# Analysis of Genetic Algorithms Optimizing Topological Layout and Synaptic Weights

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***Abstract*—The purpose of this experiment was to compare the results of training artificial neural networks through standard backpropagation and using a genetic algorithm. The genetic algorithm altered both the structure and weights of the network to attempt to further encourage learning.**

## I. Introduction

THIS experiment sought to compare the results of neural network learning by backpropagation versus using a genetic algorithm. The genetic algorithm would evolve the structure and synaptic weights of the network simultaneously, attempting to optimize all the parameters. We found that the genetic algorithm performed better overall on average, but may not have been worth the additional computation time.

## II. Background

### A. Neural Networks

A high level description of a basic Neural Network is a single directional graph without cycles or reflexive edges. It is a mathematical model wherein given some number of inputs and some number of outputs, the outputs will react to the magnitude of the input values. A visualization is given in Figure 1.

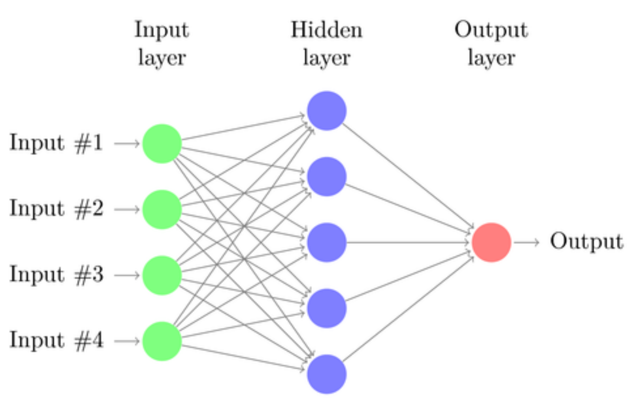


Fig. 1. An example single hidden layer neural network.

The output is *trained* to the desired output through manipulating the weights in the intermediate (hidden) and output layer edges.

A node calculates its output value by summing the output of all of its predecessors and multiplying that output by a weight assigned to that edge, this value is then squashed to a number traditionally between 0 and 1 by a Sigmoid function.

$$NodeOutput = \sum_{i=1}^{n} w_i x_i$$

Fig. 2. Where $n$ is the number of edges coming *into* this node, $w$ is the weight associated with that edge and x is the output value produced by the predecessor node.

In the Figure 1 there is only one hidden layer, but in our experiments we are evolving a network that can have up to three hidden layers.

In this experiment, `brainjs` (written by Heather Arthur) was used for the backpropagation learning. [2]

*Learning:* A neural network learns by examples. Training examples are fed into the network, and the network changes the synapse weights so that when training is complete, the network will produce the required results when fed new problems it has not seen during training. The learning process is called *Back-Propagation*. [5]

*Gradient Descent:* Gradient descent is a common first order optimization algorithm. The is the reason we use a sigmoid activation function instead of the Heaviside function; the gradient of Heaviside is undefined at $x = 0$. Gradient descent has it's basis in vector calculus. The gradient of a multi-variable function points in the direction of fastest growth of that function. The negative gradient then points in the direction where the function decreases the fastest. The function, in the case for neural networks, is the error of the system, $f(\omega_1, .., \omega_n)$, a function of all the weights of the network. The basic gradient descent weight update rule is

$$\vec{\omega} \leftarrow \vec{\omega} - \nu \vec{\nabla} \xi(\omega) \tag{1}$$

where $\vec{\omega}$ is the synapse weights, $\nu$ is the learning rate, and $\xi(\omega)$ is the error function. The error function value can be determined during the *Back-Propagation* step, then one component of $\vec{\omega}$ is updated using Equation 2, where $g(\omega_i)$ is just the activation function of the neuron. [6]

$$\omega_i \leftarrow \omega_i - \nu \frac{\partial}{\partial \omega_i} g(\omega_i) \tag{2}$$

*Back-Propagation:* A network is first initialized by setting all of the synapse weights to small random numbers, usually between $-1$ and 1. A training example is fed into the network, and the output is calculated. Since each weight is a random number, the network output is completely different from the target output. The strategy is to calculate the error produced by each neuron. At the output layer, the error is simply

$TargetOutput - ActualOutput$. According to the gradient descent equations, the error at the output layer is

$$err = \frac{\partial}{\partial \omega} g(x) \times (TargetOutput - ActualOutput) \quad (3)$$

where $x$ is the value of the weighted sum.
Propagating the error back, the error at a hidden neuron $j$ is

$$err_j = \frac{\partial}{\partial \omega} g(x) \times \left( \sum_i \omega_i \cdot err_i \right) \quad (4)$$

where $i$ is a neuron in the next layer.
Finally, with all the error function values found, the weights of all the synapses in the network are updated using Equation 1. [4]

### B. Genetic Algorithms

Genetic Algorithms or GAs are another mathematical model for finding an optimized solution in a large search space. This model is based off of Darwinian Evolution in that the best performing current solutions are bred together mixing genetic information from both parents into their children (known as a crossover operation). These children are then evaluated, just as their parents were, and subjugated to the same breeding rules.

Like in biological evolution corruption of the genetic code can happen, this is a possibly destructive mutation that encourages diversity between parents. This mutation can provide new genetic code to the child that it might benefit from that it couldn't have received from the parents.

The difficulty of this search method is pragmatically defining the layout of the genetic code (a Chromosome) and creating different mutation and crossover functions that hopefully it can benefit from. [6]

## III. Methodology

This goal of this experiment is to use a GA to optimize a neural network and compare the result to that of a vanilla neural network trained by back propagation. The following are the graph operations that were chosen as the crossover and mutation functions.

### A. Mutations

Mutations are possibly destructive operations that encourage diversity and explore the search space. All of these mutations where weighted the same and had the same chance of being used in all of the experiments.

*1) Add Node:* If the current graph allows for more nodes add one in the first possible hidden layer and connect it to any proceeding nodes behind it. For each new output edge from this node, randomize the weight associated with it. So while the node might be 'fully connected' to all proceeding nodes, as the weight approaches 0 that edge effectively becomes disconnected.

This function can only add nodes to the hidden layers of the neural networks. The input and output layers have a fixed amount of nodes that must exist, but can be disconnected.

*2) Remove Node:* This randomly selects a non-output node with connections and removes all outgoing connections. This function can disconnect input layer nodes. This could be considered beneficial to the network as 'feature selection' and could remove data that could potentially add noise to the input layer, and then get propagated down the line.

*3) Add Edge:* This method selects a random edge and changes its value.

If the edge does not exist it is created with a uniformly distributed 'weight of connectivity' ranging from $[0...1)$. If the edge does exist, a new value within the same range is given and the weight is overridden.

*4) Remove Edge:* Randomly selects a connected edge to remove. There is no restriction in what layer this can happen.

*5) Change Edge Weight:* Five random non-zero weight edges are randomly assigned a new value. By chance, they may not be five distinct edges, since they are randomly selected. This mutation, when used, was twice as likely to occur compared to any of the previous mutations discussed. The chance was higher because the other mutations would possibly be destructive, and this mutation was not as aggressive.

### B. Crossovers

Crossovers build off of existing solutions and exploit the genetic code we have found thus far to be useful.

*1) Union:* A union of all nodes and edges of the two graphs, if two edges exist on the two graphs then weights of both edges are averaged and this value becomes the new weight in the child.

This is a crossover that can easily create bloat in the child that doesn't help it in any way. This child now has the superior genetic code of both parents with all of the unhelpful (malignant) mutations from both. [1]

*2) Intersection:* The intersection function is a 'clean-up' function, but can be very destructive if there is too much diversity between two parents. Just like in biological evolution if there is too much difference between the parents (different species) the child may not be as functional as each of the parents.

When this type of crossover is selected, all edges and nodes that both parents share get passed onto the child. All other nodes/edges that are not shared by **both** parents is discarded. [1]

This function helps to reduce bloat that is created from the different mutations.

*3) Roulette Union:* An alteration to the standard union crossover. Instead of merging both parents into one child, a coin is flipped which decides which parent to take an edge from. If heads, then the edge from Parent A is copied exactly, else the edge from Parent B is copied.

If both parents have a connection from node $A \rightarrow B$ then there is a 100% chance that the edge $A \rightarrow B$ exists. If one parent has a connection $A \rightarrow B$ and the other doesn't, then there is a 50/50 chance of the child receiving the link or not, compared to inheriting all edges like the previous mentioned union.

This is done for all aspects of both parents, if both parents have the same aspect it will for sure show up in the child.

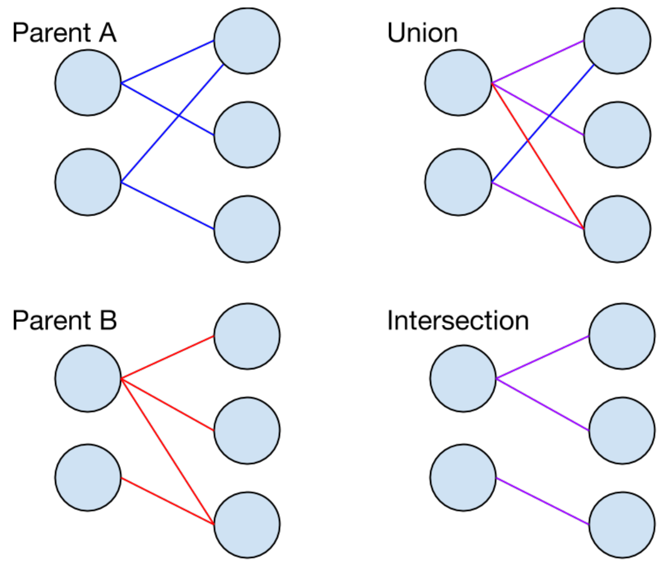


Fig. 3. Example of union and intersection crossovers.

This is more how biological evolution works wherein the Chromosome is built from a random selection of a little of Parent A and a little of Parent B.

### C. Tournament

From a population the 'best' individuals must be chosen to pass their genetic code onto future generations. The method through which these are chosen is through a tournament selection.

After all the individuals have been given a fitness, the best $n$ individuals are taken from the generation to be bred against each other, using the following function …

```
for i in new_population
  if(mutation)
    i := best_individuals[random()].mutate()
  else if(crossover)
    first := best_individuals[random()]
    second:= best_individuals[random()]
    while first == second
      second := best_individuals[random()]
    i = first.crossover(second)
```

## IV. Experiments

The purpose of this project is to compare results of vanilla backpropagation to the results of a Genetic Algorithm applied to optimizing a neural network's weights and topography.

Traditionally a comparison like this only focuses on the GA optimizing the weights **or** the topography of the neural net. We have attempted to do both simultaneously. We found the results from the first problem to be inconclusive and decided to run more experiments on a second problem.

The first problem is in need of feature reduction with it's many inputs and few possible outputs.

The second problem is a noisy data problem with many key variables it must compare for the final result.

### A. Connect 4

This dataset contains all legal 8-ply positions in the game of connect-4 in which neither player has won yet, and in which the next move is not forced.

The input is the full state of the board (who is in each position) and the expected output is either 'win', 'loss' or 'draw' for the 'first player'.

This experiment's description could be simplified to creating a neural network as the heuristic function of a connect-4 board.

### B. Quality of Wines

Two datasets were created, using red and white wine samples. The inputs include objective tests (e.g. PH values) and the output is based on sensory data (median of at least 3 evaluations made by wine experts). Each expert graded the wine quality between 0 (very bad) and 10 (very excellent).

These datasets were then merged together. The input layer contains "fixed acidity", "volatile acidity", "citric acid", "residual sugar", "chlorides", "free sulphur dioxide", "total sulphur dioxide", "density", "pH", "sulfates" and "alcohol" for each of the wines.

The expected output is a single value between 0 and 10. [3]

TABLE I
Genetic Algorithm Run Parameters

| Experiment | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Generations | 20 | 70 | 100 | 100 |
| Population | 200 | 200 | 200 | 100 |
| Crossover | 0.8 | 0.8 | 0.8 | 0.8 |
| Mutation | 0.2 | 0.2 | 0.2 | 0.2 |
| Tournament Size | 50 | 50 | 50 | 50 |
| Data Type | C4 | W | W | W |
| Data Size | 18000 | 6000 | 6000 | 1000 |
| Runs | 36 | 72 | 48 | 24 |

*Where 'C4' and 'W' are the 'Connect4 Data Set' and 'Wine Data Set' respectively.*

TABLE II
Backpropagation Parameters

| Experiment | 1 | 2 | 3 |
|---|---|---|---|
| Epochs | 1000 | 1000 | 1000 |
| Data Type | C4 | W | W |
| Data Size | 6000 | 2000 | 2000 |
| Runs | 30 | 30 | 30 |

*Where 'C4' and 'W' are the 'Connect4 Data Set' and 'Wine Data Set' respectively.*

## V. Analysis

### A. Connect 4

$Run_{GA}$ *1) Union/Intersect:* From Figure 4 and Figure 5 we can see that the Connect 4 problem is computationally hard to learn, and may not be worth it when each generation takes 32 minutes long.

Unfortunately when looking at Figure 4 it can be seen that very little learning occurs over the course of the experiment.

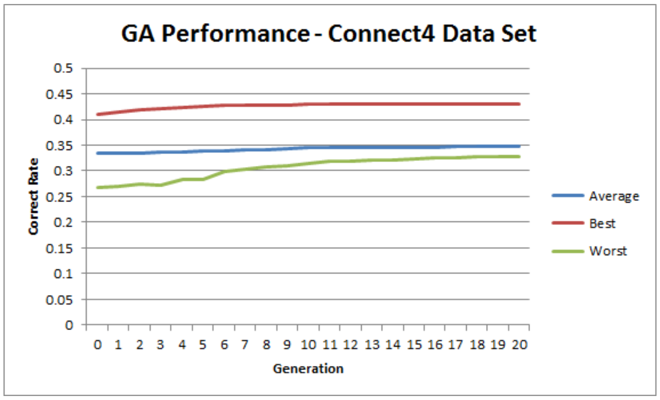


Fig. 4. Results of GA using Connect4 data set over 20 generations. No real learning appears to take place.

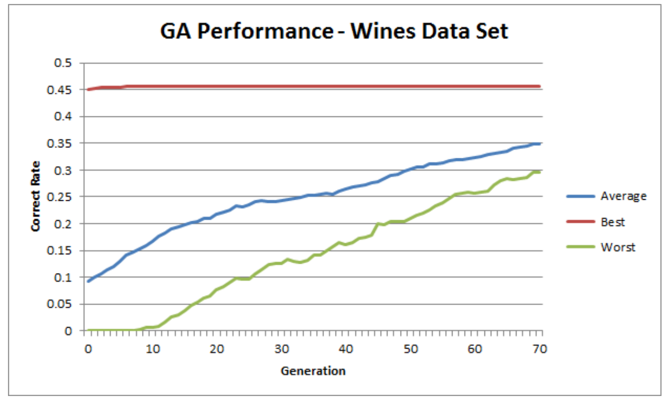


Fig. 6. Results for GA using Wines data set over 70 generations. The best never improves much, but some learning seems to occur in the average population.

Random guessing which should (for this problem) result in a fitness of 0.33. This is what the average population starts at. The average population at the end of the experiment is only 0.35 leading me to speculate that all 'learning' that occurred was a result of random search. This is further supported by the 'best' in all runs having a fitness of 0.44 in generation 0 and only increasing to 0.47 by generation 20.

With these findings it can be concluded with the standard Union and Crossover functions mentioned above would not be beneficial to encourage learning for this problem.

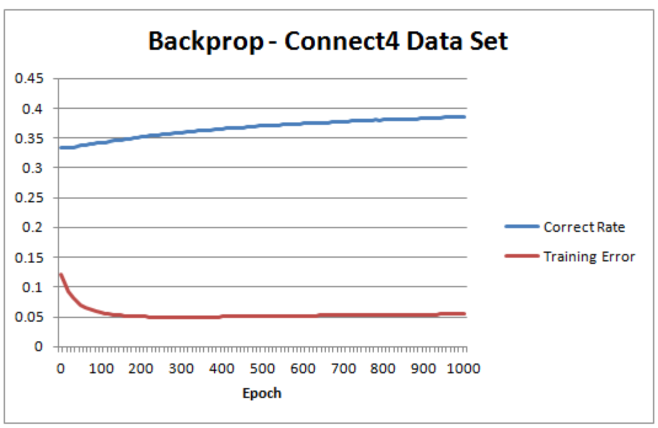


Fig. 5. Results for backpropagation learning using Connect4 data set over 1000 epochs. Not much learning appears to take place.

*$Run_{NN}$ 1) Vanilla Backprop:* When looking at Figure 5 it can be seen that vanilla backprop at generation 0 is simply guessing the answer, at the end of the experiment it can be seen that the backprop did learn increasing its' correctness on the testing set to 0.37. More than the average of the GA in the previous experiment, but clearly not very successful.

While vanilla backprop performed worst overall compared to the best of the GA, it can be argued that backprop was the 'winner' in this competition because it was able to **learn**. Compared to the GA, which found its best in generation 0 through random search.

## *B. Wine Quality*

*$Run_{GA}$ 2) Union/Intersect:* Unfortunately the learning curve is very similar to the first experiment. The GA over 6 generations quickly found the most successful solution through random search, which isn't surprising when considering that over 6 generations each with a population of 200 over 72 runs is a solution set of 86400 random permutations.

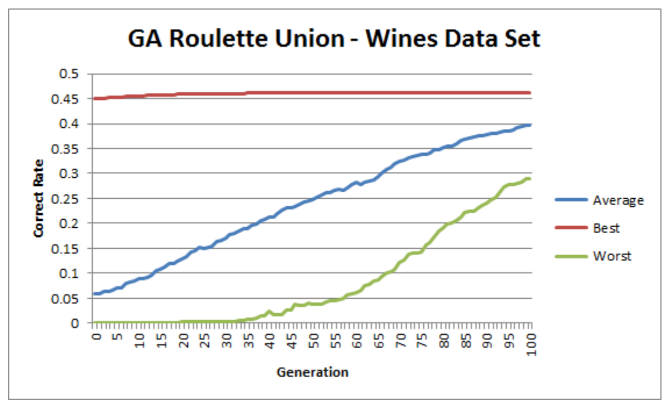


Fig. 7. Results for GA using Wines data set over 100 generations, using exclusively Roulette Union crossover. Overall, the new crossover did not change the outcome of the experiment as hoped.

*$Run_{GA}$ 3) Roulette Union:* The Roulette Union (Figure 7) does not show any improvements over the Union/Intersect crossovers (Figure 6). This crossover was introduced to attempt to add diversity to the GA population, as Union and Intersect between two parents can only produce one child each. This meant that if the same parents were selected two or more times for breeding, then their offspring would be identical. The random selection in Roulette Union leads to a very large number of potential offspring, so a more diverse population *should* appear. It does not appear that needing a more diverse population led to the poor results, but rather some other factors that not been found.

*$Run_{GA}$ 4) Change:* Introducing the alternate mutation did not affect the overall outcome of the experiment, as shown in Figure 8. Since this GA used Roulette Union as crossover, the results look nearly identical to those in Figure 7. This less aggressive mutation did change the outcome much because

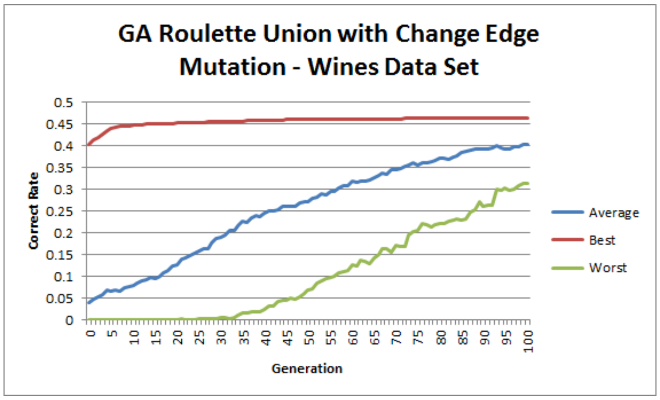


Fig. 8. Results for GA using Wines data set over 100 generations, using exclusively Roulette Union crossover, and introducing the Change Edge Weight mutation. Again, overall, the results were not astounding.

mutation happens infrequently, while crossover happens nearly every time.

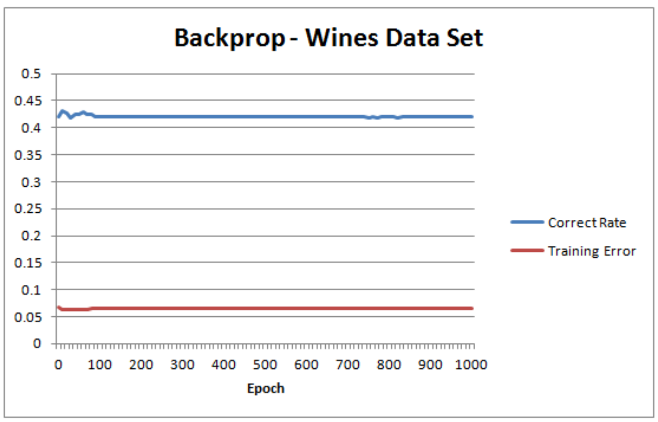


Fig. 9. Results for backpropagation using Wines data set over 1000 epochs. Absolutely no learning has taken place. Backpropagation cannot surmount this data.

*$Run_{NN}$ 2) Vanilla Backprop:* Clearly, Figure 9 shows that no learning took place. All that can be concluded from this is *perhaps* that the inputs for this particular data set do not correlate with the quality of the wine.

## VI. Conclusion

Things could have done better.

The GA was able to exploit the fact that it received more 200 times the random iterations of individuals in generation 0 than the number of backprop runs in total. Leading to a large random search performing better than backprop, which is not surprising. One could even argue that backprop could perform as good or better if given as many randomized individuals as the GA was given.

Allowing the GA to run longer may have been beneficial. The average and worst of the population had not converged in some cases, their continuing improvements could have possibly led to even 'better' results.

End of Transmission.

## References


[1] Lachlan Plant, Graph Theory Consultant

[2] "brainjs" Retrieved April 2013 from http://harthur.github.io/brain/

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