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Playing with electromagnetic waves: The science of the theremin

The physics behind the unique instrument lets players turn hand gestures into music.

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Roughly four decades before Stevie Wonder and the Doors began incorporating electronic synthesizers into their music, another electronic instrument took the world by storm. Demonstrated by the Russian physicist, inventor, and musician Leon Theremin in 1920, the unique device came to carry its creator's name. It was brought to market by RCA in 1929 and was the first commercially available electronic instrument.

Unlike earlier electromechanical musical instruments, the theremin was conceived from the beginning as an apparatus whose sound would be generated entirely electronically. Working in the laboratory of famed theoretical physicist Abram Ioffe, Theremin had developed an early wireless motion-detection alarm system and a device to measure the density and dielectric constant of gases. Both projects explored capacitance changes in circuits, which led Theremin to notice that the position of his hand in an electromagnetic field affected the pitch of the sound emitted by an electric oscillator. That observation inspired him to create a musical instrument, originally marketed as the etherophone and the thereminvox, that could play melodies based on the performer's hand position relative to an antenna.

Theremin probably never imagined that his fascinating creation would have such a significant influence on popular culture and art music. It is indelibly linked to science-fiction film soundtracks—notable examples include the classic 1951 film *The Day the Earth Stood Still* and 2018's *First Man*. Arguably the only instrument that is played without being touched, the theremin has acquired an unmistakable aura of mystery because of its eerie sound. This Quick Study provides an overview of the physics behind this unusual instrument.

The most mysterious instrument

Theremin's first prototype for his device consisted of a wooden box that housed electronic circuits, a vertical antenna for pitch control, and a pedal for volume control. He soon replaced the pedal with a horizontal loop antenna, which resulted in the design that is commonly used today. Both antennas produce an electromagnetic field.

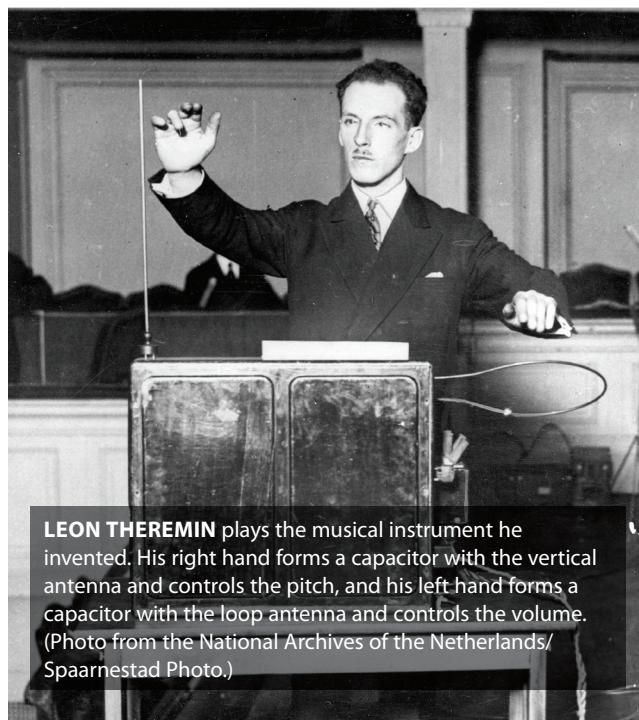
Together, the vertical antenna and the player's hand make up the two conductive plates of a capacitor whose dielectric is the air between them. As the hand approaches the antenna, the capacitance increases, which changes the frequency of the alternating current in a circuit and results in a higher pitch. Specifically, the change in capacitance—typically only a few picofarads—changes the frequency of a variable oscillator.

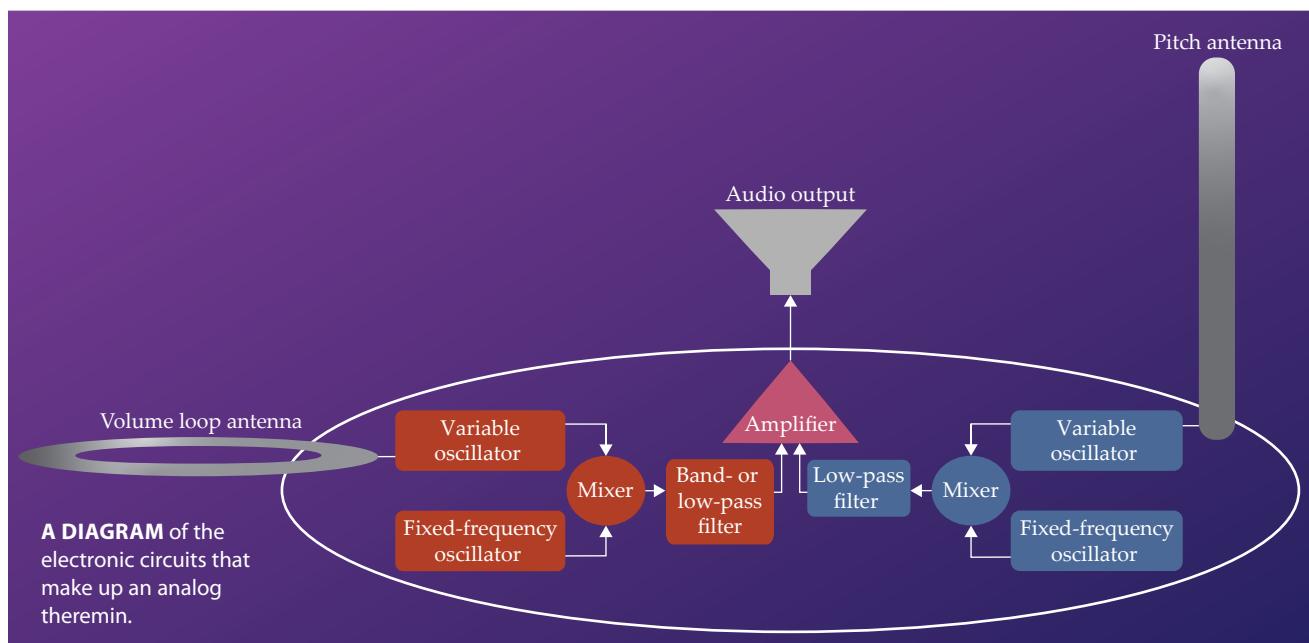
That oscillator and one of fixed frequency form the pitch-control circuit. Both oscillators typically consist of a capacitor and an inductor connected in parallel.

The player's other hand forms a capacitor with the horizontal loop antenna, which is used for volume control. Attached to it is a second circuit that is also made of a fixed-frequency oscillator and a variable oscillator. In the volume-control circuit, changes in capacitance result in changes in the volume of the produced sound: The closer the hand is to the horizontal antenna, the lower the volume. The shape of the loop antenna makes the instrument particularly sensitive to vertical motion just above and inside the loop. That sensitivity allows players to easily create nuanced dynamic changes—and even instantaneous silences—with intuitive hand motions.

How the magic happens

Both circuits operate on the heterodyne principle. Developed in the early 20th century for radio communications, the technique involves multiplying two electromagnetic oscillating signals of different frequencies to produce new signals at the sum and





the difference of the original frequencies. In the pitch-control circuit, the variable and fixed-frequency oscillators each produce a high-frequency AC signal: between 170 kHz and 1 MHz, depending on the design. The two oscillator signals are then multiplied by a nonlinear mixer (see the circuit diagram) to create a signal with two frequency components. The lower-frequency component of the new signal, which ranges from about 65 Hz to 3 kHz, is termed the beat frequency.

To obtain an audible tone that can be sent to an output, the mixed signal is sent through a low-pass filter, which isolates the audible components by attenuating higher frequencies that are still contained in the signal as harmonics and intermodulation products. The signal is subsequently routed through a voltage-controlled amplifier before being sent to the audio output, which is typically an external speaker.

In the volume-control circuit, one or two high-frequency oscillators are used, whose combined signal is routed first through another nonlinear mixer before being sent to a filter. A band-pass filter is sometimes used instead of a low-pass filter because the former gives the instrument a greater dynamic range and makes the volume response more sensitive to smaller hand motions. The signal from the filter is then routed through the amplifier.

Classic analog theremins do not produce sounds precisely tuned to traditional musical notes; instead, they generate a continuous set of tones depending on the player's ability to stabilize the position of their hands within the electromagnetic field. Some digital or hybrid theremins—those that combine analog sensor circuits with digital sound engines and processing—incorporate pitch quantization, which adjusts the sound to the nearest note in a chosen musical scale. That feature comes at the cost of the expressiveness that is possible on analog theremins.

Both classic and digital theremins have a chromatic range of up to six octaves. But players rarely use more than five octaves because the extreme high register is difficult to control with precision: Notes get closer together in the higher octaves as the hand approaches the antenna.

From circuits to sound

Analog and digital theremins differ significantly in their tonal character. The classic analog theremin design incorporates

vacuum tubes or discrete transistors in the oscillators, mixers, and amplifiers. Those components shape the harmonic coloration and the overall timbre of the tone produced. The instrument's tone, linearity, and sensitivity are influenced by the types of capacitors and inductors used, differences in the physical layout of the circuit components, and even the ambient environmental temperature. In fact, the natural nonlinearity and slight instabilities inherent in analog electronic instruments—including early synthesizers—contribute to the characteristic warm sound of classic theremins, with their lively, expressive, stringlike, and sometimes unpredictable tone.

Digital, also known as hybrid, theremins use microprocessors or digital signal processors not only to interpret the position of the player's hands relative to the antennas but also to generate sound. Those theremins often come with built-in effects, pitch quantization, and banks of preset sounds, some of which attempt to emulate the classic theremin. But digital circuitry makes the sound of those theremins more stable and less harmonically complex. Their timbre is cleaner or cooler than that of analog theremins.

The reference standard used by both builders and performers to evaluate the tone quality of a theremin is the sound emitted by the first model manufactured by RCA. Known for producing what is sometimes called the holy grail of theremin tones, it has a resonant, woody low end; a sweet high register; and the distinctive warm harmonic coloration that is characteristic of vacuum-tube circuitry. Although current technology can approximate that ideal sound, the dexterous hands of skilled performers like Theremin himself are still required to achieve sonic excellence.

Additional resources

- K. D. Skeldon et al., "Physics of the theremin," *Am. J. Phys.* **66**, 945 (1998).
- F. K. Prieberg, *Musica ex machina: Über das Verhältnis von Musik und Technik* (Musica ex machina: On the relationship between music and technology), Ullstein (1960).
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