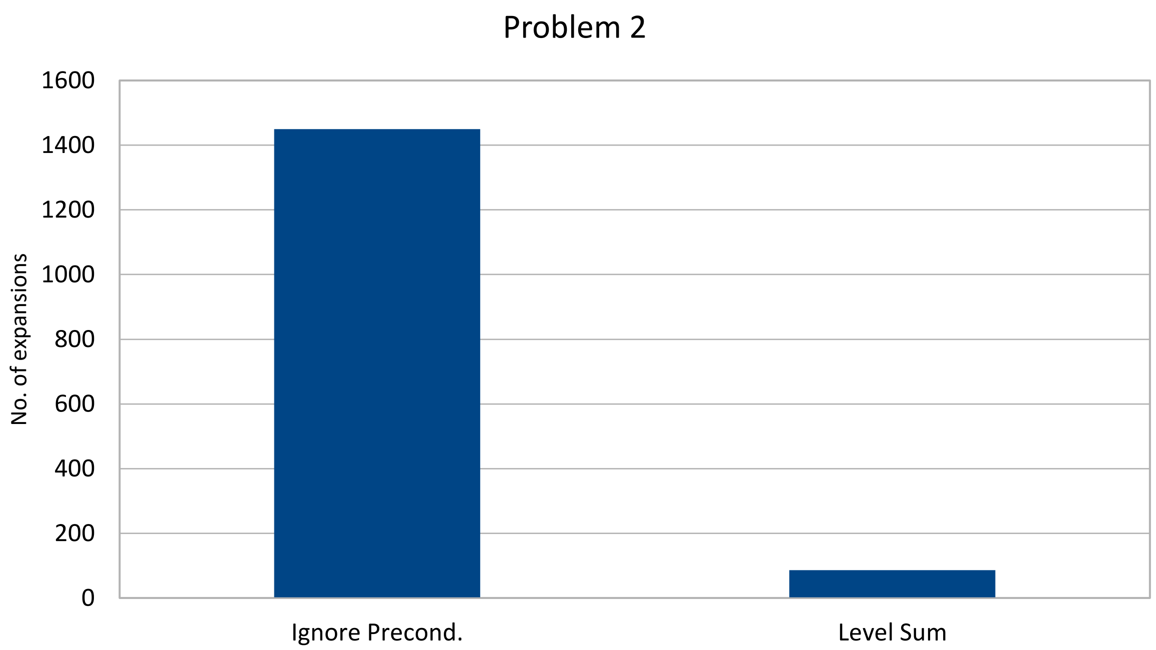
I experimented with 2 heuristics for A* search:

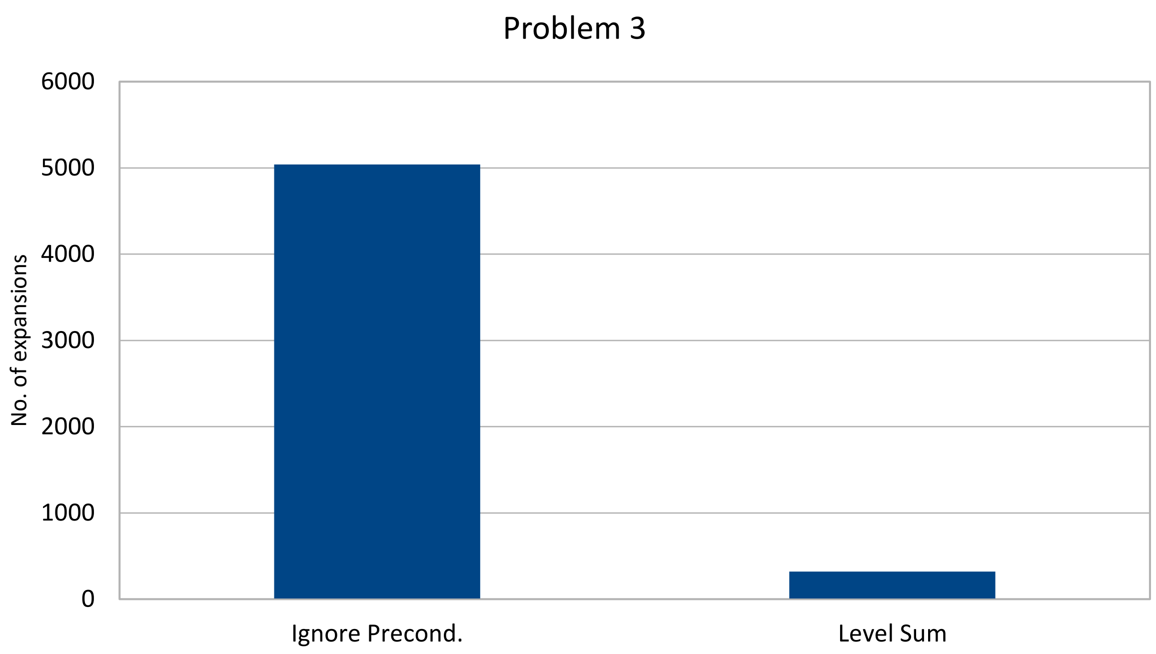
- **Ignore Preconditions**, where we relax a problem by ignoring preconditions of actions.
- **Level Sum**, where we follow the subgoal independence assumption, returning the sum of level costs of the goals.

Problem	Heuristic	No. of expansions	No. of goal tests	Plan length	Time elapsed (sec.)	Is optimal
P1	**Ignore Precond.**	41	43	6	0.028	Yes
P1	**Level Sum**	11	13	6	0.675	Yes
P2	**Ignore Precond.**	1450	1452	9	3.01	Yes
P2	**Level Sum**	86	88	9	61.425	Yes
P3	**Ignore Precond.**	5040	5042	12	12.375	Yes
P3	**Level Sum**	318	320	12	303.83	Yes

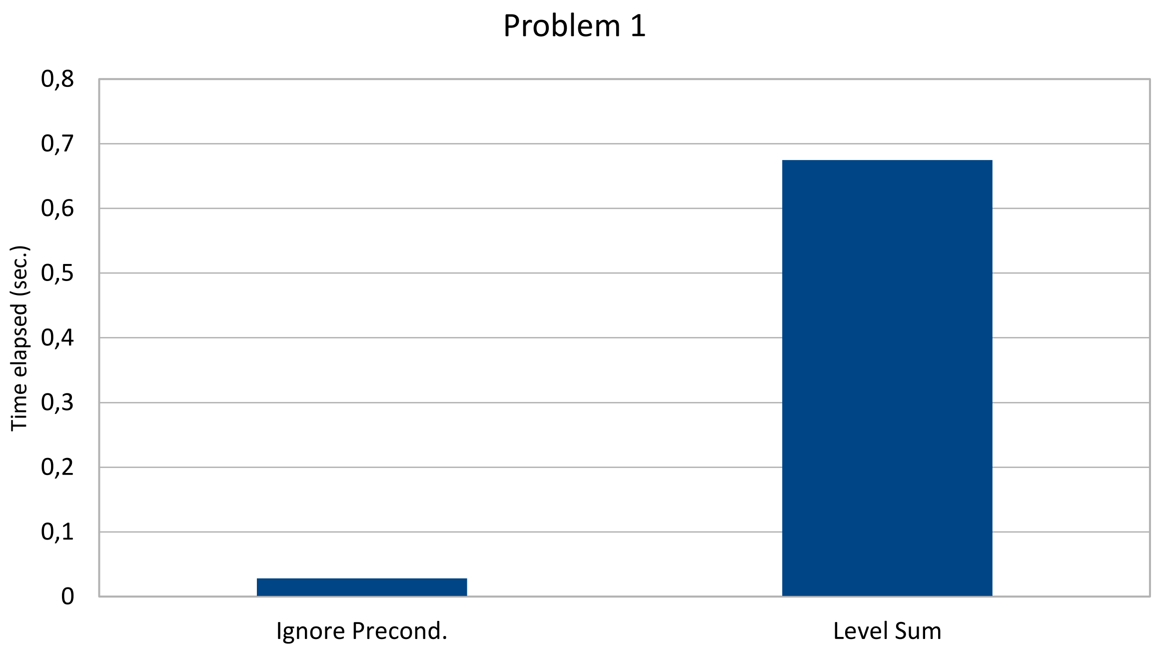
Memory consumption charts

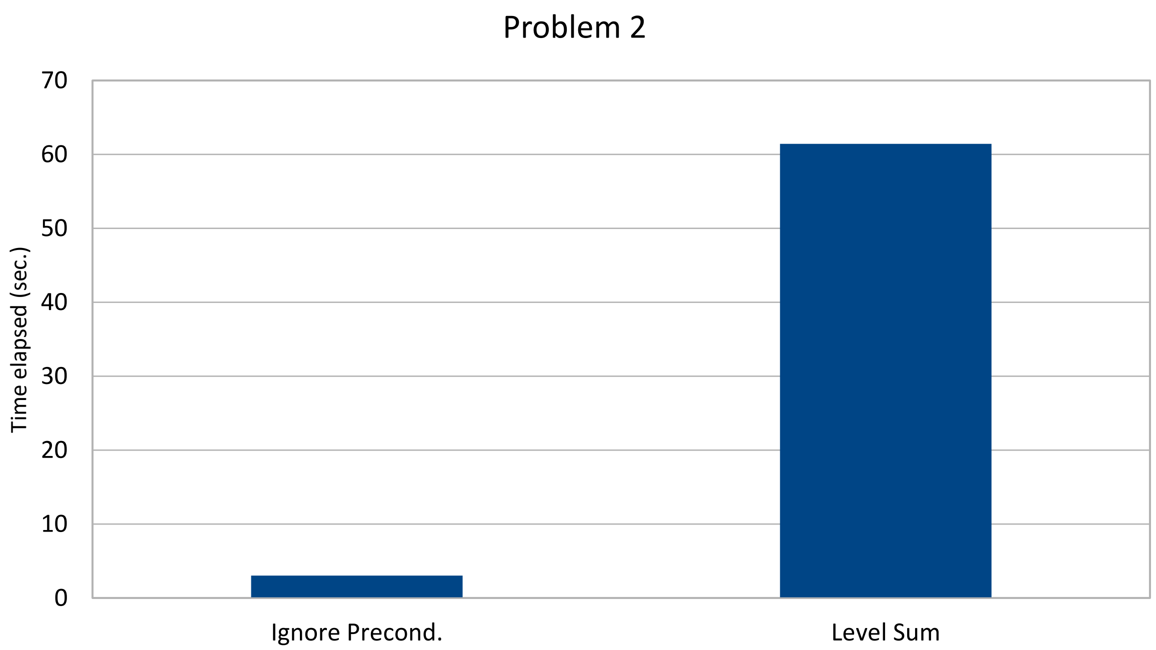


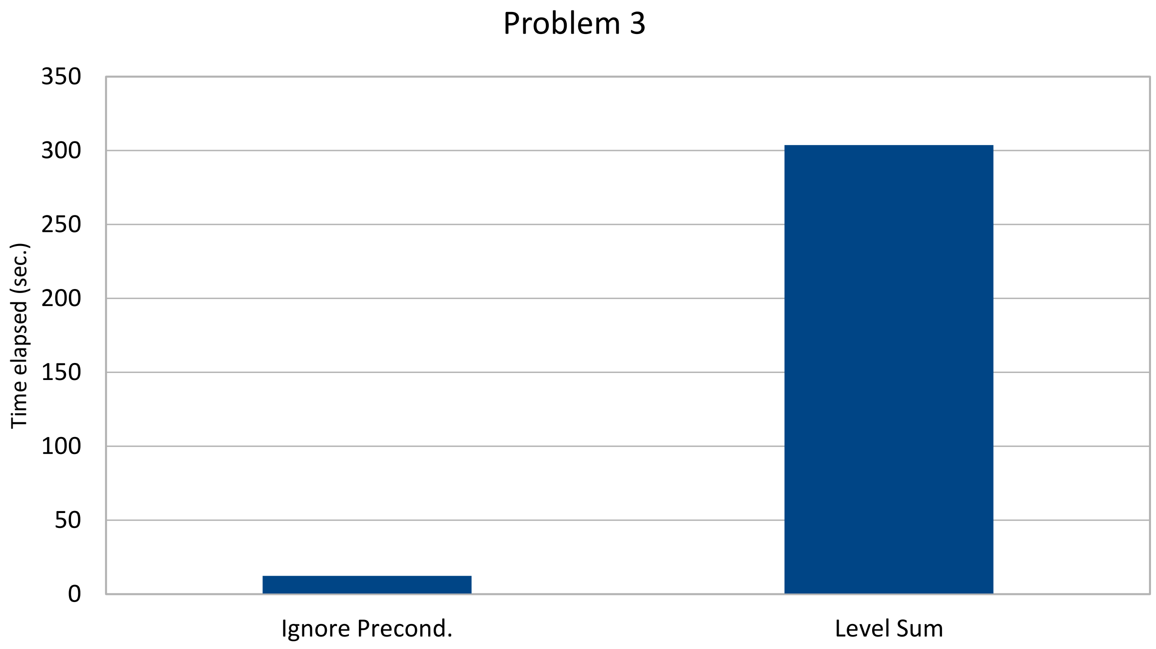



Problem 3
No. of expansions
6000
5000
4000
3000
2000
1000
0
Ignore Precond.
Level Sum

Execution time charts







Analysis

Here we have the same metrics as for non-heuristic searches, please see above the column explanation and optimal plans for the problems.

Comparing heuristics

A* search produced optimal solution with both heuristics, significant differences were memory consumption and speed. With "**Ignore Preconditions**" heuristic the A* search was **order 10 faster** than with "**Level Sum**". From the other side, "**Level Sum**" allowed **order of 10 memory saving**.

Recommendation for heuristic

Depending on the problem and requirements I recommend:

- Using of "**Ignore Precondition**" heuristic if the speed matters and A* search do not result "Out of Memory" exception.
- Using of "**Level Sum**" in a case of complex problems where a great memory consumption is expected and a problem can be decomposed well.

Conclusion

Comparing uniformed non-heuristic searches with A* search that uses heuristics I recommend using the latter, because of memory consumption and running time. My favorite is **A* search with “Ignore Precondition” heuristic** for the following reasons:

- It found optimal solutions.
- It was fastest among considered searches that produced optimal results.
- It had approx. factor 3 of memory saving comparing to non-heuristic searches, though its memory consumption was not the best.

References

1. Peter Norvig, Stuart J. Russell. “Artificial Intelligence: A Modern Approach (3rd Edition)”
2. Udacity AIND forum: https://discussions.udacity.com/t/uniform-cost-search-faster-than-breadth-first/324045/3