# A SOLID-STATE THEREMIN

Here is a project for which we have had many requests over the past years. It is the Theremin, an instrument with a reputation bordering on the mythical. Most people know that it can be used to produce weird sound effects for science fiction films and the like, but few have seen one and fewer still have been close enough to try one. In this article, construction of a Theremin is described in detail.

### By Leo Simpson

Invented by a Russian named Leon Theremin, in the early days of radio, the instrument is very simple in its principle of operation. Its sound output is controlled in pitch and loudness by the effects of hand capacitance. The player merely waves his hands near two "antennas" to produce the weird sound effects—and music!

The control functions of the instrument consist of two fairly distinct sections: (1) one of the player's hands, one antenna or capacitance plate and the associated circuitry to produce the desired note or audio frequency; (2) the player's other hand, a second capacitance plate and more circuitry to control the loudness of the sound produced. Over and above these sections, there is the amplifier system, the loudspeaker and the power supply, of which more will be said later.

Basically, the audio tone or musical note is produced by heterodyning two radio frequency oscillators to produce an audible "beat" or difference frequency. Most readers will have heard a similar kind of whistle, produced when an oscillating radio receiver is turned across the carrier frequency of an incoming station. By

carefully manipulating the receiver dial, it is possible to produce a beat ranging from a high frequency whistle to a low frequency growl.

As might be expected, the two oscillators in a Theremin, used to produce the audible beat, must be set up so that they can operate very close together in frequency, without too obvious a tendency to "pull" one another or to lock together.

One oscillator must be designed so that its frequency will change readily when a hand is brought close to a capacitance plate which is part of its circuitry. The other oscillator should not exhibit this effect and, in practice, is pre-set so that it oscillates on the same frequency as the "variable" oscillator when the latter's natural frequency is not being disturbed. With both oscillators on the same frequency, there is "zero beat" and no audible note is heard from the loudspeaker system.

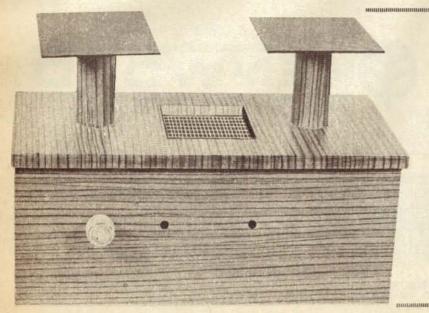
When a hand is brought near the capacitance plate, the frequency of the variable oscillator changes and a beat note is produced. With suitable design, the beat note can be changed from near zero frequency to the limit of

audibility. In part the art of playing a Theremin is in being able to move the hand with sufficient control and subtlety to produce a desired sequence of musical notes. Moving the hand from one position to the next must inevitably produce a gliding tone, or glissando effect, while a slight tremble — intentional or otherwise — will produce vibrato.

For the instrument to have any potential appeal at all, it is essential that the player have adequate control over loudness, not only to give the required emphasis to the melody notes but also to control the glissando effect first mentioned. Control could be obtained with a foot—or hand-operated potentiometer but this would be completely out of keeping with the Theremin idea. Hence the need to adapt hand capacity effects to control loudness as well as pitch and, later in the article, we shall see how this can be done.

Ideally, both the pitch and volume control effects should be as progressive as possible, with pitch and loudness changing smoothly and linearly with movement of the hands within a fairly large "active" distance from the respective plates.

Unfortunately for the present requirement, capacitance varies inversely with the distance between hand and plate, so that the closer the hand is to the plate, the greater is the capacitance change for a given small change in distance. It is quite difficult to counter this effect in a practical kind of instrument and, as a result, the player must be able to position his hands quite accurately and often quite close to the surface of the respective plates to obtain just the right pitch and the right volume level.



At left is a player's eye view of the prototype Theremin. It is played by waving the hands near the two raised plates. The plate on the left controls the pitch while that on the right controls the loudness. The two holes in the panel are screwdriver access holes for initial setting of pitch and loudness. The loudspeaker is installed under the lid but could be fitted in a separate cabinet if desired. The volume control knob is used to set the overall loudness to a suitable listening level. At right is the circuit diagram of the complete instrument. The numbers in brackets after the semiconductor type numbers are the key to their lead connection diagrams.

What would seem, superficially, to be a very simple playing technique turns out, in fact, to be one requiring a great deal of skill and co-ordination, and the Theremin is NOT are easy instrument to play. It may be an interesting electronics project, and it may readily produce audio tones but, before anyone can hope to entertain their friends with music or with designedly weird sounds, they will have to be prepared to put in some solid practice.

The two oscillators controlling pitch utilise the NPN RF transistor, BF115, connected in Colpitts configuration. Operating frequency in each case is around 470KHz. The pitch plate (antenna) is connected to the collector of one oscillator so that hand capacitance will vary its frequency. The other pitch oscillator is tuned with a 100pF rotary, ceramic trimmer capacitor. The waveform from both oscillators is very clean and, as a result the basic beat note would normally be fairly pure.

If the two oscillators were run from the same supply they would "lock" to the same frequency when they came within a few hundred Hertz of each other; this would mean that the beat frequency would not range smoothly down to the low bass region. For this reason, the supply for each oscillator is decoupled via a 1K resistor and 0.1uF ceramic capicator. With the circuit and configuration shown, the two oscillators will not lock until the beat frequency is just a few Hertz. It is desirable that the oscillators do eventually lock, otherwise it would be too difficult to tune for the hold zero frequency with the rotary trimmer.

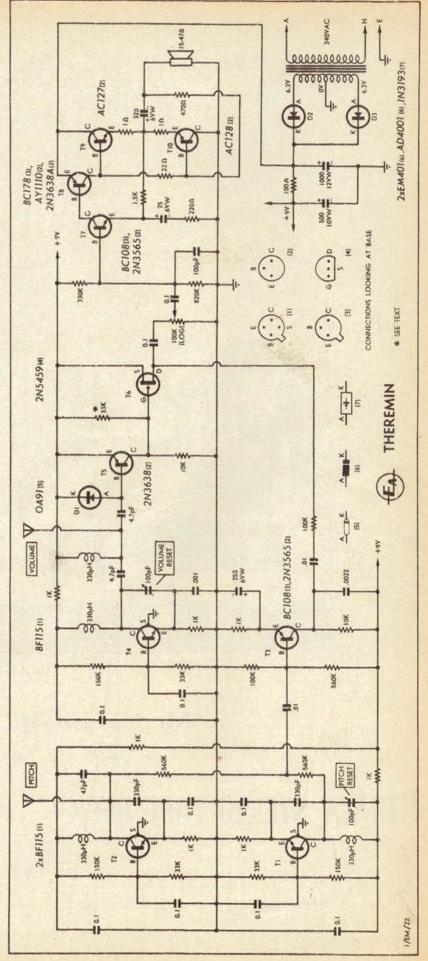
The oscillators will function down to about 5 volts, though with correspondingly reduced output, so that a long battery service life is possible if batteries are used; but more of this anon.

The output from each oscillator is fed via 560K resistors to a mixer stage, consisting of a general-purpose NPN transistor connected in common-emitter configuration. The .0022uF capacitor shunting the collector load resistor attenuates the RF component. The mixer stage is slightly overdriven, partly to ensure sufficient signal at low hattery voltages and partly to add harmonics, so that the sound will be subjectively more "interesting."

The output of the mixer is fed to a signal level voltage divider consisting of a 100K resister and the drain source resistance of an N-channel FET. type 2N5459. The resistance of the FET is dependant on the gate source bias which is provided by the volume control circuitry, involving an oscillator, capacitance plate and DC amplifier.

The "volume" oscillator is also a Colpitts, using a BF115, functioning at around 1.9MHz. This is well removed from the low-order harmonics of the pitch oscillators, minimising the risk of spurious whistles due to the fundamental of the volume oscillator beating with harmonics of the pitch oscillators. The volume oscillator also has its supply decoupled via a 1K resistor and 0.1uF capacitor.

The output of the volume oscillator is fed, via a 4.7pF ceramic capacitor, to a parallel-tuned circuit consisting of a 330uH RF choke and the capaci-



tance of the volume antenna (plate). A portion of the signal across the tuned circuit is coupled to a diode via another 4.7pF capacitor. The DC voltage so derived is amplified by a PNP transistor, T5, and applied to the gate of the FET.

The level of the audio tone being reproduced should increase when a hand is brought near the volume antenna, Initially, the volume oscillator is adjusted, by means of a 100pF rotary ceramic trimmer capacitor, to give a minimum loudness of the audio tone. This involves tuning the oscillator so that its frequency coincides with the resonant frequency of the tuned circuit. As a result, the voltage derived from the diode will be at a maximum so that T5 is forward biased and, consequently, turned on. The gate of the FET is taken toward the positive supply rail and the drainsource resistance held to a low value,

A view of the layout inside the cabinet. The mains cord should be clamped to the chassis (this has been obscured) and knotted as shown, to reduce strain.

shunting a large portion of the beat

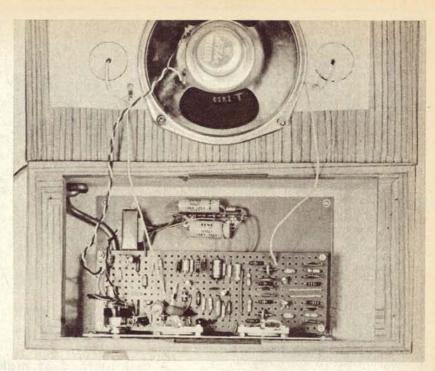
note signal to the positive supply.

When a hand is brought near the volume antenna the hand capacitance in the tuned circuit changes the resonant frequency so that the DC derived from the diode decreases. This progressively carries T5 toward cutoff so that the drain source resistance of the FET increases, and thus more of the audio tone signal is fed to the following amplifier. At this point, a particular characteristic of the FET

becomes apparent. For small voltages of either polarity (or AC) applied between drain and source electrodes, the FET behaves as a resistor which can be varied in linear fashion by a voltage applied between source and gate. From zero to about minus 4 volts between source and gate, the relationship between gate-source voltage and drain-source resistance may be relatively linear but this is no longer true as the gatesource voltage approaches the "pinch-off" voltage of the FET. In this region the relationship becomes very non-linear, a small increase in gatesource voltage resulting in very large change of drain-source resistance; i.e., the FET is turned off over a small voltage range.

The above means that, in a certain region near the volume antenna, a small hand movement will result in a large change in loudness so that it tends to act almost as a switch. To reduce this effect, a 33K resistor is connected between collector and emitter of T5. When the transistor is turned off, the 33K and the 10K collector load resistor form a voltage divider. load resistor form a voltage divider which limits the FET gate-source volt-age to about minus 6 yolts. This has the effect of making the volume control action more progressive but it does reduce the available range of the control.

Note that it is not possible for the volume control circuitry to give zero sound output, since the minimum re-sistance of the FET is typically 300 ohms and it cannot shunt all the signal to the positive supply.



To sum up, then, we see that the pitch of the Theremin is controlled by beating two RF oscillators together, one of which is sensitive to hand capacitance. The resulting beat note can be varied over the whole of the audible range. The loudness of the beat note is controlled by a third oscillator feeding a tuned circuit which has its resonant frequency shifted by hand capacitance. A DC voltage, derived from the tuned circuit, is used to vary the drain-source resistance of a FET, which is part of a voltage divider to which the beat note signal is applied. Having grasped this, the rest of the Theremin is straightforward. Theremin is straightforward.

The signal from the generator and

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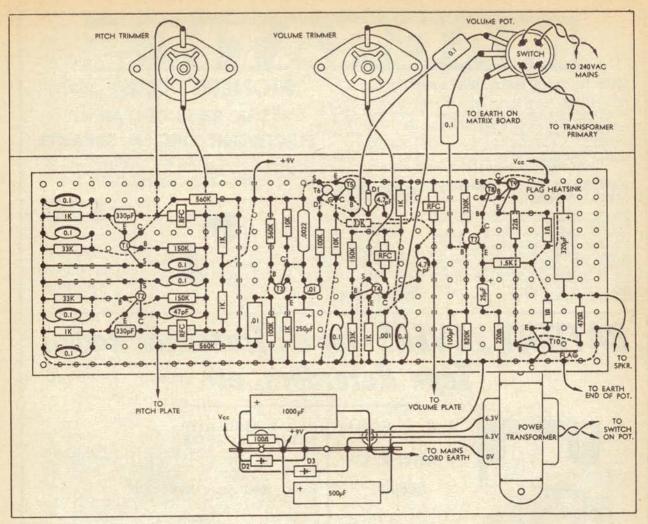
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The above wiring diagram shows all the necessary details so that construction will be straightforward. Note that flag heat sinks should be fitted to the output transistors and the chassis must be earthed via the mains cord.

volume control system is fed to a 100K potentiometer and then to an audio amplifier and loudspeaker. The amplifier used in the prototype is the same as featured in the Keyless Organ in the January, 1969 issue, except that it does not incorporate vibrato.

Four transistors make up the amplifier, with the output transistors connected in the complementary-symmetry mode. The amplifier has low current drain of 10mA at no signal and a maximum power output of 400mW into a 15-ohm speaker with a 9-volt power supply. Sensitivity of the amplifier is approximately 300mV for full output, with an input impedance of 200K. We used a particular 15-ohm speaker but any speaker with an impedance from 15 to about 47 ohms could be pressed into service, provided it is not one of the miniature variety which have low sensitivity and a poor bass response. A voice coil impedance of greater than 15 ohms will reduce the available output power and lower the current drain.

Some readers may wish to incorporate the facility of vibrato and this is simply a matter of using the amplifier and phase-shift oscillator featured in the Keyless Organ. However, this would be "cheating." Vibrato should be achieved manually, not electrically!

Instead of using the amplifier featured in the prototype, an existing amplifier may be used, provided it has sufficient sensitivity and an input impedance of 100K or greater. The signal may be fed to the amplifier via the 0.1uF capacitor connected to the drain of the FET.

Mention was made earlier of the use of battery supply for the instrument. There is, however, a possible drawback in the use of batteries in that the whole unit could be left "floating," electrically. If the circuitry is not tied to earth, the hand capacitance affecting the volume control may also affect the pitch oscillator, giving considerable interaction between volume and pitch controls. Clearly, this is undesirable. The theremin may be battery-powered but it must be connected to earth or to some other large metal mass otherwise its operation may be completely unsatisfactory.

In the face of this requirement, there is little advantage in battery operation and we used a mains power supply in the prototype which enables the theremin to be automatically tied to earth. Any small power transformer with a 6.3 volt or centre-tapped 12.6 volt secondary winding will suffice. At the voltage available, maximum signal current drain is of the order of 90mA.

A full-wave rectifier is used, feeding a 1000uF electrolytic filter capacitor. This supplies the current requirements of the audio amplifier. The bias resistors for the input stage of the amplifier and the remaining circuitry are run from a supply decoupled from the 1000uF capacitor via a 100 ohm resistor and 500uF capacitor. This is to ensure low hum and minimise risk of instability.

If, in spite of what we have stated above, readers wish to use a 9-volt supply battery, the decoupling network consisting of the 100 ohm resistor and 500uF capacitor should be retained. Ideally, the 1000uF capacitor should also be retained across the battery to minimise distortion as the battery nears the end of its service life.

CONSTRUCTION: The prototype theremin was installed in a cabinet made of 3/8-inch particle-board covered with a plastic adhesive contact material with a simulated wood grain. If particle board is used, ensure that the surface is free of dust and wood chips before applying the covering material. Do not use a metal case as it will render the instrument less sensitive to hand capacitance.

All the circuitry, apart from the power supply, is accommodated on a piece of matrix board, 9 x 3 inches. The actual wiring uses no tags or eyelets, the component leads being pushed through the board, bent over and soldered point to point. The details of wiring underneath the board can be obtained from the wiring diagram.

1 chassis (see text).

- I miniature power transformer, with centre-tapped 12.6 volt secondary.
- 1 piece of matrix board, 9 x 3 inches.

- 1 8-terminal tagstrip.
  4 330uH RF chokes.
  1 100K(log) potentiometer (mains
- switch optional).
  2 100pF Ducon TDB rotary ceramic trimmers.
- 1 15-ohm loudspeaker.
- 1 knob.

#### **SEMICONDUCTORS**

- 3 BF115 or similar silicon NPN RF transistor.
- 2 BC108, 2N3565 or similar silicon NPN transistor.
- 1 2N3638 or similar silicon PNP transistor.
- 1 BC178, 2N3638A, AY1110 or similar high gain PNP transistor.
- 1 AC127/128 complementary ger-manium pairs (with flag heatsinks).
- 1 2N5459 N-channel FET.
- 1 OA91 or similar diode.
- 2 EM401, AD4001, 1N3193 or similar power diode.

#### RESISTORS

(‡ or ‡ watt unless specified) 1 x 820K, 3 x 560K, 1 x 330K, 3 x 150K, 2 x 100K, 4 x 33K, 2 x 10K, 1 x 1.5K, 7 x 1K, 1 x 470 ohms, 1 x 220 ohms, 1 x 100 ohms, 1 x 22 ohms, 2 x 1 ohm/ watt.

#### CAPACITORS

- 1 x 1000uF/12VW electrolytic. 1 x 500uF/10VW electrolytic.
- 1 x 300uF/10VW electrolytic.
  1 x 320uF/6VW electrolytic.
  1 x 25uF/6VW electrolytic.
  1 x 25uF/6VW electrolytic.
  8 x 0.1uF/25VW ceramic disc (see

- 2 x 0.1uF polyester or ceramic. 2 x 0.01uF polyester or ceramic. 1 x .0022uF polyester or ceramic.
- 1 x .001uF polystyrene or ceramic. 2 x 330pF polystyrene or ceramic. 1 x 100pF polystyrene or ceramic.
- 1 x 47pF polystyrene or ceramic. 2 x 4.7pF ceramic.

#### MISCELLANEOUS

Timber for cabinet, contact cover-ing, sheet metal for pitch and volume plates, 3-core mains flex and power plug, hook-up wire, mains cord clamp, screws, nuts, solder, etc.

The layout is not really critical but the wiring diagram should be followed fairly closely for best results.

All the RF chokes are 330uH, honeycomb wound on a ferrite former by Aegis Manufacturing Co. Pty. Ltd., and available from most component suppliers. All the 0.1uF capacitors in the RF portion of the circuit are low voltage ceramic discs rated at 25 volts working; a lower rating may be used, if available. Mica or polystyrene capacitors may be substituted, if they are

Electrolytic capacitors shown on the circuit diagram and in the parts list are specified with the minimum suitable voltage rating currently available. As always, higher voltage units may be used if size is not a problem. old electrolytics should not be used, as their capacitance may have decreased and leakage and power factor will be

The AC127/128 output transistor pair should be fitted flag heatsinks, (Miniwatt part No. 56200) which are normally supplied with each complementary pair. Under normal conditions the transistors will be cold to the

A simple chassis was used in the prototype, made from a piece of 22 gauge aluminium 9½ x 8½ inches bent so that it has a 3 inch flange to accommodate the volume potentiometer and two trimmer capacitors. The matrix board is mounted on the chassis so that it is spaced above it by a distance of one inch, by 1/8-inch screws and nuts. The chassis reduced the tendency of the two pitch oscillators to lock.

The rotary ceramic trimmers are type TDB, made by Ducon division

of the Plessey Components Group and are available from most component suppliers. These trimmers were used since they are fully adjustable and do not lose their ability to be adjusted, as do compression trimmers. The trimmers are adjusted by a screwdriver, through an access hole in the chassis and cabinet. They are spaced off the and cabinet. They are spaced on the chassis by the thickness of one nut to ensure that the rotor has sufficient clearance. When wiring the trimmer for the pitch oscillator, connect the rotor terminal (terminal going to centre of ceramic former) to the positive supply rail, as in the circuit diagram. If it is connected in contrary fashion, it will be impossible to "zero" the pitch oscillator because of the capacitance of the screwdriver blade.

To take advantage of the wide frequency range available, a speaker with good frequency response should ideally be used. If an economy speaker is used it should have as large a diameter as is practical. For this reason we used a 6-inch diameter speaker which enables a conveniently sized cabinet to be obtained.

An exploded diagram illustrates the method of assembly of the cabinet and gives the major dimensions of a cabinet suitable for a six-inch diameter speaker. If desired, the output of the amplifier can be fed to an external speaker system. If this is done, be sure to connect the speaker with a twopin plug and socket to reduce the possibility of shorting the output of the amplifier which would almost certainly be damaged.

Antennas or plates associated with the pitch and volume controls may be any reasonable size and shape. made two rectangular plates 6 x 41 in.

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(BCY33)	SOC		
OC 440		TS3 (AF185)	25c
(BCY430)	50c	2SC92	50c
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#### RESISTORS

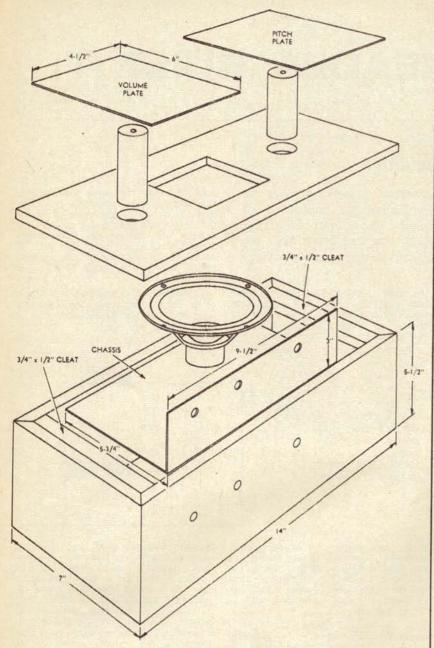
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### MAIN DIMENSIONS OF CABINET



The above diagram shows the major details of a cabinet suitable for a six-inch diameter speaker.

and these were mounted above the lid by two 1-3/8-inch dowels. These were driller right through to take a piece of hookup wire for connection in the circuit. The method of mounting the plates, however, is non-critical and readers may use whatever method is convenient. Note that the plates should not be too close together, otherwise the controls will interact.

Finally, we covered the plates with black vynex to contrast with the simulated wood of the cabinet. Contact adhesive is suitable for sticking the material to the plates.

SETTING UP: First, adjust the pitch control trimmer for an audible note. Set the volume control potentiometer for a suitable level. Then adjust the volume control trimmer for minimum loudness. Note that it is not possible for the volume trimmer to

completely turn off the sound, for the reason already explained. Finally, with your hand close the volume plate, adjust the pitch trimmer for zero pitch. These adjustments will have to be repeated each time the unit is set up in a different position.

You will find the theremin capable of an endless variety of sounds. Low grunts and growls can be produced by a quick, sweeping motion of the hands. Similarly, one can obtain wails and squeaks in the high range. To produce a vibrato effect, hold the "volume hand" in a fixed position and flutter the "pitch hand" at the desired rate. Similarly, to create a "tremolo" effect, hold the "pitch hand" in a fixed position and flutter the "volume hand." Do not practice these effects in the vicinity of someone with a headache!

Go to it.

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