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29 October 2009

From Physical Law to Artistic Expression: An Analysis of the Theremin

I. Introduction to the Theremin

The Theremin (or Thereminovox) is a continuously sounding, monophonic instrument controlled by moving one's hands through free space in proximity to two antennae – one that controls the frequency of the generated sound and another that controls its amplitude. It is one of the few instruments that receives input from the musician without requiring any physical contact. Such an instrument offers considerably different potential for artistic expression than any of the commonly played acoustic instruments, but also presents a set of unique difficulties to the musician making it as challenging to master as the violin or the cello. Whereas acoustic instruments rely on the mechanical manipulation of oscillatory phenomena (plucking strings, vibrating reeds, etc.), the Theremin electrically manipulates an oscillatory phenomenon known as heterodyning to produce its unique sound.

In the case of string instruments, the musician adjusts the position of his fingers on the finger board to change the apparent length of the strings, which determines the natural frequency at which they will resonate when plucked (or bowed). In the case of the Theremin, the musician adjusts the position of his fingers in free space to change the apparent capacitance of the frequency sense antenna, which determines the natural frequency at which an LC oscillator will resonate. While the violinist changes the natural frequency of a mechanical oscillator by adjusting the position of his fingers in one dimension, the Thereminist changes the natural frequency of an electrical oscillator by adjusting the position of his fingers in three dimensions. Both instruments offer the ability to produce a continuous range of frequencies, as opposed to brass instruments that offer only discrete frequency control. In more ways than one, the Theremin is analogous to the violin, and is capable of performing the same musical role in an ensemble. However, although the Theremin is analogous to the violin in terms of input and output, no acoustic instrument shares the same physical principles of operation with the Theremin and hence no acoustic instrument can offer its unique musical capabilities.

The Theremin is a remarkable innovation in both electronics and music, and unlike the violin its design did not evolve over centuries eventually resulting in its present day form. The Theremin is the product of a single electrical engineer, Lev Sergeyevich Termin, known in the United States as Leon Theremin. Theremin's engineering expertise in RF electronics led him to develop the instrument as well as several others, each with unique properties and musical capabilities. This study aims to trace the historical trajectory of the Theremin, beginning with its inventor and ending with its virtuosos. In doing so, the progression from physical law to musical expression will be described in detail.

Another aim of this study is to explain how Theremin designed the electronics of the instrument from a theoretical perspective for specific sonic capabilities, and how musicians eventually came to manipulate these sonic capabilities from a musical perspective by understanding the Theremin as an instrument as opposed to an electronic circuit. This analysis will attempt to bridge the gap between the science and the art of manipulating sonic systems.

Section II of this paper will examine the life of Leon Theremin and the motivations for his inventions. Section III will go into considerable technical detail about the electronics of the Theremin and summarize the physical principles on which it operates. Finally, section IV will characterize the use of the Theremin by its most famous virtuosa, and how from an artistic perspective she interpreted the device that Leon Theremin devised from a theoretical perspective. Section V will draw conclusions.

II. The Career and Inventions of Leon Theremin

Leon Theremin was born in 1896 in the city of St. Petersburg, Russia. During his youth, Leon Theremin took a particular interest in physics, electricity, and oscillatory motions such as that of the pendulum[1]. During high school, Theremin studied cello at the St. Petersburg Conservatory of Music and graduated as “free artist on the violoncello”. After high school, Theremin studied physics and astronomy at the University of St. Petersburg, and eventually also received training as an electrical engineer during his Russian military service in World War I.

Following the Bolshevik revolution, a surge of academic energy permeated the Soviet Union. Scientists, engineers, and students of all fields were heavily encouraged to conduct research and experimentation in new and ground-breaking subjects. The Soviets hoped to usher in a new era of discovery to accompany their newly created “egalitarian” society. Part of this effort involved the founding of the Institute of Physical Engineering in St. Petersburg, by Abram Fedorovich Ioffe, a Soviet physicist who went on to win the Stalin Prize in 1942.

After the war, Theremin received an invitation to begin working at the Institute of Physical Engineering. Ioffe intended for Theremin to work in the field of high frequency

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[1] "Leon Theremin: Pulling Music Out of Thin Air", by Olivia Mattis and Robert Moog, *Keyboard*, February, 1992, pp.46-54.

electrical oscillators. Theremin proceeded to work with contemporary radios and study the effect of body position on radio signals[2]. The original application for Theremin's research was a security system that involved sensing the presence of humans by detecting fluctuations in radio signals. In 1920, Theremin extended the idea of detecting humans based on signal fluctuations to creating signal fluctuations that were controllable by body position. In a certain sense, Theremin's idea for a musical instrument was that a human could “play” the detector by adjusting body position to create a controllable signal in the audio range.

An important question that arises naturally at this point in the timeline is what motivation would Theremin have for applying the basis for his security device as the basis for a musical instrument – a seemingly completely unrelated technology. Conveniently, Theremin answered exactly this question in his 1991 interview with Olivia Mattis and Robert Moog. When asked, “Why did you make this instrument,” Theremin replied,

> “I became interested in bringing about progress in music, so that there would be more musical resources. I was not satisfied with the mechanical instruments in existence, of which there were many. They were all built using elementary principles and were not physically well done. I was interested in making a different kind of instrument. And I wanted, of course, to make an apparatus that would be controlled in space, exploiting electrical fields, and that would use little energy.”[3]

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[2] “Musical Applications of Electric Field Sensing”, by Joseph A. Paradiso and Neil Gershenfeld, *Computer Music Journal*, Vol. 21, No. 2 (Summer, 1997), pp. 69-89.

[3] "Leon Theremin: Pulling Music Out of Thin Air", by Olivia Mattis and Robert Moog, *Keyboard*, February, 1992, pp. 46-54.

At the beginning of the Bolshevik era, engineers were racing to find new and exciting uses for electricity. Theremin's goal was to harness the power of electricity to eliminate the need for mechanical work in operating an instrument. Theremin intended to build an instrument that required very little energy to operate but could produce sounds that varied widely in amplitude and pitch. In this sense, the Theremin is also analogous to the baton a conductor uses to conduct an orchestra. Simple swift hand motions are all that is necessary to control an audio signal with considerable power. The power is introduced into the audio signal via electronic amplification, as opposed to the manner in which musicians of acoustic instruments generate powerful sounds by means of mechanical work. Theremin's attitude toward bringing about the opportunity for musical change reflects the general attitude toward radical innovation in the beginning of the Bolshevik era. Part of the reason for Theremin's striking success with his instrument was that this attitude was shared among scientists and political figures alike.

Theremin first showcased his instrument at an electronics conference in Moscow, where it was received with great enthusiasm by his fellow engineers and inventors. The instrument gained so much popularity and publicity at the conference that once Vladimir Lenin learned of its existence, he requested that Leon Theremin give him a personal demonstration of this new and ground-breaking musical apparatus. To demonstrate the musical potential of the instrument, Theremin played “The Lark” by Glinka's during his visit with Lenin. Lenin enjoyed the selection so much that after the applause subsided, he asked Theremin to show him to play the instrument himself.

The Theremin was not the only electronic instrument that Leon Theremin devised during his career. He also designed an electronic cello that Edgard Varése (one of the first composers to pioneer electronic music) included parts for in his 1934 composition Ecuatorial. Theremin's cello was controlled by making contact between the musician's fingers and the fingerboard. So long as a finger was depressed, a tone was generated with frequency dependent on the position of the finger. In addition to the electronic cello, Theremin also designed a machine called the Rhythmicon – a precursor to the modern sequencer and drum machine. The Rhythmicon produced one fundamental pitch and gave the musician the ability to control which of its harmonics were also played. Each harmonic was played as a sequence of repeating tones, with the repetition rate dependent on the number of the harmonic. By selecting combinations of harmonics, the musician could generate complex rhythmic patterns electronically – another radically new "musical resource" that Leon Theremin designed.

Lastly, Theremin designed an instrument called the Terpsitone. The Terpsitone was a platform on which a dancer moved in space to control the pitch and amplitude of a generated sound. Like the Theremin, the properties of the generated sound depended on the effect of the position of the human body on an electric field; however, the Terpsitone required full body movements as opposed to small hand gestures. It effectively converted the motions of a dance into sound. The dancer would raise or lower his arms to control the pitch of the sound, while moving forward or backward to control the amplitude.

III. The Design and Operation of the Theremin

Theremin's space-controlled instruments gave the musician the ability to control sound through a completely novel interface that relied on the exploitation of physical principles to operate. The method by which the motion of the musician's hands control the Theremin's sound without physical contact is known as capacitive sensing, and is the same zero-contact detection mechanism by which Theremin's security device worked. The basis for capacitive sensing is that the position of the human body relative to an antenna changes the capacitance of the antenna.

The antenna is connected to a circuit in which its capacitance determines the resonant frequency of an inductor-capacitor (LC) oscillator. Changing the antenna's capacitance changes the frequency at which the LC circuit oscillates, and this is the basis for controlling sound. However, as we will soon see, the Theremin's audio output signal is not taken directly from the body position controlled LC oscillator. The fluctuations in antenna capacitance due to changes in body position are extremely minute, and thus it is necessary to combine the LC oscillator accompanying electronics to turn the small frequency fluctuations into audible ones. The signal processing technique that Theremin implemented to accomplish this task is called heterodyning, and we will examine it in detail after first describing the physics of how body position determines the antenna capacitance.

The capacitance of a cylindrical antenna in isolation (with no human present) is given by the following expression[4]:

$$C_a(\infty) = \frac{2\pi\varepsilon_0 h}{\log(\frac{2h}{d}) - k}$$

in which h is the antenna height, d is the antenna diameter, k is a constant depending on high the antenna is positioned above the ground, and ε_0 is the permittivity of free space (8.854 picofarads per meter). The expression effectively tells us the capacitance of the antenna when the hand is

[4] "Physics of the Theremin", by Kenneth D. Skeldon and Lindsay M. Reid, American Journal of Physics, Volume 66, Issue 11, pp. 945-955 (1998).

not present, or infinitely far away. The change in the antenna's capacitance that results from the hand being positioned at distance x from the antenna is given by[5]:

$$\Delta C_a(x) = \frac{\pi \varepsilon_0 h}{10 \log(\frac{4x}{d})}$$

The total capacitance of the antenna with the hand positioned at distance x is:

$$C_a(x) = C_a(\infty) + \Delta C_a(x)$$

Now that we have a formula for the antenna's capacitance as a function of hand position, we may examine LC oscillator network that surrounds it to determine how the oscillator's resonant frequency fluctuates depending on the antenna's capacitance, and hence on the position of the musician's hand.

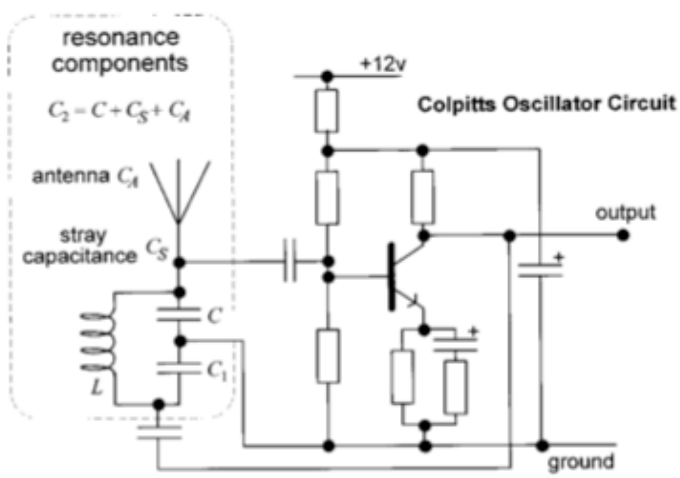

Figure 1: Oscillator circuit with output frequency dependent on antenna capacitance.[6]

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[5] "Physics of the Theremin", by Kenneth D. Skeldon and Lindsay M. Reid, American Journal of Physics, Volume 66, Issue 11, pp. 945-955 (1998).

[6] "Physics of the Theremin", by Kenneth D. Skeldon and Lindsay M. Reid, American Journal of Physics, Volume 66, Issue 11, pp. 945-955 (1998).

The resonant frequency of the LC oscillator seen on the left-hand side of the schematic for the Colpitts oscillator circuit is given by[7]:

$$f_0 = \frac{1}{2\pi\sqrt{L}}\left(\frac{1}{C_1}+\frac{1}{C_2}\right)^{1/2}$$

in which C_1 is the value of the capacitor C_1 as shown in the schematic and C_2 is the parallel capacitance of the capacitor C (as shown), any stray capacitance between the antenna and the rest of the circuit (C_s), and the antenna capacitance (C_A). It seems reasonable to assume that the output of the Colpitts oscillator could be used as the audio output of the Theremin, since the frequency of this signal can be manipulated by hand position. However, due to the mathematical relation between hand position and resonant frequency, large variations in hand position lead to very small variations in the output signal of the Colpitts oscillator. Theremin implemented a technique called heterodyning to transform the small fluctuations in the frequency of the Colpitts oscillator to large fluctuations in the frequency of an audible output signal.

The concept of heterodyning was first applied to the design of a musical instrument in 1915 by Lee DeForest in his invention of the Audion Piano[8]. The basis for heterodyning is that when two sinusoidal signals are mixed, the output signal has two frequency components equal to the sum and the difference of the input signals. In signal processing, the mixing operation

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[7] "Physics of the Theremin", by Kenneth D. Skeldon and Lindsay M. Reid, American Journal of Physics, Volume 66, Issue 11, pp. 945-955 (1998).

[8] "Electronic and Experimental Music: Technology, Music and Culture", by Thom Holmes. New York: Scribner, 2008.

corresponds to multiplying two signals. We can verify the output of the mixing operation with a simple trigonometric identity[9]:

$$V_{out} = V_{in,1} \times V_{in,2} = A_1 \sin(\omega_1 t) \times A_2 \sin(\omega_2 t)$$
$$V_{out} = \frac{A_1 A_2}{2}\left(\cos((\omega_1 - \omega_2)t) - \cos((\omega_1 + \omega_2)t)\right)$$

We can eliminate the frequency component equal to the sum of the two frequencies easily by cascading the mixer with a low-pass filter, outputting a waveform with frequency equal to the difference of the two input frequencies, called the "beat" frequency. By pairing two high-frequency Colpitts oscillators together, one oscillating at a fixed frequency and one with a frequency fluctuating due to changes in antenna capacitance, and applying the necessary heterodyning circuitry to their outputs, Leon Theremin was able to transform minute fluctuates in antenna capacitance into large fluctuations in the audible beat frequency of the two oscillators.

Recall that changes in antenna capacitance are small, and hence they produce very small fluctuations in the output frequency of the antenna dependent Colpitts oscillator. If the antenna dependent Colpitts oscillator rings nominally at 1 MHz, a small change in antenna capacitance might have the effect of changing its frequency by 1 kHz (a 0.1% fluctuation)[10]. However, assuming that the fixed oscillator also rings at 1 MHz, the difference of the two signals would be 1 kHz - an audible signal. In order for the beat frequency to sweep the entire audible frequency range (20 Hz to 2 kHz), the nominally 1 MHz frequency would need to fluctuate by at most 0.2%. A musician moving his hand in close proximity to the antenna is certainly capable of

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[9] "Physics of the Theremin", by Kenneth D. Skeldon and Lindsay M. Reid, American Journal of Physics, Volume 66, Issue 11, pp. 945-955 (1998).

[10] "Physics of the Theremin", by Kenneth D. Skeldon and Lindsay M. Reid, American Journal of Physics, Volume 66, Issue 11, pp. 945-955 (1998).

producing this fluctuation by means of changing the antenna capacitance. In an actual Theremin, the antenna-dependent Colpitts oscillator would be configured to ring at the same frequency as the fixed oscillator when the antenna capacitance was set to $C_a(\infty)$, effectively producing a beat frequency of 0 Hz (no sound) when the operator's hand was far enough away from the antenna. As the operator moved his hand closer, the antenna capacitance would change, causing greater and greater fluctuations in the antenna-dependent oscillator frequency, which caused the beat frequency of the two oscillators to increase through the audible range.

Theremin also included another heterodyned oscillator pair for the purpose of volume control. The beat frequency of the two oscillators was controlled in exactly the same manner as that of the pitch oscillators (antenna capacitance); however, the beat frequency instead of being used as an audio output was passed through a band-pass filter. As the musician moved his hand in close proximity to the volume antenna to change the beat frequency of the volume oscillators, he effectively tuned the beat frequency into the pass-band of the filter[11]. The filter's output was then applied to an envelope follower and used as the control voltage for a voltage controlled amplifier (VCA) that amplified the audio output of the Theremin (the beat frequency of the pitch oscillators). In this manner, a certain range of hand positions would maximize the amplitude of the band-pass filter's output, and hence the control voltage of the VCA, in effect maximizing the volume of the Theremin's audio output. Overall, the Theremin required moving two hands in proximity to two antennae, one for pitch and one for volume. Theremin engineered the instrument to allow for smooth, continuous control over pitch and similarly a wide range of control over dynamics. The virtuosos of the Theremin, provided with this engineered space-

[11] "Musical Applications of Electric Field Sensing", by Joseph A. Paradiso and Neil Gershenfeld, *Computer Music Journal*, Vol. 21, No. 2 (Summer, 1997), pp. 69-89.

controlled interface, were able to develop an intuition for understanding its subtleties and learned how to skillfully manipulate its sound.

IV. Clara Rockmore

One of the most famous Thereminists of the 20th century was Clara Rockmore, a classically trained violinist who was accepted as the youngest ever violin student at the St. Petersburg Imperial Conservatory at the age of four[12]. In 1977, Robert Moog gave Rockmore an interview to be published at the same time as her newest record, *The Art of the Theremin*. In this interview she explained how she manipulated the Theremin as a musical instrument, as opposed to a merely sound-generating electronic circuit. When asked to explain the musical limitations of the Theremin, Rockmore replied:

> "The violin has four strings, which makes a big difference. What I do on the theremin is the same as a cellist would do if he had one string. It's that much more difficult. For instance, there is a very easy Handel violin sonata where you play rapidly from string to sting. It's very difficult on a theremin, because you have to use time to go the distance ... I adopted the violin vibrato for the theremin, but it's with the other hand. I try to emulate the violin bowing technique with my left hand. Since the theremin tone is constant, I have to artificially create a 'breath'."[13]

Although the Theremin circuitry gives the musician only the simple facility to control the volume and pitch of the generated sound, Rockmore developed techniques to emulate the sound

[12] "The World of Women in Classical Music", by Dr. Anne K. Gray. San Diego: WordWorld Publications, 2007. http://www.nadiareisenberg-clararockmore.org/clara_biography.htm

[13] "In Clara's Words", by Robert Moog. October 27, 2002. http://www.thereminvox.com/article/articleview/21/1/22/

of the violin by skillfully combining the two interface controls simultaneously. When asked what the unique advantages of the Theremin were, Rockmore answered:

> "...Very fine violinists have a long bow. But as long as their bow may be, mine is longer. You have a musical nuance right there. A singer may have to take breaths even when it's not musically desirable, because he cannot continue to sing. I take the breaths when I think it's musically valid or necessary. I create a breath. I do it deliberately. I never do it because it's necessary. I can choose when I take it so it suits the music."[14]

It is clear that because of her extensive experience with the violin, Rockmore interpreted in terms of its relationship to the violin and relative capabilities. Rockmore explained that she uses her Theremin techniques ("bowing", "breathing", and vibrato) to liken the sound of the Theremin to that of a common instrument. However, the same features (continuously sounding tone, continuous pitch and volume) of the Theremin that require the musician to use special techniques to shape its sound into something musical are the features that give the Theremin the capability to exceed the performance of a common instrument. Rockmore remarked that with the Theremin, she has absolute control over when (or never) to breath.

One of Rockmore's most significant comments involves her interpretation of the Theremin as a musical interface:

> "There are certain nuances and qualities that you can obtain because you don't have anything in your hand. It really comes out of the air. That's why Prof. Theremin called it

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[14] "In Clara's Words", by Robert Moog. October 27, 2002. http://www.thereminvox.com/article/articleview/21/1/22/

> the Ether Wave Instrument. There is a certain terrific freedom. You feel like a conductor in front of an orchestra. There is no instrument between you and the music."[15]

This quotation proves Leon Theremin's success as the engineer of the instrument. His original design goal was to empower the musician with extensive freedom over the produced sound by eliminating the need for the expenditure of mechanical energy. In his 1991 interview with Robert Moog, Theremin remarked, "I conceived of an instrument that would create sound without using mechanical energy, like the conductor of an orchestra."[16] And this is exactly the freedom that Clara Rockmore harnessed to become the leading virtuosa of the Theremin in her time.

V. Conclusions

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[15] "In Clara's Words", by Robert Moog. October 27, 2002. http://www.thereminvox.com/article/articleview/21/1/22/

[16] "Leon Theremin: Pulling Music Out of Thin Air", by Olivia Mattis and Robert Moog, *Keyboard*, February, 1992, pp.46-54.