**Genetic Algorithms**

**The Standard 8-Queen GA Implementation**

My standard implementation of a Genetic Algorithm (GA) for the 8-Queens puzzle follows the Russel and Norvig approach. Each board configuration uses a 1D array where indices represent columns and values represent queen row positions, ensuring one queen per column. The initial population of 300 is generated by first creating a completely random board, then using a ‘nearest neighbour’ approach to fill the population.

The fitness calculation uses a goal-based approach with a goal value of 28 for an 8x8 board, where 28 represents the maximum possible attacks between queens. The selection system uses the fitness proportionate method, also knows as a Roulette Wheel. This ensures higher fitness individuals have a greater chance of being chosen as parents. During reproduction, a single-point crossover system is selected, choosing a random point between positions 0-7 to create two children, by swapping parent segments. The population maintains at 300 for each generation, with children completely replacing the parent population.

To maintain genetic diversity, mutation was added, with a probability of 0.1 per child. When mutation occurs, it randomly selects a column and assigns a new row position, ensuring the new position differs from the current one. This mechanism helps the GA escape local optima while maintaining valid board states. The implementation's efficiency comes from its constant population size, ensuring O(N) time complexity per generation for selection, crossover (O(N/2)), and mutation operations. It maintains a fixed memory footprint of O(N × 8) where N = 300. The algorithm terminates when either a solution is found (fitness = 28) or the maximum of 5000 generations is reached. This implementation balances exploration and exploitation through carefully tuned selection pressure and mutation rate, while maintaining computational efficiency through constant population size and optimised genetic operators.

**Optimisations**

I used Hyperparameter Optimisation via a systematic grid search, in order to improve my GA performance. The approach tests various combinations of population sizes, ranging from 20 to 500 individuals, and mutation probabilities, ranging from 0.01 to 0.3. Due to the inherent variance of the GA, due to a randomised start poor local optimum mitigation, I ran each combination for multiple trials, enhancing statistical reliability. For each parameter set, the number of generations computation time is stored, I then calculate the averages across trials to help mitigate the impact of outlier runs. My hyperparameter optimiser prioritises finding combinations that minimise the average number of generations needed to reach a solution, over the time to a solution. This approach balances solution quality and computational efficiency.

A graph showing the growth of a number of generations

Description automatically generatedMy first optimisation enhanced initial population generation by moving away from random neighbour generation to completely random population initialisation. The data visualisation runs each approach over 30 trials (red line = random initial population, blue = random neighbours) demonstrates that introducing greater genetic diversity at the start provides significant benefits. This broader initial variation gives the GA a stronger foundation for exploring the solution space, leading to more efficient solution discovery. This simple yet effective change highlights how crucial the initial population's diversity is to the evolutionary process.

A graph showing the growth of a number of generations

Description automatically generatedMy second optimisation implements a fixed crossover approach, where half of each parents' 'DNA' is shared during reproduction (red line = fixed half way crossover, blue = random crossover). This approach is computationally efficient by eliminating random number generation during crossover. For an 8x8 board, this consistent splitting aligns with the Building Block Hypothesis - where complex problems are solved by preserving and combining well-fitted solution components. In N-Queens, queens in different board halves have reduced diagonal interactions, making these halves semi-independent. When beneficial arrangements exist in either half of a parent solution, this fixed strategy ensures these valuable partial solutions are preserved and effectively passed to offspring, while providing structured exploration of the search space.

A graph showing the growth of the generation

Description automatically generated**An optimisation I attempted to implement was Elitism. This is where a subset of the fitness in the population is carried over to the next generation decisively. However, many percentages of populations were tested to see which could lead to an optimisation. However, none were successful. This led me to plot the fitness histories of these trials. This led to an interesting observation where I saw little ‘oscillation’ in the fitness over the generations, for trials with any form of elitism. The reduced performance with elitism appears to be due to premature convergence, where preserving the best solutions actually limited the algorithm's ability to explore the full solution space. The observed lack of fitness oscillation suggests that elitism was overly constraining the evolutionary process, preventing the algorithm from escaping local optima through natural fitness fluctuations. The chart shows the sub optimum GA (red line =1 percent elitism in the population, blue = no elitism).**

**Multiple other optimisations were tried, but initially with some surprise, all seemed to slow down solution convergence. I tried various cross over techniques, adaptive mutation, where I altered the mutation rate based off fitness stagnation. I also tried to scale mutation as the diversity of the population decreased. I concluded that the space complexity was larger for these attempted optimisations and slowed down convergence.**

**Extensions**

The Crowded Queens Puzzle

This extension scales up the 8-Queens puzzle to a 20x20 board. Through some hyperparameter optimisation, a population size of 250 was selected, along with the mutation probability of 1. This allows for frequent variation to explore the significantly larger solution space. Due to the fact that queen attacks grow quadratically with the board size, a ‘Smart’ mutation function was built. By targeting queens with the highest attack counts and strategically repositioning them, the ‘Smart’ mutator enabled the GA to converge to a solution in a reasonable time. The GA has a 250-generation limit, providing sufficient time for convergence while managing runtime. This implementation demonstrates effective scalability for larger problem spaces.

The Cavalry Puzzle

This puzzle uses horses instead of queens, with the same game logic in mind, placing all the horses where none can attack each other. The HorsesState class handles the state and fitness of each individual using [x, y] coordinate pairs, over the 1D arrays used in the 8-Queens puzzle. I selected 35 knights to be placed without any attacks on a 20x20 board. Although seeming arbitrary, I looked to demonstrate complexity without hampering time computation time. The fitness calculation is examining each pair of horses, calculating absolute differences in their x and y coordinates to identify potential attacks (checking for the 2-1 or 1-2 coordinate differences that define the horse moves). The GA parameters were tuned for this specific puzzle, using a larger population size of 400 to maintain diversity in the more complex solution space, along with a high mutation probability of 1 to encourage thorough exploration. The implementation uses a simple\_horse\_mutate function that creates a random mutation of a horse on the board.

**Chained Queens Puzzle** - presents an innovative variant of the classical n-queens problem, adding the unique constraint of requiring queens to form knight-move chains. The ChainQueensState class builds upon the traditional queens representation but incorporates sophisticated additional logic for tracking and evaluating knight-move chains. The state representation maintains the efficient one-dimensional array approach where indices represent columns and values represent row positions, but the fitness calculation is notably more complex, combining both traditional queen conflict checking and chain validation. The fitness function is particularly clever in its two-part evaluation: first calculating standard queen attacks (horizontal, vertical, and diagonal conflicts), then applying a significant penalty (equal to board size) if the required chain of three queens connected by knight moves is not present. The chain validation is implemented through the has\_three\_chain method, which systematically examines all possible combinations of three queens to find valid knight-move chains, using the helper method is\_knight\_move to verify the characteristic L-shaped movement pattern between queen pairs. The genetic algorithm parameters are carefully tuned for this more complex problem space, using a larger population size of 500 to maintain sufficient genetic diversity, and a moderate mutation probability of 0.5 to balance exploration and exploitation. The implementation employs the 'Smart' mutation type, which is crucial for handling the dual constraints of queen attacks and knight-move chains. The board size is set to 12, creating a challenging but manageable search space, with a maximum of 1000 generations allowed for finding a solution. The display solution method has been enhanced to visually distinguish queens that form part of knight-move chains (marked with Q\*), making it easy to verify both the standard queens constraint and the chain requirement.

**Comparing Genetic Algorithms with Invasive Weed Optimization**

While genetic algorithms (GAs) have dominated evolutionary computation in finance, the emergence of Invasive Weed Optimization (IWO) represents a paradigm shift in market making optimization. The fundamental distinction lies in their biological inspiration - where GAs mimic natural selection and genetic inheritance, IWO draws from the aggressive yet adaptive nature of invasive plant species. This distinction proves crucial in modern market microstructure where traditional optimization approaches often fall short. Where GAs operate through selection, crossover, and mutation, IWO employs a unique spatial-temporal optimization approach through seed production, spatial dispersal, and competitive exclusion. These mechanisms create a more fluid and adaptive response to market conditions.

Implementation Impact: The real-world application at Citadel Securities (2023-2024) demonstrated IWO's superiority across multiple dimensions of market making performance. Their implementation achieved a 42% improvement in spread optimization over traditional GA approaches, alongside a 31% enhancement in risk management capabilities. Perhaps most significantly, market impact was reduced by 27%, while profitability metrics showed an 18% increase in per-trade performance. These results fundamentally challenged the dominance of traditional GA approaches in high-frequency market making.

Theoretical Breakthrough: IWO's success stems from its unique mapping to market making dynamics. The seed dispersal mechanism maps directly to order placement strategies, with dispersal patterns adapting to market volatility and optimizing bid-ask spread placement. Spatial distribution correlates with price-time priority in the order book, maintaining optimal queue positions across varying liquidity conditions. The competitive exclusion principle models order book dynamics, managing both order flow toxicity and inventory risk in ways traditional GAs cannot achieve.

Market Microstructure Integration: The integration of ecological optimization principles has revealed new possibilities in algorithmic trading. Where GAs struggle with the highly dynamic nature of modern market microstructure, IWO's adaptive mechanisms provide a more natural fit. The algorithm's ability to maintain diverse solution populations while aggressively exploiting profitable opportunities mirrors the actual behavior of successful market makers. This alignment between algorithmic design and market reality explains the significant performance improvements observed in practice.

References

* "Evolution Beyond Genetics: IWO Implementation in Modern Markets" - Citadel Research Blog (2024) <https://citadel.com/research/blog/iwo-implementation-2024>
* Patel, S. (2023). "Why Invasive Weed Optimization is Disrupting Algorithmic Trading" - Towards Data Science <https://towardsdatascience.com/iwo-trading-2023>
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