The Evolution of Audio Synthesis

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Abstract

This paper will encompass the history of audio synthesis, and the evolution of the audio synthesizer. The concept of audio synthesis, in that one may manipulate the very building blocks of sound itself, is one that carries with it enormous potential in the realm of audio analysis, research, and musical creativity. However, like the ability of many other ideas to be fully realized, it too is subject to the technological limitations of any given time. In this paper, we will analyze the technological advancements made over the past 130 years, and see the direct effect they have on the evolution of the synthesizer. It is thanks to the rapid maturation of our current state of technology that audio synthesis has gone from an experimental and inaccessible idea to a staple in the lives of millions around the world today.

1 Introduction

The technological advancements over the past few centuries have provided the possibility of making what was once seen as futuristic and impossible not only possible, but ubiquitous in our daily lives. Our technical abilities as a species are improving at relentlessly increasing rates; this not only gives us the opportunity to form simple and far-fetched ideas into commonplace, staple aspects of our lives, but also the opportunity to render that process in increasingly smaller time frames. The concept of Audio Synthesis is equally subject to this phenomenon; from its inception and first iterations in the late 19th century, its evolution through the 20th century and up until today has allowed it to mature and become a standard and necessary part of the musician's workspace.

As seen with different technologies in many unique fields, the rippling effects of the last two centuries' technological advancements carried swiftly into the world of audio synthesis. These effects include cost and size reduction, as well as increased production and usage amongst its users. This allowed for the audio synthesizer to go from its first iteration in the form of a 200 ton, steam powered behemoth of hardware, to today, where one may download a 4 megabyte software synthesizer instead. To say that the evolution through which audio synthesis has gone has increased its portability would be an understatement.

In this paper, we will cover the evolution of audio synthesis chronologically, organized by the milestones in technology we have observed in the past two centuries and how they manifested themselves in the eventual transformation of the synthesizer. In the first section, we will begin with its inception in the late 19th century, outlining the first proof-of-concept realizations of hardware as permitted by the current state of technology at the time. This state would include motor and steam-powered hardware devices. In the next section, we will describe the first leap in technology, the invention of the transistor, and how it lead to a drastic change in the function and form of the synthesizer in the 1950's. Following this evolutionary leap, section 3 will cover the transition to the digital world, as the synthesizer became increasingly less dependent on dedicated audio hardware. This transition serves as the final jump into what we know today as the modern software synthesizer. Finally, in section 4, we will explore what makes all of these evolutionary milestones significant with regards to their physical manifestations, as well as for the creative world.

2 What is Audio Synthesis?

Audio synthesis is defined as the generation of sound through the creation and combination of signals of different frequencies. It would follow that an audio synthesizer is a device that executes this process.

One of the first iterations of an electronic device that generated sound for the purpose of music actually came from a device accomplishing the same task, but for a different purpose. The tonewheel, invented in the early 20th century by Rudolph Goldschmidt, is an electromechanical device that can generate musical notes. Its initial purpose included translating waves containing Morse code into an audible signal. Until the point of the first synthetic instrument's creation in 1897, there was no recorded use of electronically produced analog waveforms within the context of music. Soon after, inventors started to take note of the musical capability of these tonewheels, and started inventing devices that would capitalize on this feature.

The type of wave generated by hardware methods such as the tonewheel is called an analog waveform. As seen in Figure 1, an analog waveform is an electronic signal that is continuously varied in signal strength or frequency. A keyword in this definition is *continuously*, as continuity in the signal's modulation is a key distinction between analog waveforms, and its counterpart, digital waveforms, whose signal variance is *discretely* modulated. Further explanation regarding extent of this difference will be described in detail further into this paper.

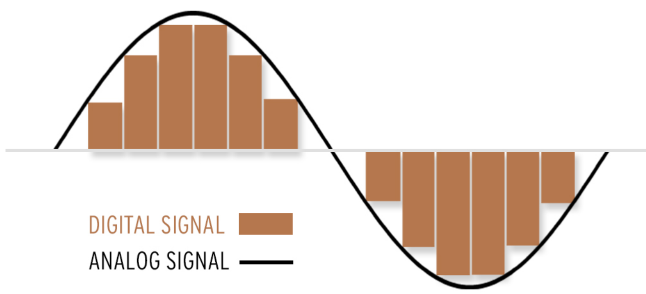

Figure 1: Comparison of graphical representations of a Digital and Analog Waveform

To be more specific with regards to the signal the tonewheel produces, those used in early organs were designed to produce pure sin waves. Doing so would provide functionality to these early instruments such that the fundamental frequencies produced by several of these tonewheels allow for the creation of more complex sounds through their combination. Adding several waveforms together in a manner similar to this falls under the category of additive synthesis. This intentional manipulation of sound with respect to their placement in the frequency spectrum laid the groundwork for the increasingly complex and unique types of audio synthesis to come in the next 130 years.

3 Hardware Roots

The state of technology in the late 1800's and early 1900's consisted of motor and steam-powered devices. Given that this was the most advanced form of mechanical automation around, it should come as no surprise that early inventors looking to create a musical tone-generating machine looked to use this type of mechanics to fulfill this goal.

3.1 The Dynamophone

One of the first of the inventors to repurpose the tonewheels for musical purposes was Thaddeus Cahill. His invention of the Telharmonium (or Dynamophone) became one of the first electric organs. Much like previous organs and pianos of the time, this synthesizer which was controlled by velocity-sensitive keys. Weighing in at a staggering 200 tons in its first three versions, this steam-powered organ was one of the earliest incarnations of synthesizers using additive synthesis, creating a certain distinct timbre through the addition of multiple sine waves.

3.2 The Trautonium

Another important iteration of the hardware synthesizer was the Trautonium, invented in 1929. This synthesizer carried with it special characteristics with respect to the tones it created - primarily, one of its unique features was its ability to create variable pitches - that is, the tones generated by the Trautonium were not subject to the standard chromatic scale as seen on the typical keyboard layout. Instead, one could generate any fractal tone in between the orthodox chromatic scale, resulting in quite unorthodox soundscapes. This produced much dissonance, leaving many with a less than favorable impression of its sound, as it contrasted heavily with established norms in music, including that of assonant chordal structures generally heard in classical music.

However, that is not to say that its unique sound did not have a place in the hearts and ears of some, nor in the world's culture surrounding it. In fact, one notable case of its use comes from world-renowned filmmaker Alfred Hitchcock. Known for his success with horror film production, he found that the Trautonium's dissonant, eerie, and discomforting sound complimented his vision perfectly. He went on to score much of the soundtrack and sound effects heard in his film *The Birds* with this fascinating instrument.

As with many manifestations of the current day's technologies, though novel in concept, accessibility of audio synthesis was severely limited for many reasons. The idea of audio synthesis was so uniquely new that being an early adopter necessitated not only access to an obscene amount of disposable income, but also the tools, expertise, and desire to create a synthesizer oneself! As an experimental medium of art, becoming an owner of a synthesizer the first half-century of the audio synthesizer's existence was limited to the aforementioned restraints. For one, the Telharmonium was worth something to the tune of $200,000. Additionally, due to the commanding and inconvenient size of early synthesizers, transportation of units proved virtually impossible. Commercial distribution of synthesizers was hardly an afterthought as well, considering the cost and lack of suitable manufacturing methods. The Telharmonium was one of the first to break the barrier into commercial distribution, though one may consider it more so as a metaphorical dipping of their toes in the water, as the extent of the Telharmonium's commercial distribution was limited to about 200 units.

4 The Introduction of Electricity

Though audio synthesis in its current form back in the mid 20th century faced much technological adversity, it persisted in its existence and the interest of inventors and curious musicians alike. Those waiting out for the world's next technological leap would benefit greatly come 1949, when the first transistor was invented. The transistor allowed for synthesizer technology to transition away from its dependence on tube circuitry, and served as the gateway to more affordable and portable synthesizers, and thus the commercial world.

As previously mentioned, the extreme complexity of the design of a synthesizer served to inhibit its success in the commercial world - it was simply too much to ask the average layman to configure the myriad of cables and connections, let alone take on the task and burden of an audio engineer debugging and routing the sound correctly.

An inventor and innovator by the name of Robert Moog then came along in the 1960's and expanded on the synthesizer technologies of the day. Known as the father of the synthesizer, he invented the first voltage-controlled synthesizer, driving the hardware dependency of synthesizers away from motor power and towards electric power. He saw commercial potential in his experimentation with creating interconnected modules that would produce electronically-generated waveforms, but became well-aware of the aforementioned complexity that would serve as a large hurdle in bringing the synthesizer into the life of the day-to-day musician.

Moog came up with a solution by 1970 to tackle the problem of complexity for the average layman. Approaching the problem as a user, he decided that instead of giving complete manipulative access to the set of all ports and connections to this already complicated device, he would only provide access to the relevant controls necessary to control the synthesizer as a musician. He came to the conclusion that a user would not want to, and should not have to deal with the burden of debugging and routing - rather, that user should be focused instead on what matters - the seamless experimental modulation and modification of sound from the get-go. Leaving only the bare essential parameters to be adjusted by the musician necessitated that all of the previously changeable connections between the hardware modules could no longer be exposed - therefore, these connections were instead hard-wired 'in the background', so to speak, in the sense that the only parameters available to a user would be the relevant knobs as well as the keyboard itself.

Figure 2: The Minimoog Model D Synthesizer

After several versions of Moog's first synthesizers, his 1970 model, the Minimoog Model D (as seen in Figure 2), catapulted to success. Though his commercial production steadily increased with previous versions, the Minimoog quickly established itself as the frontrunner in modular synthesis, selling over 13,000 units over a decade following its release in 1970. With this milestone release, the analog synthesizer not only found a place within the studios of countless more musicians, but also in the realm of music creation in general.

5 Intrinsic Setbacks of Monophony

The ever-increasing popularity of analog synthesis did not cease to continue, thanks to the technology and intuitive user-oriented changes made by Moog and others in the 1980's. The trend of technological advancements drastically influencing the world of audio synthesis persisted still, though with additional reason and necessity. Despite the widespread use of hardware synthesis, there remained one crucial hurdle to jump - that of the gap between the then-existing monophony and the desired polyphony. Monophony means single voice, while polyphony means multiple voices. In the context of music, these terms would refer to a synthesizer's ability to generate either one tone at a time, or multiple. At the point of the Model D's peak in 1981, the polyphonic ability of most synthesizers then was limited to that of monophony. As most traditional instruments are intrinsically polyphonic, (especially that which the synthesizer takes its input from, it made sense that coming to this new, unusual, monophonic instrument would leave a musician an inherently incomplete performance device. It was generally thought that the ability to synthesize should not be a tradeoff.

However, creating a polyphonic synthesizer was not a simple as the concept suggests, relative to its monophonic counterpart. Solutions to this problem fall under two subcategories - semi-polyphony and full polyphony. Semi-polyphonic solutions consisted of a certain number of independent, monophonic synthesizers whose waveform generation would be dynamically triggered by input from the keyboard. For example, a synthesizer with five synthesizers hardwired together would provide 5-voice polyphony - in other words, the user would be able to play chords of up to five notes at a time. Fully polyphonic solutions had no dynamic assignment to the keys being played at any given moment unlike its semi-polyphonic counterpart, as there was no need - a fully polyphonic synthesizer would have an individual monophonic synthesizer dedicated to every single key on the keyboard. That would mean that a fully-polyphonic synthesizer with 72 keys would have to have 72 individual monophonic synthesizers!

Both of these types of hardware-oriented polyphony yield unique problems both in regards to polyphony in general, as well as specific to their dynamism. In general, needing more than one voice would mean needing more than monophonic synthesizer - seeing as how the standard for synthesizers at the time was to be monophonic, as limited by the technological state of the 1980's, buying multiple synthesizers for the sole purpose of polyphony was unreasonably inaccessible. Though the Minimoog Model D and others gained massive popularity thanks to their ease of use and portability, they were still financially out of reach for many. Despite the improvements in manufacturing, Minimoogs still sold for thousands of dollars apiece. Therefore, technological cutbacks had to be made in order to provide polyphony to the people. With full polyphony, having such a high number of monophonic synthesizers necessitated a drastic cutback in their functionality, resulting in extremely basic waveforms with low customizability. In the case of semi-polyphony, they faced similar setbacks, although with a significantly lower amount of background monophonic synthesizers, they were allowed some room for more complex sound generation. Though both solutions yielded their benefits and detriments, the tradeoff persisted. It was through the transition towards complete digital synthesis that this weight would finally be lifted off the musician's shoulders.

6 Digital synthesis

The move towards the digital world in the realm of audio synthesis was fueled by this desire for polyphonic performance and recording. This transition away from a dependence on monophonic synthesis would become the next disruptive jump in the development of audio synthesis and eventually bring us to its current state.

This transition to complete software synthesis introduced another setback, in that availability of the synthesizer's services would again be limited to those with personal computers. Though, as with previous hurdles we have observed, it would be only a matter of time before the eventual ubiquity of personal computers in daily life would provide ample opportunity for synthesis to achieve the same status, at least within the personal computers of the home musician.

The move towards the digitization of audio synthesis would relieve the synthesist from the previously established setbacks of monophonic synthesis, as permitted by the ever increasing power of computers. In progressing to using the computer as a host, a lot of flexibility in customization and modulation is provided to the audio synthesis process. The potential of this flexibility was first seen in early computer music compositional programs, such as The Music I, written in 1957 [3]. It took the power of an entire university mainframe, which was powered by an IBM 704 [1]. Seeing as how the IBM 704 could have cost close to a million dollars, and too took up the size of a room (much like the original Dynamophone synthesizer, as mentioned in section 3), the move to the digital world seemed to be backwards momentarily, both spatially and financially. Another example of an early music program were the Music V and BLODI from Bell Laboratories, which took full advantage of the fact that digital signal processing algorithms are much more easily implemented in software rather than hardware.

However, with the elimination of one tradeoff comes another, as introduced by taking advantage of this new host. General purpose computers had not yet began to make their way into the lives of laymen, due to its own problems making its way into the commercial world. It was not without its power and potential, though - it was clear to many computer scientists that its emulative power in music had yet been exploited to its greatest ability. The tradeoff that would come with this territory would be that of speed and computering power, or lack thereof. Despite the downsides of hardware synthesis as it existed in the latter half of the 20th century, it had an ability that may have been overlooked - the fact that it could be played in real time. The aforementioned Music I, despite being powered by one of the most powerful computing systems of the time, could only muster out a simple triangle wave. No computer would begin to approach real-time audio synthesis for years to come after it was first implemented.

Though this performance lag would prove to make real-time performance impossible, the benefits of digital audio synthesis outweighed this detriment. Manipulating the synthesis process through the computer had many benefits - for one, having a graphical user interface with which to edit and further refine the synthesis at hand in and of itself garnered much attention, as it created many new opportunities for features such as cut-and-paste editing, variable polyphony (the ability to choose how many voices one would like to have synthesized), and more. Additionally, unlike the hurdle facing hardware synthesis, the problem of performance handicaps would be fixed by Moore's law, in that the processing power of the day would eventually catch up to the workload that audio synthesis begs.

By the mid 1970's, Moore's law allowed the necessary technical specifications of computers to catch up to the levels synthesizers asked for. The Fairlight CMI, released commercially in 1976, was one of the first digital synthesizers with performance capability. It used its computing ability to hammer out synthesized sounds using sample synthesis, which is the type of synthesis that takes a small sample of a waveform and loops it, applying the requested modulations and modifications as necessary. Three years later, the competing Synclavier would be released in 1979, the first to feature completely digital audio synthesis.

6.1 A Decreased Reliance on Dedicated Audio Hardware

As the world of audio synthesis makes its way towards its digital implementation, we observe a decreasing reliance on audio hardware. Instead of tube circuitry as seen in the very first synthesizers, we see much smaller components, such as the dedicated audio processor. The previously mentioned Synclavier was one of the first to use these processors and the first to *completely* synthesize its sounds digitally. What this entails is that the waveform generated is no longer a pure analog waveform, as described in section 2, but a digital waveform, whose representation can be seen in Figure 1. The digital waveform is meant to emulate its analog counterpart as close as possible. It does so by *discrete* production of signal variance, as introduced in section 2. This is intrinsic to the way a computer works, as it must output one value at a time. With a high enough sample rate, digital waveform generation can be done to the point where the difference between it and an analog waveform virtually indistinguishable.

6.2 Computing Power

Up until this point, the physical nature of synthesizing analog waveforms limited us to one type of synthesis. That type, additive synthesis, is the formation of complex sounds through the addition of different sound waves. Digital synthesis with the aide of a host computer allows the user to program much more complex algorithms that may be applied to a sound wave, resulting in more creative types of synthesis. These new types would begin to appear starting in the 1970's and branch off into their own subcategories, each of which produces varied timbres. The duo of a Emulator II polyphonic digital sampling keyboard and a Macintosh personal computer served as one of the first instances of digital synthesis, and some of the first types of novel synthesis to appear on this system would become staple branches of synthesis used by millions of people today [10]. These would include Frequency Modulation (FM) Synthesis [2], which modulates the frequency of a wave with the intent of changing its timbre, and Non-Linear Waveshaping, which would allow the user to create custom waveforms by hand, resulting in forcibly unique sound. This ability in and of itself serves as a proper metaphor for the creative doors audio synthesis allows for its eventual users, allowing full manipulative control over the very basic foundation of sound.

6.3 DSP

The newly adopted focus of dedicated audio processors was taken one step further, in that a smaller-scale transition was made from processors specifically created processors to general-purpose processors. These types of processors would be called, Digital Signal Processors, or DSP's. Shifting away from specially made first party audio processors, these DSP's were created by a third party manufacturer and repurposed for their audio-related tasks. The current day's unprecedented computing power paired with what the synthesizer's evolution has allowed us to learn about the very foundation of sound has unlocked a myriad of new types of synthesis with which to experiment.

Finally, as we continue to see our dependence on hardware wean even further, it was only a matter of time until we saw the dedicated processor's demise in the manifestation of a newer implementation of digital synthesis. That solution was to run the synthesizer as an application on the host computer, delegating all of the computational burden onto the host computer's CPU. This completely eliminated any need to specific, dedicated hardware, and leads us to audio synthesis in its current and most prominent form. In addition to the previously mentioned newer types of synthesis, others to come into existence thanks to a better understanding of sound, and the properties of timbre, include granular synthesis, which is synthesizing with the use of extremely small sample slices (the possibility of which is due to high CPU power), and physical modelling synthesis, the act of emulating a real instrument by recreating its fundamental frequency and partials (thanks to our understanding of harmonic partials and how they relate to different timbres of real instruments) [3].

7 Conclusions and Significance

It is hard to describe or quantify exactly the impact or the significance of the changes through which audio synthesis has gone, from what it means for the world of music and creativity, to what it means for the world of computer science in general. As a symbol of humanity's technological advancements, it serves as a fitting example for what the last 150 years of technology can provide for a tool, and in turn to the people using this tool.

One interesting debate that has been elicited from paradigm of audio synthesis is the argument of analog synthesis versus digital synthesis. The former, as the original form of synthesis in its roots, holds a fond place in the hearts of many, for the argument that the tones produced are 'pure', 'unadulterated', and some some sense of the word, natural. The nature of digital synthesis by comparison is thought by the same group to be too artificial and perfect, being mathematically produced. The 'warmth' brought by classic synthesizers, along with all of its imperfections as induced by the mechanical nature of the device, is allegedly impossible to truly replicate. One interesting note to consider is that in some of today's software synthesizers, aimed at replicating its hardware counterparts, have built in algorithms specifically written to reproduce these imperfections. As we saw how long it took before something as unorthodox as audio synthesis was accepted by the mainstream music society, so too is this symbolic of a group being hesitant of change.

Though a subjective matter at the end of the day, one may argue that the most substantial and intangible effects of audio synthesis and its evolution over the years is what its ubiquity has done for the collective creativity of mankind, in outlook and recreation. From being limited to the hands and minds of inventors and the wealthy, to becoming available to virtually anyone at all, it has allowed for us to have a deeper understanding of the fundamental building blocks of sound, and given us the power to manipulate sound itself [7]. We are thus provided the experience the opportunity of scientific and musical exploration, and are free from the limiting timbres of more traditional musical instruments. The life of the audio synthesizer is in its peak, demonstrating the wonders that can be provided to the art world through technological and scientific achievement.

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