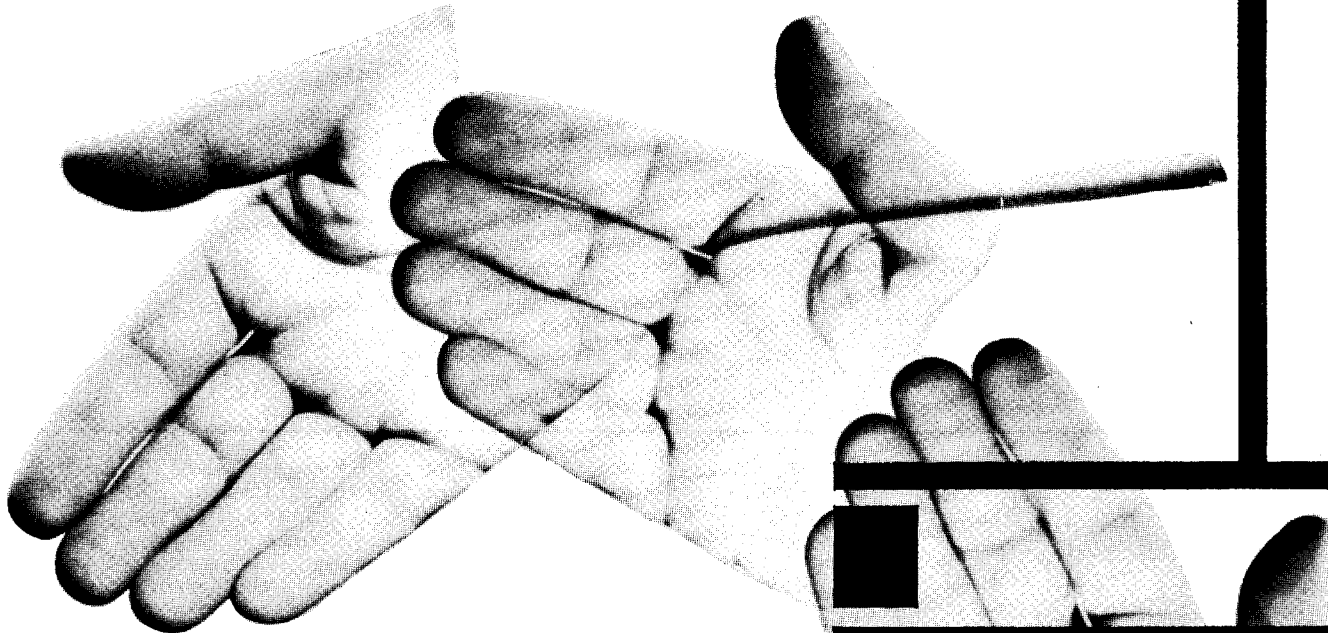
A TRANSISTORIZED THEREMIN

By ROBERT A. MOOG

Build this self-powered, three-octave instrument that will bring "music from the ether." Self-contained unit may be connected to any external amplifier and speaker.



IN 1928, electronics was a new and mysterious field. Radio News magazine (as Electronics World was then called) featured articles describing a novel type of radio receiver called the superheterodyne; hi-fi, television, and electronic computers were yet to come. And in 1928, Professor Leon Theremin, a young Russian physicist, introduced to this country a musical instrument which he had invented. The instrument, named for its inventor, had two remarkable features. First, it was entirely electronic and, except for its loudspeaker, had no moving parts. Second, and equally remarkable, the performer played the instrument *without touching it*.

The first public demonstration of the Theremin was given on January 31, 1928 at the Metropolitan Opera House in New York City. The program cover set the mood for the evening: "Music from the Ether," emanating from a pair of slender hands which were reaching out of a raging fire. A fascinated audience heard Rudolf Wurlitzer introduce Professor Theremin and explain that Theremin would play his instrument by varying the position of his hands in the space around it. The audience became even more fascinated when Professor Theremin began to play. The music was unlike anything they had heard before, but was reminiscent of a musical saw. However, the feature of the performance which undoubtedly amazed the audience most was the manner of performance; it was difficult for them to understand how the movement of the performer's hands in space could be used to create music.

Today, "electronics" is a household word. There are millions of color TV sets and stereo sound systems in our homes. We are accustomed to reading newspaper accounts of scientists controlling satellites which are hundreds of thousands of miles distant. Yet the Theremin, invented over thirty years ago, still mystifies and fascinates all who hear it. This may seem surprising at first, since the instrument is basically simple. However, the Theremin's main element of fascination is its completely unique method of playing. It is truly the most modern and original of musical instruments.

The instrument to be described is a transistorized Theremin, powered by a small battery, and designed to be connected to any external amplifier. Although it is quite simple and inexpensive to build, it is a true musical instrument. Its pitch range covers more than three octaves. Its tone quality is pleasing and rich in harmonics. The playing technique can easily be mastered by

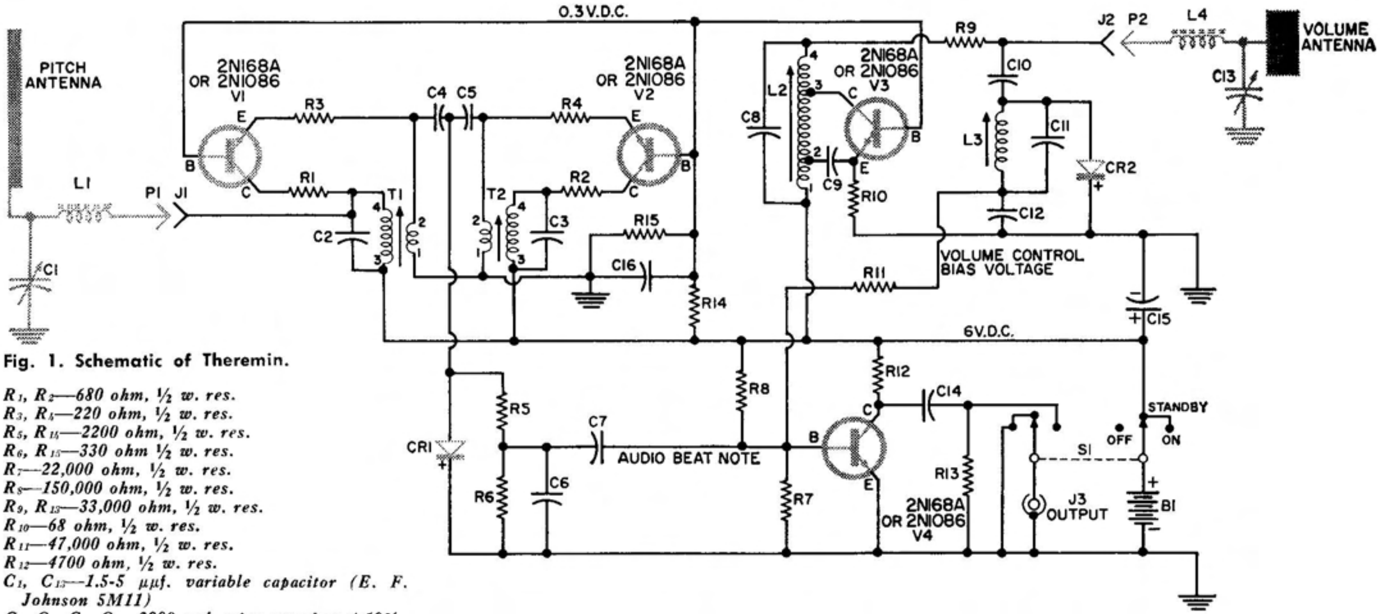


Fig. 1. Schematic of Theremin.

R_1, R_2—680 ohm, ½ w. res.
R_3, R_4—220 ohm, ½ w. res.
R_5, R_{14}—2200 ohm, ½ w. res.
R_6, R_{15}—330 ohm ½ w. res.
R_7—22,000 ohm, ½ w. res.
R_8—150,000 ohm, ½ w. res.
R_9, R_{13}—33,000 ohm, ½ w. res.
R_{10}—68 ohm, ½ w. res.
R_{11}—47,000 ohm, ½ w. res.
R_{12}—4700 ohm, ½ w. res.
C_1, C_{13}—1.5-5 μμf. variable capacitor (E. F. Johnson 5M11)
C_2, C_3, C_4, C_5—3900 μμf. mica capacitor ±10%
C_6, C_9, C_{12}—.1 μf., 10 v. ceramic capacitor
C_7, C_{14}—.47 μf., 10 v. ceramic capacitor
C_8, C_{11}—560 μμf. mica capacitor ±10%
C_{10}—.005 μf. ceramic capacitor
C_{15}—2 μf., 12 v. elec. capacitor
C_{16}—2.2 μf., 3 v. ceramic capacitor
L_1—75 mhy. pitch antenna coil (Moog 11-311) or three 25 mhy. ferrite-core r.f. chokes in series (J. W. Miller 6308 or Meissner 19-1053). See text.
L_2—Volume oscillator coil (Moog 11-302, see text)
L_3—Volume control coil (Moog 11-303, see text)
L_4—10 mhy. volume antenna coil (Moog 11-312) or two 5 mhy. ferrite-core r.f. chokes in series (J. W. Miller 6304 or Meissner 19-1051).
T_1, T_2—Pitch oscillator transformer (Moog 11-301, see text)
J_1, J_2—Pin or banana jack
J_3—Phono jack
P_1, P_2—Pin or banana plug
S_1—D.p. 3-pos. shorting rotary switch (Mallory 3123J)
B_1—6-volt battery (Eveready 724 or equiv.)
CR_1, CR_2—1N34 or equiv.
V_1, V_2, V_3, V_4—"n-p-n" transistor (G-E 2N168A or 2N1086 or equiv.)
NOTE: Coils for this unit may be purchased direct from R. A. Moog Co., Box 263, Ithaca, N.Y. Price for a complete set of coils (T_1, T_2, and L_1 through L_4) is $12.50 plus postage. Individual coils are also available. In addition, a complete kit of parts for the construction of the Theremin is available. Orders for coils or requests for information on the kit should be sent direct to the company.

anyone with a musical ear. And, most important from a musician's viewpoint, the instrument is exceptionally stable and reliable.

How it Works

The Theremin works by taking advantage of the fact that the hand is a conductor of electricity, and that its connection to the rest of the body effectively grounds it. Thus, the hand can be regarded as a grounded plate of a capacitor. If the hand is moved with relation to another electrical conductor, we have a variable capacitor. In playing the Theremin, the performer varies the capacitance between his right hand and a "pitch-control antenna" to determine the pitch of the tone, and varies the capacitance between his left hand and a "volume-control antenna" to determine the loudness of the tone.

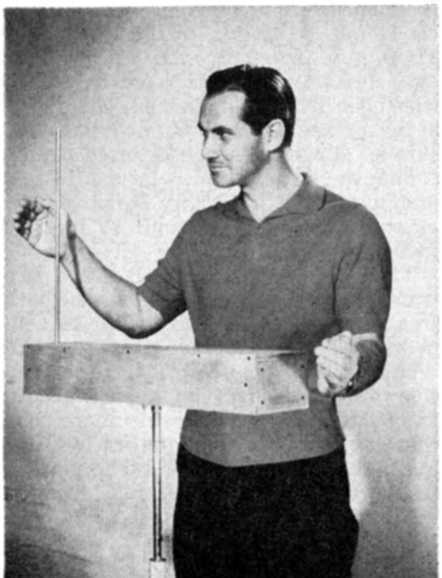
How does the Theremin utilize capacitance to control the pitch (frequency) or loudness of a tone? To answer this question, let us first examine the pitch-generator section of the schematic diagram (Fig. 1). The pitch-generator consists of two stable r.f. oscillators, V_1 and V_2, both of which operate at about 150 kc. The signals from these two oscillators are mixed through C_4 and C_5, and rectified by CR_1. The frequency of the signal appearing at the junction of C_6 and C_7, which is the output of the rectifier circuit, is equal to the difference between the frequencies at which V_1 and V_2 oscillate. If V_1 and V_2 are oscillating at the same frequency, then the difference frequency is zero and no a.c. voltage appears at the junction of C_6 and C_7. If the oscillation frequency of V_1 is one per-cent lower than that of V_2, then the difference frequency appearing at the output of the rectifier circuit is one per-cent of 150 kc., or 1.5 kc. This frequency is in the middle of the audio-frequency spectrum, and is about two and one-half octaves above middle C on the piano. Thus, by lowering the oscillation frequency of V_1 by only one per-cent, the difference frequency can be swept through a wide pitch range, starting at "zero beat" and going continuously up in pitch through all but the highest notes on a piano.

This one per-cent change in the oscillation frequency of V_1 is caused by the change in hand capacitance. Hand capacitance never exceeds a fraction of a micromicrofarad. If this capacitance were to be applied directly across the tank of oscillator V_1, the oscillation frequency would change by only a few hundredths of a per-cent. Naturally, this change is not enough to produce an adequate pitch range for a musical instrument.

To increase the effect of the hand capacitance on the frequency of oscillation of V_1, a coil with high inductance, low distributed capacitance, and low loss (L_1) is connected between the pitch-antenna and the tank of oscillator V_1. This antenna coil forms a series-resonant circuit with the combined capacitance of C_1 and the pitch-antenna, the resonant frequency of which is slightly below the resonant frequency of the oscillator tank. The total impedance of this series-resonant circuit, as seen by the oscillator tank, is much lower than the impedance of just the pitch-antenna alone In addition, the *change in impedance* of the series-resonant circuit resulting from variation in capacitance at the pitch-antenna is also much greater than the *change in impedance* of just the pitch-antenna alone. These two factors combine to greatly increase the effectiveness of the pitch-antenna, so that a change of a fraction of a micromicrofarad at the pitch-antenna does, in fact, cause the difference frequency to change by as much as 1.5 kc.

The coupling of oscillators V_1 and V_2 through capacitors C_4 and C_5 produces two effects which are desirable in a Theremin. First, the oscillators tend to synchronize when their frequencies are very close together, making it easy for the performer to adjust for "zero beat." Second, even when the oscillators are

Performer's right hand determines pitch while his left hand controls the volume.



not synchronized, they "pull" each other. This pulling is characteristic of any beat oscillator circuit in which the oscillators are coupled. As a result of the pulling, the waveform of the audio difference frequency signal is saw-tooth-like, and contains a succession of overtones that impart a pleasing quality to the tone. The degree of coupling has been set to give a moderate amount of pulling, but not enough to cause instability at low difference frequencies.

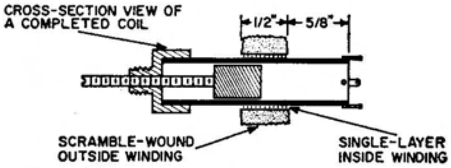
Now let us turn our attention to the volume-control section. In this section, as in the pitch-generator section, the combined capacitance of the control antenna and C_{13} is in series with a high-inductance, low-loss coil L_4, forming a series-resonant circuit. L_4 is connected to a fixed-frequency oscillator V_3 through a large resistance R_9. The impedance of the antenna series-resonant circuit is lowest when its resonant frequency is equal to the oscillator frequency, and increases as its resonant frequency is lowered, for instance by the addition of hand capacitance to the volume-control antenna. When the impedance of the antenna circuit increases, the r.f. voltage at the junction of R_9 and L_4 also increases. This r.f. voltage is applied across the parallel-resonant circuit C_{11} and L_3, and is rectified by CR_2. A negative d.c. voltage, which is proportional to the r.f. voltage, is thus developed at the junction of R_{11} and C_{12}. When the resonant frequency of the antenna circuit is equal to the oscillator frequency, the d.c. voltage at the junction of R_{11} and C_{12} is only a few tenths of a volt. As the resonant frequency of the antenna circuit is lowered, this voltage increases to about five volts.

Although the pitch-antenna circuit and the volume-antenna circuit are similar, they are applied in different ways. The pitch-antenna circuit is connected directly across the tank of oscillator V_1, and is used to change the *frequency* of oscillation. The volume-antenna circuit is connected to the tank of oscillator V_3 through a large resistor, and is used to change the *amplitude* of the r.f. voltage at the junction of R_9 and L_4.

The d.c. voltage developed at the junction of R_{11} and C_{12} is applied through R_{11} as bias to the base of control amplifier V_4. By increasing the d.c. bias voltage, the collector current of V_4 can be decreased until it is completely cut off. The audio signal from the pitch-generator section is also applied to the base of V_4. The a.c. output signal appearing at the collector of V_4 can be varied in amplitude from about 0.5 volt (minimum d.c. control voltage) to zero (maximum d.c. control voltage), and is fed to the output jack through isolating capacitor C_{14}.

The instrument is powered by a small six-volt battery. The current drawn by each of the three oscillators is stabilized by its emitter resistor, the base voltage being fixed by the resistive voltage divider R_{14} and R_{15}. Total battery current is about 8 ma.

A three-position switch is used to turn the instrument on. The first position is "off," and no battery current flows. The second position is "silent" or "standby," in which battery current flows but the output jack is shorted to ground. The third position is "play" or "on," and the short across the output is removed. This arrangement is needed to eliminate the transient accompanying the initial flow of battery current from getting into the amplifier and being heard as a thump at the loudspeaker.



General Instructions:
1. *Use one-half-inch diam., slug-tuned coil forms (CTC LS4/K or J. W. Miller 22A000 RB1)*
2. *Use #36 enamelled and cotton-covered wire.*
3. *Space the windings 5/8" from the lug end of the form and wind the coils 1/2" wide (see diagram above).*
4. *Always wind in the same direction around the coil form, for a given coil.*
5. *Coat the completed coils with a polystyrene-base coil dope.*

Specific Instructions:
1. *T_1 and T_2: First, wind 20 turns in a single layer. Start of this winding is terminal #1 and the end is terminal #2. Next, scramble-wind 145 turns over the 20-turn layer. Start of the 145-turn winding is #3 and the end is #4. Do not wind tape or other insulation between the first and second windings.*
2. *L_2: Start at terminal #1. Wind 5 turns in a single layer and bring a tap out to terminal #2. Next, scramble-wind 30 more turns and bring another tap out to terminal #3. Finally, scramble-wind 95 more turns and connect the end of the winding to terminal #4.*
3. *L_3: Scramble-wind 130 turns.*

Fig. 2. Details on coils employed in unit.

Construction

Building a transistor Theremin is a relatively easy matter. Since the two control antennas have to be separated by at least twenty inches and have to be about three and one-half feet from the ground, we found it convenient to mount everything on a plywood board, and fasten a flange with a standard microphone-stand thread (*Atlas* AD-11) to the bottom of the board. The entire instrument can then be supported by a microphone stand. The photos reveal the layout of components on the board. The board is 1/2" plywood, 24" long by 5 1/2" wide. Two pieces of wood 5 1/2"x 3"x1 1/2" are fastened at either end of the board. These pieces of wood hold the antennas. The pitch antenna, which goes on the right end of the board if you are right-handed, is an aluminum rod 3/8" in diameter and 21" long (3/8" aluminum rod is sold in hardware stores that carry *Reynolds* "do-it-yourself" aluminum). A vertical hole slightly larger in diameter than the 3/8" rod is drilled through the block that goes at the right end of the board. A wood screw is put into the board beneath the block hole, so that with the block in place, the rod can be dropped in the hole, and will rest on the screw head. A wire is fastened to the wood screw before the block is screwed to the board.

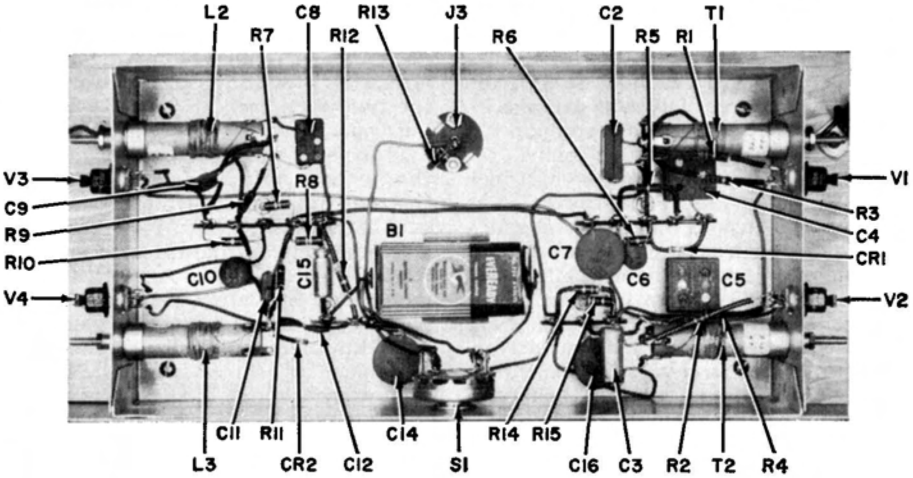
The volume-control antenna is a sheet of aluminum, 5 1/2"x 3 1/2", fastened to the outer face of the block at the left end of the board. Connection to the antenna is made by a wire under one of the mounting screws.

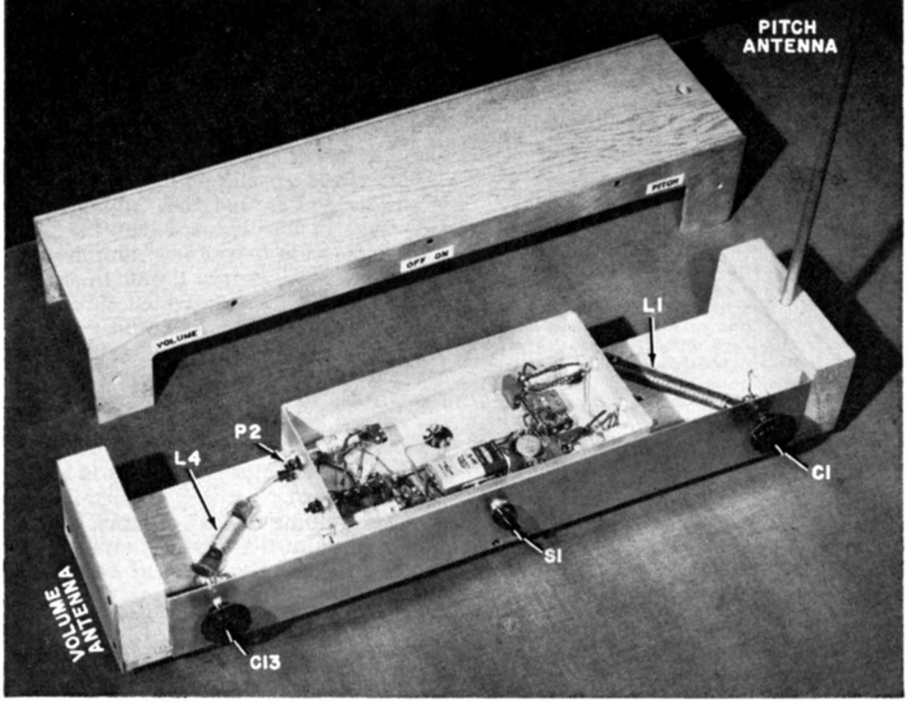
All components, except the antenna circuit components, are mounted on a 5"x 10"x 3" aluminum chassis (*Bud* AC-404) on the middle of the board. The antenna coils L_1 and L_4 are mounted on the board between the chassis and the end blocks, and tuning capacitors C_1 and C_{13} are mounted on a 3"x 22" sheet of aluminum that runs across the entire front of the instrument between the two end blocks. This arrangement minimizes the stray wiring capacitance in the antenna circuits, but provides shielding between the performer's hands and the antennas when he adjusts C_1 or C_{13}.

Other layouts may be employed as long as two requirements are heeded: First, the two antennas must be separated by at least twenty inches, so that the motion of the right hand does not affect the left antenna, and *vice versa.* Second, the antenna capacitances must be kept small. Don't mount the antennas near large pieces of metal. Keep the leads coming from the antennas as short as possible. And, finally, use only wood or other insulating materials for the bottom board and the cover.

The chassis layout is not critical, but it is most convenient to mount the components in the pitch-generator section on the side of the chassis nearest the pitch antenna, and the components in the volume-control section on the side

Looking into the open top of the chassis reveals this simple component layout.





Over-all view of the entire instrument with its wooden cover removed to show layout.

nearest the volume antenna. It is also convenient to mount the output jack on the bottom of the chassis, so that the cord going to the external amplifier can be plugged in through a hole in the plywood board, out of the way of the performer.

Placement of the coils in the chassis is important. The centers of the pitch-oscillator coils should be at least three inches apart, in order not to increase the coupling between the oscillators. Similarly, the volume-oscillator coil should be at least three inches from L_3. Also, none of the coils should be closer than one-half inch to the sides of the chassis. A suitable layout is shown in one of the photos. Regular lug strips are used to mount most of the components. The use of transisitor sockets, rather than soldering the transistors directly in the circuit, is desirable in the long run.

The layout, as shown in the photographs, is correct for a right-handed person. If you are left-handed, simply reverse the layout so that the pitch-antenna is on the left end of the board. Of course, a left-handed person can play a right-handed instrument, simply by standing behind the instrument instead of in front of it.

Coils

The coils T_1, T_2, and L_1 through L_4 have been specially designed for this instrument and are available direct from the manufacturer. The coils can also be assembled from standard components and materials. The variable coils T_1, T_2, L_2, and L_3 are wound on one-half-inch diameter slug-tuned coil forms. The winding dimensions and material specifications are given in Fig. 2. A partially completed pitch oscillator coil and a completed coil are shown in one of the photos. If the instructions in Fig. 2 are followed carefully, the electrical characteristics of the hand-wound coils will be nearly the same as those of their commercially produced counterparts.

The antenna coils are machine-wound by a special method called "progressive-universal," and cannot be duplicated by hand-winding. However, satisfactory substitutes for the antenna coils may be assembled from standard ferrite-core r.f. chokes. For L_1, connect three 25 mhy. ferrite-core chokes in series, and for L_4, connect two 5 mhy. ferrite-core chokes in series. Because of their low *"Q"* and high distributed capacitance, air-core or powdered-iron-core chokes cannot be used in place of ferrite-core chokes to make up the antenna coils.

Setting the Coil Slugs

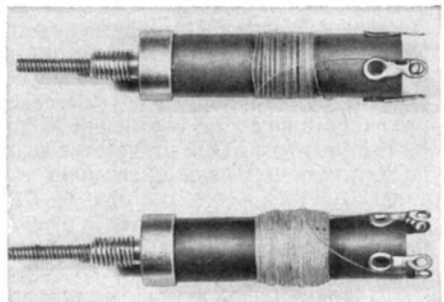
After checking the wiring thoroughly, turn the instrument on and check the voltages at the two points shown in the schematic. If the voltages check, connect an external amplifier to the output jack, and short the junction of R_{11} and C_{12} to ground. If a loud hum is heard when the base terminal of V_4 is touched with the finger, the amplifier stage is working and the pitch adjustments may now be set. Place the Theremin on a microphone stand, and at least two feet from any large objects. Set the slug in T_1 all the way out, and the slug in T_2 half way in. Turn C_1 so that its plates are half meshed. With the junction of R_{11} and C_{12} still shorted to ground, advance the slug in T_1. When the resonant frequency of T_1 approaches that of T_2, a loud, high beat note will be heard, which decreases in pitch as the slug in T_1 is advanced, and disappears entirely when the two pitch oscillators are zero-beating (operating at the same frequency).

If the slug in T_1 is advanced still further, a beat note is again heard. Leave the slug in T_1 at the point where the beat note starts again. Now check the pitch-antenna as follows: Set C_1 so that, when you stand away from the instrument, the oscillators zero-beat, but a beat note is heard as soon as your hand is within eighteen inches of the pitch-antenna.

Now move your hand slowly toward the antenna and listen closely. The pitch of the tone will go up gradually. If at one point it jumps suddenly to a very high note, then the resonant frequencies of T_1 and T_2 are too low. Retract the slug in T_2 a couple of turns and repeat the adjustment procedure. If no jumps in frequency are heard as the hand approaches the pitch antenna, touch the antenna and listen to the pitch of this note. If it is about three octaves above middle C on the piano, then T_1 and T_2 are adjusted correctly.

If the note is much higher than three octaves above middle C, then the resonant frequencies of T_1 and T_2 are too low. Retract the slug in T_2 one turn and repeat the adjustment procedure. Similarly, if the note is much lower than three octaves above middle C, then the resonant frequencies of T_1 and T_2 are too high. Advance the slug in T_2 one turn and repeat the adjustment procedure.

If you don't have a piano, you can whistle a high note and this will be close



If the instructions in Fig. 2 are followed carefully, the coils will look like this. Top view shows just single-layer inside winding of T_1. Completed coil is below.

to three octaves above middle C. By repeating the above procedure a couple of times the correct setting of T_1 and T_2 will be achieved.

To set the slugs in L_2 and L_3, remove the short from the junction of R_{11} and C_{12} to ground, and place it from the junction of C_6 and C_7 to ground. Connect a 20,000 ohms-per-volt voltmeter from the junction of R_{11} and C_{12} to ground, retract the slugs in both L_2 and L_3 all the way and set C_{13} so that the plates are about one quarter meshed. The voltmeter should read a couple of volts. Standing away from the volume-antenna, advance the slug in L_2. The meter reading will drop, reach a minimum, then slowly start to climb. Set the slug where the meter reading is at a minimum. At this point, the frequency of oscillation of V_3 is equal to the resonant frequency of the volume-antenna circuit. Next, place your hand on the volume-antenna and advance the slug in L_3. The meter reading will now increase, reach a sharp maximum, then decrease. Set the slug in L_3 where the meter reading is at its highest value (about five volts). This completes the setting of L_2 and L_3.

You are now ready to try your Theremin. Set the instrument on a microphone stand, and at least two feet from walls or large pieces of furniture, and connect it to the amplifier. The Theremin is tuned first by setting the volume

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Transistorized Theremin

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adjustment (C_{13}) and then by setting the pitch adjustment (C_1). To set C_{13}, place your hand near the pitch antenna, in order to produce an audible note. Increase the capacitance of C_{13} until the note begins to get softer. You will then find that the tone gets softer when you bring your left hand near the volume-antenna, until it is inaudible when your left hand is within an inch or so of the antenna. Now set C_1 so that the pitch oscillators zero-beat when you stand away from the instrument, but the tone begins when you bring your right hand within eighteen inches or so of the pitch-antenna.

Tuning adjustments set? Then play a song! But if you can't quite manage that on your first try, don't get discouraged. The Theremin, like any other musical instrument, takes some practice to be played correctly. Try these simple exercises:

1. Think of a note. Hum it to yourself. Then play it on the Theremin. Hold it steady for a few seconds. Concentrate on keeping your body motionless and erect, and your arms relaxed.
2. Think of two notes, and hum one and then the other to yourself. Play the first note on the Theremin, then glide to the second note. Glide slowly at first, then make the glides more abrupt as you become more proficient.
3. Practice scales and *arpeggios,* slowly at first, then faster as you become more efficient.
4. Do exercises 2. and 3., but bring your left hand near the volume antenna to silence the tone when going from one note to another. This exercise teaches you to "feel" where the notes are.

After you have mastered these exercises, try playing some simple songs. At first, special care should be given to playing the notes correctly. Later, shadings can be added with the left hand. A *vibrato* can be introduced into the tone simply by moving the right hand back and forth a few times a second. This motion should not be more than one-quarter inch, and should be done primarily from the wrist. The *vibrato* gives the Theremin tone warmth and expressiveness.

Once you become a proficient Thereminist, you will find many opportunities to display your talents. Theremin music is ideal for providing backgrounds for amateur plays, for melodic classical and religious music, or for adding a novel touch to dance bands and vaudeville acts. Even if you never take the time to become an accomplished Thereminist, the instrument will provide you and your friends with hours of entertainment. But whether you use the Theremin for playing "serious" music or just for experimenting, you will have an instrument that evokes as much mystery and fascination today as it did in 1928. In short, you will be able to produce "Music from the Ether." -30-