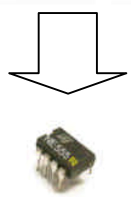
Theremaniac

Bringing Leon Theremin and his instrument from the twenties to the twenty first century

Leon Theremin demonstrates his invention, c. 1928
Photo collection of Thomas Rhea



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April 2002

Term paper and project for
Physics 489
Professor Daniel Axelrod
Winter 2002

Section/Topic Index

Introduction

The Theremin (also Termenvox, Aetherophone) is a unique electronic musical instrument played without touch by waving one's hands. One hand waving in front of a vertical antenna controls the pitch while another hand waving above a horizontal ring antenna controls the volume. The odd way of playing this instrument and ethereal sounds it produces lends itself to the alternate name of the Aetherophone. Invented in 1920 by Leon Theremin (Lev Sergeivitch Termen), the Theremin is the first fully electronic musical instrument to reach a large audienc and still be used in music today. There is quite a story behind both the instrument and the man.

This paper was written as my term project for Physics 489 at the University of Michigan for Professor Daniel Axelrod. Along with this paper, I built and tested a few Theremin designs until I had a working optical Theremin. This paper will walk through the history of Leon Theremin and his original instrument, followed by a few newer Theremin designs and my experience over the term with building them.

A Short History of Leon Theremin

Invention in Russia

Leon Theremin led quite an amazing and at times, harrowing, life. He was born in St. Petersberg, Russia in 1896 to the name Lev Sergeivitch Termen. He took interest in both electronics and music at an early age before he turned 10. Leon started playing the cello around this time. By the age of 13, he had become interested in high frequency electricity and the work of Tesla. (Termen) He entered the University of St. Petersburg and majored in both physics and astronomy. His studies eventually brought him to the institution of Physics, Technology and Radio Sciences in 1920. Here, he worked on many things, one of which was an electronic alarm system using radio waves to measure the presence and movement of a human body. (Termen)

Theremin's work on the alarm system led the invention of the *Termenvox* using the same principles. Leon was not content with the musical instruments of the time. He believed that no instrument properly related the performer to the music. In a 1989 interview with Olivia Mattis he said: "I wanted to invent some kind of an instrument that would not operate mechanically, as does the piano, or the cello and the violin, whose bow movements can be compared to those of a saw. I conceived of an instrument that would created sound without using any mechanical energy, like the conductor of an orchestra. The orchestra plays mechanically, using mechanical energy; the conductor just moves his hands, and his movements have an effect on the music artistry [of the orchestra]." Theremin was first able to demonstrate his device to his colleagues in September of 1920 and by November, he had perfected it. (Termen)

The first prototype Termenvox was built in 1917 was a simple oscillator with a foot pedal volume control and switching mechanism for pitch control. By 1920, the Termenvox had evolved into the dual control-antenna design we see today and recognize as a Theremin. One vertical antenna is used to control pitch and a horizontal loop antenna is used to control volume. As the performers hands get closer or farther away from the antennas, the capacitance of the antenna changes and the circuitry changes the pitch or volume in turn. (Crab) The name Termenvox was used until Leon came to America in 1927 and anglicized his name at which point the Termenvox became known as the Theremin.

The invention of the Theremin came at a time when everyone in the Soviet Union was fascinated in the new uses of electricity. At a large electronics conference in Moscow, Leon

Theremin made a splash that opened the door so to speak for him. The then leader of the USSR, Vladimir Lenin showed immediate interest in Theremin and asked for a personal demonstration. In May of 1922, Leon demonstrated his Termenvox to Lenin within his personal chambers. Amazingly, Lenin was not only enthralled with the device, but due to his good ear, able to play it quite naturally. (Mattis) Lenin and Theremin talked extensively on electricity and other subjects including the electrification of the entire USSR. Theremin was given the right to travel freely throughout the entire country and devote himself to electronic art, which at the time was quite a freedom. During this time, Leon worked on some amazing devices, including the first color television, years before television even existed. (Termen)

Coming to the United States

At the same time Theremin was given freedom, he was required to be an assistant to the Soviet government. He was not against this but actually a strong supporter of socialism and communism and especially of Lenin whom he looked up to. (Galeyev) It was in 1925 that he was sent abroad to Europe to demonstrate his invention. In Europe he met and performed for both music and science greats such as Ravel, Respighi and even Einstein. (TVOX) Finally, he arrived in the United States at the end of 1927, where he and the USSR diplomatic service fought to be accepted. (Termen) Theremin was to legitimately work on his experiments and selling his inventions. However, he was also to spy on U.S. military technology for the Soviets. Although this may be alarming, Theremin was convinced he wasn't hurting anyone. He liked America and the Americans seemed to like him in return. (Galeyev)

In the United States, Theremin set up a laboratory and musical workshop in New York. Companies like RCA and GE constructed and sold Theremins commercially while Leon set to other inventions. One of the inventions would actually affect his personal life. The Terpsitone was like a gigantic Theremin for dancers. A dancer's full body movements were made into music by the effect of the Terpsitone. Lavinia Williams was a student of the Terpsitone at Leon's music workshop. It was not long before she and Theremin were married. What made this marriage notable that Lavinia Williams was black, and this was at a time when interracial marriages were taboo. (Mattis)

In the end, the Theremin was not a commercial success due to its best feature: total freedom. Most people did not deal well with having no point of reference at all and the Theremin took a precise ear and accurate movements to produce a good sound. To most people, this would be like singing but with someone else's voice. However, there were some composers at the time that took note of the Theremin and started to compose music for it that could not be played on any other instrument. At the same time, Hollywood also took an interest in the Theremin and began using the instrument for sound effects and eerie music most commonly connected with mid-century science fiction movies. (TVOX) Some major movies to use the Theremin include <u>Spellbound</u> by Alfred Hitchcock, <u>The Day the Earth Stood Still</u> and <u>The Lost Weekend</u>. One artist that was noticed however was Clara Rockmore. Once a violinist, she became probably the one and only master of the Theremin and her performances are still moving today. (Sirin)

Return to Russia

Leon's happy life in the United States was not to last. In 1938, he disappeared. Many people believe that he was kidnapped by the NKVD, the precursor to the KGB, and brought back to the Soviet Union. They thought the NKVD had accused him of anti-Soviet activities, placed him in a Siberian Labor camp and then forced him to work on spy technology. People in the West were led to think that Leon Theremin had been kidnapped and executed. (Crab) However, Leon himself disputed in at least two separate interviews. He said that he was in the New York on assignment only and actually had requested to go home with his wife at least three times before his wish was granted. When it worked out, Leon did get back to the USSR but his wife did not. They exchanged many letters and this was when he was arrested. (Mattis)

Leon said that he was put to work in a special isolated lab within the Ministry of Internal Affairs as a prisoner. There, he worked on many military electronic devices, such as television and communications equipment, but would not give any specifics when interviewed about them either due to security requirements or memory. During this time he was under investigation twice and always under suspicion and supervision. (Mattis)

Release

After all this hardship, in 1947 he was given not only his freedom but also the First Class Stalin Prize. The Stalin Prize was the most prestigious award in the USSR at the time and would be like receiving the Nobel Prize. The award was for the invention of the *Buran* bugging system for surveillance and eavesdropping of U.S. embassies. Some of the bugging devices were so advanced that the U.S. did not discuss them until 1960, over ten years since their discovery. (Galeyev)

Little is known of the next twenty years of Leon's life. After he gained his freedom, he continued to work for the KGB until 1966. Although freed from isolation and suspicion, most people in the West did not learn of his survival until 1960s. (Mattis) On this, Galeyev says: "Our planet is probably not completely sane if the military industry can succeed in transforming an artist into a James Bond and a musical instrument into an alarm system. I ask the reader to make an allowance for Theremin, whose suffering far outweighed his guilt. "

Theremin finally returned to teach at the Moscow conservatory of music. However, when the administration found out he was working on his electronic musical instruments, he was stopped after only a year. The New York Times had interviewed Theremin and the article found its way into the administration. According to Theremin, an administrative assistant said: "electricity is not good for music; electricity is to be used for electrocution." (Mattis)

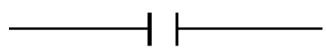
Theremin and his instruments have been undergoing a kind of revival over the last fifteen years or so and has gathered almost a cult following. The last ten years of his life were spent actively promoting his inventions. He did travel once back to the United States to give a lecture. He died in 1993, only two day after the release of the American documentary "Theremin. An Electronic Odyssey." (TVOX) The documentary helped lead to the foundation of the Theremin Enthusiasts Club International, where the members call themselves "theremaniacs" (Galeyev) His work also lives on today indirectly as he has inspired others such as Robert Moog of the Moog synthesizer, giving rise to almost all electronic music today. (Sirin)

Basic Theory Behind the Operation

Oscillation

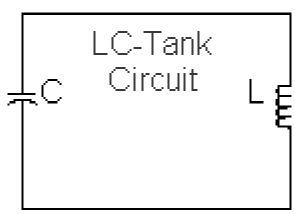
The simplest sound is a sine wave produced by some body oscillating in the air with a motion that is a function of sine. How fast the body is oscillating with respect to time is the frequency, which is measured in cycles-per-second (cps) or Hertz (Hz). In mechanics and acoustics, a vibrating body connected to a spring is a example of this simple motion. The body is initially moved and the restoring force of the spring pulls the body back to its resting place. However, as the body moves it gains momentum because it has mass and this causes it to overshoot its resting place. Therefore, the spring again pulls the body back in the opposite direction to its resting place but the same problem with momentum occurs. This cyclic action is known as Simple Harmonic Motion. The properties of the restoring force and the mass give the system a characteristic frequency, also known as its resonant frequency. (Backus, 23)

An electrical circuit, known as an LC Tank, can be constructed to operate like the vibrating string as an electrical analog to simple harmonic motion. The LC Tank is comprised of two two-terminal circuit elements: an inductor (L) and a capacitor (C). An inductor is a coil of wire that current can flow though. The current creates a magnetic field in the inductor that stores energy. The most important property of an inductor is that it restricts the change of current through it but the voltage across it can change instantaneously. The voltage across an inductor is proportional to its inductance measured in Henries (H) and the change in current over time through the inductor. A capacitor on the other hand stores energy in an electric field between two insulated conductors. The most important property of a capacitor is that it restricts the change in voltage across its two terminals but the current through it can change instantaneously. The current in a capacitor is proportional to its capacitance as measured in Farads (F) and the change in voltage across its terminals over time. (Nilsson & Riedel, 230-242)

Mathematical Formula:	$V_{inductor} = L\frac{di}{dt}$	$I_{capacitor} = C\frac{dv}{dt}$
Symbol:		

When the inductor and capacitor are connected together, they form a parallel resonant circuit. The inductor acts like the mass, giving a pseudo-momentum to the electric current in the system. The capacitor acts like a spring that stores up energy and provides a restoring force in the opposite direction of the current. ("Electrical..", 34d) The resonant frequency is inversely proportional to both the inductance and capacitance of the circuit. The resonant frequency f_r and schematic of a tank is:

$$f_r = \frac{1}{2p \cdot \sqrt{L \cdot C}}$$



("Electrical..", 35a)

An LC tank circuit needs an initial displacement to start oscillating or nothing will happen. Once oscillating, it also needs to be "recharged" so to speak, because the inductor, capacitor and connecting wires all have resistance. The resistance is like friction in the mechanical oscillator and over time it will cause the oscillations to be dampened out. Therefore, some form of recurring excitation is needed to turn the simple LC tank circuit into a full oscillator. What is used is an active element such as a transistor or vacuum tube (discussed later) that is connected to the tank with some sort of feedback element. The arrangement makes the oscillator self-sustaining by supplying pulses of energy at least once each cycle to keep the oscillation going. ("Electrical..", 35a)

Body Capacitance

In order to change the frequency of an LC oscillator, one needs to change one of the two characteristics of the LC tank. Between inductance and capacitance, capacitance is the easiest to change. Since capacitance is created by two conductors separated by an insulator, a human body can be part of a capacitor. The capacitance is dependent on both the distance between the conductors and the area of their faces. So therefore, it stands to reason that a person moving near a metal antenna will change the capacitance seen by the circuit connected to that antenna. If the circuit happens to be an LC tank circuit, a person can control the resonant frequency of that circuit. (Max)

However, the change in capacitance will be very small, measured in only pico-Farads. If the LC circuit was set up to operate at audio frequencies (between 20Hz and 20kHz) then the inductor would have to be outrageously huge to let a pico-Farad change in the capacitance to noticeably change the resonant frequency. In order for the minute change in capacitance to have an effect and the device to be feasible, the oscillator must operate in the radio frequency band upwards of 500kHz. Here a small 1% change in capacitance could change the resonant frequency by around 5kHz. (Max)

Heterodyning and Detection

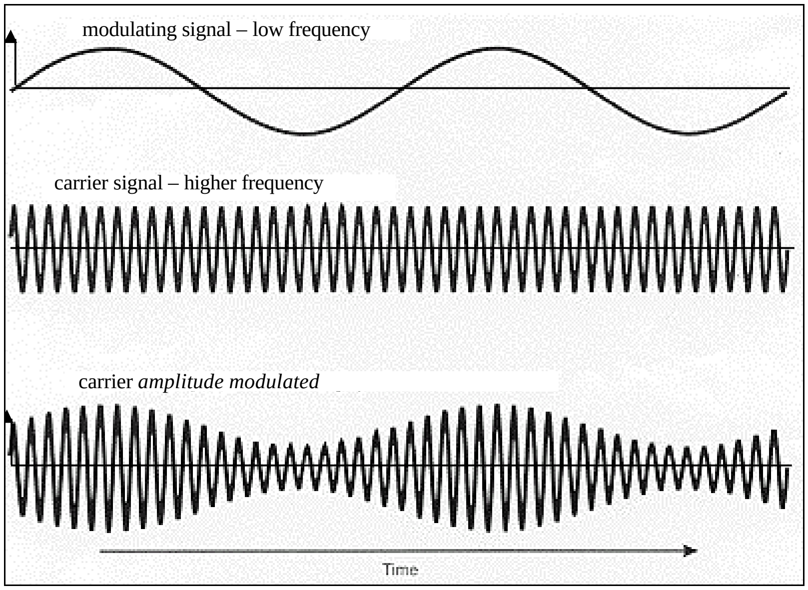
An oscillator producing a signal at 500kHz is pretty useless musically as it is far beyond the audible range. However, this signal is being frequency modulated, or changed, by a person at the antenna and it is the modulation that we want to hear. The method used here is exactly the same as used in almost every radio receiver for most of the past century and is based on trigonometry. When two sine waves of different frequencies are mixed together, it produces two related sine waves: one at the sum of the two frequencies and one at the difference of the two frequencies. This is shown mathematically in two ways: (Jared Mehl)

$$\cos(w) + \cos(w + dw) = 2 \cdot \cos\left(\frac{dw}{2}\right) \cdot \cos\left(w + \frac{dw}{2}\right)$$

$$\cos(a) + \cos(b) = 2 \cdot \cos\left(\frac{b - a}{2}\right) \cdot \cos\left(\frac{b + a}{2}\right)$$

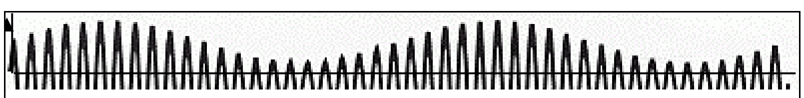
In the first equation, ? is some base frequency and d? is the frequency by which ? is shifted by the change in capacitance. The second equation is a substitution of the first and means the same thing where a and ß are two arbitrary frequencies. In both cases, the result is the same with the first sine being low frequency modulating (changing the amplitude) the second sine at a higher frequency. The next diagram below shows a graphical representation of a low frequency amplitude modulating (AM) a higher frequency. When this process of mixing sine waves is applied to signals and electrical systems, it is known as *heterodyning*.

The important thing to note is that two oscillators (a and ß) are needed instead of just one. Both oscillators are tuned to the same frequency ? with one being fixed and one being variable by the antenna. Changing the capacitance of the antenna will cause a deviation from the base frequency by d? . When the signals from the two LC oscillators are mixed, the result will be a signal that contains a high radio frequency modulated by a lower audio frequency. The third graphic in the following diagram shows what this looks like. However, the result is generated from heterodyning two frequencies that are close together, not a high and low frequency as shown in the first two graphics, which would be amplitude modulation.



Example of AM modulation. http://www.radio.gov.uk

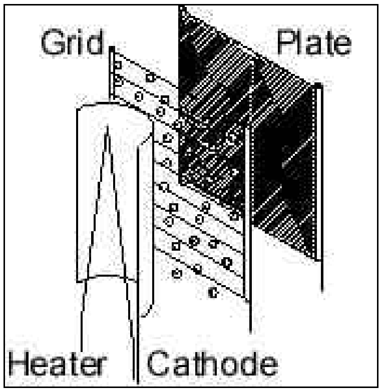
In order to get just the lower frequency of a the heterodyned or AM modulated signal, we need to demodulate or *detect* the lower frequency, again just like a radio receiver. This is usually done using a diode square law detector which rectifies the signal. A diode only allows current to flow through it in one direction so the resulting signal is one polarity with all the negative peaks cut off. An example of this signal is shown in a graph below. The rectified signal is then low pass filtered to recover its envelope which is clearly visible in the graph. This envelope is the detected difference signal d? . The math behind square law detection is beyond the scope of this paper but can be found in many textbooks and online. One source is the Electrical Engineering II Laboratory Manual for EECS211 (University of Michigan) by Professor Gabriel Rebeiz.



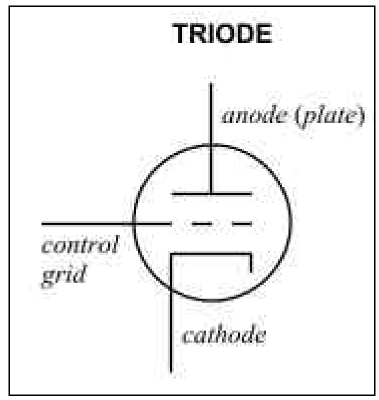
Example of Rectified AM signal

Vacuum Tubes

Above in the section on oscillators, the vacuum tube was introduced but not discussed. The vacuum tube, also known as the valve, was really an invention that drove the electronics revolution in the early part of the twentieth century. The simplest vacuum tube has *heated cathode* and a *plate* within a vacuum glass envelope. The cathode could be a conductor heated by a heater filament, or just the heater filament itself. The heat causes free electrons to boil off the cathode by the Edison Effect. If an electric potential is applied between the plate and cathode with the plate being more positive, the electrons from the cathode will accelerate to the plate and an electric current will be set up. If the electric potential is higher on the cathode side, electrons cannot jump off the plate and go towards the cathode so no there is no current. This type of tube is a diode, because electrons can only flow in one direction from cathode to plate. However, this type of tube is unable to do what we want which is switching and amplification. By adding a *grid* electrode between the cathode and plate, the current can be controlled. A negative voltage on the grid builds up a negative electric field, which repels electrons and keeps electrons from reaching the plate, hence decreasing current or even stopping it completely. The effect of the grid allowed the triode vacuum tube to operate both as a current switch and a voltage controlled current amplifier. (Simonton) More grids can be added and the configuration of the parts changed to have different effects. A diagram and schematic symbol are shown below:



Physical Diagram of Triode
John Simonton



Schematic symbol for Triode
Michael S. McCorquodale

The vacuum tube was replaced about mid-century by the semiconductor transistor. With the advent of semiconductors, electronics could become smaller, lighter, more robust and more efficient. Yet some applications of tubes still exist in high power radio applications and the ubiquitous television and computer monitor. In the 1920s however, the vacuum tube was the only available amplifying device and was used in almost all electronic equipment at the time. It is for this reason that knowing about the tube is important to understanding the Theremin.

Original Theremin Design and Operation

Now that the fundamental theories behind the Theremin are understood, it is time to dive into original Theremin design per the 1928 U.S. patent of the same. Theremin was granted number 1,661,058 for an exhaustively detailed patent application. It covered not only his original design, but also many modifications for various styles of volume control, polyphony (multiple pitches), and timbre controls.

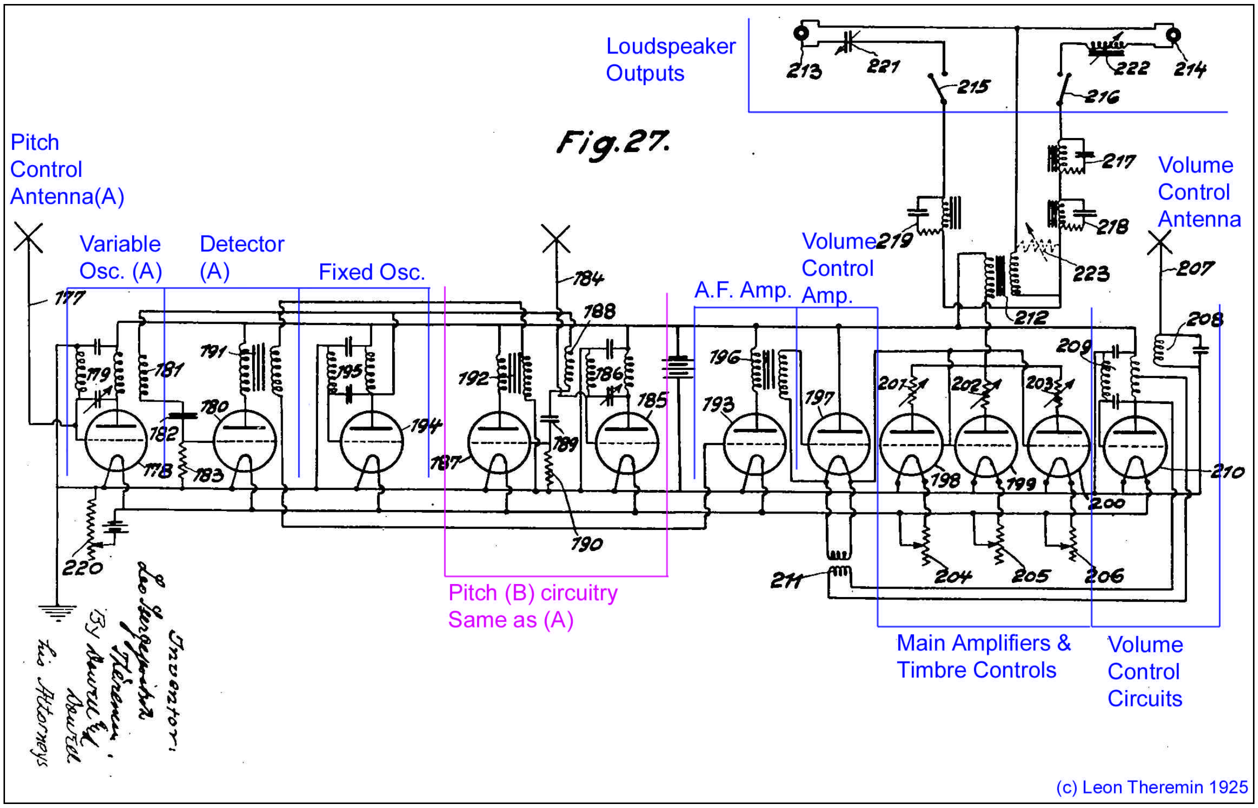
Below is an edited schematic of Figure 27 from the original patent. I have labeled the individual sections of the circuit. Figure 27 “illustrates a complete system for simultaneously producing a plurality of sound or musical tones on the same or different pitches, and embodying means for controlling the characteristics thereof.” (Theremin)

On the left is an Antenna marked with an X connected to an LC tank oscillator comprised of 178 and 179. This is the variable oscillator and antenna for one of the two tone generators. Two sections over is a fixed LC tank oscillator 194 and 195. This signal from this fixed oscillator is actually shared between the two separate pitch circuits. The signal from the variable oscillator and the fixed oscillator is mixed, which is the described process of heterodyning. Then the detector, marked as 180, detects the heterodyned signal. The second tone generator is marked in purple and is identical to the first one and is not important to the understanding of the device. The audio frequency output of the two detectors is sent to a first stage audio frequency (A.F.) amplifier (193) with fixed gain. The next amplifier stage (197) is a variable gain amplifier

/

for volume control. The gain is controlled by another LC tank oscillator and the volume antenna. (Theremin) However, as a volume control instead of pitch generator, the operation is slightly different and rather ingenious.

In the volume control circuits section, 210 and 209 form another LC oscillator. The volume control antenna is connected to an LC tank circuit (208). This time, the LC tank circuit is not used as another oscillator but as an "absorption" system. (Theremin) The absorption tank and the oscillator are coupled together. As the hand is brought near the volume control antenna, it changes the resonant frequency of the absorption tank. The farther away the resonant frequencies get, the lower the amplitude of the output signal gets. This output signal is used to control the volume control amplifier (197) and that is how the volume control circuit works. (Max)



Original Theremin Schematic from Patent

The remaining two sections of the Theremin design shown are the main amplifiers and loudspeakers. The main amplifiers include some additional circuitry to control the timbre and tone quality of the sound but are not required to the functioning of the Theremin. Also output to the loudspeakers includes some filters to correct for any unwanted resonance in the loudspeakers themselves. (Theremin)

One interesting quality of the original Theremin is the sound it produces. Although the theory put forth in earlier sections says the output should be purely sinusoidal, the final waveform in a Theremin is filled with harmonics. The harmonics are due to the multiple oscillators trying to match frequencies through coupling. Furthermore, harmonics are generated in all circuits with non-linear distortion. Tubes are the most notorious generators of this distortion by clipping the top and bottom of a waveform when it gets to big, but inductors can also cause distortion whey they magnetically saturate. (Max) Below is a picture of Leon Theremin and one of his instruments.   The large triangular object in the upper right is actually the loudspeaker.

Leon Theremin playing one of his instruments

Modified and Modernized Designs

Building an original style Theremin with vacuum tubes and large hand wound inductors and large open-air plate style capacitors would be a wonderful project. However, it would also be a very difficult and expensive project. The difficulty and cost of obtaining parts put this option out of reach. However, many tested an interesting designs exist from tube Theremins. A great source of schematics is available from Max “Whistler” online at http://www.maxiespages.com/theremin/schematics2.shtml

In lieu of building a vacuum tube Theremin, the only other option is to use modern semiconductor devices, either discrete transistors, or integrated circuits with hundreds (or more) of transistors on one chip. Once again, Max provided a good starting ground to build and test modern Theremin designs. (http://www.maxiespages.com/theremin/schematics.shtml)

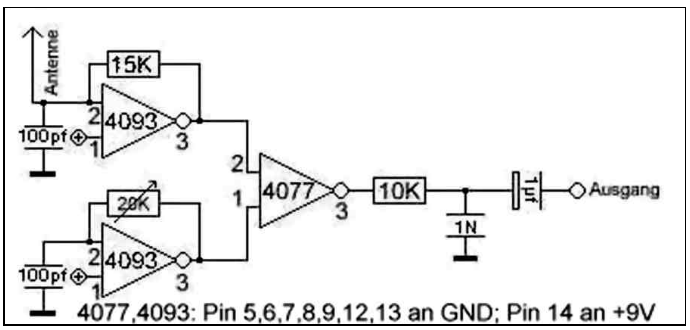
There are a few types of modernized Theremins ranging from extremely simple to very complex and sometimes straying very far from Leon’s original design but getting the same result. The most unchanged type of Theremin replaces the vacuum tubes of Leon’s designs with solid-state transistors with little change to the overall circuit design. However, these designs still require somewhat difficult to find inductors. Other designs use CMOS logic, similar to the chips in a computer, but operate them in an analog manner. This type of hacked up design actually worked for many people and was nice due to its simplicity and low cost. Still others use light instead of an electric field to control their circuit. My favorite Theremin actually uses a computer and a video camera to create a truly digital Theremin.

I wanted to find a design where I could forgo the need to use inductors and have a simple and cheap circuit. To do this, I would need to use a different type of oscillator known as an astable RC oscillator or astable multivibrator. The astable RC oscillator works on a different principle than the LC tank. A resistor and capacitor are connected in series and connected to a power source. The time it takes for the capacitor to charge to a certain voltage is determined by the values of the resistor and capacitor. This is analogous to an hourglass where a higher resistance means a smaller hole for the sand to flow through and a larger capacitance is more sand. The RC circuit is connected to some kind of circuit that triggers when the capacitor reaches a certain voltage. When triggered it shorts the circuit out which is like flipping the hourglass. The voltage on the capacitor now drains until the circuit is triggered to connect it back to power and the cycle repeats. ("Electrical..", 36a)

Troubles with Construction

I tried about five different circuits on Max's page, each of them using CMOS logic chips as astable RC oscillators but basically following the same system layout as Theremins original design. Each of these circuits also did not have a volume control; they were pitch only for simplicity. I won't go into the details of each one of the designs because they were fairly similar but I will give an overview of two of the circuits. The first is a very simple design and should worked well.

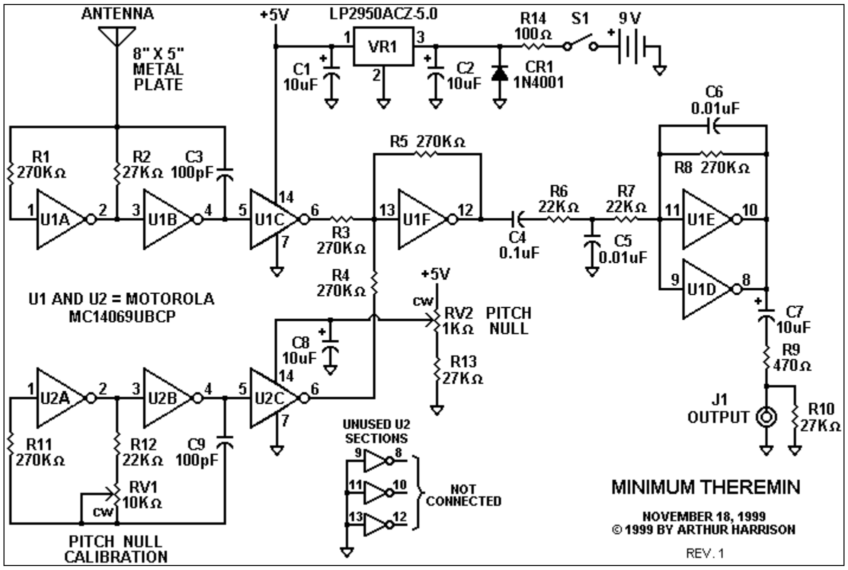
The first circuit is shown as a schematic below. The triangles with the circle on the point are inverting CMOS logic gates. The 4093 is acting like a NOT gate or just an inverter, and the 4077 is an XOR gate or exclusive Or function. An inverter has a high output for a low output and a low output for a high input. A OR gate has a high output as long as at least one of its inputs is high. Each 4093 is configured as an astable RC oscillator. The top one has an antenna for controlling it while the bottom one acts as the fixed oscillator but has an adjustable resistor to tune the circuit. The 4077 XOR acts like a mixer and detector rolled into one. I was able to get sound out of this circuit but no matter how much I tried, I could not get any response due to hand motion around the antenna.



Schematic for Simple CMOS Theremin (Max)

One of the other circuits, named Minimum Theremin, (below) I built had much more complexity but again, I was having the same problems. In this circuit (below), the each triangle represents on inverter but six inverters are combined onto one chip. On the left are two astable RC oscillators comprised of two inverters (A&B). These are buffered each by another inverter (C) and mixed by R3 and R4 before being fed to U1F. Because of the non-linear transfer function of the inverter, U1F effectively detects the heterodyned signal and the following resistors and capacitors filter out all the high frequencies. On the far right, two remaining inverters buffer the output signal. An in depth analysis of this circuit by the designer, Arthur Harrison, can be found at http://home.att.net/~theremin1/minimum/minimum.html#Circuit.

This circuit should have performed well but it did not. I followed the design and construction recommendations of Arthur Harrison except for I was building the circuit on breadboard instead of directly to circuit board. Since none of these circuits performed as expected, I came to the conclusion that either the parts I am using are faulty or my construction and troubleshooting skills are not up to par. After reviewing my parts purchases, I am more willing to accept faulty parts.



Schematic for Minimum Theremin by Arthur Harrison

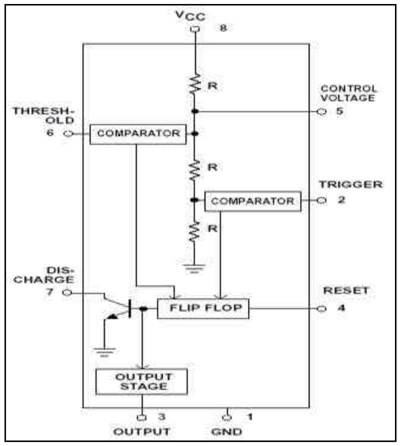
The schematics all specify either general-purpose CMOS logic gates like the type common ten years ago, or a specific part, namely the Motorola MC14069UBCP. The parts I had ordered from DigiKey were manufactured by Texas Instruments. They were supposed to be drop in replacements because the 40xx series of CMOS logic chips are industry wide standards. However, it turns out that the Texas Instruments chips I had contained pulse shaping input and output circuitry to make them more robust against electrical shock and increase noise immunity, which included varying capacitance. Basically, although the logic functionality of the chips I had was exactly what I needed, the small-signal operation was completely different and made my circuits at best non-operable.

Optical Design

The NE-555 Integrated Circuit

After disappointment with the CMOS logic based circuits that followed the circuit topology of the original Theremin, I took a break and thought about other methods of sound generation. I remembered one of the first things I built when I got into electronics as a kid was a little tone generator using a NE-555 general-purpose timer chip. The NE-555 was first introduced in 1972 but has become a mainstay in the electronics world. It is a very versatile chip that can operate in many modes.

The NE-555 is an 8 terminal device that contains a resistor ladder, two comparators, a flip-flop and an output stage. The resistor ladder divides the power supply voltage into two references at 1/3Vcc and 2/3Vcc, which are used as the reference points for the two comparators. (Vcc is the supply voltage referenced to ground) Each comparator is like a decision maker; it looks at its two inputs and turns its output on or off depending on which input is higher. The *Threshold* comparator turns on if the voltage on the threshold pin is greater than 2/3Vcc. The *Trigger* comparator turns on if the voltage on the trigger pin is less than 1/3Vcc. The flip-flop is like a single memory cell that can hold only one value. It sets to a one only when the *threshold* comparator goes high and sets to a zero only when *trigger* comparator goes high. The flip-flop holds its state until the other input goes high, even if the other input goes low some time before that. The flip-flop can also be reset with the *Reset* input pin. The *output* is capable of supplying or sinking current (Jung, 25-32)



NE-555 Block Diagram
Philips Semiconductors Linear Products

The NE-555 can easily be configured into an RC astable multivibrator. An RC chain is connected from the *output* to the ground with the capacitor connected to ground. The *threshold* and *trigger* inputs are tied together and connected to the middle of the RC chain at the top of the capacitor to sense the capacitor voltage. When powered on, the *output* will be high and the capacitor will start to charge through the resistor. Once the capacitor voltage reaches 2/3Vcc the *threshold* comparator will set the flip-flop and the output will go low. Now the capacitor discharges through the resistor until it reaches 1/3Vcc and the *trigger* comparator resets the flip-flop sending the output back high and restarting the cycle. (Jung, 149-151) The voltage on the capacitor is somewhat triangular. The frequency is easily selectable using the formula:

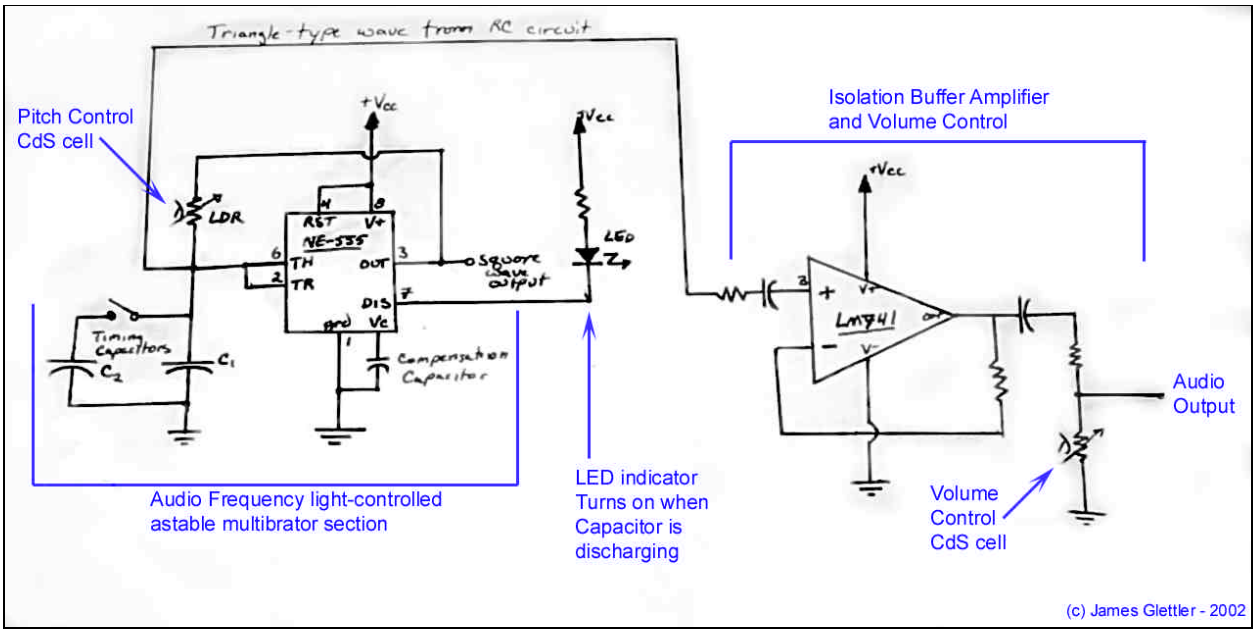
$$f_0 \cong 1.4 \cdot R \cdot C$$

Circuit Design for Optical Control

Instead of operating this circuit at radio frequencies, I want to create the audio frequencies directly. However, using reasonable values for the circuit makes varying capacitance absolutely useless. Instead, I have to vary the resistance of the circuit in some way but do it without touch. The easiest way to do that is with a Cadmium-Sulphide (CdS) photocell. This is a simple device that acts exactly like a resistor with one catch. More light causes the CdS cell to decrease resistance and less light causes the CdS cell to increase in resistance. The more general name for the CdS cell is a light dependent resistor (LDR). The CdS cell I'm using varies from about 1kohm to about 300kohms over the range of its use. Without changing the capacitance, this gives a few octaves of range. The catch is that it must be played in bright light and unlike the Theremin, which is based on absolute distance, the pitch is based only on light falling on the CdS cell. This turned out to be both bad and good but it was definitely fun.

The output of the NE-555 multivibrator is an imperfect square wave. This is just a little too rich in harmonics to be pleasing to the ear but it was powerful enough to drive an amplifier directly. I could pass the output through a resistive divider with another CdS cell to act like a volume control but there was still the problem with the harsh sound. The waveform across the capacitor however was somewhat triangular and had much less harmonic content. Taking the output from the capacitor loaded down the multivibrator circuit due to current leaking into the audio output. This basically ceased the operation of the instrument.

In order to utilize the waveform on the capacitor without loading down the circuit I used an LM741 general-purpose operational amplifier (op-amp). An op-amp is just a special amplifier for signals that has an inverting and non-inverting input. By using the LM741 and some other circuitry I was able to isolate the multivibrator but still read the waveform of the capacitor. Then I could put the output of the LM741 though the same resistive CdS cell divider for volume control. The final circuit is shown below with the individual sections labeled:



Final Schematic of Optical Theremin

The RC chain with the CdS cell that controls the frequency of the astable oscillator is easily seen on the leftmost part of the circuit. A second capacitor (C_2) can be connected to the circuit with a switch to decrease the range of frequencies. Switching in C_2 doubles the capacitance in the circuit and drops the frequency range by about an octave. In the middle of the circuit is an LED, which is just a solid state light. The LED is used as both a power indicator and for troubleshooting. It blinks once for each cycle of the oscillator. At audio frequencies this is too fast to see, but when the frequency is low (because light is blocked from the pitch control LDR, the LED slowly blinks on and off. The rest of the circuit is exactly as described above with some added components for stability and isolation. The audio output can be coupled directly to any high input impedance amplifier like a stereo.

Results

The 555/CdS based optical Theremin I designed has a minimal parts count and was easy to build. Because it operates at low audio frequencies and is just based on ambient light, there is

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no need to worry about circuit layout, radio radiation concerns and tuning. The cheap and abundant parts made cost of the final design under $5. The simplicity of this circuit and the ability to build it on a bread board would make it a good project for students interested in getting involved in electronics.

The sound coming from this circuit isn't too exciting but succeeds because it is neither pure like a sine wave nor harsh like a square wave. The sound color or timbre is pretty constant from the lowest to highest pitches. The very lowest frequencies (those below about 40Hz) aren't produced very well. This is due for the most part to the capacitive coupling in the isolation amplifier, which blocks DC and low frequencies. Also, because the output resistance of this Theremin is variable, its sound is somewhat dependent on the amplifier connected to it. If the amplifier had a highly capacitive input, changing the volume control could possibly change the frequency content of the signal.

Modifications could be added to this circuit to improve its performance. For instance, the volume control LDR could be incorporated into the feedback loop of the LM741 op-amp to make the output independent of the connected amplifier. A second op-amp or other non-linear element configured as an overdrive or distortion circuit could be added to increase the harmonics in the signal. For a more complex circuit, the LDRs could be replaced by infrared phototransistors and a modulating circuit. In this circuit, modulated infrared light would shine up from the circuit and be reflected by objects in front of it and demodulated by the phototransistors. The result would be a circuit producing a light field to interact with, analogous to Theremin's original design producing an electric field.

Further Studies

Many musicians and composers throughout the years have used the Theremin as an instrument. It would be a great project to compile a list of all the different pieces and styles of music that used the Theremin. Some classic thereminists are Clara Rockmore, Lydia Kavina and Dr. Samuel Hoffman. Clara Rockmore is by far the greatest Theremin player of all time. She developed techniques for greater control and articulation that had been seen before in the 1930s. Today, Lydia Kavina is the leading thereminist and just so happens to be the granddaughter of Leon's first cousin. Dr. Hoffman was a major thereminist and was involved not only in instrumental music but also movie scores. (Max)

But the Theremin is not only made for traditional chamber and classical music. Many popular bands throughout the years from Air, to Led Zeppelin, have used the Theremin. A very good list of bands that have used the Theremin are listed on a webpage hosted by Theremin World at http://www.thereminworld.com/bands.asp.

I would like in the future to build a full vacuum tube Theremin. This is a large jump in complexity from what I accomplished here, but I would really like an instrument that I could learn to play. I would also like to work on additional effects and circuit optimizations to utilize the non-contact control effects in other ways.

Figure, Picture and Formula Index

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