Build this Theremin

Build Theremax, a theremin for the 90s!

JOHN SIMONTON

SINCE IT'S INTRODUCTION TO THE general public in the late 1920s, the image and tone of the theremin has captured the imagination. Eyes widened at the sight of a musician producing sound using only a conductor's gestures. And the theremin's pure tones, able to stand out without distortion against even the full fortissimo of a symphony orchestra, were like nothing anyone had ever heard before.

Was it a hit? You bet! Theremin concerts were performed in front of standing-room-only crowds in halls where audiences were ordinarily sparse. The place of the theremin in a "modern" orchestra was a given for such maestros as Leopold Stokowski, who used one or more in numerous concerts of the Philadelphia Orchestra during the late 1930s. RCA thought that every cultured home would have a theremin, but things didn't work out that way for a lot of reasons.

We'll talk more about these things shortly and also look at how to build a theremin that is based on the same heterodyneing principles that were key to the original. Theremax produces the classic sound while adding embellishments made possible by the economy of transistors and integrated circuits. It can function as a stand-alone instrument or as a gesture-sensing controller for other musical instruments or in performance art applications.

The theremin Zeitgeist

The *aetherphon* that Lev Termen showed to a Russian physics conference in 1920 was an adaptation of his earlier invention, the Radio Watchman. What has this to do with our story? Just this: Lev shortly moved to New York, Anglicized his name to Leon and began calling the instrument by his new American surname of Theremin. And this: Both the Aetherphon and the Radio Watchman, which emitted a squeal in a pair of headphones when a person entered a protected area, were among the earliest applications of heterodyneing, a principle that in one form or another underlies all forms of electronic communication. In fact, if Theremin's work did not precede the invention of the superheterodyne by Edwin Armstrong in 1918, it was at least happening at the same time.

You likely already know that when two signals are combined in a mixer the result is a signal with new frequency components that are the sums and differences of the frequencies that were in the originals, as well as the original themselves. This is the basic principle behind AM radio. For example, if 100 kHz and 99 kHz sine waves are combined in this way, the result will be a new waveform that also has 1-kHz and 199-kHz components. There are a couple of neat things about this, the first being that while the two original frequencies are both well above the range of human hearing, as is the sum frequency of 199 kHz, the 1 kHz difference frequency is right in the middle of what we hear best. The second neat thing is that relatively small changes in either of the source signals will produce a relatively large change in the difference frequency. If the 100 kHz signal changes by ½%, to 99.5 kHz, the output signal will halve (an octave change) to 500 Hz.

All of this is important in Radio Watchmen and Aetherphons because the presence of a human body can easily produce a few picofarad change in the capacitance of a piece of wire hanging off in space. If the capacitance of the wire is part of a tuned circuit the result is a small change in the resonant frequency. In much electronic equipment, such parasitic capacitance is a flaw that must be overcome through shielding, buffering oscillator circuits, and so on. Here, however, it's the whole point.

Here you have your basic theremin: A pair of high frequency oscillators are running at essentially the same frequency, one fixed and the second connected to a sensing antenna. As the hand of the performer approaches the antenna the frequency of the sensing oscillator goes down, so the frequency difference between the two oscillators increases. The outputs of the oscillators are combined and a low pass filter used to allow only the lower difference frequency to pass, which is the sound you hear. The original Aetherphon was little more than this: a foot pedal was used to control the volume and a switch was provided to mute the tone completely.

But on the way to becoming a theremin, some changes were made. By the time the design was licensed by RCA in 1929, a circuit had been added so the performer controlled the volume and could articulate notes with movements of his left hand relative to a horizontal "volume"

Clara and Leon

Lev Termen, who later changed his name to Leon Theremin, was born in St. Petersburg Russia at the turn of the century. So was Clara Reisenberg, who later took her husband's name of Rockmore. Although destiny was to join their lives, the two didn't meet one another until after they both had emigrated to the US in the late 1920s.

Leon began his studies of physics and music composition at the University of St. Petersburg. While continuing his study of physics at the Petrograd Physico-Technical Institute in 1919, he became director of the Laboratory of Electrical Oscillators. In this environment, he was able to combine his interests in music and physics to produce what is generally accepted as the first electronic musical instrument. He began demonstrating the aetherophone, as he originally called the instrument, in 1920, and it is known that Lenin, the revolutionary father of communism, was among those who saw a demonstration. Lenin may have been responsible for Leon's trips to western Europe and the USA in search of cultural acceptance of the revolution and capital for Leon's many inventions.

Clara was a musical prodigy who began playing the violin at the age of 4 and the following year was the youngest student ever admitted to the Imperial conservatory of Music in St. Petersburg. It is difficult to reconcile the time lines of various accounts, but by 1927 she and Leon were both in New York after successful independent concert tours.

During this time, Clara's hand muscles began to show the devastating effects of childhood malnutrition, which was wide-spread in Russia during the transition from czarist to Bolshevik control. It appeared that her career as a concert violinist would soon be over. She realized that the theremin was her only hope of continuing her musical career and over a period of several years she worked closely with Leon to develop an instrument that would allow her the expressive control needed for concert work. To the end of his days, Leon was never able to provide her with her greatest wish, a polytonic theremin capable of playing more than one note at a time.

While it is said that there was a romantic relationship between the two, Clara eventually married a prominent impresario of the time to become Clara Rockmore. This arrangement had a very beneficial effect on her career and, consequently, on the the exposure that the theremin received. Leon married a dancer and established an acoustical laboratory in New York where he continued the development of various electronic musical instruments.

Clara spent the rest of her life in New York and gave many coast-to-coast concert tours, but in the late 1930s Leon disappeared. It isn't known whether he was responding to the pressures of his inter-racial marriage and yearning for his homeland, or if his homeland was yearning for him. Following the purges of the 1917 revolution, Russia was short of technical talent and some sources say he was taken involuntarily. It is typical of the romanticism of the theremin mythology that by some accounts he was kidnapped by the KGB, an organization that did not exist until 1954. In any case, one morning in 1938 he was missing from his New York apartment and never again contacted his wife and children or any of his associates. Now it is known that he did return to Moscow and was involved in electronic research for the government until 1964 when he retired to became a professor of acoustics at the University of Moscow.

In 1991, as a consequence of glastnost and with permissions obtained by John Chowning of Stanford University, Leon was able to return to the US for lectures and to participate in the filming of Steven Martin's "Theremin: An Electronic Odyssey." At one of the lectures where Leon was only to speak, he gave a spontaneous solo concert that was a moving performance for a man in his 95th year. Clara, always proud of her appearance, is said to have had great reservations about seeing him again in her old age, but she finally agreed and they were reunited on this trip.

After a brief stay in the US, Leon returned to Moscow where he died in 1993.

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antenna which, interestingly enough, was *not* part of a heterodyne circuit. The right hand controlled pitch by its proximity to a vertical "pitch" antenna. There were several different package configurations for the theremin including one that looked like a music stand with antennas and a massive "U" shaped case with antennas on the vertical arms of the U. The most common was the lectern style case like we've used.

One of the more unusual configurations was the Terpsitone, a dance platform with theremin antennas spread around it so that the dancers would create the music as they danced to it. That seems to be a pretty cool idea even when compared to today's world of hip performance art. Theremax has control-voltage and gate outputs that make it even more appropriate for these kinds of applications.

For a number of reasons the theremin never replaced the spinet in the parlors of America; the depression was not a good time to be introducing new musical instruments. But also, the RCA design was one that was deemed unplayable by the leading thereminist of any age, Clara Rockmore. In that design, volume, and consequently articulation, were controlled by varying the power to the filaments of a tube. Thermal lag of the filaments meant that everything had to be played glissando—it was essentially impossible to add quiet spaces between notes played quickly. The theremin used by Clara Rockmore in all of her concerts was a unit custom made by Leon Theremin that used a different approach to controlling volume. After a single run of a couple of hundred units, RCA discontinued theremin production.

Yes, and let's be honest: The biggest reason that theremins have never become overwhelmingly popular is that, spooky sci-fi noises aside, they are much more difficult to play than you might think—despite's RCA's claim that "anyone who can hum can play one."

Well, actually, riffs like the theremin lick in Brian Wilson's "Good Vibrations" aren't too bad, and the one in Led Zeppelin's "Whole Lotta Love" won't take forever to master either. The common complaint is that there is no tactile feedback, no keys or frets, and the pitch response to hand position is nonlinear. That attitude might not get you much sympathy from violinists, but they do at least have a fingerboard to touch.

You've been warned. Let's see about building one of these beasts.

Design analysis

The main Theremax schematic is shown in Fig 1. Its power-supply section is shown in Fig. 2. At the heart of the circuitry are four oscillators, two of which are mixed to produce the pitch signal, and two of which are mixed to produce the volume-control signal. If it occurs to you that one oscillator could

Continued on page 56

THEREMIN

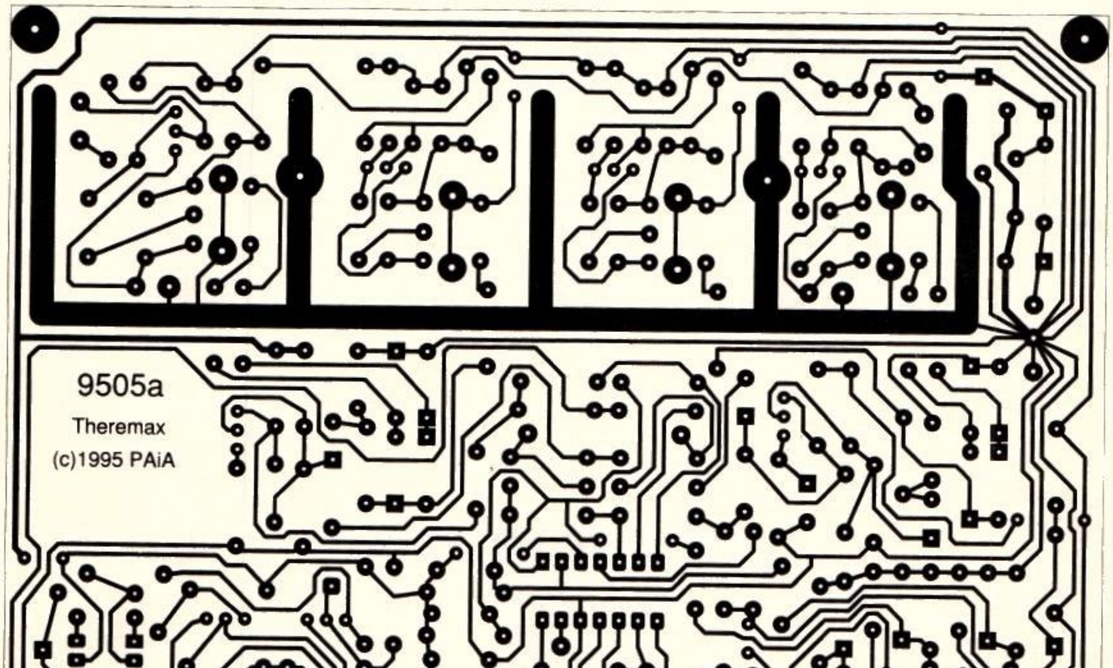
continued from page 32

serve as reference for both pitch and volume sensing you have a good designer's instincts—it would be more economical. Unfortunately, multiple oscillators operating near the same frequency have a tendency to "pull" and lock to exactly the same frequency—just like the swing of multiple compound pendulums will tend to synchronize. It's not too difficult to minimize this tendency in a single pair of oscillators by physically isolating them from one another, putting guard bands around them on a circuit board and decoupling them from their common power supply, but three oscillators, all heading for essentially the same frequency is considerably more difficult.

If the oscillators lock, there is no more difference frequency, so the output goes to zero. It would be bad enough if at the lowest notes the sound suddenly stopped, but the worst part is that just prior to locking, the oscillators go through an unstable region where the synchronization is chaotic. Instead of just suddenly going quiet, you first hear a burst of noise. These are very unmusical characteristics. Having four oscillators allows us to offset the frequency ranges of the pairs so that they do not interact.

The basic oscillator is a classic Hartley type as typified by transistor Q2 and associated circuitry. The primary winding of oscillator coil L2 and capacitor C10 form a resonant tank circuit load for the transistor, which is configured as a common-base amplifier stage. A tap on the coil is coupled by C11 to the input of the amplifier (the emitter of Q2) for feedback. Resistors R7 and R10 set the operating point of Q2 to provide the gain necessary to maintain oscillation. R8 and C8 provide decoupling between the power supply and the oscillator to minimize unwanted interactions between the four oscillators. In this oscillator, and the identical one built around Q3, the frequency is set solely by the combination of C10 and the inductance of the primary winding of L2 and is adjusted by varying the ferrite slug in the oscillator coil.

The sensing oscillators, typified by the one for pitch comprising Q1 and associated components, have a couple of tweaks. The capacitive reactance of the tank has the additional component of the pitch-sensing antenna, which is effectively in parallel with capacitor C6. The parasitic capacitance of this antenna is greatly affected by the presence of objects, particularly flesh-and-blood objects. As an object approaches the antenna, capacitance increases causing the resonant



FULL-SIZE PRINTED CIRCUIT board foil pattern.

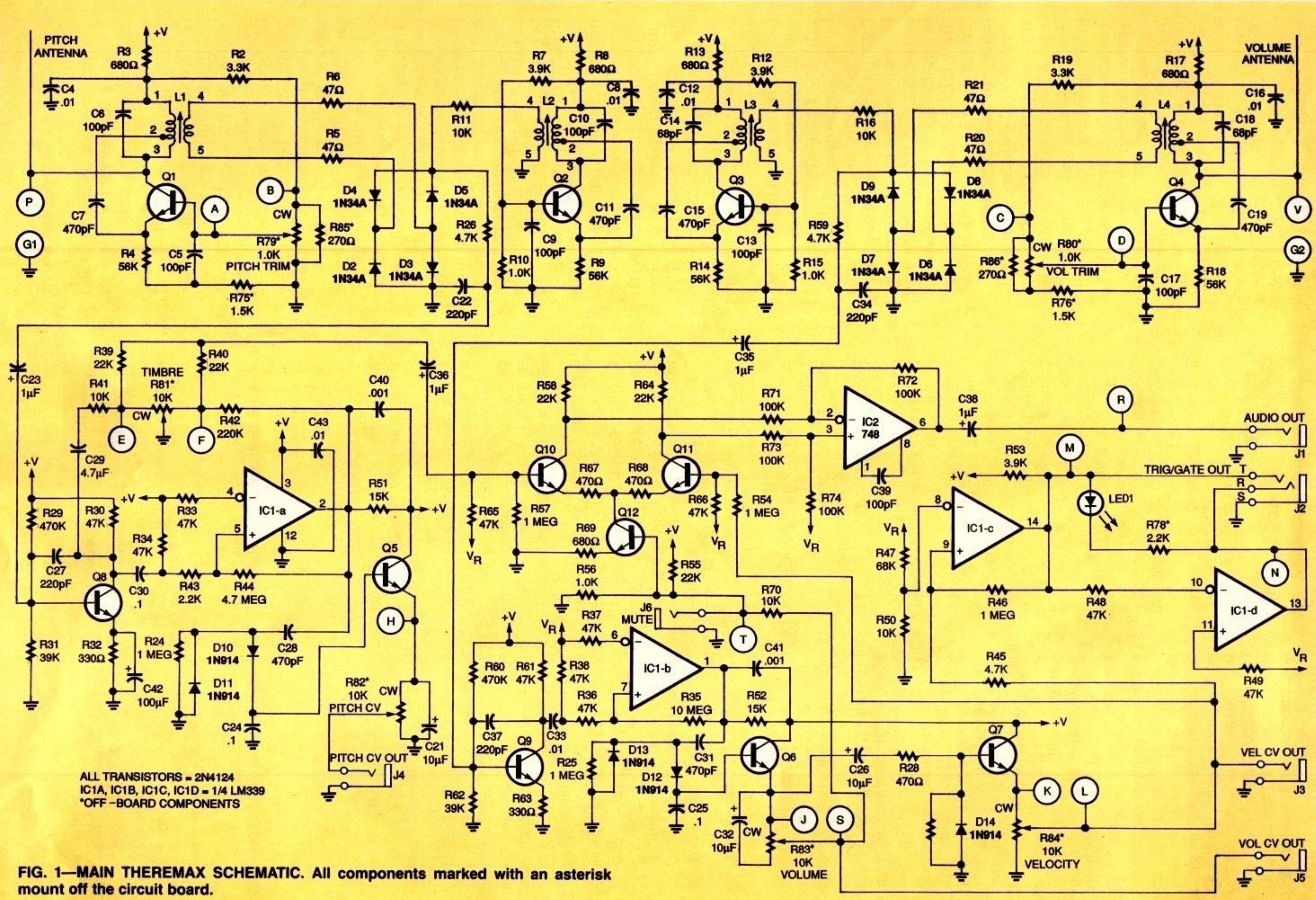


FIG. 1—MAIN THEREMAX SCHEMATIC. All components marked with an asterisk mount off the circuit board.

frequency of the circuit to go down.

The sensing oscillator also provides for vernier control of frequency using potentiometer R79, which allows a variable setting of the operating point of Q1. Varying the operating point changes frequency by increasing or decreasing the DC current flow through the Primary of L1, which changes the permeability of the core slightly and consequently the reactance of the inductor. The volume sensing oscillator (built around Q4) follows this same design.

For both pitch and volume, the outputs of the reference and sensing oscillators are taken off the secondary windings of their respective transformers to buffer them from the effects of loading by the rest of the circuitry. Taking the pitch circuitry as typical, the oscillators are mixed in the ring modulator consisting of D2-D5. The output of the modulator consists almost entirely of the sum and difference frequencies with some small leakage at the frequencies of the oscillators. The higher frequencies are rejected by the low-pass filter consisting of R26 and C22, and only the audible difference frequency passes. Transistor Q8 and associated components comprise a single-stage amplifier that boosts the output of the modulator to a more usable level with C27 providing a second pole of filtering for further suppression of the higher frequencies. The comparable circuit elements in the volume-sensing side of the circuit should be apparent from inspection of the schematic.

Pitch and volume control voltages are produced in the same way: A comparator converts the sine wave difference frequency to square waves, which are differentiated to a string of pulses, which are then integrated to a control voltage (CV). Taking the pitch CV as typical, the output of the amplifier Q8 is coupled by C30 to the Schmitt trigger wired around IC1-a. The inverting input of the comparator is tied to a half-of-supply reference, V_R, that comes from R22 and R23. R38 ties the non-in-

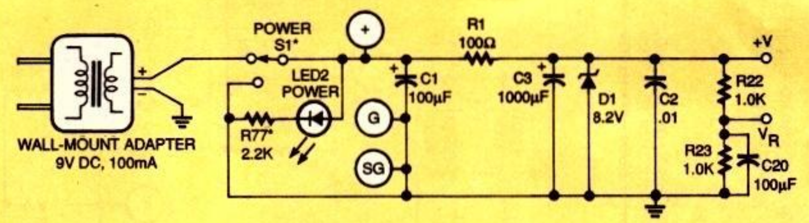


FIG. 2—THEREMAX POWER SUPPLY. A 9-volt DC adapter provides power for the circuit.

PARTS LIST

All resistors are ¼-watt, 5%, unless otherwise noted.

R1—100 ohms
R2,R19—3300 ohms
R3,R8,R13,R17,R69—680 ohms
R4,R9,R14,R18,R48,R49,R61, R65,R66—56,000 ohms
R5,R6,R20,R21—47 ohms
R7,R12,R53—3900 ohms
R10,R15,R22,R23,R56—1000 ohms
R11,R16,R41,R50,R70—10,000 ohms
R24,R25,R54,R57—1 megohm
R26,R45,R59—4700 ohms
R27,R29,R60—470,000 ohms
R28,R67,R68—470 ohms
R30,R33,R34,R36,R37,R38—47,000 ohms
R31,R62—39,000 ohms
R32,R63—330 ohms
R35,R46—10 megohms
R39,R40,R55,R58,R64—22,000 ohms
R42—220,000 ohms
R43,R77,R78—2200 ohms
R44—4.7 megohms
R47—68,000 ohms
R51,R52—15,000 ohms
R71,R72,R73,R74—100,000 ohms
R75,R76—1500 ohms
R79,R80—1000 ohms, panel-mount potentiometer
R81,R82,R83,R84—10,000 ohms, panel-mount potentiometer
R85,R86—270 ohms

Capacitors

C1,C20,C42—100 µF, 10 volts, electrolytic
C2,C4,C8,C12,C16,C33,C43—0.01 µF, ceramic disc
C3—1000 µF, 10 volts, electrolytic
C5,C9,C13,C17,C39—100 pF, ceramic disc
C6,C10—100 pF, NPO, ceramic disc
C7,C11,C15,C19,C28,C31—470 pF, ceramic disc
C14,C18 —68 pF, NPO, ceramic disc
C21,C26,C32—10 µF, 10 volts, electrolytic
C22,C27,C34,C37—220 pF, ceramic disc
C23,C35,C36,C38—1 µF 10V, electrolytic
C24,C25,C30—0.1 µF, Mylar
C29—4.7 µF, 10 volts, electrolytic
C40,C41—0.001 µF, ceramic disc

Semiconductors

D1—8.2 volts, 400 milliwatts, Zener diode
D2–D9—1N34A germanium diode
D10–D14—1N914 silicon diode
D15,D16—red LED
IC1—LM339 quad comparator
IC2—748 op-amp
Q1–Q12—2N4124 NPN transistor

Other components

J1,J3,J4,J5,J6—¼-inch phone jack
J2—¼-inch stereo phone jack
S1—SPST switch
P1—DC wall-mount adapter, 9 volts, 100 mA.
L1,L2,L3,L4—796 kHz. (nom.) oscillator coil

Miscellaneous: knobs, circuit board, wire, solder, hardware, case, etc

Note: The following are available from: PAiA Electronics, Inc., 3200 Teakwood Ln., Edmond, OK 73013; Tel: 405-340-6300; Fax 405-340-6378; Online: http://www.paia.com/paia:

- **Complete kit of all electronic parts including power supply, circuit board and knobs less antennae and case (#9505K): $88.75**
- **Case kit with pieces cut from white pine and drilled for assembly. Includes hardware, formed antennae, bottom plate and punched, anodized and legended control panel (#9505C): $77.25**

Please add $7.00 for shipping and handling with each order.

verting input to V_R, and R43 and R44 combine to provide a slight hysteresis that speeds switching and prevents "chattering" when the Schmitt trigger fires.

The output appears across the load resistor R51, and it is coupled by C28 to R24 so that the rising edge of the square wave produces a positive-going pulse. On falling edges of the square wave, D11 becomes forward-biased and quickly charges C28 for the next pulse while also clamping to ground the negative spike that would be produced. As the frequency increases, the constant-width pulses come closer together so the equivalent DC value of the pulse train increases. The average value of the pulse train is recovered by charging C24 through D10. The voltage on the capacitor is "read out" by the high-impedance emitter follower consisting of Q5 and R82, which is also the panel control that sets the control voltage available at the PITCH CV jack. The volume CV is generated in the same way using the comparator built around IC1-b.

Potentiometer R81 allows either the sine wave at the collector of Q8, the square wave at the output of the IC1-a, or a mix of the two to serve as the audio signal. At the counterclockwise end of the rotation of R81, its grounded wiper shorts out the junction of R40 and R42 allowing only the sine wave to pass to the next stage through C29, R41 and R39. At the other end of its rotation, the wiper shorts out the sine wave. At intermediate settings, the two are mixed. This audio signal is coupled by C36 to the voltage-controlled amplifier or VCA.

In the VCA, the gain of a differential pair of transistors (Q10, Q11) is controlled by setting the current flow through them with a third transistor, Q12. The volume CV, as set by front-panel control R83, is converted to a current by R70. This current sets the collector current of Q12. As this current increases, the gain of Q10 and Q11 increases as well. The significant shift in DC voltage at their collectors is canceled out in the differential amp built around the 748 op-amp IC2. The output of IC2 is coupled by C38 to J1.

The volume CV is also used to derive a velocity CV. Natural instruments are sensitive to how hard you play them. With MIDI instruments, this quality has come to be know as velocity. In Theremax, velocity is proportional to the rate of increase of volume—the "velocity" with which you hand approaches the volume antenna. Changes in the volume CV are coupled by C26 through current-limiting resistor R28 to the base of the emitter-follower Q7. When the volume CV is decreasing, D14 forward biases to clamp the velocity CV to ground and provide a high-current recharge path for C26. Panel-mounted potentiometer R84 serves as a load resistor for the emitter follower and an attenuator for the CV.

The velocity CV is available at the front-panel jack J3. It also routes to the base of Q11 in the VCA differential pair, where it makes the response non-symmetrical, which adds even harmonics to the output to give the sensation of being played hard. The velocity CV also is routed to the Schmitt trigger consisting of IC1-c and associated components. When velocity exceeds a threshold, the Schmitt changes state to provide a triggering pulse to external equipment. Since many vintage analog synthesizers initiate musical events with a switch closure to ground (or "S" trigger), the final comparator in IC1 is used as an open collector to ground turned on by the gate. Both of these signals appear at the stereo phone jack J2, with the gate connected to the tip and the open collector to the ring. A mono plug may be used to access the gate since the open collector tied to the ring can be grounded with no problem.

The 8.2-volt Zener diode D1 stabilizes the voltage from the wall-mounted DC adapter so that power-line transients don't cause pitch glitches.

Next month, we'll show you how to build, test, and tune Theremax. Ω