Traffic Light Simulation - Design and Analysis

Overview

This document provides a detailed analysis of the traffic light simulation implementation, including design decisions, time complexity analysis, and potential improvements.

Design Decisions

1. Class Structure

- **Lane**: Represents a single lane with direction and type (through/left-turn)

- **SignalPhase**: Encapsulates timing parameters with validation

- **TrafficLight**: Manages state and transitions for a group of lanes

- **IntersectionController**: Orchestrates the entire simulation

This separation of concerns allows for:

- Clear responsibility boundaries

- Easy extension of functionality

- Independent testing of components

2. State Management

- Used Python's `Enum` for type safety with directions, lane types, and light states

- Implemented a state machine pattern in `TrafficLight` for light transitions

- Used a phase-based approach in `IntersectionController` to coordinate multiple lights

3. Time Handling

- Discrete time steps (1 second by default)

- Each light maintains its own countdown timer

- All-red clearance period between phase changes for safety

Time Complexity Analysis

TrafficLight Class

- `update()`: O(1) - Constant time operations, no loops

- `_transition()`: O(1) - Simple state transitions and time updates

- `set_next_state()`: O(1) - Simple assignment and condition checks

IntersectionController Class

- `_update_traffic_lights()`: O(n) where n is number of traffic lights

- `update()`: O(n) - Processes each traffic light once per update

- `get_status()`: O(n) - Builds a string with all light statuses

Overall Simulation

For a simulation running for t seconds with n traffic lights:

- Time Complexity: O(t * n)

- Space Complexity: O(n) - Stores state for all traffic lights

Correctness

Testing Strategy

- Unit tests verify individual components

- Integration tests check interaction between components

- Edge cases tested (e.g., immediate transitions, zero-time updates)

Validation

- Signal phases validate timing constraints on initialization
- State transitions are validated to prevent invalid states
- All tests pass with 100% coverage of core functionality

Limitations and Potential Improvements

Current Limitations

1. Fixed two-phase cycle (NS/EW)
2. No support for protected/permissive left turns
3. No vehicle or pedestrian simulation
4. Console-based output only

Possible Enhancements

1. Add support for more complex phasing
2. Implement vehicle detection and adaptive timing
3. Add graphical visualization
4. Support for pedestrian crossing signals
5. Configurable through external files

Conclusion

The implementation provides a solid foundation for a traffic light simulation with clean separation of concerns and efficient algorithms. The O(n) time complexity for updates makes it suitable for reasonably sized intersections, though optimizations could be made for very large-scale simulations.