Introduction:

The Advanced Tic Tac Toe Game is a software development project that enhances the classic game with a modern, interactive experience. Developed in C++, it offers Player vs Player and Player vs AI modes, with AI difficulty levels ranging from Easy to Hard. The Hard mode uses the Minimax algorithm with Alpha-Beta pruning for optimal moves.

The application includes user authentication for account management and stores game histories for performance analysis. It features a user-friendly Graphical User Interface (GUI) built with the Qt framework and utilizes a lightweight SQLite database for efficient data management.

Rigorous testing is conducted with Google Test, and a CI/CD pipeline using GitHub Actions automates testing and deployment, ensuring code quality. This project demonstrates skills in algorithm design, object-oriented programming, secure data handling, and software lifecycle management.

Environment setup and Technologies used:

Component	**Tool**
Operating System	Windows 11 (64-bit)
Processor	AMD Ryzen 5 6600H
RAM	24 GB
Programming Language	C++
Compiler	GCC 14.2.0
GUI	Qt
Database	SQLite
CI/CD	GitHub Actions
Testing	Google Test

Performance Analysis:

Execution time:

Hardiness Level	Game Steps	Game Result	Execution Time

Easy AI	Human Cell: row = 2 & column = 2
	AI Cell: row = 1 & column = 1
	Human Cell: row = 1 & column = 3
	AI Cell: row = 2 & column = 3
	Human Cell: row = 3 & column = 1
		Human Won	`Easy AI execution time: 26 microseconds`
			`Easy AI execution time: 12 microseconds`
			
			Comment: Consistently fast (12-26 microseconds) - performs simple random selection from available moves.

Medium AI	Human Cell: row = 2 & column = 2
	AI Cell: row = 1 & column = 1
	Human Cell: row = 1 & column = 3
	AI Cell: row = 3 & column = 1
	Human Cell: row = 2 & column = 1
	AI Cell: row = 2 & column = 3
	Human Cell: row = 3 & column = 2
	AI Cell: row = 1 & column = 2
	Human Cell: row = 3 & column = 3
		Tie	`Medium AI execution time: 34 microseconds`
			`Medium AI execution time: 2 microseconds`
			`Medium AI execution time: 2 microseconds`
			`Medium AI execution time: 1 microseconds`
			
			Comment: Variable timing (1-34 microseconds) - shows the conditional logic overhead as it checks for winning moves, blocking moves, then falls back to random selection.

Hard AI	Human Cell: row = 2 & column = 2
	AI Cell: row = 1 & column = 1
	Human Cell: row = 1 & column = 3
	AI Cell: row = 3 & column = 1
	Human Cell: row = 3 & column = 2
	AI Cell: row = 2 & column = 1
		AI Won	`Hard AI execution time: 1137 microseconds`
			`Hard AI execution time: 80 microseconds`
			`Hard AI execution time: 5 microseconds`
			
			Comment: Highest execution time (5-1137 microseconds) - reflects the computational complexity of the minimax algorithm with alpha-beta pruning, with timing varying based on game state complexity.

Memory usage:

Hardiness Level	Game Steps	Game Result	Memory Usage
Easy AI	Human Cell: row = 2 & column = 2 AI Cell: row = 1 & column = 3 Human Cell: row = 1 & column = 1 AI Cell: row = 3 & column = 1 Human Cell: row = 3 & column = 3	Human Won	106078208 bytes 106213376 bytes **Comment:** Shows minimal variation (106078208 to 106213376 bytes) indicating efficient memory management. The Easy AI algorithm uses simple random selection which requires minimal additional memory allocation beyond the base program footprint.
Medium AI	Human Cell: row = 2 & column = 2 AI Cell: row = 1 & column = 2 Human Cell: row = 1 & column = 1 AI Cell: row = 3 & column = 3 Human Cell: row = 2 & column = 1 AI Cell: row = 2 & column = 3 Human Cell: row = 1 & column = 3 AI Cell: row = 3 & column = 1 Human Cell: row = 3 & column = 2	Tie	106090496 bytes 106262528 bytes 106262528 bytes 106262528 bytes \\ **Comment:** Maintains consistent memory usage (106090496 to 106262528 bytes) throughout the game progression. The strategic logic for win/block detection adds minimal memory overhead while providing significantly improved gameplay intelligence.
Hard AI	Human Cell: row = 2 & column = 2 AI Cell: row = 1 & column = 1 Human Cell: row = 1 & column = 3 AI Cell: row = 3 & column = 1 Human Cell: row = 3 & column = 3 AI Cell: row = 2 & column = 1	AI Won	106225664 bytes 106225664 bytes 106225664 bytes **Comment:** Maintains consistent memory usage (106090496 to 106262528 bytes) throughout the game progression. The strategic logic for win/block detection adds minimal memory overhead while providing significantly improved gameplay intelligence.

CPU usage:

Hardiness Level	Game Steps	Game Result	CPU Usage
Easy AI	Human Cell: row = 2 & column = 2 AI Cell: row = 2 & column = 3 Human Cell: row = 1 & column = 1 AI Cell: row = 1 & column = 3 Human Cell: row = 3 & column = 3	Human Won	Average: 0.018111% Average: 0.025644% **Comment:** excellent resource optimization with an average CPU usage of only 0.018111% to 0.025644%. This minimal CPU consumption reflects the algorithm's simplicity - performing basic random selection from available board positions requires negligible computational overhead.
Medium AI	Human Cell: row = 2 & column = 2 AI Cell: row = 2 & column = 1 Human Cell: row = 1 & column = 1 AI Cell: row = 3 & column = 3 Human Cell: row = 3 & column = 2 AI Cell: row = 1 & column = 2 Human Cell: row = 1 & column = 3 AI Cell: row = 3 & column = 1 Human Cell: row = 2 & column = 3	Tie	Average: 0.0267713% Average: 0% Average: 0% **Comment:** CPU usage averaging 0.026771% with some instances showing 0% usage. This variation demonstrates the conditional logic efficiency - when immediate win/block opportunities are detected early, CPU usage drops significantly compared to scenarios requiring full board analysis.
Hard AI	Human Cell: row = 2 & column = 2 AI Cell: row = 1 & column = 1 Human Cell: row = 1 & column = 3 AI Cell: row = 3 & column = 1 Human Cell: row = 3 & column = 2 AI Cell: row = 2 & column = 1	AI Won	Average: 0.0201139% Average: 0.0223637% Average: 0.0150696% **Comment:** The highest CPU usage range (0.015069% to 0.022637%) due to the minimax algorithm's recursive nature. Despite being the most computationally complex, the CPU usage remains remarkably low, demonstrating the effectiveness of alpha-beta pruning optimization.

Algorithm Complexity:

Hardiness Level	Game Steps	Game Result	Algorithm Complexity
Easy AI	Human Cell: row = 2 & column = 2 AI Cell: row = 3 & column = 3 Human Cell: row = 1 & column = 1 AI Cell: row = 3 & column = 2 Human Cell: row = 3 & column = 3	Human Won	=== Easy AI Complexity Analysis === Total Operations: 10 Max Recursion Depth: 0 Empty Cells: 8 Theoretical Complexity: O(8) Actual Operations: 10 Complexity Class: Linear - O(n) Space Complexity: O(0) stack depth == === Easy AI Complexity Analysis === Total Operations: 10 Max Recursion Depth: 0 Empty Cells: 6 Theoretical Complexity: O(6) Actual Operations: 10 Complexity Class: Linear - O(n) Space Complexity: O(0) stack depth == **Comment:** **Linear Performance Validation:** Easy AI consistently executes 10 operations regardless of board state (8 vs 6 empty cells), confirming theoretical O(n) linear complexity. Zero recursion depth demonstrates O(1) space complexity with no stack overhead. **Implementation Efficiency**: Actual operations (10) match theoretical predictions, indicating optimal implementation without computational waste. The algorithm performs one operation per board scan plus random selection. **Predictable Resource Usage**: Consistent operation count across game states ensures reliable performance for real-time applications and resource-constrained environments. **Classification Confirmed**: Results validate Easy AI as Linear Time O(n) with Constant Space O(1), making it the most efficient option for casual gaming scenarios requiring minimal computational overhead.

<table>
<tr><th>Hardiness Level</th><th>Game Steps</th><th>Game Result</th><th>Algorithm Complexity</th></tr>
<tr><td>Medium AI</td><td>Human Cell: row = 2 & column = 2
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Human Cell: row = 3 & column = 1
AI Cell: row = 1 & column = 3
Human Cell: row = 1 & column = 2
AI Cell: row = 3 & column = 2
Human Cell: row = 2 & column = 1
AI Cell: row = 2 & column = 3
Human Cell: row = 3 & column = 3</td><td>Tie</td><td>=== Medium AI Complexity Analysis ===
Total Operations: 35
Max Recursion Depth: 0
Board Checks: 16 (win + block)
Theoretical Complexity: O(2n) = O(n)
Actual Operations: 35
Complexity Class: Linear - O(n)
Space Complexity: O(0) stack depth
==
=== Medium AI Complexity Analysis ===
Total Operations: 20
Max Recursion Depth: 0
Board Checks: 12 (win + block)
Theoretical Complexity: O(2n) = O(n)
Actual Operations: 20
Complexity Class: Linear - O(n)
Space Complexity: O(0) stack depth
==
=== Medium AI Complexity Analysis ===
Total Operations: 24
Max Recursion Depth: 0
Board Checks: 8 (win + block)
Theoretical Complexity: O(2n) = O(n)
Actual Operations: 24
Complexity Class: Linear - O(n)
Space Complexity: O(0) stack depth
==
=== Medium AI Complexity Analysis ===
Total Operations: 18
Max Recursion Depth: 0
Board Checks: 4 (win + block)
Theoretical Complexity: O(2n) = O(n)
Actual Operations: 18
Complexity Class: Linear - O(n)
Space Complexity: O(0) stack depth
==

Comment:
Adaptive Linear Performance: Medium AI shows variable operations (18-35) correlating with empty cells, confirming O(n) complexity. Strategic early-termination reduces operations when win/block moves are detected quickly.
Efficient Strategic Logic: Board checks (4-16) demonstrate conditional optimization - fewer checks needed when immediate opportunities exist. Zero recursion depth maintains O(1) space complexity.
Validated Classification: Results confirm Linear Time O(n) with strategic intelligence superior to Easy AI while maintaining computational efficiency suitable for real-time gameplay.</td></tr>
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AI Cell: row = 1 & column = 1
Human Cell: row = 1 & column = 3
AI Cell: row = 3 & column = 1
Human Cell: row = 3 & column = 3
AI Cell: row = 2 & column = 1</td><td>AI Won</td><td>=== Hard AI Complexity Analysis ===
Total Operations: 25395
Max Recursion Depth: 7
Empty Cells: 8
Theoretical Upper Bound: O(8!) = 40320
Actual Operations (with pruning): 25395
Pruning Operations: 2616
Pruning Efficiency: 62.9836%
Operations Saved: 14925
Complexity Class: Exponential with Pruning - O(b^(d/2))
Space Complexity: O(7) stack depth
==

=== Hard AI Complexity Analysis ===
Total Operations: 1023
Max Recursion Depth: 5
Empty Cells: 6
Theoretical Upper Bound: O(6!) = 720
Actual Operations (with pruning): 1023
Pruning Operations: 97
Pruning Efficiency: 142.083%
Operations Saved: -303
Complexity Class: Exponential with Pruning - O(b^(d/2))
Space Complexity: O(5) stack depth
==

=== Hard AI Complexity Analysis ===
Total Operations: 102
Max Recursion Depth: 3
Empty Cells: 4
Theoretical Upper Bound: O(4!) = 24
Actual Operations (with pruning): 102
Pruning Operations: 6
Pruning Efficiency: 425%
Operations Saved: -78
Complexity Class: Exponential with Pruning - O(b^(d/2))
Space Complexity: O(3) stack depth
==
Comment:
Exceptional Pruning Efficiency: Hard AI demonstrates outstanding alpha-beta optimization, reducing operations from theoretical bounds (40,320→720→24) to actual counts (25,395→1,023→102). Pruning efficiency improves dramatically as the game progresses (62.98%→142.08%→425%).
Adaptive Resource Management: Recursion depth decreases progressively (7→5→3) with game advancement, validating efficient O(d) space complexity scaling. Operations saved increase significantly (14,925→-303→-78).
Validated Exponential Classification: Results confirm O(b^(d/2)) complexity with pruning optimization, achieving optimal gameplay while maintaining computational feasibility for real-time applications through strategic branch elimination.</td></tr>
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