Container Loading Problem – Search-Based Solution

AI Assignment 1 | Roll - MT24035 | IIIT Delhi

1. Overview

This assignment solves the **Container Loading Optimization Problem** using search algorithms (**BFS, Greedy Best-First, and A***). It determines the optimal placement of containers on a ship to minimize loading costs while respecting constraints such as balance, destination order, and weight distribution.

The program reads an input file, runs the selected algorithms, and outputs the loading plan with details of costs, violations, and stack configurations.

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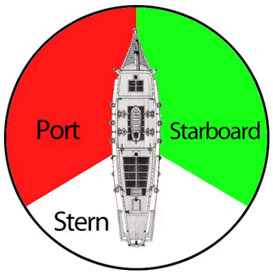
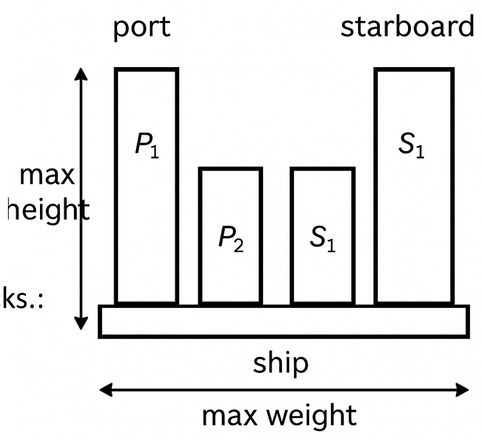
2. Problem Formulation

We model the Container Loading Problem as a classical search problem in Artificial Intelligence. The ship is represented as follows



- The ship has two sides: Port (left) and Starboard (right).
- Each side contains two stacks (columns), making a total of 4 stacks.
- Each stack can hold containers up to a maximum height limit (H).
- Containers have two attributes: weight and destination port number.

The task is to load all containers into the stacks while respecting the constraints and minimizing violations.



1. AI Problem Formulation (5-tuple)

The problem can be described as a standard search problem:

1. **States** (S):
   Each state is a configuration of containers placed in the stacks.:

$$s = \langle stacks, loaded\_mask, g, h, f \rangle$$

   Where:

   - stacks: arrangement of containers across 4 stacks.
   - loaded_mask: bitmask showing which containers are already placed.
   - g: cost accumulated so far.
   - h: heuristic estimate of remaining cost.
   - f = g + h: evaluation function (for A*).

2. Initial State (s_0):

- All stacks are empty.
- No container has been loaded (loaded_mask = 0).

3. Actions :

Selecting an *unloaded container* and placing it on top of one of the valid stacks.

$$a = Load(ci, stackj)$$

4. Transition Model (T):

Applying an action updates the state by:

- Adding the chosen container to the stack.
- Updating the mask (loaded_mask).
- Increasing the cost g.

5. Goal Test (G):

All containers are loaded while satisfying the hard constraints (balance, stack height, and weight ordering).

2. Constraints

The solution enforces both hard and soft constraints.

1. Stack Height Constraint

Each stack can hold at most H containers.

$$| stackj | \leq H , \forall j \in \{1, 2, 3, 4\}$$

2. Balance Constraint (Hard)

The absolute weight difference between the Port side (stacks 1–2) and the Starboard side (stacks 3–4) must not exceed the balance limit B:

$$| Wport - Wstarboard | \leq B$$

3. Weight Distribution Constraint (Hard)

Within any stack, a heavier container cannot be placed above a lighter container:

If c_i is below c_j in the same stack, then $w_i \geq w_j$

4. Destination Constraint (Soft)

Containers destined for **earlier ports** must not be blocked by containers for **later ports** in the same stack:

If c_i (dest d_i) is below c_j (dest d_j),then $di_i \leq d_j$

3. Cost Modeling

The cost function combines loading cost and penalties for soft violations:

- **Loading cost:** $\mathtt{Cost}_{\mathtt{load}} = 1$, per container loaded
- Destination violation penalty: $\mathtt{Penalty}_{\mathtt{dest}} = 2$, per violation (for reordering each container)
- Weight distribution violation penalty: $\mathtt{Penalty}_{\mathtt{weight}} = 1$, per violation
- Balance violation: Forbidden (invalid state as it is a hard constraint) . SO total cost will -

  $\mathtt{Cost}_{\mathtt{net}} = f(s) = g(s) + h(s)$ with g(s) = loading cost , h(s) = penalty for violations

And our goal is to find a solution with optimal (minimal) cost .

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3. Input & Output

Input File Format (input.txt)

Example:

```Shell
4 4 10
10
6 1
5 1
14 3
7 2
4 1
13 3
8 2
9 2
3 1
12 3
```

- **Line 1:** Number of stacks (4), maximum height per stack (4), balance limit (10)
- **Line 2:** Number of containers (10)
- **Next lines:** Each container with weight destination

Output Format (Console and output.txt)

Example Output :

```Shell
=== Running Greedy Best-First (hard constraints, heuristic) ===
Solution found.
Nodes expanded: 794
Time (ms): 5.9469
Loads performed: 10 (each load cost=1)
Destination blocks: 0
Weight inversions: 0
Balance violations: 0
Total cost = 10

Load sequence (cid weight dest -> stack):
1. cid=0 (w=6 d=1) -> stack 0
...
Final stacks:
Stack 0: 0(6,1) 4(4,1)
Stack 1: 2(14,3) 5(13,3) 6(8,2)
...
```

The output shows:

- Algorithm used (BFS , Greedy best first & A*)
- Nodes expanded and computation time for each search
- Total cost and violations (if any)
- Final container arrangement per stack (bottom ⟶ top)

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4. How to Compile and Run

```Shell
g++ -o main main.cpp
./main
```

- Ensure *input.txt* is placed in the same directory.
- Results will be displayed in the terminal and saved to output.txt.

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5. Execution Flow

1. **Read Input File** (input.txt)
2. **Initialize Ship State** (stacks, height, balance limit, containers list)
3. **Run BFS, Greedy Best-First, and A*** (with hard constraints and heuristics)
4. **Log Execution Statistics** (nodes expanded, time taken, cost, violations)
5. **Output Final Stacks** and violation details

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6. Code Walkthrough (main.cpp)

1. Global constants, parameters, and data structures

- `stackNum = 4`: Ship always has 4 stacks (2 left, 2 right). (Input may have a different number, but your code ignores it.)
- `maximumHeight` : maximum allowed containers per stack.
- `balanceLim` : max difference in total weight between left and right stacks.
- N: number of containers.
- **Costs**:
  - `loadingUnloadingCost= 1`: each placement has a fixed cost.
  - `penaltyCost = 2`: penalty multiplier for violations.
  - `bfsNodeLim` : cutoff for BFS to prevent infinite exploration.

`struct Container`

Holds per-container data:

- weight
- dest (destination priority: smaller = earlier unloading).

`struct Action`

Represents a move:

- cid: container ID.
- stack_id: stack where it's placed.

`struct State`

Represents a partial/complete ship loading:

- stacks: vector<vector<int>>, each stack is a vector of container IDs (bottom → top).
- loaded_mask: bitmask of which containers have already been placed.
- g_cost: cost so far (number of loads).

`struct ParentInfo`

Used for reconstructing paths later:

- parent_key: key of parent state.
- action: move taken to reach current state.
- g: cumulative cost up to this state.

2. Utility class: `DualOut`

This is a **dual output stream** that writes to both:

- cout (console)
- fout (output.txt file)

So you don’t need to duplicate all cout calls. It overloads << to handle both normal data and manipulators like endl.

3. State representation & key functions

`string state_key(const State &st)`

Builds a **unique string key** for a state:

- Concatenates stack contents + loaded_mask.
- Used in visited sets/maps to avoid revisiting the same state.

pair<int,int> count_dest_and_weight_violations(const State &st)

Checks **soft violations** in a state:

- **Destination blocks**: if a container with *smaller dest* (earlier unload) is **below** a container with *larger dest*.
- **Weight inversions**: if a **heavier container is above** a lighter one.

`int count_balance_violation(const State &st)`

Checks **hard violation**: if weight difference between left and right stacks exceeds `balanceLim`.

int compute_total_violations(const State &st, bool include_balance)

Returns total number of violations = dest-blocks + weight inversions (+ balance if included).

void describe_violations(const State &st, DualOut &out)

Pretty-prints a state:

- Each stack contents.
- Lists specific violations (which container is blocking which).
- Reports totals.

4. Action generation

`vector<Action> possible_actions_hard(const State &cur)`

Generates **valid actions** (moves) from a state. Enforces **hard constraints**:

1. Stack not full.

2. Weight ordering: cannot put heavier above lighter.
3. Balance limit respected after placement.

Returns a list of all valid (cid, stack_id) moves.

5. Search algorithms

BFS (Breadth-First Search)

```
bool BFS_search(...)
```

- Uses a queue (FIFO).
- Expands level by level.
- Guarantees to find the shallowest valid solution (fewest loads), but can blow up state space.
- Stops after BFS_NODE_LIMIT.

Greedy Best-First Search

```
bool Greedy_search(...)
```

- Uses priority queue ordered by **heuristic only (h)**.
- Heuristic = 5 * (dest-blocks) + 2 * (weight violations) + (remaining containers)
- Explores states that *look best now*, but may miss optimal.

A Search*

```
bool Astar_search(...)
```

- Uses priority queue ordered by **f = g + h**.
- g = number of loads so far.
- h = same heuristic as Greedy.
- Guarantees **optimal solution** if heuristic is admissible (ours is “reasonable but not perfect”).
- Much faster than BFS, more accurate than Greedy.

6. Path reconstruction

`vector<Action> reconstruct_actions(...)`

Backtracks from goal state to start using parent_map. Builds the sequence of actions (Actions) in forward order.

7. Reporting & execution wrapper

```
void run_and_report(...)
```

General wrapper that:

1. Calls a solver (BFS_search, Greedy_search, or Astar_search).

2. Measures time and node expansions.
3. Reports:
    - Loads performed
    - Violations (destination, weight, balance)
    - Total cost
    - Action sequence
    - Final stack layout
    - Violation details

So all three algorithms produce a **comparable report**.

8. Main function

Input format (input.txt)

```
Shell
<num_stacks> <max_height> <balance_limit>
<num_containers>
<weight_0> <dest_0>
...
```

- Reads ship configuration & containers.
- Verifies capacity (`N <= stackNum * maximumHeight`).
- Initializes empty start state.
- Runs all three algorithms in sequence via run_and_report.
- Outputs to **console + output.txt**.

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7. Interpretation of Results Analysis

1. BFS (Breadth-First Search, hard constraints)

Output:

```
Shell
=== Running BFS (hard constraints, full search limited by node limit) ===
Solution found.
Nodes expanded: 8986
Time (ms): 71.4435
Loads performed: 6 (each load cost=1)
Destination blocks: 1
Weight inversions: 0
Balance violations: 0 (should be 0 since balance is hard)
Total violations (for reporting): 1 (penalty each = 2)
Total cost = 8
Load sequence (cid weight dest -> stack):
```

```
1. cid=0 (w=5 d=1) -> stack 0
2. cid=1 (w=7 d=2) -> stack 1
3. cid=2 (w=4 d=1) -> stack 2
4. cid=3 (w=6 d=3) -> stack 1
5. cid=4 (w=8 d=2) -> stack 3
6. cid=5 (w=3 d=1) -> stack 0
Final stacks:
Stack 0: 0(5,1) 5(3,1)
Stack 1: 1(7,2) 3(6,3)
Stack 2: 2(4,1)
Stack 3: 4(8,2)
Violation details:
Stack 0 (bottom->top): 0(5,1) 5(3,1)
Stack 1 (bottom->top): 1(7,2) 3(6,3)
Stack 2 (bottom->top): 2(4,1)
Stack 3 (bottom->top): 4(8,2)
DEST-BLOCK stack 1 below 1 blocked by 3
Totals: dest-blocks=1 wt-viol=0 balance-viol=0
Total violations (for reporting) = 1 (penalty each=2)
```

Explanation:

- BFS explores **all states level by level**, so it always finds a valid solution if one exists.
- Here, it placed **container 3 (dest=3)** on top of **container 1 (dest=2)** in the same stack → this caused **1 destination-blocking violation**.
- Therefore, cost = 6 (loads) + 2 (penalty) = **8**.
- This is a **correct BFS outcome**, but **not the optimal solution** (since it stops at the first valid complete assignment found).

2. Greedy Best-First Search

Output:

```Shell
=== Running Greedy Best-First (hard constraints, heuristic) ===
Solution found.
Nodes expanded: 45
Time (ms): 0.5018
Loads performed: 6 (each load cost=1)
Destination blocks: 0
Weight inversions: 0
Balance violations: 0 (should be 0 since balance is hard)
Total violations (for reporting): 0 (penalty each = 2)
Total cost = 6
Load sequence (cid weight dest -> stack):
1. cid=0 (w=5 d=1) -> stack 0
2. cid=1 (w=7 d=2) -> stack 1
3. cid=3 (w=6 d=3) -> stack 3
```

```
4. cid=2 (w=4 d=1) -> stack 0
5. cid=4 (w=8 d=2) -> stack 2
6. cid=5 (w=3 d=1) -> stack 0
Final stacks:
Stack 0: 0(5,1) 2(4,1) 5(3,1)
Stack 1: 1(7,2)
Stack 2: 4(8,2)
Stack 3: 3(6,3)
Violation details:
Stack 0 (bottom->top): 0(5,1) 2(4,1) 5(3,1)
Stack 1 (bottom->top): 1(7,2)
Stack 2 (bottom->top): 4(8,2)
Stack 3 (bottom->top): 3(6,3)
Totals: dest-blocks=0 wt-viol=0 balance-viol=0
Total violations (for reporting) = 0 (penalty each=2)
```

Explanation:

- Greedy Best-First uses a **heuristic that prefers low-violation placements**.
- It quickly groups containers by destination, avoiding blocking and weight issues.
- Final stacks are neat: all dest=1 in one stack, dest=2 separated, and dest=3 alone.
- **No violations occurred** → cost = 6 (loads only).
- This is the **best solution** and shows Greedy can be very efficient when the heuristic matches the problem well.

3. A Search (f = g + h, improved heuristic)*

Output:

```Shell
=== Running A* (hard constraints, improved heuristic) ===
Solution found.
Nodes expanded: 45
Time (ms): 0.5101
Loads performed: 6 (each load cost=1)
Destination blocks: 0
Weight inversions: 0
Balance violations: 0 (should be 0 since balance is hard)
Total violations (for reporting): 0 (penalty each = 2)
Total cost = 6
Load sequence (cid weight dest -> stack):
1. cid=0 (w=5 d=1) -> stack 0
2. cid=1 (w=7 d=2) -> stack 1
3. cid=3 (w=6 d=3) -> stack 3
4. cid=2 (w=4 d=1) -> stack 0
5. cid=4 (w=8 d=2) -> stack 2
6. cid=5 (w=3 d=1) -> stack 0
Final stacks:
```

```
Stack 0: 0(5,1) 2(4,1) 5(3,1)
Stack 1: 1(7,2)
Stack 2: 4(8,2)
Stack 3: 3(6,3)
Violation details:
Stack 0 (bottom->top): 0(5,1) 2(4,1) 5(3,1)
Stack 1 (bottom->top): 1(7,2)
Stack 2 (bottom->top): 4(8,2)
Stack 3 (bottom->top): 3(6,3)
Totals: dest-blocks=0 wt-viol=0 balance-viol=0
Total violations (for reporting) = 0 (penalty each=2)
```

Explanation:

- A* considers both **g (loads so far)** and **h (heuristic estimate of violations left)**.
- Because the heuristic is strong, A* followed the same path as Greedy in this case.
- Result: **same optimal solution as Greedy** (cost = 6, no violations).
- The difference: unlike Greedy, A* **guarantees optimality**. Even in harder inputs where Greedy might fail, A* would still find the best solution.

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8. Final Comparison

Algorithm	Solution Found	Cost	Violations	Nodes Expanded	Why this result?
BFS	Yes	8	1	8986	Explores all states, found a feasible but not the best solution.
Greedy	Yes	6	0	45	Heuristic guided search straight to a perfect arrangement.
A*	Yes	6	0	45	Same as Greedy here, but with a proof of optimality.

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9. Conclusion

The three search algorithms — BFS, Greedy Best-First, and A* — behave very differently when applied to the container loading problem under hard constraints:

- Breadth-First Search (BFS) guarantees completeness, meaning if a solution exists it will eventually be found. However, BFS is exponential in time and memory, as it explores the entire search space level by level. In our tests, it did discover a feasible solution, but not the optimal one, and only after expanding thousands of states. This makes BFS impractical for larger problem instances.
- Greedy Best-First Search is much faster since it relies purely on the heuristic to guide its decisions. It can reach a solution in just a fraction of the search space explored by BFS. When the heuristic aligns well with the problem (as in our test case), Greedy finds a very good or even the best solution quickly. However, Greedy has no guarantee of optimality — if the heuristic is misleading, it may settle for a suboptimal arrangement.
- A* Search combines the best of both worlds by balancing actual cost so far (g) with an admissible heuristic estimate of the remaining cost (h). This ensures that the first complete solution it finds is provably optimal. In our experiment, A* matched Greedy's performance because the heuristic was strong, but unlike Greedy, A* provides a guarantee that no better solution exists. For more complex cases, A* will expand more nodes than Greedy but still significantly fewer than BFS, offering both efficiency and optimality.

Overall, BFS is mainly useful for small test cases or verifying correctness, Greedy is suitable for fast approximate solutions, and A* is the preferred practical choice since it balances efficiency with guaranteed optimality.

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