# Final Project Report

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Section: 1

Group Number: 2

Project Topic: AI-Based Logic Puzzle Solver Using Constraint Satisfaction

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# Logic Puzzle Solver: A Comprehensive Implementation

## Abstract

This paper presents a comprehensive implementation of a Logic Puzzle Solver utilizing constraint satisfaction algorithms, specifically focusing on Sudoku and Kakuro. Employing techniques such as backtracking, constraint propagation, and domain reduction, the system is built on a modular architecture using Python. A graphical user interface (GUI) developed with Tkinter supports interactive puzzle solving. The framework is designed to be extensible, efficient, and user-friendly, allowing for future integration of additional puzzle types and solving heuristics. This project bridges the gap between theoretical CSP algorithms and practical application in a user-centric system, demonstrating a scalable and educational approach to logic puzzle solving.

**Keywords**: Constraint Satisfaction, Sudoku, Kakuro, Puzzle Solver, Backtracking, Constraint Propagation, Python, GUI, Tkinter.

# I. Introduction

Logic puzzles such as Sudoku and Kakuro offer a compelling domain for applying artificial intelligence and constraint satisfaction programming (CSP). These puzzles are non-trivial, rule-based, and require deductive reasoning — making them ideal candidates for CSP frameworks. The primary goal of this project is to build a robust and extensible software system capable of solving such puzzles efficiently while maintaining an intuitive user experience.

## A. Objectives

- Develop a flexible, extensible puzzle-solving framework.
- Implement efficient algorithms based on constraint satisfaction techniques.
- Design an intuitive graphical user interface.
- Support multiple puzzle types with varying rule structures.
- Provide puzzle-solving feedback, scoring, and progress tracking.
- Integrate best practices in software engineering for maintainability.
- Demonstrate educational value through algorithmic transparency and user feedback.

## B. Technical Stack

- **Language**: Python 3.x
- **GUI Toolkit**: Tkinter
- **Data Structures**: NumPy arrays
- **Design Paradigms**: Object-Oriented Programming, Abstract Base Classes
- **Code Quality**: Static typing with type hints, modular design, and clean separation of concerns
- **Development Tools**: Virtual environments, linters, automated tests (unit tests for puzzle logic)

# II. System Architecture

The architecture is based on object-oriented principles, encapsulating each puzzle and algorithm into isolated classes. This modularity allows for the seamless addition of new puzzle types and solving strategies. The layered structure ensures clear separation of concerns between logic, data, and presentation.

## A. Core Class Hierarchy

1. LogicPuzzle (ABC): Defines abstract methods for grid initialization, constraint application, and validity checking. Manages grid state and generic logic.

2. SudokuPuzzle: Inherits from LogicPuzzle. Implements validation rules specific to 9x9 Sudoku puzzles.
3. KakuroPuzzle: Inherits from LogicPuzzle. Implements logic for Kakuro puzzles, including sum constraints and clue-based validations.
4. LogicPuzzleGUI: A user interface class built using Tkinter. Provides visual puzzle interaction, user input handling, and display of scores and messages.

### B. System Data Flow

1. User Input → 2. GUI Layer → 3. Puzzle Logic → 4. Solving Algorithm → 5. Output Display

### C. Extensibility

Future puzzle types can be added by creating new subclasses of LogicPuzzle and implementing domain-specific constraints and validation logic. The GUI and logic components are designed to work with any subclass without significant changes.

# III. Core Components

### A. LogicPuzzle (Abstract Base Class)

```
class LogicPuzzle(ABC):
    def __init__(self, size: int):
        self.size = size
        self.grid = np.zeros((size, size), dtype=int)
        self.constraints = {}
```

This class provides foundational grid structure, initializes constraints, and declares interfaces for domain-specific implementations. It serves as the template for all puzzle types.

### B. SudokuPuzzle Implementation

- Grid: Fixed 9x9 matrix
- Constraints: Rows, columns, and 3x3 subgrids
- Methods: `is_valid_placement`, `get_domain`, `propagate_constraints`
- Features: Fast checking of row/column/box constraints
- Optimizations: Early constraint elimination, local scope domain checking

### C. KakuroPuzzle Implementation

- Grid: Variable-sized with blocked and clue cells

- Constraints: Sum-based across runs
- Initialization: Clue handling via dictionary mapping
- Methods: Run identification, dynamic domain calculation, clue validation
- Advanced Features: Overlapping constraints management, dynamic run reconstruction

# IV. Algorithm Implementation

## A. Backtracking Algorithm

```
def solve(self) -> bool:
    empty_cell = self._find_empty_cell()
    if not empty_cell:
        return True
    row, col = empty_cell
    domain = self.get_domain(row, col)
    if not self.propagate_constraints(row, col):
        return False
    for value in domain:
        if self.is_valid_placement(row, col, value):
            self.grid[row][col] = value
            if self.solve():
                return True
            self.grid[row][col] = 0
    return False
```

## B. Constraint Propagation

```
def propagate_constraints(self, row: int, col: int) -> bool:
    for i in range(self.size):
        for j in range(self.size):
            if self.grid[i][j] == 0:
                domain = self.get_domain(i, j)
                if not domain:
                    return False
    return True
```

## C. Domain Reduction

```
def get_domain(self, row: int, col: int) -> Set[int]:
```

**domain = set(range(1, 10))**

**# Remove values already used in row, column, and box**

**return domain**

This function can be enhanced in Kakuro to account for sum and length of runs.

# V. User Interface Design

## A. GUI Elements

1. **Score Display**: Tracks score, high score, and remaining attempts.
2. **Puzzle Grid**: 9x9 interactive matrix with editable cells.
3. **Control Buttons**: Options for checking solution, revealing answer, and starting a new game.

## B. Interaction Flow

- Puzzle selection screen
- Live validation of user input
- Real-time solution checking and visual feedback
- Score updates and game state persistence

## C. Accessibility Features

- Keyboard shortcuts
- Highlighting invalid inputs
- Optional solution reveal and hints
- High contrast mode for visibility
- Colorblind-friendly themes

# VI. Performance Analysis

## A. Time Complexity

- Backtracking: worst case (Sudoku), exponential in nature
- Constraint Propagation: O(n) per cell
- Domain Reduction: O(1) per cell

### B. Space Complexity

- Grid Storage: O(n^2)
- Constraint Data: O(n)
- Domain States: O(1) per cell, dynamic during recursion

### C. Optimization Strategies

- Forward Checking
- Early Termination
- Heuristic Selection (Future): MRV, LCV, Degree Heuristic
- Reuse of Partials: Caching of partial valid configurations
- Memoization
- Dynamic Pruning

## VII. Future Improvements

### A. Puzzle Expansion

- Add support for Nonogram, KenKen, Crosswords, and custom user-defined puzzles.
- Integration with online puzzle sources

### B. Solver Enhancement

- Integrate heuristics: MRV, LCV, Degree Heuristic
- Enable multi-threaded solving
- Explore AI-based solvers using reinforcement learning
- Auto-difficulty detection for imported puzzles

### C. GUI Enhancement

- Implement difficulty levels and progress tracking
- Add animation and hint mechanisms
- Theme and accessibility customizations
- Multi-language support
- Export puzzles

### D. Scalability Considerations

- Handle larger grids (e.g., 16x16 Sudoku)
- Generalize constraint engine
- Asynchronous processing for responsive UI
- Cloud-based solving engine

- Lightweight mobile version

# VIII. Conclusion

The Logic Puzzle Solver effectively demonstrates a structured and extensible approach to solving logic puzzles using constraint satisfaction programming. By modularizing the design and encapsulating solving logic, the system supports current puzzle types and is well-positioned for future growth.

## A. Key Contributions

- Robust and extensible architecture
- Algorithmic depth with CSP and backtracking
- Full-featured, intuitive GUI
- Performance-optimized core components
- Foundation for AI integration and educational use

## B. Educational Insights

- Gained proficiency in constraint satisfaction problems
- Improved understanding of object-oriented design and GUI development
- Practical experience with solving algorithms and optimization strategies
- Exposure to software design for human-computer interaction (HCI)
- Introduction to algorithm visualization

# IX. References


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