The Versatile 555: How It Works, How To Use It

A comprehensive examination of one of the most popular integrated circuit timers along with guidelines on how you can use it in your own projects.

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Working with integrated circuit timers can provide you with some of the most interesting and enlightening experiences you're ever likely to encounter in electronics experimenting. They can be used for building clocks, triggering automatic devices, pulsing test gear—or in other experiments limited only by your imagination.

One of the most popular IC timers is the versatile 555, which is intended for use as a multivibrator in either a monostable or an astable mode. The following is an explanation of how the 555 works and how you can use it in your own projects.

The 555 contains two comparators, a flip-flop, an inverting amplifier, a voltage-divider network, an npn transistor and a pnp transistor, all connected internally as shown in Figure 1. Although you could build your own timer with discrete components, the ready-to-use 555 timer in its 8-pin DIP package is a great deal simpler to use and costs only a fraction of what you would have to pay for discrete components.

Power Supply

The supply potential that can be applied to a 555 timer IC can be as great as 15 volts or as small as 5 volts. This means that the 555 can be directly interfaced with TTL and most other families of digital ICs. Its output can source or sink 200 mA, a current sufficient to drive devices that consume modest amounts of power, including small relays, loudspeakers, low-power incandescent lamps, motors, or the primary of a suitable transformer.

Internal Functions

Each resistance element of the voltage divider is the same, about 5000 ohms (5k). If pin 5 is open, two-thirds of V_{CC} is applied to the inverting (−) input of the threshold comparator, and one-third is applied to the nonin-

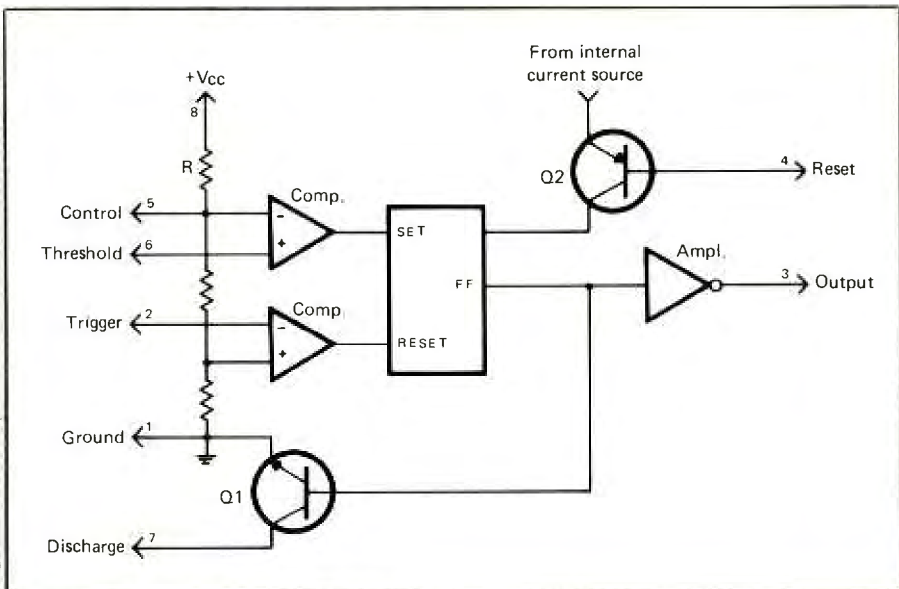

Fig. 1. Though not as complex as most computer chips, the 555 timer IC is nevertheless a tiny package with lots of circuitry. In addition to containing a pair of comparators, an RS flip-flop, and two transistors, it has an amplifier that can drive low-power speakers, relays, and more.

verting (+) input of the trigger comparator. These reference voltages can be varied by a current source or sink connected to pin 5, but the trigger reference voltage will be one-half the control voltage at pin 5 in any case. A low-value capacitor (0.001 to 0.1 μF, depending on the frequencies involved) should be connected between pin 5 and ground. This helps hold the control voltage steady and assures a more accurately timed output pulse.

The flip-flop is activated to change state by a high-level input from the output of one of the comparators. A low-level input has no effect. The RESET input overides the SET input, so if both are high, the flip-flop will reset. The output of the flip-flop is high when set and low when reset.

The amplifier inverts the output from the flip-flop and sinks or sources up to 200 mA. When the flip-flop is set, the output at pin 3 is low (near ground potential). When the flip-flop is reset, the output at pin 3 is high (near V_{CC}).

If pin 4 is held low, *Q2* conducts. This will set the flip-flop (overiding the RESET input if it is high), making *Q1* conduct and the output at pin 3 to go low. Pin 4 should be held high for normal timing operation by connecting it, either directly or through a resistor, to V_{CC}.

For as long as pin 4 is held high, the state of the flip-flop will be controlled by the inputs to the comparators. If pins 2 and 6 are both high (relative to their respective reference voltages), the flip-flop will be set. If pin 2 goes low, to less than half the control voltage, the flip-flop will reset regardless of the voltage at pin 6 and will remain reset when pin 2 goes high, provided that pin 6 is at a potential less than the control voltage. In this way, a high output pulse is triggered by a low pulse at pin 2. The width of the pulse is determined by the interval between the instant pin 2's potential goes low and the instant pin 6's potential exceeds the control voltage.

When the flip-flop is set (output at pin 3 low), *Q1* conducts and pin 7 sinks a large current. This is the means provided for discharging an external timing capacitor.

Any truth table for operation of the 555 will reveal to you that the trigger and threshold inputs have no effect on the output at pin 3 or the state of *Q1* when pin 4 is held low.

Although our explanations assume that positive logic is used internally for setting and resetting the flip-flop, the actual device may utilize negative logic. In this case, the inputs to the comparators would be reversed. From an external point of view, either type of logic is functionally equivalent to the other.

Monostable Operation

When the external circuit is configured for monostable operation, as in Fig. 2, the output remains low as long as pin 2 is held high. With the flip-flop set, *Q1* conducts and holds pin 7 near ground potential. The capacitor cannot charge and pin 6 also is held at a logic low.

A negative-going pulse at pin 2 of less than half the voltage at pin 5 causes the output of the trigger comparator to go high and reset the flip-flop. This cuts off *Q1* and makes the output at pin 3 high. Timing capacitor *C* begins to charge through *R1* and *R2* in series.

When the voltage at pin 6 exceeds the voltage at pin 5, the output of the threshold comparator goes high and sets the flip-flop, provided pin 2 has been returned to a potential greater than half the control voltage. The output at pin 3 then goes low and *Q1*

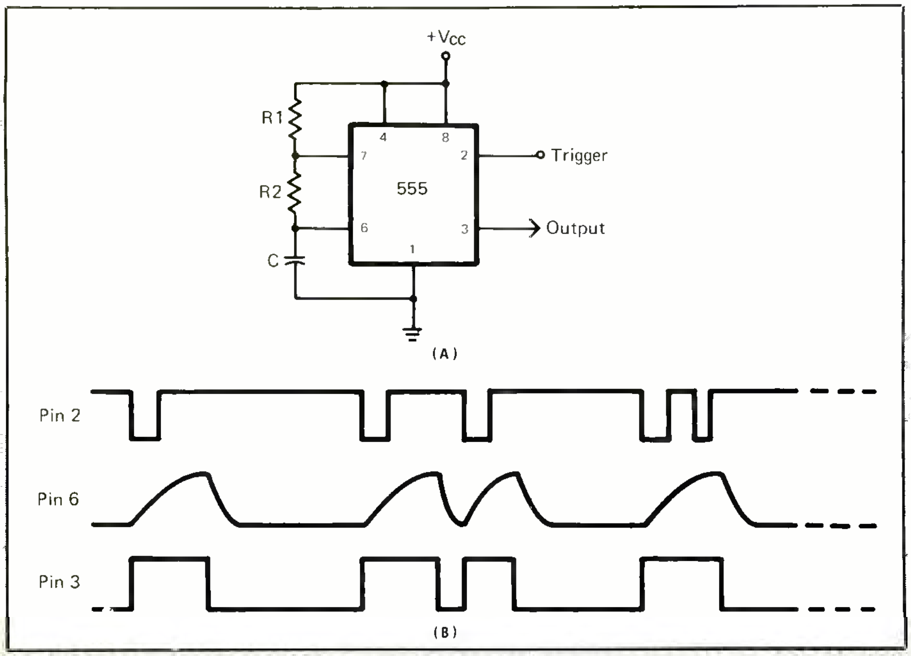

Fig. 2. With just two resistors and a capacitor added externally and connection to a source of dc power, the 555 is transformed into a monostable multivibrator (A); input, threshold, and output waveforms are as in (B).

FORMULAS

A. $t_c = C(R1 + R2)\left[\ln(1 - \frac{V_d}{V_{cc}}) - \ln(1 - \frac{V_c}{V_{cc}})\right]$

B. $V_d = V_c e - \frac{t_d}{CR2}$

C. $t_c = C(R1 + R2)\left[-\ln(1 - \frac{2V_{cc}}{3V_{cc}})\right] = 1.1\ C(R1 + R2)$

D. $t_c = \frac{C(V_c - V_d)}{I}$

E. $t_d = CR2(-\ln.5) = 0.693\ CR2$

F. $f_o = \frac{1}{C(R1 + R2)\left[\ln(1 - \frac{V_c}{2V_{cc}}) - \ln(1 - \frac{V_c}{V_{cc}})\right] + .693CR2}$

G. $t_c = C(R1 + R2)\left[\ln(1 - \frac{1}{3}) - \ln(1 - \frac{2}{3})\right] = 0.693\ C(R1 + R2)$

H. $f_o = \frac{1}{.693C(R1 + 2R2)} = \frac{1.44}{C(R1 + 2R2)}$

I. $f_o = \frac{1.44}{10 \times 10^{-6} \times (10^3 + 2 \times 3.3 \times 10^6)} = 0.0218$ Hz

begins to conduct. The capacitor will discharge through R2.

When the voltage at pin 6 drops to less than voltage at pin 5, the output of the threshold comparator goes low. However, the flip-flop will remain set, since its state can be changed only by a high input. The capacitor will continue to discharge until another trigger pulse arrives.

The width of the output pulse is a function of the time required for the capacitor to charge to the voltage at pin 5. Variations in V_{cc} have little effect because both the reference and charge voltages are equally affected, provided that V_{cc} is the source for both. Charge time is calculated from formula A (see "Formula" box), where t_c is the charging interval; V_d is the voltage on the capacitor at the beginning of interval t_c; V_c is the control voltage at pin 5; and ln is the symbol in mathematics for the natural logarithm function.

The voltage on the capacitor at the instant the trigger pulse arrives can be calculated as in formula B. Here is the base of the natural logarithms,

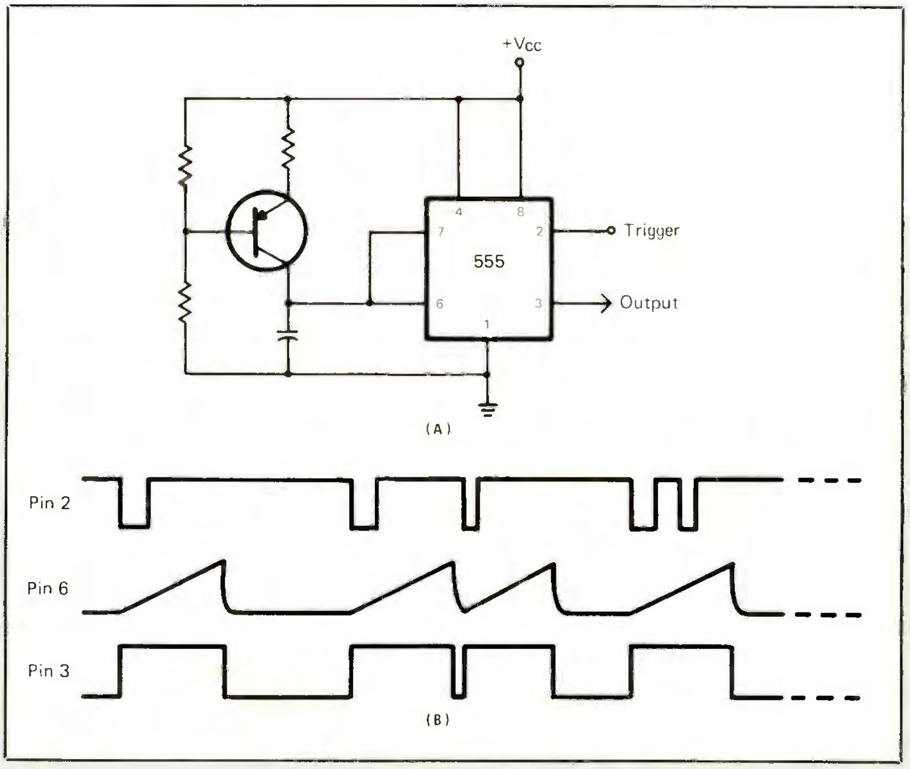

Fig. 3. By adding a constant-current source—the transistor shown in (A) —you can design and build a timer circuit that generates a sawtooth waveform, as in (B), that can be used to drive the horizontal amplifier of an oscilloscope, other applications.

and t_c is the interval between the arrival of the trigger pulse and the end of the preceding output pulse. If t_d is at least *5CR2*, V_d can be assumed to be zero, in which case the term $\ln [1-(V_d/V_{cc})]$ is zero. Assuming pin 5 is open and the control voltage is two-thirds V_{cc}, formula C gives the result calculated.

For example, if $C = 0.1\mu F$ and $R1 + R2 = 1k$ ohms, then $t_c = 1.1 \times .1 \times 10^{-6} \times 10^3 = 110$ microseconds.

In most applications, the discharge time should be made as short as possible to allow the trigger pulses to be as close together as possible without affecting the width of the output pulse. This is accomplished by eliminating *R2* and connecting the capacitor and pin 6 directly to pin 7. The discharge will then be as rapid as possible, and the interval will depend only on the value of the capacitor.

By selecting the lowest value of capacitance that will give the required pulse width in combination with *R1*, the discharge time will be minimized. Because the comparators have a very high input resistance, the value of *R1* can be as great as 3.3 megohms.

Any trigger pulse that occurs during an output pulse is simply ignored, because the flip-flop is already reset. However, if pin 2 is held low beyond the end of the normal charging interval, the capacitor will continue to charge and the output will remain in the high state for the duration of the trigger pulse.

If the trigger pulse is generated by a mechanical momentary-contact switch, the multiple pulses resulting from contact bounce will have no effect, provided the pulse width exceeds the period of contact bounce. A clean pulse of constant width will be generated each time the switch is momentarily closed.

If the charging rate is held constant, the voltage-versus-time curve will be linear and the charging interval will be linear with respect to the control voltage. This can be accomplished by supplying the charging current from a constant-current source such as the transistor circuit shown in Fig. 3.

Charging rate can be controlled by varying base-bias current in the transistor. When the circuit is triggered, the charge build-up results in a sawtooth waveform voltage at pin 6. Such a waveform can be used to drive the horizontal amplifier of an oscilloscope.

Since the sweep occurs only when the circuit is triggered, this current can be used as the basis for a triggered-sweep oscilloscope. The sweep time can be set by controlling the rate of charge.

With a constant rate of charge, the charging interval is given by formula D, where I is the charging current. For example, if $V_c = 10$ volts, V_d is zero, $C = 0.1\mu F$ and $I = 10mA$, then

$$t_c = \frac{0.1 \times 10^{-6} \times 10}{10 \times 10^{-3}}$$

$$= 100 \text{ microseconds.}$$

t_d is calculated as in formula E.

Pulse width can be changed by varying the voltage at pin 5. However, the variation will not be linear unless the charging rate is constant.

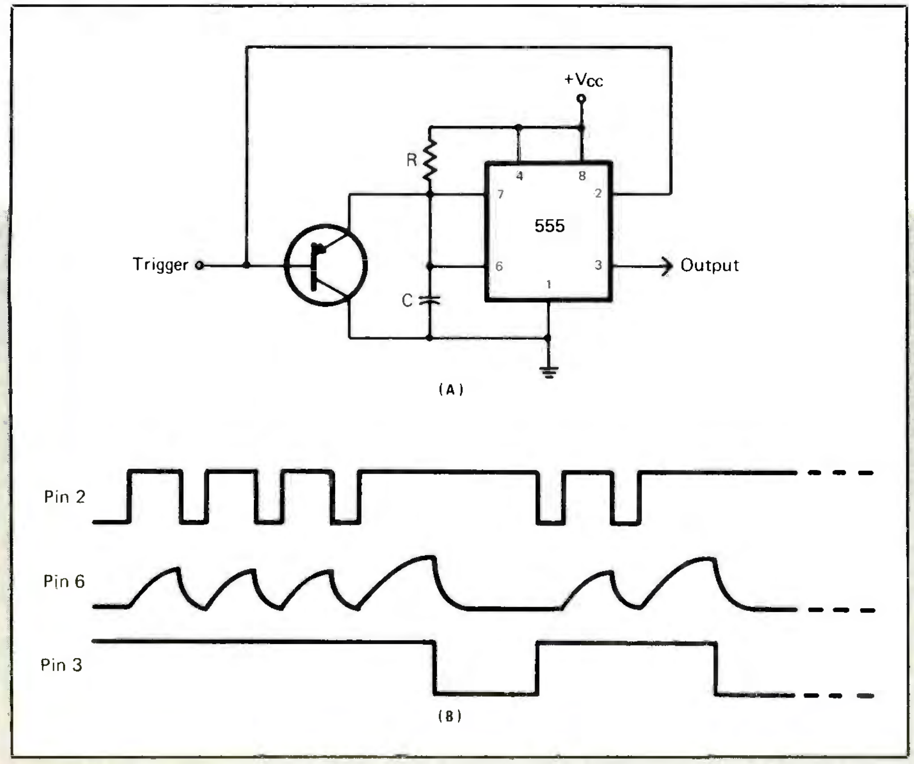

Fig. 4. A slight modification of the Fig. 3 circuit, as shown in (A), produces a timer circuit that can continually be retriggered whenever a pulse is applied to the trigger in-out at the base of the transistor.

With the constant-current charging source shown in Fig. 3, charging rate can be varied by coupling a signal to the base of the transistor. Pulse width will vary linearly with signal voltage variation. The charging interval must be shorter than the triggering interval, and the trigger pulse should be short to prevent holding the output high beyond the length of the charging interval.

Voice-frequency signals can also be transmitted on the pulses with good results, but only if the carrier frequency (input at pin 2) is many times the highest audio frequency component of the signal.

If the output of a monostable circuit is used to actuate a voltmeter (or a milliameter in series with a suitable resistance), the meter reading will be proportional to the trigger frequency. Since pulse width is fixed, the ratio of pulse width to triggering period will increase with frequency. The meter will respond to the average voltage level because of the inertia of the pointer's movement.

At low frequencies, a capacitor can be used to integrate the pulses and prevent vibration of the meter's pointer. To prevent the meter reading from being affected by supply voltage variations, regulate either the supply voltage or the output current. A circuit like this can be the basis for a frequency meter or tachometer.

If there is a provision in the external circuit that allows the timing capacitor to discharge whenever a trigger pulse arrives, the circuit can be continually retriggered during the charging interval. Such a circuit is shown in Fig. 4. The output remains high as long as the interval between trigger pulses is shorter than the charging interval set by the timing capacitor and resistors. The circuit functions as a missing-pulse detector, since the output goes low if a trigger pulse does not arrive before the charging interval has elapsed.

One possible use for the Fig. 4 circuit would be to start and stop a cassette recorder under voice control. An amplified signal from the microphone provides the trigger pulses, and the output could be used to operate a relay that opens or closes a circuit to the remote control jack of the cassette recorder.

Astable Operation

In its astable mode, the 555's circuit is free-running. To obtain free-running operation simply connect pin 2 to pin 6. When the charge on the capacitor drops to less than half the voltage at pin 5, the trigger comparator output goes high, resetting the flip-flop. The timing capacitor then begins to charge. When the charge voltage exceeds the potential at pin 5, the threshold comparator goes high and sets the flip-flop. The cycle repeats continuously.

The frequency of oscillation can be determined by calculating the sum of the charge and discharge times, and taking the reciprocal of the result. The charge on the capacitor will vary between the two limits set by the reference voltages on the comparators. The charging interval can be calculated using the formula given above for the monostable circuit, recognizing that V_d will be one-half of V_c.

The discharge interval is calculated from formula F, and the frequency of oscillation with formula G.

If pin 5 is open, the charging interval is determined using formula H, and the frequency will be calculated as in formula I.

The maximum possible frequency is limited by two considerations. Attempts to reduce the value of the timing capacitor below about 0.001 μF will be significantly affected by internal capacitance. The device can sometimes be made to oscillate on internal capacitance alone, but if the frequency is to be determined by the value of the timing capacitor, it should not be less than 0.001 μF.

Attempts to reduce the resistance of $R1 + R2$ will increase the current through *Q1* during the discharge interval. This current is the sum of V_{cc} divided by *R1* plus the instantaneous discharge current. While the value of *R2* can be safely reduced to zero, the value of *R1 must* be high enough to avoid swamping *Q1* or even destroying it with excessive current. A current of 15 mA is within the safe range. Frequencies well beyond 100 kHz are attainable.

The minimum possible frequency is limited only by the value of the timing capacitor, but care must be taken to assure that the current through *Q1* is not excessive. With a high-value capacitor and a low value for *R2*, the high discharge current could destroy *Q1*. However, the resistance of $R1 + R2$ should not exceed about 3.3 megohms and should be low compared to the actual leakage of the timing capacitor used.

If $R1$ = 1k, $R2$ = 3.3M, C = 10 μF and there is no leakage, then formula J applies and the period will be one cycle every 45.9 seconds.

The astable circuit can be triggered at any time during the discharge interval. This can be accomplished by connecting a resistor between pins 2 and 6 and coupling the trigger pulse to pin 2 through another resistor. The resistances must be chosen so that the potential at pin 2 will go below the trigger reference level while pin 6 is high. In this way, the circuit can be made to lock-in on a frequency that is somewhat greater than the free-running frequency.

If the trigger frequency is slightly greater than a multiple of the free-running frequency, the trigger pulses that occur during the charging interval will be ignored and the circuit will lock-in on a submultiple of the trigger frequency. The circuit then acts as a frequency divider. The monostable circuit will act in the same manner but will not be free running in the absense of trigger pulses.

The astable circuit is not capable of generating a symmetrical square wave. The charging interval must exceed the discharge interval because the capacitor charges through *R1* and

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R2 in series but discharges through *R2* alone. The output pulse must be wider than half the period of oscillation. If the output of an astable circuit is used to trigger a monostable circuit, the pulse width of the monostable circuit can be adjusted to any fraction of the period that is at least the width of the trigger pulse. The astable circuit will establish the frequency, and the monostable circuit will determine the pulse width.

In the circuit shown in Fig. 3, connecting pin 2 to pins 6 and 7 will result in an astable oscillator. The frequency can be varied by changing the charging rate. A signal coupled to the base of the transistor causes the frequency to vary linearly with the signal. As with pulse-width modulation, the carrier frequency should be many times greater than the highest-frequency component of the signal. If the output is used to trigger a monostable circuit with pulse-width modulation, as discussed earlier, two independent signals can be transmitted on the same carrier.

The average voltage over the period of one cycle of the carrier frequency will vary in proportion to the sum of the two signals. The FM component can be separated by a phase-locked loop (PLL). If this component is subtracted from the sum of the two signals, the difference will be the signal resulting from pulse-width modulation.

If pin 4 is momentarily held low, the circuit will reset (output low) and remain that way for the duration of the reset pulse. As soon as pin 4 goes high, the capacitor begins to charge and the output goes high. Since the capacitor may be fully discharged during the reset pulse, the first charging interval may be longer than normal, but oscillation resumes at the free-running frequency after that.

If the circuit generating the reset pulses is operating at a much lower frequency, the output from the higher-frequency oscillator will be in bursts that are synchronized with the reset pulses. Such a circuit could be the basis for a sonar device, such as a depth finder, that generates short bursts of sonic or supersonic waves and listens for the echo during the interval between bursts.

Limitations

While the range of potential applications for the 555 is very broad, it does have its limitations. Temperature changes cause less than 0.005 percent change in the timing interval or frequency per degree celsius. Slow changes in the supply voltage also have little or no effect.

However, the effect of voltage and temperature changes on the external circuit components must be considered. Rapid supply voltage variations that occur during the timing interval will affect the operation of the circuit. The supply voltage should be held constant by regulation and/or suitable decoupling where accuracy is an important requirement.

Even with these measures, alternatives should be considered if an accuracy of better than one percent or a frequency of greater than 100 kHz is required. **ME**

A Universal Coil Tester

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directly under one of the ¼″ holes. Make sure the diaphragm is pointing outwards, facing the outside world.

The LED can be installed in the circuit board as soon as the glue has set. First, push the dome of the LED through the front panel and glue it in place. Now adjust the length of the leads so that one end of the PC board rests against the earphone, all the while keeping the board parallel to the front panel. Solder the LED in place and then attach the PC board to the back of the earphone with a dab of glue.

While the assembly is drying, drill a hole in one end of the plastic case large enough to accommodate a pair of wires. These wires will serve as the test leads for the coil-tester. You may make a nifty pair of test leads by cutting a jumper clip lead in half and pushing the cut ends through the hole. Tie a knot in the wires and solder them to the PC board so that they can't be pulled back through the hole.

Using The Tester

Your instrument is now ready for use. All you need do is insert the battery into its holder. No provision has been made for an on/off switch; it really isn't necessary. The circuit draws very little power, so a fresh battery will provide many months of service.

Here are some helpful hints, though, that will make your coil-tester even more useful. Your coil-tester is extremely frequency sensitive, so you must make a good connection to the inductor. Just a couple of ohms of series resistance make a big difference in how audio sounds.

Shunt resistance also plays an important role in the quality of the sound. If the coil has a short—even if it's just a couple of turns—there is a noticeable change in the tone. It may sound very strained or not be audible at all. The LED will probably light under these conditions, however, indicating that you are making proper connection to the coil. In this manner, leakage resistance as large as 100 ohms is easily detected with this tester. Try that with your ohmmeter!

If you happen to have an identical coil on hand, you can even be more critical in your testing. Test the good coil first, then the suspect coil. Listen for a difference in the sound. The questionable coil should produce an identical sound it it's good. This same technique can be used to identify unmarked coils in your junk box.

Other uses include the testing of induction motors, auto ignition coils and power transformers. Although this is not the most sophisticated coil-tester around, it is extremely versatile, portable for field work, and costs very little when compared to commercial models. **ME**