Baskin School of Engineering Capstone Project

Genetic Algorithms for FM Resynthesis of Complex Signals

by Dylan Sutro

Introduction

The digital computing revolution of the 21st century has allowed for the exploration of many new musical avenues. Among these revolutionary technological advancements in the music industry, the digital frequency modulation (FM) synthesizer has allowed musicians to emulate a wide array of instruments from a single device. However, accurately generating complex tones such as the rich harmonic information conveyed by a trumpet player can be difficult to perform by hand. Genetic algorithms (GA) are one method of automatically performing what is called signal re-synthesis by digitally programming a synthesizer to recreate an input sound. Similarly, GAs can be leveraged toward music composition by re-synthesizing a piece of music.

Biological Evolution

Biologically, evolution is change in the heritable characteristics of biological populations over successive generations. These characteristics are the expressions of genes that are passed on from parent to offspring during reproduction. [1] The genotype is the genetic composition of an individual which contains recessive and dominant genes from the parents. Correspondingly, the phenotype is how this genetic information is expressed or observed in the organism. An example of this would be the expression of petal color for a flower where purple is the dominant trait and white is the recessive trait. When a new flower is fertilized, it contains one half of each of the parents genes. These individual genes are called alleles and combine to determine the phenotype of the offspring. This process is visually represented by the Punnett square which shows the possible genotypes for an offspring given the parents' genotypes. In the case of the pedal color trait, capital 'B' represents the dominant purple allele while 'b' is symbolic for the recessive white allele.

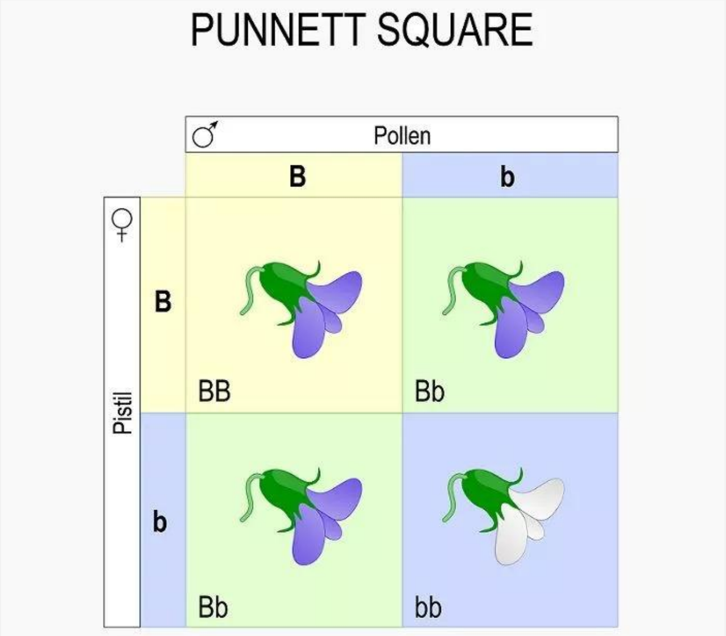

Figure 1: Punnett Square for Pedal Color [2]

This genetic inheritance allows for the process of natural selection to occur in a population in which the fittest individuals are most likely to reproduce and propagate their genes. Over the course of many generations species undergo evolution and adapt to increase their fitness in their environment. Additionally, the possibility of mutations in which offspring contain genes that are not found in either of the parents allow for new adaptations to be selected for. Biologically, the process of evolution requires very large populations and many generations to occur. Luckily, when modeling evolution on a computer we can often represent individuals at a low cost and iterate through many generations very quickly.

Genetic Algorithms

Genetic algorithms have a wide range of applications from solving complex engineering problems, image processing, logistic optimization, and time series analysis to name a few. The core requirements of a genetic algorithm are to:

1. Initialize a population
2. Evaluate fitness
3. Reproduce
4. Repeat until the maximum number of generations or termination conditions are met.

These general steps allow digital information to mimic the process of biological evolution. In order to implement this, an evolutionary model attempts to define genetic and observable characteristics corresponding to the biological genotype and phenotype respectively. This requires some function to determine phenotype given genotype as well as a fitness function to calculate the quality of the expressed phenotype using some criteria or metric. The GA begins by initializing a population of genotypes (typically random values between zero and one). These genotypes are then converted to phenotypes and evaluated by the fitness function. The GA then selects the individuals with the highest fitness and "breeds" them. Reproduction in a GA is performed by crossover, a process in which an offspring is generated using a random half of one parent's genotypes and the corresponding opposite half of the other parent's genotypes. It is also possible in this stage of the GA to implement mutation which randomly alters some of the genotypes of the offspring to produce more variation in the population. This procedure is then repeated until a maximum number of generations is reached or the fitness of the population is acceptable. An overview of the basic structure of a GA is shown below.

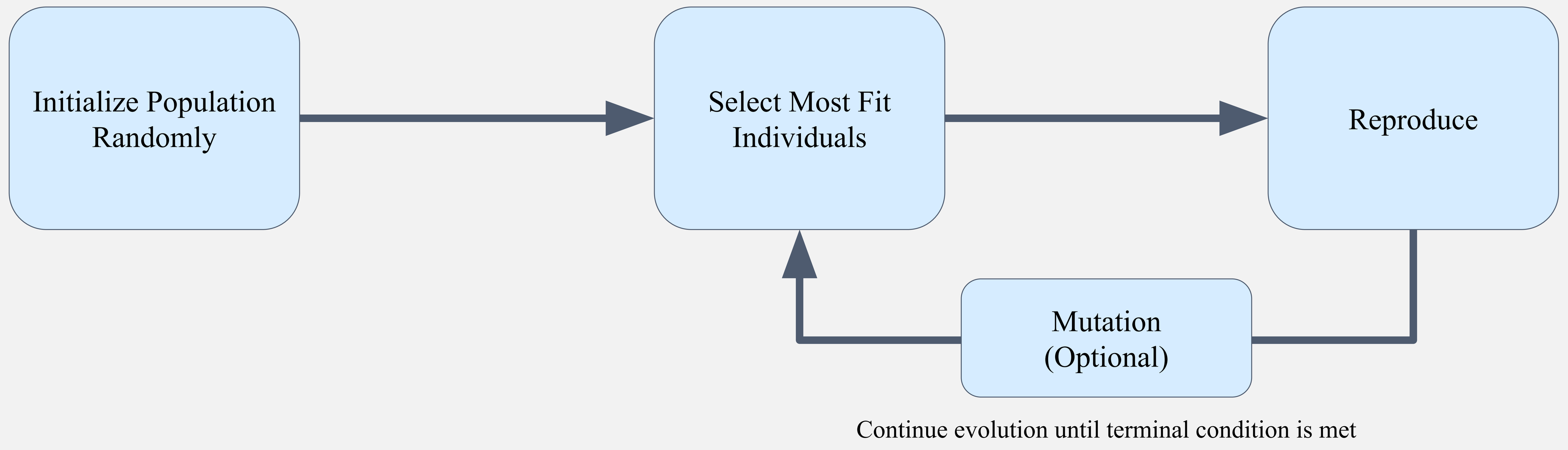

Figure 3: Genetic Algorithm Evolution Overview

Frequency Modulator Synthesis

Frequency modulator (FM) synthesis is the process of signal generation using multiple periodic oscillatory signals to produce a richer, more complex signal. A basic FM Synthesizer requires 6 fundamental parameters that are needed to produce a valid signal: carrier frequency, modulator frequency, index start, index end, attack, and release. The modulator oscillator modulates the frequency of the waveform generated by the carrier oscillator within the audio range, thus producing new harmonics. These harmonics are known as sidebands, and are responsible for the overtones produced by most instruments that give them a richer sound. Where there is a mathematical relationship between the carrier and modulator waveforms, the sound produced is harmonic. Where the modulator is a non-integer multiple of the carrier waveform, inharmonic sidebands are produced, resulting in an inharmonic sound. [3] The other parameters are responsible for controlling the envelope and filter of the signal which is define characteristics such as how long a note takes to reach maximum volume or how long a note lasts before becoming silent.

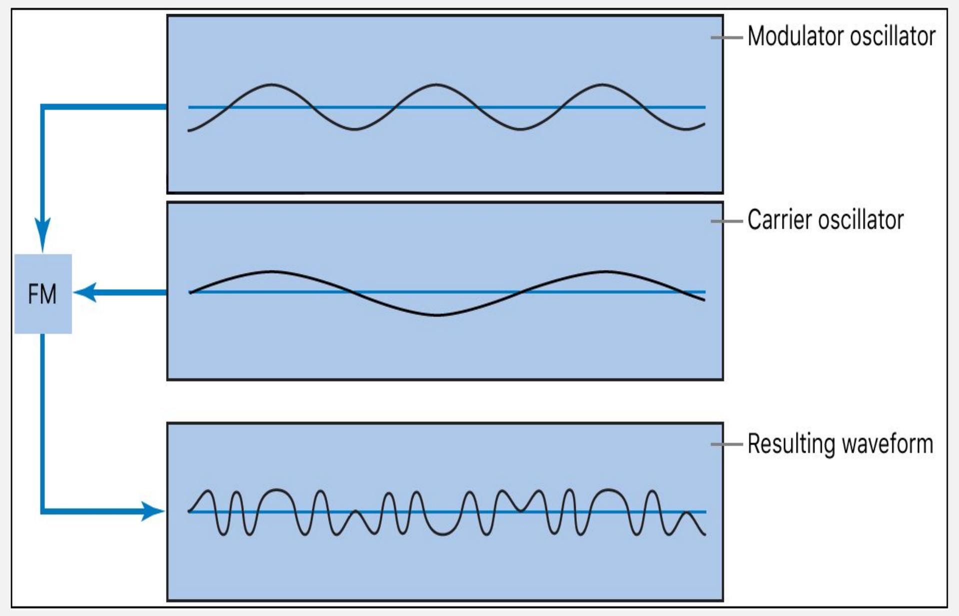

Figure 2: FM Synthesis Overview [3]

FM Resynthesis

With the advent of the FM synthesizer, it suddenly became possible to recreate sounds on the synthesizer that had not been possible with previous synthesizers which used additive and subtractive synthesis to generate analog signals from combinations of simpler waveforms. In the infancy of FM synthesis, sound engineers manually programmed presets to mimic the timbre (sonic characteristics) of various instruments by tweaking the parameters until the desired sound was reached. However, this proved to be very difficult to do manually and time intensive for resynthesizing large varieties of timbres digitally such as creating sound banks for big band arrangement or orchestration which requires many different complex sound presets. Genetic algorithms can be used to automate this process and aim to take a target waveform, such as a single note from a trumpet, and recreate it digitally using FM synthesis. To implement this, we define our genotype as unscaled weights for the various parameters of our FM synthesizer. Our phenotype conversion function then scales and maps these to physical values to be supplied to the FM synthesizer. The fitness function then uses some loss or deviation metric to calculate the difference between the target waveform and the generated waveform. Individuals (collections of parameter weights) most similar to the target waveform (said to have the highest fitness) are then selected to reproduce. In the context of FM resynthesis this involves creating new individuals for the next generation by randomly assigning half of one parent's genotype and the corresponding opposite half of the other parent's genotype to the offspring. We can implement mutation by randomly making small changes to the genotypes of the offspring before repeating the process. We continue to evaluate fitness, reproduce, and mutate until the GA has reached the maximum number of generations defined by the programmer or the fitness function returns above a set threshold indicating that the generated waveform is similar enough to the target waveform. Below, we can see an example of a GA training various target waveforms by plotting the fitness function's loss metric against the progression of generations. As is clear by the figure, each of the generated waveforms became progressively more similar to the target demonstrating the evolution of the resynthesized sounds. We can also see that most waveforms reached roughly their maximum similarity around 30 generations. Genetic algorithms are a powerful tool and in this context provide a very useful alternative to manual FM signal design.

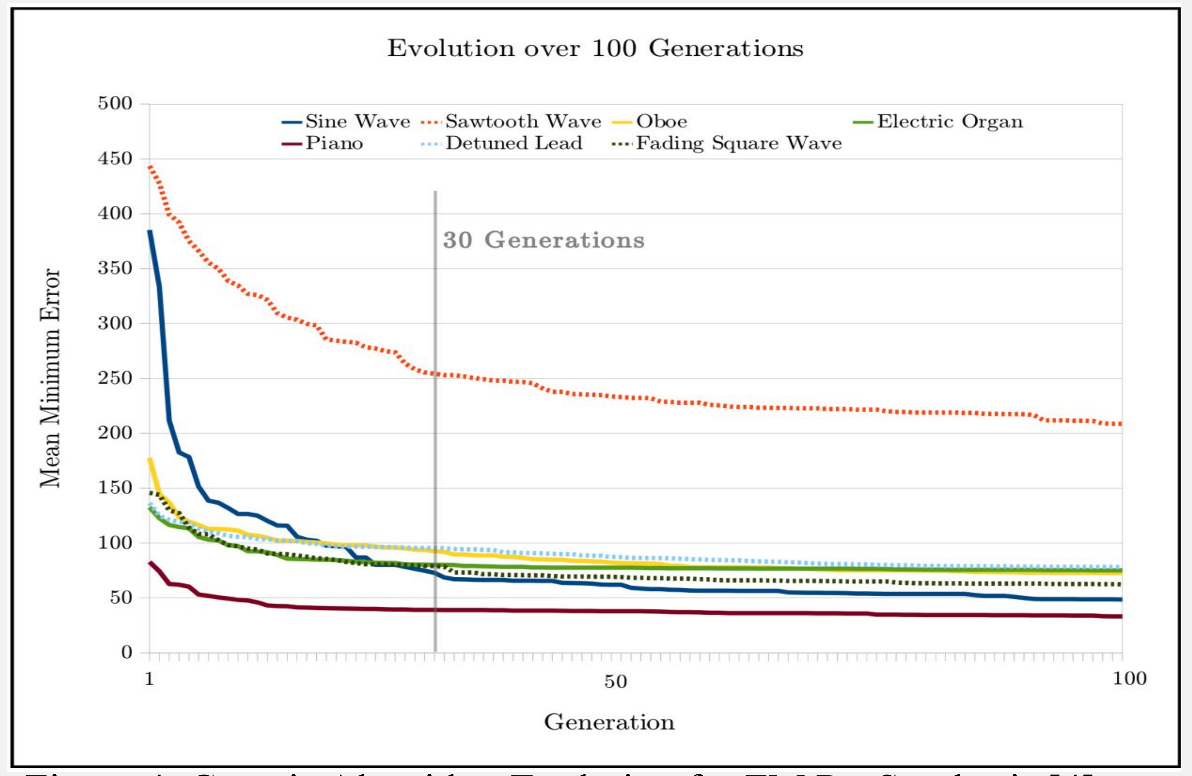

Figure 4: Genetic Algorithm Evolution for FM Re-Synthesis [4]

References

[1]: Biology Dictionary. "[LS3-3] Variation Statistics." https://biologydictionary.net/ngss-high-school-tutorials/ls3-3-variation-statistics/

[2]: Wikipedia, "Evolution." https://en.wikipedia.org/w/index.php?title=Evolution&oldid=1085305450

[3]: Apple Support. "Frequency Modulation (FM) Synthesis." https://support.apple.com/guide/logicpro/frequency-modulation-fm-synthesis-lgsife418213/mac

[4]: Adam Johnson. "Sound Resynthesis with a Genetic Algorithm." https://www.doc.ic.ac.uk/teaching/distinguished-projects/2011/a.johnson.pdf