The Transition from Analog to Digital Sound Production

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Throughout the middle of 20th century, computers were undergoing an enormous transition. Technology was slowly moving from a well-established analog method towards a digital approach. Actual commercialization of these digital types of computers did not occur until the late 1950s. The initial focus of these systems did not incorporate sound or music. However, the military and others associated with sound production saw a way to integrate computers into their fields allowing them to work with more robust options for recording, generating, and transmitting sound and music. Computers aided in establishing a new level of precision to the production process and also allowed for very accurate reproduction of individual sounds and music. Military applications were used to secure voice communications through a speech scrambling device. The scrambling device had large speed and security advantages over traditional enciphered code transmission. Early digital music pioneers were developing programs that essentially turned a computer into a musical instrument. In doing this, they could compose simple melodies or even full symphonic pieces. The software allowed for quicker production times and ease of use.

Finally, the development of digital recording technology changed the format of recorded sound. The ability to easily manipulate the digital audio signal significantly increased the efficiency of audio recording and was able to extend the technology beyond simply music. During the transition from analog to digital sound production, three specific technologies proved to be particularly significant. The SIGSALY speech scrambler secured top secret communications during World War II and pioneered many general techniques in digital sound manipulation. The MUSIC I software allowed for digital composition of music and sounds through one computer system. NHK’s PCM recording device established a new way to utilize
pulse code modulation technology for recording purposes.

**SIGSALY Speech Scrambler**

The 1940s was a decade of firsts for the computer industry. The Second World War stimulated military-oriented computer research. An important initiative was to develop advanced encrypted digital communications which became the forefront of research for the military in the United States and abroad. The first military application of digital sound was the SIGSALY voice scrambling system developed by the Allies and deployed in 1943.

In 1942 the need for a secure voice encryption system was paramount to communication between the mainland United States and allies such as the United Kingdom. Prior to the development of SIGSALY there was a system in place to scramble voice communication to some degree. The previous system named “A-3” was developed by AT&T.\(^1\) While this system was useful enough to thwart directly listening to conversations; it was not secure enough to stop decryption by the Germans.\(^2\)

The development of a new voice encryption scheme faced many technical challenges. Many of the inventions necessary to create such a device had been in the works, but the potential for such research was not realized until the early 1940s, when the need for a system became apparent. The most convincing evidence for the need of such a system came on December 7, 1941 when General George Marshall was unable to warn Pearl Harbor of an imminent Japanese


\(^2\) J.V. Boone, 1.
attack in a timely matter.\textsuperscript{3} The technology of the era could not communicate the necessary information securely and with the essential speed. Had a technology like SIGSALY been in place, the losses at Pearl Harbor could have been minimized.

One key technological process used for voice transmission in the SIGSALY device was known as “pulse code modulation.” Pulse code modulation (PCM) was a technique to turn an analog waveform into a digital representation.\textsuperscript{4} While a waveform passed through a PCM convertor, it was sampled at a fixed interval. The waveform could then be stored or transmitted as discrete values. When received or played back at an end-device, these discrete values could be reconstructed into voltages representative of the original waveform.\textsuperscript{5} Developed in 1937 by Alec Reeves, PCM has remained the foundation for many techniques in digital recording and communication.\textsuperscript{6}

The second development that made SIGSALY possible was inspired by work at the Bell Telephone Laboratories. In 1936, Homer Dudley began work on a project that would be known as the (voice encoder) VOCODER.\textsuperscript{7} The device allowed human speech to be broken into various frequency spectrums, divided, and transmitted. VOCODER provided many conversations to be simultaneously held on the same telephone line.\textsuperscript{8} Many of the ideas from


\textsuperscript{5} Pohlmann, 51.

\textsuperscript{6} Pohlmann, 51.

\textsuperscript{7} H.W. Dudley. 1936. Vocoder project. Patent US #2,121,142.

VOCODER and Dudley’s later work, the Voice Operating Demonstrator (VODER), were directly incorporated into the SIGSALY project. When the Army began looking for a solution to the shortcomings of its obsolete A-3 voice scrambling system, Bell Labs provided a demonstration of the new VOCODER technology. The Army awarded Bell Labs the contract to build the innovative SIGSALY communications system in 1942.

Many successes arose from the development of the SIGSALY system. The most prominent is probably the manipulation of digital voice. Previously, all audio transmission were done with strictly analog waveforms; the signal going into the microphone was the same signal coming out of the speaker, with no interaction in between those two points. Not only did SIGSALY convert speech into a PCM signal, the device enciphered it on the fly and allowed it to be deciphered in real time on the other end. Not only was this a great step forward in communication technology, it was also a monumental step forward in security technology.

The most widely used secure communication tools during the 1940s were coded radiotelegraph. The radiotelegraph process was slow and not as robust a secure telephone system could be. The coded telegraph, known as the “Vernam telegraph” method, had been used since World War I. The Vernam method used a single-use random binary key added to a standard telegraph. The value of the binary key was added to the signal and then subtracted at

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9 J.V. Boone, 1.
10 J.V. Boone, 1.
12 Bennett, 98.
the other end to reconstruct the original. This code was unbreakable due to the random nature of the keys used.\textsuperscript{13}

Ideas from the Vernam telegraph were applied to the SIGSALY device. However, the SIGSALY device used the encryption methods on the PCM signals generated by a user’s voice. To accomplish this, SIGSALY had to bring a whole new level of sophistication to the enciphering methods of the time. The keys used to encode the transmissions were generated with completely random data gleaned from mercury-vapor rectifier vacuum tubes.\textsuperscript{14} These tubes would generate noise that was sampled on to vinyl phonographs to be distributed, used once and then destroyed.\textsuperscript{15} These discs were used to encode the PCM signals at the transmitting side and reconstruct the signal on the receiving side. By using noise generated encryption keys, SIGSALY was completely secure as long as the vinyl encryption disks were secure.\textsuperscript{16} This is in stark contrast to the “secure” A-3 system. The A-3 system had a less sophisticated voice scrambling system without a randomly generated key. Transmissions from an A-3 system could be decrypted in real time by German code breakers.\textsuperscript{17}

SIGSALY was first used on July 15\textsuperscript{th}, 1943 to conference London and the Pentagon. Later the system was deployed to Algiers; Australia; Hawaii; Oakland, California; Paris; Guam; and eventually Berlin. One terminal was even installed on a ship to allow conferences with General MacArthur during his Pacific campaign.\textsuperscript{18} Each SIGSALY terminal weighed at least 50

\textsuperscript{13} Bennett, 98.
\textsuperscript{14} J.V. Boone, 2.
\textsuperscript{15} J.V. Boone, 2.
\textsuperscript{16} J.V. Boone, 2.
\textsuperscript{17} J.V. Boone, 1.
\textsuperscript{18} Weadon, 2.
tons and included 40 racks of equipment. Each terminal included two sophisticated turntables that would allow the “noise” records to be swapped out without interrupting a secure call (each record only held about 15 minutes of noise).

An entire military company was assigned to operate the complex SIGSALY equipment. The Army Signal Corps created the 805th Signal Service Company to accommodate this need. The members of the 805th Company were trained by Bell Labs. The company included 356 military personnel that were tasked with keeping the secure communication channels open at all hours. Maintenance consumed the majority of the company’s time. Vacuum tubes, power supplies and stepping circuitry were in need of constant inspection and adjustment. These duties were vital to the operation of these machines, fortunately little downtime occurred.

The SIGSALY communication system was a far reaching success for both the military and the communications industry. Over the course of SIGSALY’s lifetime it provided the means for over 3,000 top secret conversations. The total benefit to the military may never be fully realized, however many instances of potentially lifesaving conversations have been documented. In particular a conversation from the research of R. Price speaks to the value of such a system,

“Before the invasion of Normandy, the volume of replacement tank antennas available was based on the needs of homeland training exercises. When Normandy’s unique terrain caused many more antenna failures, reserve supplies of antennas ran out. During this emergency SIGSALY allowed General Rumbough to make a direct secret link with

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19 J.V. Boone, 2.
20 J.V. Boone, 5.
21 Weadon, Sigsaly Story, 2.
General Ingles in the states, and an air delivery of the necessary antennas was almost immediately underway.”

Without an encrypted voice communication, emergency situations like the Rumbough-Ingles example would have been handled in a much less efficient manner. The demand for a robust communication system only grew as successes like this became more apparent.

It is clear from the research that SIGSALY stretched the limits of the technological capabilities of the early 1940s. The SIGSALY system was the first to develop many communication and digital computer technologies. Many of the innovations that were produced for SIGSALY were almost immediately applied to the commercial and industrial world. In many ways SIGSALY wasn’t just part of the transition for analog to digital sound production; it was a transition in many areas digital computing and communication. SIGSALY combined all of the new processes devised in the 1930s with new digital hardware of the 1940s and proved the application was possible and useful.

Digital Music Generation

It is general scientific fact that electrical signals travel much faster through wires than sound waves travel through air. This idea is the basis behind all telecommunications, but was especially important in the transformation from analog to digital audio production. An electrical engineer by the name of Max Mathews developed an extraordinary way to digitally record sound

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using a computer. Mathews knew through his experience working at Bell Labs that technology had advanced to the point where digitally speech could be sent in the form of electric signals through wires. With this technology in mind he figured that the same could be done with music. The new technology was called music synthesis. Through Mathew’s program MUSIC, the computer would become a musical instrument of its own.

In 1957 the first version of MUSIC was released. This work revolutionized the way the sound, namely music, was generated. Even today a direct descendant of the MUSIC family, Csound, is the most widely used audio programming software. Using his electrical engineering background, Mathews began to explore sound synthesis in the form of computing. Basic mathematical principles of waveform calculation were used to create the very primitive MUSIC I software. The program was written and developed on an IBM 704 and only allowed for the formation of one lone triangle-wave function. This limited the types of sound that could be generated via the MUSIC I system. However, the later versions of MUSIC became increasingly advanced with each release.

When the first version of MUSIC I was released in 1957, users were quite surprised that sounds could be generated and recorded to produce musical tones all via one computer. Before this program was written, the only source of music production was through the recording of

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24 Moore, 27.
27 Manning, 187.
28 Manning, 187.
analog instruments. The program was actually quite complex. The idea of creating sounds from thousands of numbers was astonishing at the time. Mathews developed the idea that each number in a large sequence of computer generated numbers could be represented as a sample of a basic sound pressure wave. The computer would start generating music by converting numbers into digital, electronic pulses. The amplitude of each pulse directly corresponded to the number. This wave of electric pulses was then converted into an actual sound wave through the use of a standard, external speaker. The speed at which these numbers were put through this process would affect the sound wave frequencies. With the help of storage systems such as magnetic tape, thousands of numbers could be converted from analog to digital which allowed for musical sounds to be played.

Controlling such large sequences of numbers at varying frequencies was seemingly incomprehensible in 1957. The MUSIC I program created a complete set of steps that would narrow down such complex sequences into a simple set of parameters. For example, one parameter was labeled “instrument type.” This type was merely a number that corresponded to a specific frequency saved on the computer’s memory. Each respective frequency would emit a different sound. Typically, a conventional music score would consist of a five bar chart with many different notes denoting the pitch of an instrument’s sound. The MUSIC I software’s musical score resembled something that looks more like a modern day statistics spreadsheet. The data consisted of parameter headings followed by long strings of numerical data. Typical

30 Mathews, 555.
31 Mathews, 554.
32 Mathews, 556.
33 Mathews, 554.
parameters included duration in seconds (of each individual sound), loudness, frequency, and periodic vibration. 

All of these numbers had a different effect on the final output.

An interesting compromise grew out of the release of this program. Musical composers found the software quite easy to use and the time it took to create music was seemingly far less than traditional, manual methods. Although the procedure was quite simple, the limiting factors of obtainable sounds proved to be too great. Later versions of MUSIC, namely MUSIC III, instituted a solution for this problem.

MUSIC III was split into two sections. The first section allowed the composer to set specific characteristics of different groups of musical instruments to a corresponding program unit. This took all the parameters listed above and situated them into one labeled instrument type. The composer would then create the notes using strings of numbers that were later converted into electrical impulses. This revised process allowed for a more complex and realistic sound. In order to actually play the music, the program would prompt the computer to read an individual line from the digital score. As each instrument unit was activated, it would generate strings of numbers that directly matched the notes. From there, MUSIC patched together each sequence and provided a clean, finalized product.

This form of digital sound recording was different from other methods referred to because it involved the actual generation of sounds on a computer. During this transition phase, no one else was attempting to actually compose music via a computer. One of Mathews’

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34 Mathews, 554.
35 Mathews, 554.
36 Mathews, 555.
primary motivations for wanting to develop MUSIC involved reproducibility. The precision that a computer provided proved to be an astounding advantage over traditional methods of music production. The sounds could be reproduced quickly and effectively.

In later versions of MUSIC, more complex effects could be added to sounds to provide more robust music. Using the instrument-unit method developed by Mathews’ 1960 release of MUSIC III, virtually every possible sound could be replicated and produced. In an interview with Computer Music Journal in the winter of 1980, Mathews stated that he “wanted to give the musician a great deal of power and generality in making the musical sounds, but at the same time [he] wanted the complexity of the program to vary with the complexity of the musician’s desires.” The program was very easy to use, but Mathews always found areas for improvement. Mathews goes on to say that he did not want to incorporate predefined instruments into MUSIC I so that he would no influence the work of others. Instead, the initial tools were provided to allow musicians to explore different frequencies and effects. In turn, musicians became much more experimental in their composition.

However, the initial reaction to MUSIC was poor. The transition from analog to digital music production was difficult, but the composition element of digital music production was particularly challenging for many people to understand. Many people were skeptical of MUSIC I’s ability to compose aesthetically pleasing sounds. Others were in a state of absolute confusion. Since the traditional method of music production was so well established, many

38 Mathews, 556.
39 Roads, 21.
40 Roads and Mathews, 18.
groups felt the program was unnecessary and that it was taking music production in the wrong
direction.

Some users, mainly composers, were incredibly interested in the potential that MUSIC I
had and were willing to take the time to learn how to use it. Mathews thought that composers
would also enjoy using the program because many times, their work is not played by an
orchestra until years later. The MUSIC I software would potentially allow them to compose a
piece and then get immediate feedback through a loud speaker. Mathews figured that it would
eventually catch on with the general public. The idea that real instruments were so incredibly
hard to play for many people gave him hope that those individuals would sit down on a computer
and play music that way.

The MUSIC program revolutionized the way that music was created. By allowing for
faster production times and the ability to replicate specific pieces of work, composers and
hobbyists were able to increase efficiency. Mathew’s first release of MUSIC laid down the
framework for many similar products in the future. At first, the public was not incredibly
enthusiastic, but soon realized its potential. After the introduction of unit generator in MUSIC
III, composers were able to write music and hear it played back soon after it was composed. The
typical user was able to add effects to their compositions. The MUSIC software truly
expedited the transition from analog to digital music production.

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41 Roads and Mathews, 18.
43 Park, 10.
NHK Pulse Code Modulation

The idea of digital audio had been around and in use many years before it was actually recorded in its digital format. Pulse code modulation (PCM) in its early uses, which were primarily for telecommunications, was easily implemented into different forms of technology because the transmission of a digital signal was already possible to encode over wires like those of a telegraph or telephone. The problem preventing the recording of digital audio was an adequate medium that could handle the rate at which the data would be written on to it as well as support the large capacity for the information. Potential solutions included computer hard-disk systems and tape, which was already being used for analog recordings. The hard disk had the necessary data rate but lacked the necessary capacity. Tape had the opposite problem; its essentially unlimited length provided the necessary capacity but in order to achieve the necessary data rate it would have to be spun at an impractically high speed. Tape was not completely out of the question, however. One of the most useful features of the digital signal was its ability to be easily manipulated to fit other formats such as those in a video tape recorder (VTR). The system used to record video tape provided both the necessary data rate as well as large capacity. Due to this capability, many of the early digital audio recording devices utilized VTR technology by converting the digital audio signal into one that was VTR compatible and then using the exiting VTR technology to write the information. In 1967, the first public display of one of these devices was by the NHK Technical Research Institute in Tokyo, Japan.

The device presented by NHK in 1967 was described as 12-bit companded with a 30 kHz

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44 Pohlmann, 51.
sampling rate, meaning that every 30,000th of a second the sample audio would be evaluated, compressed, and stored with 12-bit resolution. The compression through companding was used to reduce the data rate. The resulting file would be written to videotape. The tape used for the NHK device was 1-inch two-head helical scan VTR. The helical scan describes how the recorder writes the data onto the tape. In this system, the tape moves horizontally across a drum – or head. The head is also spinning, but at a slightly tilted axis. This tilt makes the head write its information on to the tape in a diagonal pattern. If visible, the lines of data on the tape would resemble diagonal lines in a parking lot. The diagonal pattern allows the recorder to maximize the space on the tape for recording and therefore drastically decrease the required amount of tape to record a given amount of audio. By 1969, NHK had upgraded the device to 2-channel stereo, 32 kHz sampling rate, and 13 bit resolution.48

Despite the apparent success of the NHK system, further development was not made by NHK itself due to a belief within the company that it would be impractical. The Japanese recording company Nippon Columbia, better known by its subsidiary brand, Denon, however, did see a practical use. Engineers from Denon collaborated with those from NHK and in the years between 1969 and 1971, used one of NHK’s stereo PCM recorders in order to run a series of test recordings. As a result of these tests, two of the first albums to be made using PCM technology were released in 1971. Happy with these results, the engineers at Denon believed that the improvements made with PCM digital technology surpassed the quality of analog tape. The experience gained over the previous three years work with NHK made Denon familiar with

48 Fine, 8.
the technology and now sought to develop their own system.\textsuperscript{49}

By 1972, Denon had developed their own recording device based on the NHK systems. The final product was called the DN-023R – an 8-channel system – an upgrade from the 2 in NHK’s – with a 13 bit resolution and a 47.25 kHz sampling rate.\textsuperscript{50} The DN-023R utilized a 4-head open-reel broadcast VTR from Hitachi, but Denon was able to alter some of its internal electronics as well as design their own editing system. This change allowed for new features such as confidence monitoring which would not emerge in other VTR-based systems until many years later.\textsuperscript{51}

What appealed to recording companies like Denon about digital recordings was their longevity and easy duplication. The main difference between an analog and digital signal is that an analog signal is continuous whereas the digital is made up of many discrete values that are blended together to sound continuous. The discrete values make duplication easier and more reliable because there is a definite measure to which all duplicates can be compared. What this means for the recording companies is that although the format of the music they release to the public would be on an analog LP, the digital recording used to make that LP would assure that each copy would be identical.

In addition, the digital recordings were very versatile in that they could be easily altered and formatted to be compatible with a different medium. For example, the compact disc was one of the first major digital media to be available to the public. The release of the compact disc was in 1982. Denon had been making digital recordings since 1971, so by this time they already had

\textsuperscript{49} Fine, 7.
\textsuperscript{50} Fine, 8.
over 400 digital recordings.\textsuperscript{52} This allowed them to easily produce compact discs of recordings that were made in a different format. Although the NHK system was quickly made to be obsolete, its original breakthroughs provided the foundation for the later Japanese systems. Japanese electronics companies like Sony, JVC, and Sharp all developed digital recording devices based on the PCM to VTR systems used by NHK. These Japanese companies dominated the recording technology industry for the years to come. The Sony system, in particular, became so popular that its format was the preferred standard for compact disc manufacturers which all others had to follow.\textsuperscript{53}

**Conclusion**

New sound production techniques were a significant step in the transition from analog sound recording, generation, and transmission to digital. The United States military’s SIGSALY computer started a new generation of protected covert communication and command. Max Mathew’s development of the MUSIC family of software eventually allowed composers and music hobbyists to use their personal computers as a means to create new and exciting sounds. The NHK PCM digital recording device laid down new standards for recording digital sound. Most of the methods introduced with the inception of these types of technologies still persist in modern day applications.

\textsuperscript{52} Fine, 8.

Works Cited


Editing & Revision Evaluation

- Revised paper thoroughly using Purdom’s edits
- Added many more foot note citations where needed
- Corrected errors pointed out by fellow peers
- Made paper more formal
- Created concise sentences
- Combined shorter paragraphs into more comprehensive ones
- Created stronger transitions between thoughts
- Rearranged some aspects of the paper to create better flow