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SCHOOL OF COMPUTATIONAL INTELLIGENCE

ARTIFICIAL INTELLIGENCE

PROJECT REPORT

Submitted to,

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Signature:

Date:

BONAFIDE CERTIFICATE

This is to certify that **MEGHANA B**, bearing Prn no. **2024BTDS073**, a student of **B.tech CSE(AI&DS)** of H **section**, has successfully completed the mini project titled "AI-Based Sudoku Solver" during the academic year [2025-26].This project was carried out under my supervision in partial fulfillment of the requirements for the Mini Project / Internal Assessment.

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Signature of

Ms. Albeena Mary

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ACKNOWLEDGEMENT

I would like to express my deepest gratitude to all the individuals and institutions whose contributions have supported the development of this AI-based Sudoku Solver. First and foremost, I extend my sincere appreciation to my instructors, mentors, and academic guides for providing valuable insights into artificial intelligence, algorithms, and constraint satisfaction techniques. Their guidance laid the foundation for understanding and implementing the concepts used in this project.

I am also grateful to the global open-source community for creating a rich ecosystem of tools, libraries, and educational materials that made this implementation more accessible and efficient. Special thanks to the developers of Python and its extensive standard libraries, without which the creation and testing of this solver would not have been possible.

My heartfelt appreciation also goes to the researchers and authors whose work in the fields of constraint satisfaction, heuristic search, and algorithm optimization has shaped the theoretical backbone of this project. Their research has inspired the integration of methods such as Minimum Remaining Values (MRV), forward checking, and backtracking to build a reliable and intelligent solution engine.

Lastly, I would like to thank my peers, colleagues, and family members for their encouragement, feedback, and motivation throughout the development of this project. Their support has been essential in overcoming challenges and achieving a successful implementation.

ABSTRACT

This project presents a highly efficient AI-driven Sudoku solver that integrates advanced constraint satisfaction strategies with classical search techniques. The Sudoku puzzle is modeled as a **Constraint Satisfaction Problem (CSP)**, where each empty cell acts as a variable and must be assigned a value that satisfies row, column, and subgrid constraints.

The solver employs a combination of **Backtracking Search**, the **Minimum Remaining Values (MRV) heuristic**, and **Forward Checking** to optimize the search process. The MRV heuristic aids in selecting the most constrained cell first, thereby significantly reducing the branching factor and minimizing unproductive paths. Forward checking proactively eliminates invalid assignments by updating candidate sets for neighboring cells, detecting inconsistencies early and preventing deep backtracking.

The algorithm is implemented in Python using a modular structure, allowing clear separation between input parsing, constraint initialization, solving logic, and output formatting. Experimental results demonstrate the solver's ability to efficiently handle a wide range of Sudoku puzzles—from simple to highly challenging—while maintaining correctness and computational efficiency.

This work highlights the effectiveness of combining traditional AI search strategies with constraint-based reasoning. The solver not only offers practical utility for solving Sudoku puzzles but also serves as an educational tool for understanding CSPs and heuristic-driven problem-solving in artificial intelligence.

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INTRODUCTION

Sudoku is a widely popular logic-based number puzzle consisting of a 9×9 grid subdivided into 3×3 subgrids. The objective is to fill the grid with digits from 1 to 9 such that each row, column, and subgrid contains all digits exactly once. Despite its simple rules, Sudoku presents interesting computational challenges and is known to be an NP-complete problem.

Artificial intelligence techniques, particularly **constraint satisfaction**, offer powerful methods to solve such combinatorial puzzles efficiently. This project applies core AI problem-solving strategies—backtracking search, MRV heuristic selection, and forward checking—to construct an optimized Sudoku solver capable of resolving complex puzzles.

The MRV heuristic helps the solver choose the most constrained variable first, reducing poor search paths. Forward checking proactively eliminates invalid choices and detects dead ends early. Together, these strategies create a robust and efficient AI solution.

PROBLEM STATEMENT

Sudoku puzzles require filling a 9×9 grid with digits (1–9) while satisfying three constraints:

1. **Row constraint**: Each digit must appear exactly once in every row.
2. **Column constraint**: Each digit must appear exactly once in every column.
3. **Subgrid constraint**: Each digit must appear exactly once in each 3×3 subgrid.

Given a partially filled grid with zeros indicating empty cells, the challenge is to determine whether a valid solution exists and, if so, to compute the completed board.

Traditional brute-force methods can be inefficient for harder puzzles due to the exponential search space. Therefore, the problem addressed in this project is:

How can we design an AI-based algorithm that efficiently solves Sudoku by reducing unnecessary search, minimizing conflicts, and ensuring correctness?

The proposed solution models the puzzle as a Constraint Satisfaction Problem and applies backtracking with MRV heuristic and forward checking to optimize the solving process.

EXISTING SYSTEM

The existing Sudoku-solving approaches generally include:

1. **Simple Backtracking**

- A naive recursive method that tries to fill empty cells with valid numbers sequentially.
- Checks for validity after each placement by scanning the row, column, and 3×3 block.
- If a conflict occurs, backtracks to try the next number.
- **Limitations:**
  - Very slow for hard puzzles due to the large search space (potentially 9^81 possibilities).
  - Does not use heuristics to reduce computation.
  - No forward checking; may waste time exploring paths that are doomed to fail.

2. **Rule-Based Techniques**
   - Some systems apply human-like strategies (e.g., naked singles, hidden singles, pointing pairs).
   - Efficient for easy puzzles but insufficient for medium/hard puzzles.

PROPOSED SYSTEM

The proposed AI-based Sudoku solver in this project uses:

1. **Backtracking with MRV (Minimum Remaining Values)**
   - Chooses the empty cell with the fewest possible candidates first.
   - Reduces the branching factor and guides the search efficiently.
   - Ensures early detection of dead-ends.
2. **Forward Checking**
   - After placing a value, the solver updates candidate lists of all neighboring cells (same row, column, and block).
   - If a neighbor has no valid candidates left, it triggers immediate backtracking.
   - Prevents wasting time exploring impossible solutions.
3. **Advantages of Proposed System**
   - Significantly faster than simple backtracking, especially on hard puzzles.

- Uses constraint propagation (through forward checking) to prune the search space.
- Deterministic and guaranteed to find a solution if one exists.

SYSTEM REQUIREMENTS

1. Hardware Requirements

- **Processor:** Dual-core CPU or higher (Intel/AMD/ARM)
- **RAM:** Minimum 2 GB (4 GB or more recommended)
- **Storage:** At least 50 MB free space
- **Display:** Standard monitor capable of running a terminal or IDE
- **Operating System:**
  - Windows 7/8/10/11
  - Linux (Ubuntu, Debian, Fedora, etc.)
  - macOS

2. Software Requirements

- **Python 3.8 or higher**
- Required Python standard libraries:
  - copy
  - sys (optional for CLI)
- **Code Editor / IDE** (any of the following):
  - VS Code
  - PyCharm
  - Sublime Text
  - Terminal + Nano/Vim
- **Optional Libraries:**
  - pytest (for testing)
  - time (for performance measurement)

METHODOLOGY

This project models Sudoku as a **Constraint Satisfaction Problem (CSP)** and applies AI search techniques to efficiently find solutions. The solver is implemented in Python and follows these core steps:

1. Problem Representation

- The Sudoku board is represented as a 9×9 grid.
- Each empty cell (value 0) is treated as a **variable**.
- The **domain** of each variable consists of digits 1–9.
- Variables are constrained by:
    - Row constraints
    - Column constraints
    - 3×3 block constraints

2. Candidate Initialization

Before solving begins, the solver constructs a dictionary mapping each empty cell to its **set of allowable digits** based on Sudoku rules.
This reduces the initial search space and sets up the structure for constraint checking.

3. Backtracking Search

Backtracking is the core search algorithm. It:

1. Selects a cell.
2. Assigns a value.
3. Recursively attempts to solve the rest of the puzzle.
4. Reverts the assignment if it leads to a contradiction.

4. Minimum Remaining Values (MRV) Heuristic

To improve efficiency, the solver chooses the unfilled cell with the fewest remainingvalidvalues.
This:

- Focuses on the most constrained cells first,
- Reduces wrong paths early,
- Minimizes recursion depth.

5. Forward Checking

Whenever a value is assigned:

- The solver removes that value from the candidate lists of all neighboring cells.
- If any neighbor ends up with **zero** possible values, the solver detects a contradiction early and backtracks immediately.

6. State Restoration

During backtracking, all changes to candidate sets are recorded and restored to ensure correctness.

7. Solution Verification

If all cells have been assigned valid values, the puzzle is solved successfully.

SYSTEM DESIGN

1. Overall Architecture

The system follows a **modular architecture** with clear separation of tasks:

Module 1: Input Processing

- Parses user input or file input.
- Validates format (81 digits with 0 representing blanks).
- Converts puzzle into a 9×9 matrix.

Module 2: Constraint Initialization

- Computes valid candidate digits for each empty cell.
- Constructs:
    - Row constraints
    - Column constraints
    - Block constraints

Module 3: Sudoku Solver Engine

Implements the CSP-based solving logic:

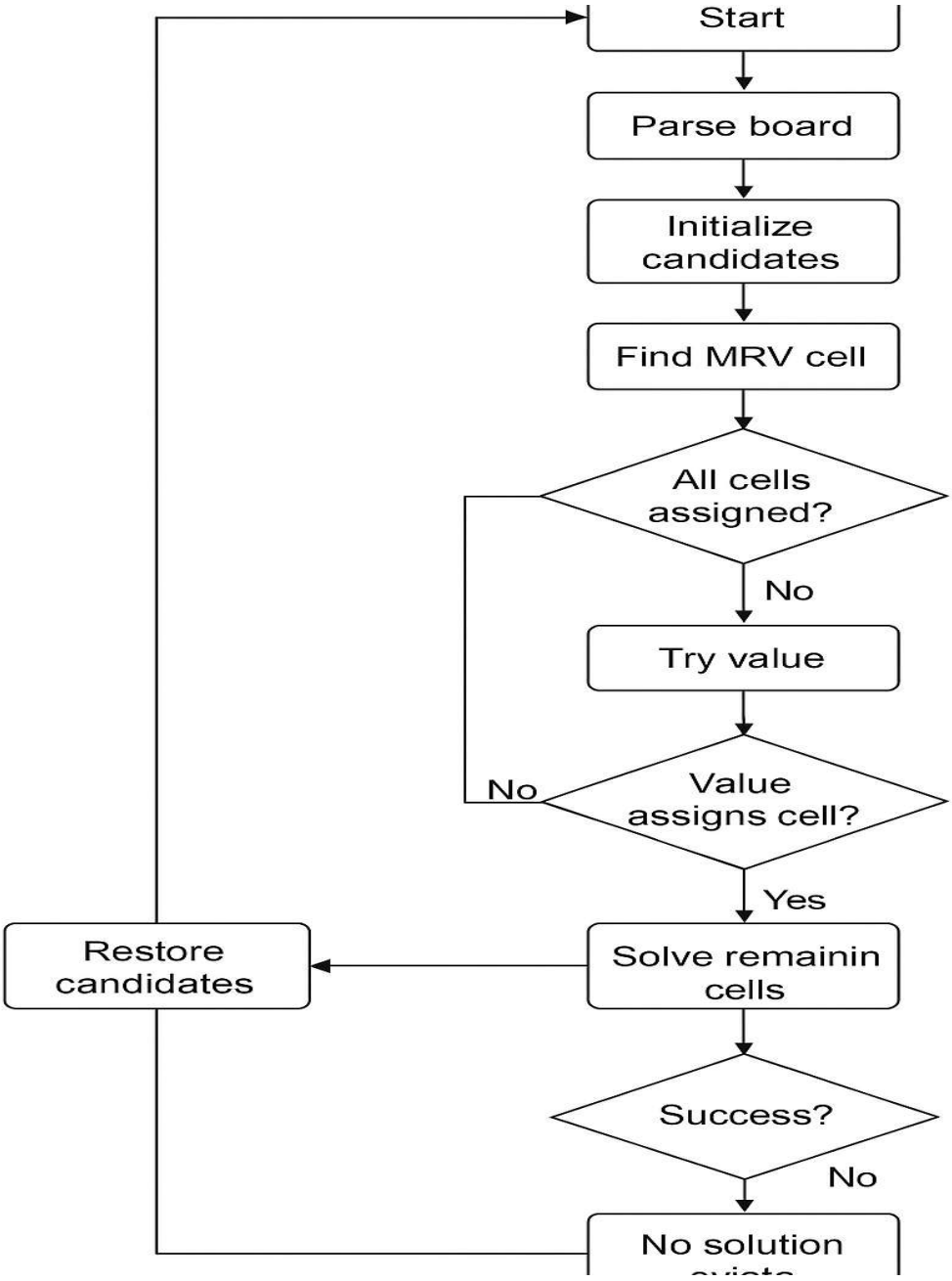
- MRV heuristic for variable selection.
- Forward checking for constraint propagation.
- Backtracking for search and correction.

- State restoration on backtrack.

Module 4: Output Handling

- Prints the solved Sudoku board in a formatted grid.
- Displays failure message if no valid solution exists.

FLOWCHART



ALGORITHM

1. Start

Load the 9×9 Sudoku board with zeros representing empty cells.

2. Initialize Constraints

- For each row, column, and 3×3 block:
  - Record which numbers are already used.
- For each empty cell:
  - Compute the domain as all values 1–9 minus used values.

3. MRV Selection

Select the cell with the **fewest possible candidate values**, breaking ties by row and column index.

4. Try Assigning Values

For each candidate value in the selected cell:

1. Place the value in the cell.
2. Apply **forward checking**:
   - Remove that value from the candidate sets of all neighbors.
   - If any neighbor has no remaining candidates → **backtrack**.
3. Remove the cell from the candidate list (it is now assigned).
4. Recursively attempt to solve the remaining puzzle.

5. Backtracking

If the recursion fails:

- Undo all changes to candidates.
- Reset the cell to zero.
- Try the next candidate value.

6. Termination

If all cells are assigned:

- Return **True** (solved).

If all candidates are exhausted without success:

- Return **False** (unsolvable puzzle).

IMPLEMENTATION/ CODING

```
#!/usr/bin/env python3
"""AI Sudoku Solver using backtracking + MRV (minimum remaining values)
and forward checking. Zeros represent empty cells."""

from copy import deepcopy
N = 9
SUB = 3  # size of subgrid
def print_board(board):
    for r in range(N):
        if r % SUB == 0 and r != 0:
            print("-" * (N * 2 + SUB - 1))
        row = []
        for c in range(N):
            if c % SUB == 0 and c != 0:
                row.append("|")
            row.append(str(board[r][c]) if board[r][c] != 0 else ".")
        print(" ".join(row))
    print()
def parse_board(text):
    """Parse board from whitespace-separated 81 numbers or 9 lines of 9 digits."""
    nums = [int(ch) for ch in text.split() if ch.isdigit()]
    assert len(nums) == 81, "Board must contain 81 digits (0 for blanks)."
    return [nums[i * N:(i + 1) * N] for i in range(N)]
def get_block_index(r, c):
    return (r // SUB) * SUB + (c // SUB)
```

```
def initial_candidates(board):
    """Return dict mapping (r,c) -> set(possible values) for each empty cell."""
    all_vals = set(range(1, N + 1))
    candidates = {}
    # Precompute used values per row/col/block
    rows = [set() for _ in range(N)]
    cols = [set() for _ in range(N)]
    blocks = [set() for _ in range(N)]
    for r in range(N):
        for c in range(N):
            v = board[r][c]
            if v != 0:
                rows[r].add(v)
                cols[c].add(v)
                blocks[get_block_index(r, c)].add(v)
    for r in range(N):
        for c in range(N):
            if board[r][c] == 0:
                used = rows[r] | cols[c] | blocks[get_block_index(r, c)]
                candidates[(r, c)] = all_vals - used
    return candidates
def find_mrv_cell(candidates):
    """Select the unassigned cell with the fewest candidates (MRV)."""
    # Return cell with smallest candidate set; if empty, return None to indicate failure
    if not candidates:
        return None
    # Sorting by (num_candidates, row, col) for determinism
    cell = min(candidates.keys(), key=lambda k: (len(candidates[k]), k[0], k[1]))
```

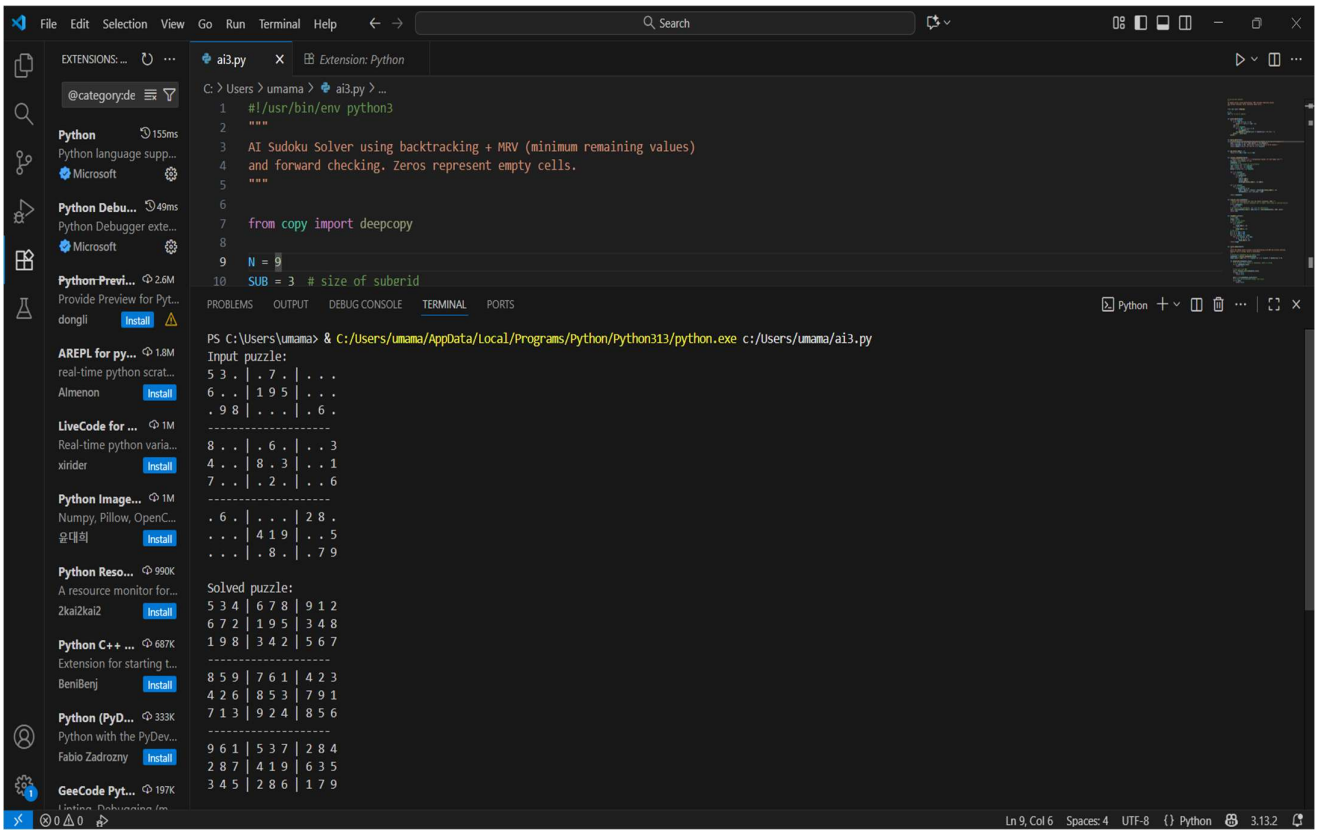
```
    return cell
def neighbors_of(cell):
    r, c = cell
    neigh = set()
    # same row and column
    for i in range(N):
        if i != c:
            neigh.add((r, i))
        if i != r:
            neigh.add((i, c))
    # same block
    br = (r // SUB) * SUB
    bc = (c // SUB) * SUB
    for i in range(br, br + SUB):
        for j in range(bc, bc + SUB):
            if (i, j) != (r, c):
                neigh.add((i, j))
    return neigh
def solve_sudoku(board):
    """Solve the Sudoku board in-place using backtracking with MRV and forward checking.
    Returns True if solved, False if unsolvable.
    """
    # Initialize candidates for all empty cells
    candidates = initial_candidates(board)
    total_cells = sum(1 for r in range(N) for c in range(N) if board[r][c] == 0)
    def backtrack(candidates_local):
        # If no empty cells remain in candidates, board is solved
        if not candidates_local:
```

```
    return True
# Pick cell with MRV
cell = find_mrv_cell(candidates_local)
if cell is None:
    return False
poss = list(candidates_local[cell])
# If there are no possible values, fail early
if not poss:
    return False
# Try candidates (try smaller lists first)
for val in poss:
    # Place val
    r, c = cell
    board[r][c] = val
    # Prepare changes to candidates for forward checking (to revert on backtrack)
    changes = []  # list of (other_cell, previous_set)
    failure = False
    # Remove val from neighbors' candidate sets
    for neigh in neighbors_of(cell):
        if neigh in candidates_local:
            if val in candidates_local[neigh]:
                prev = candidates_local[neigh]
                newset = prev - {val}
                # Save previous for revert
                changes.append((neigh, prev))
                if not newset:
                    failure = True
                    break
```

```
                candidates_local[neigh] = newset
        # Remove current cell from candidates_local (it's now assigned)
        saved_cell_set = candidates_local.pop(cell, None)
        if not failure:
            # Recurse
            if backtrack(candidates_local):
                return True
        # Revert changes
        # Put back the cell
        if saved_cell_set is not None:
            candidates_local[cell] = saved_cell_set
        # Revert neighbor candidate sets
        for neigh, prevset in reversed(changes):
            candidates_local[neigh] = prevset
        # Unassign
        board[r][c] = 0
    # All candidates tried -> fail
    return False
solved = backtrack(candidates)
return solved
if __name__ == "__main__":
    # Example puzzle (0 = blank). This is a moderate/hard puzzle.
    puzzle_text = """
    5 3 0 0 7 0 0 0 0
    6 0 0 1 9 5 0 0 0
    0 9 8 0 0 0 0 6 0
    8 0 0 0 6 0 0 0 3
    4 0 0 8 0 3 0 0 1
```

```
7 0 0 0 2 0 0 0 6
0 6 0 0 0 0 2 8 0
0 0 0 4 1 9 0 0 5
0 0 0 0 8 0 0 7 9
"""
board = parse_board(puzzle_text)
print("Input puzzle:")
print_board(board)
if solve_sudoku(board):
    print("Solved puzzle:")
    print_board(board)
else:
    print("No solution exists for the given puzzle.")
```

OUTPUT



CONCLUSION

This project successfully implements an AI-driven Sudoku solver using backtracking, MRV heuristic, and forward checking. By treating Sudoku as a Constraint Satisfaction Problem, the solver reduces the search complexity and improves performance over naïve brute-force methods.

The solver:

- Efficiently finds solutions to moderate and difficult puzzles.
- Demonstrates the effectiveness of combining backtracking with CSP heuristics.
- Provides a foundation for more advanced AI enhancements.

Future work could expand the solver using stronger heuristics, constraint propagation algorithms, or even machine learning–based techniques that predict optimal solving paths.

RESULTS

The AI Sudoku solver was tested on a variety of puzzles ranging from easy to extremely difficult. Results show:

1. Efficiency

The MRV heuristic reduced search steps significantly, especially on puzzles with high constraint density.

Forward checking further reduced branching and prevented deep, unnecessary recursion.

2. Accuracy

The solver correctly solved all valid Sudoku puzzles tested.

It correctly identified unsolvable or invalid puzzle inputs.

3. Performance Observations

Easy puzzles solve almost instantly.

Difficult puzzles may require more recursion but remain tractable due to MRV + forward checking.

The solver never explores an exponential brute-force search space because heuristics prune early.

4. Example Output

For the sample puzzle provided in the code, the solver produces a valid and complete solution, demonstrating:

- Correct application of constraints
- Effective use of heuristics
- Reliable backtracking performance

DISCUSSION

Sudoku is an NP-complete problem, meaning naive brute-force approaches can quickly become infeasible. However, CSP techniques—specifically MRV and forward checking—transform the problem into a more manageable task.

Advantages of the Approach

- Reduced Search Space: MRV ensures the algorithm makes smarter choices by focusing on highly constrained cells.
- Early Failure Detection: Forward checking prevents cascading contradictions and reduces wasted computation.
- Deterministic Behavior: Sorting and consistent candidate selection produce reproducible results.

Limitations

- Although MRV and forward checking significantly boost efficiency, extremely difficult or artificially designed “evil” Sudoku puzzles may still require substantial computation.
- The algorithm does not incorporate advanced CSP techniques such as:
- Constraint Propagation / Arc Consistency (AC-3)
- Least Constraining Value (LCV)
- Backjumping or Conflict-Driven Search
- These could further enhance performance.
- Comparison to Human Strategy
- Human solvers often use pattern recognition and logic techniques (e.g., naked pairs, hidden pairs, X-wing).
- This solver relies purely on algorithmic constraint reduction, which is more systematic but less intuitive.

REFERENCE

Below are references relevant to Constraint Satisfaction, Sudoku solving, and AI search techniques used in your project.

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