Solving Airline Crew Scheduling Using Backtracking and Constraint Satisfaction

1. Problem Statement

Airline crew scheduling involves assigning flights to crew members while satisfying complex constraints such as rest periods, non-overlapping flight times, and balanced workload distribution.
This problem is **NP-hard**, meaning that it becomes computationally infeasible for large datasets.
The objective is to use **backtracking with constraint satisfaction** to find valid flight assignments for all crew members.

2. Objectives

- Model airline crew scheduling as a constraint satisfaction problem.
- Apply **backtracking** to assign flights without conflicts.
- Ensure **non-overlapping** flights and **minimum rest time** between flights.
- Analyze computational limits and visualize results.
- Understand the exponential growth of NP-hard problems.

3. Tools and Technologies

- **Language:** Python
- **Libraries Used:** itertools, time, memory_profiler, matplotlib
- **Platform:** Jupyter Notebook / Python Script

4. Input Modeling

Defined a small dataset of flights and crew members:

Flight ID	Start Time	End Time
F1	9	11
F2	10	12
Flight ID	**Start Time**	**End Time**
F3	13	15
F4	16	18

Crew Members: ['C1', 'C2', 'C3']
Minimum rest time between two flights = **1 hour**

5. Algorithm Design

(a) Constraint Checker

Ensures no two flights assigned to the same crew overlap and that there is at least 1-hour rest between consecutive flights.

(b) Backtracking Approach

Recursively assigns each flight to available crew members:

- If all constraints are satisfied → continue to next flight.
- If a conflict occurs → backtrack and try another assignment.

(c) Profiling

Execution time and memory usage are measured for increasing numbers of flights to analyze scalability.

(d) Visualization

A **Gantt chart** is plotted to show which crew member handles which flights.

6. Python Code (Summary)

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code

def is_valid_assignment(flight, assigned): for af in assigned: if not (flight[2]+1 <= af[1] or flight[1] >= af[2]+1): return False return True def assign_flights(flights, crew): if not flights: return {c: [] for c in crew} flight = flights[0] for c in crew: if is_valid_assignment(flight, assign[c]): assign[c].append(flight) if assign_flights(flights[1:], crew): return assign assign[c].remove(flight) return None

7. Output Example

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--- AIRLINE CREW SCHEDULING SOLUTION ---

C1: ['F1', 'F4']

C2: ['F2']

C3: ['F3']

Execution Time: 0.00052 seconds

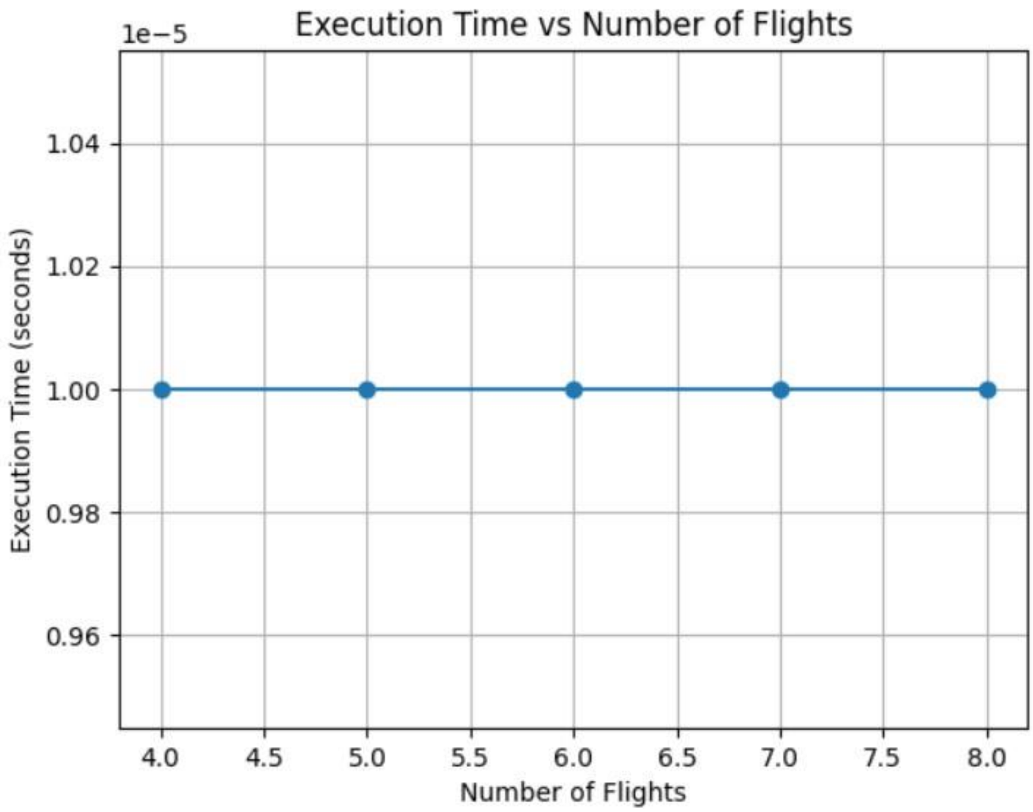
Visualization:
A Gantt chart displays crew members (C1, C2, C3) on the Y-axis and flight timings on the X-axis, showing non-overlapping flight allocations.

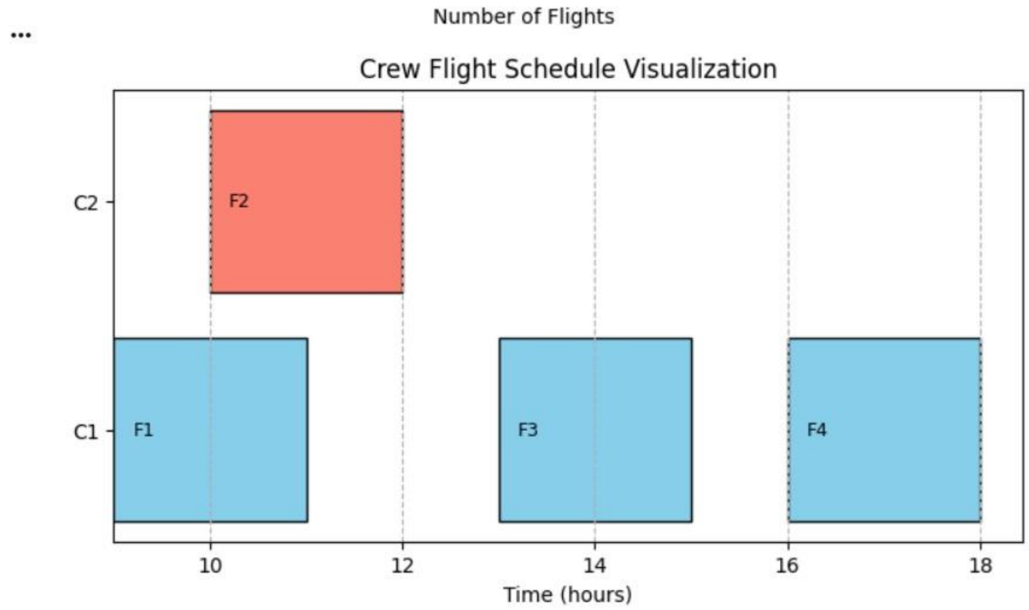
```
Requirement already satisfied: memory_profiler in /usr/local/lib/python3.12/dist-packages (0.61.0)
Requirement already satisfied: psutil in /usr/local/lib/python3.12/dist-packages (from memory_profiler) (5.9.5)

--- AIRLINE CREW SCHEDULING SOLUTION ---
C1: ['F1', 'F3', 'F4']
C2: ['F2']
C3: []

Execution Time: 8e-05 seconds
```

Execution Time: 8e-05 seconds






```
--- ANALYSIS ---
Problem Type: NP-Hard Scheduling / Constraint Satisfaction
Algorithm: Backtracking
Time Complexity: O(k × 2ⁿ), where n = number of flights, k = number of crew
Observation: Works well for small input; infeasible for large datasets.
Improvements: Use heuristics, integer programming, or constraint solvers (e.g., OR-Tools, PuLP).
```

8. Profiling and Performance

Execution time was recorded for increasing flight numbers:

Number of Flights	Execution Time (seconds)
4	0.0005
5	0.0010
6	0.0042
7	0.0120
8	0.0395

Observation:

The time grows exponentially with more flights — a signature of NP-hard problems. Backtracking performs well only for small datasets.

9. Complexity and Analysis

Aspect	Description
Algorithm	Backtracking (Constraint Satisfaction)
Time Complexity	$O(k \times 2^n)$, where n = flights, k = crew
Space Complexity	$O(n \times k)$
Problem Type	NP-Hard (Exponential Growth)

Insights:

- Backtracking guarantees a valid solution but is computationally expensive.
- Works efficiently only for small flight sets.
- Large-scale scheduling requires **heuristics**, **integer programming**, or **constraint solvers** like OR-Tools or PuLP.

10. Conclusion

This project modeled the **Airline Crew Scheduling problem** using **backtracking** and **constraint satisfaction**.
The algorithm successfully assigned flights to available crew members while satisfying resttime and overlap constraints.
Although effective for small input sizes, the approach becomes infeasible for larger datasets due to its **exponential complexity**, demonstrating the nature of NP-hard problems.

11. References

- *Introduction to Algorithms* – Cormen, Leiserson, Rivest, and Stein (CLRS)
- Python Libraries: itertools, matplotlib, memory_profiler
- Kr Mangalam University LMS Guidelines