How To Get Started In Electronics

Part II: Inside Integrated Circuits

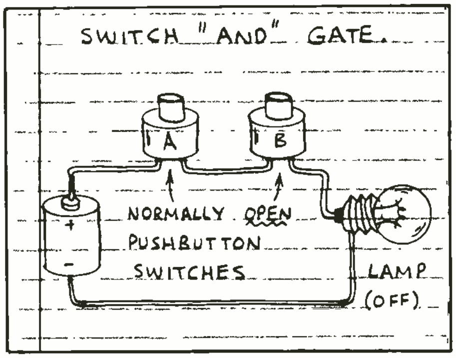
By Forrest M. Mims III

The material for this article is extracted from the author's book Getting Started In Electronics, *published by Radio Shack. Copyright 1983 by Forrest M. Mims III.*

Electronic circuits can be made by simultaneously forming individual transistors, diodes and resistors on a small "chip" of silicon. The components are connected to one another with aluminum "wires" deposited on the surface of the chip. The result is an "integrated circuit." An integrated circuit, or IC, can contain as few as several to as many as hundreds of thousands of transistor. ICs have made possible affordable personal computers, video games, digital wristwatches, and many other very sophisticated products.

Some integrated circuits can be of extremely high circuit density to perform tremendously complex operations. For example, one kind of IC contains 262,144 transistors on a silicon chip only about ¼" square! Imagine building a project in which only one of these ICs was needed, using just discrete transistors and resistors. The cost would be staggering, the size of the circuit enormous, and the finished project so heavy you couldn't carry it around. Your power requirements would be ridiculously high, too. Yet, the IC version is small and light enough to fit into the palm of your hand and can reasonably be powered by a battery.

Though not all ICs are as tremendously complex as the one cited above, you can readily see why the integrated circuit has become the backbone of modern electronics and can even be regarded as a fundamental building



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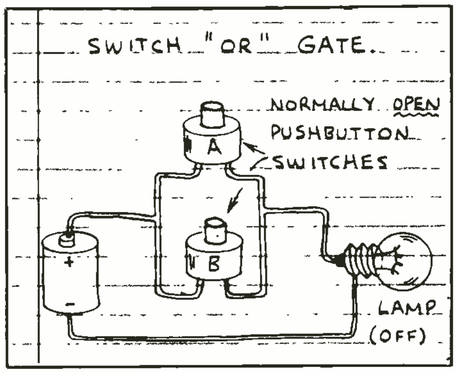


(B)

block for the electronics experimenter and hobbyist. In this concluding part of our serialization from Forrest Mim's book, *Getting Started In Electronics,* we'll introduce you to the fascinating world of ICs and take some of the mystery out of its use and operation.

IC Categories

Integrated circuits are grouped into two major categories. *Analog* (or linear) ICs produce, amplify, or respond to variable voltages. They include many kinds of amplifiers, timers, oscillators, and voltage regulators. *Digital* (or logic) ICs respond to or produce signals that have only two voltage levels. They include microprocessors, memories, and many kinds of simpler chips.

Some ICs combine analog and digital functions on a single chip. For example, a digital chip might include a built-in analog voltage regulator section. And an analog timer chip might include an on-chip digital counter to give much longer time delays than are possible with the timer alone.

IC chips are supplied in many different types of packages. By far the most common are variations of the dual in-line package (or DIP), which is made from plastic (cheap) or ceramic (more robust). Most DIPs have 14 or 16 pins, but the pin count can range from 4 to 64.

Digital ICs

No matter how complicated they may ultimately be in terms of functions performed, all digital ICs are made from simple building blocks called *gates*. Gates are like electronically controlled switches. That is, they are either on or off.

The three simplest (mechanical—not IC) gates can be demonstrated with some pushbutton switches, a battery and a lamp. For example, in (A), an AND gate, the lamp glows only when switches A *and* B are closed. In OR-gate (b), the lamp glows whenever switch A *or* switch B or both are closed. Finally, in NOT-gate (C), the lamp is on continuously (note that the switch is a normally-*closed* type, unlike the normally-*open* type in the previous two circuits). Only when the switch is opened is the lamp off. In other words, the NOT gate reverses (inverts) the usual action of a switch.

In all three circuits, the switches

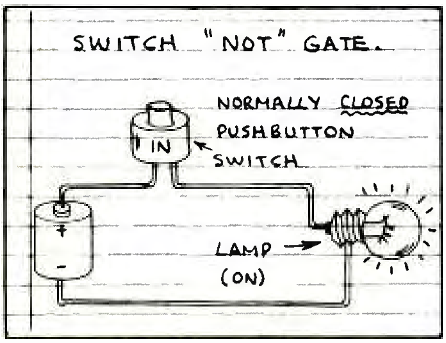
are the gates' inputs. The lead without switches in these circuits is the common or "ground" lead.

Diode Gates

It's often desirable to control a gate electrically, rather than mechanically. The simplest electrically controlled gate uses *pn*-junction diodes that are switched on (forward biased) or off (reverse biased) by an input signal of several volts (high or binary 1) or an input that is near or at ground (low or binary 0) potential.

In diode OR-gate circuit (D), when the input voltage at A *or* B is more positive than ground, it passes through the forward-biased diode(s) and appears at the output. Otherwise, the output is at or near ground. Diode AND-gate circuit (E) requires that the input voltage at A *and* B be more positive than ground for current to flow from the battery through the resistor to the output. If either A or B is at or near ground, one or both diodes become forward biased and current flows away from the output.

The outputs do not reach a full 6 volts when high because the diodes require a forward voltage of 0.6 volt. This voltage is subtracted from the output voltage. (In electronics jargon, a silicon diode causes a "voltage drop" of 0.6 volt.)



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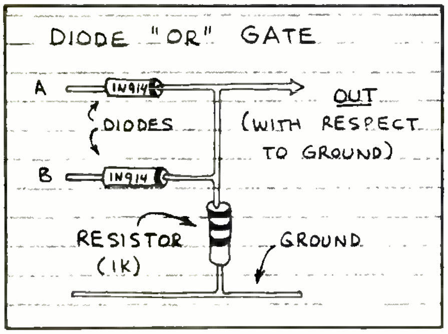
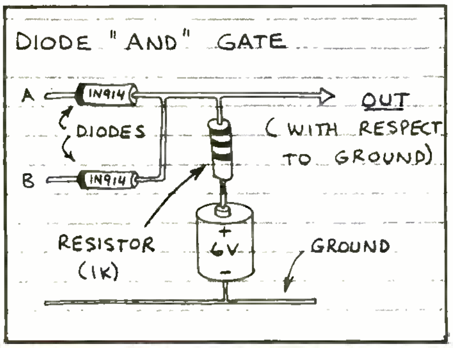


(D)

(E)



Transistor Gates

The voltage drop of diode gates means amplification is required to connect together a series of such gates. While transistors could be used to provide the necessary amplification, they can also function directly as gates! In (F) are shown circuit diagrams for some of the simplest bipolar transistor gates. Alongside each is a *truth table* that explains basic operation. The Ls and Hs in the truth tables stand for logic 0 (low) and logic 1 (high), respectively. Together, these circuits form the resistor-transistor logic (RTL) family of digital ICs.

Note in the circuits on the right that two new logic functions have been introduced. These are the NAND and NOR gates, which contain a built-in NOT function that provides outputs exactly the opposite of those provided by the AND and OR gates. That is, if the two inputs to the NAND gate are high, the gate's output will be *low*. Similarly, if either or both inputs to the NOR gate are high, its output will also be low.

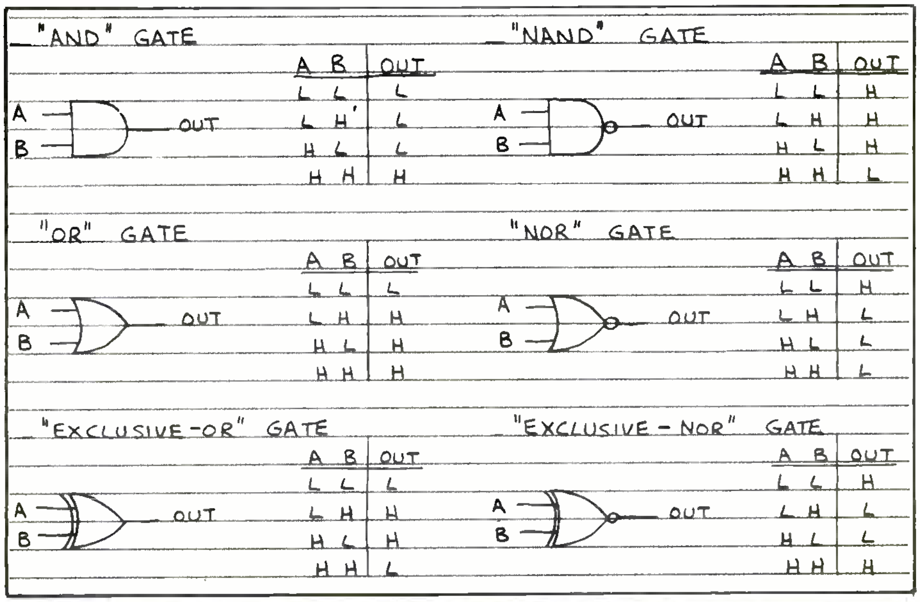
All gates shown in (F) are called logic *circuits* because they make logical "decisions." Logic gates often have more than the two inputs shown. Additional inputs increase the decision-making power of a gate. They also increase the number of ways gates can be connected to one another to form advanced and complex digital-logic circuits.

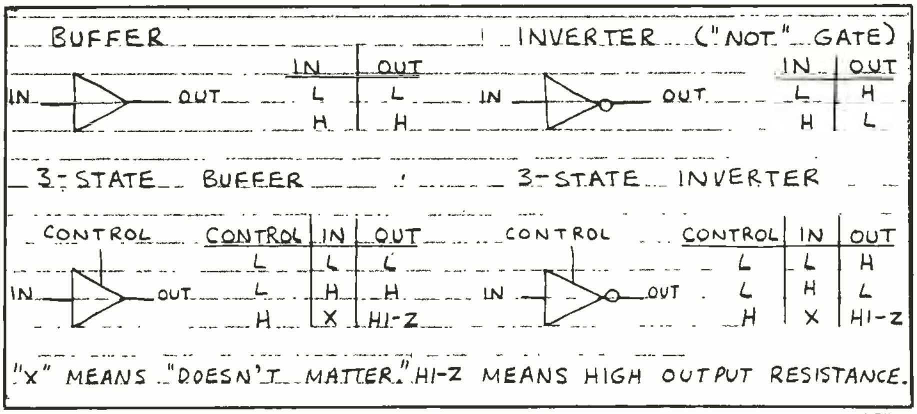
The NOT gate, or inverter, is very important, since it can *invert* (reverse) the output from another gate. Strictly speaking, however, the inverter is *not* a decision-making circuit, as gates with two or more inputs are, because it has only one input.

A close relative to the inverter is the *buffer,* a noninverting circuit that isolates gates from other circuits or allows them to drive loads that draw greater than normal current.

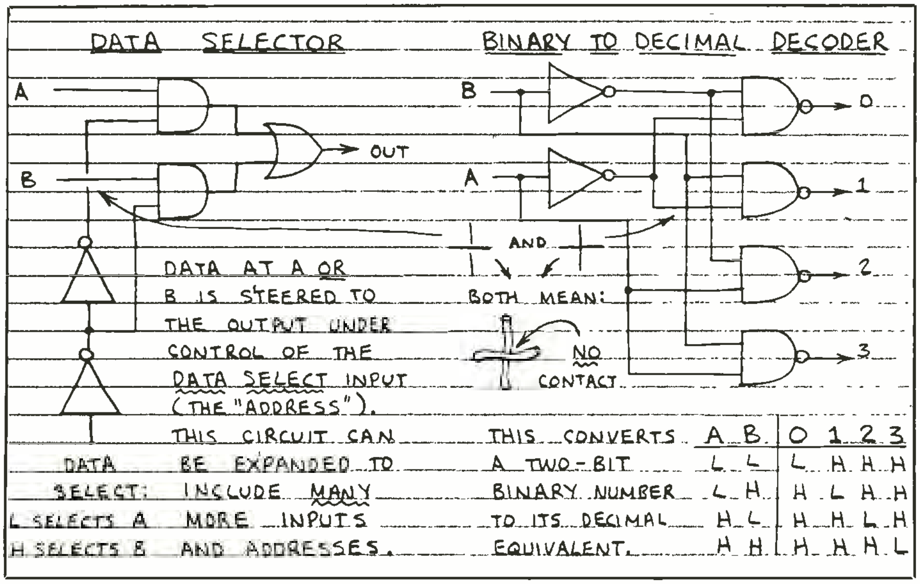
Three-state (sometimes called "tri-state") inverters and buffers have outputs that can be electronically dis-

(F)





(G)



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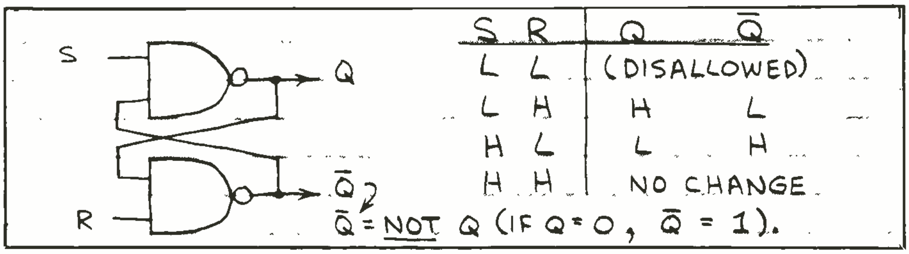


(I)

connected from the remainder of the circuit. The output is then neither high nor low. Instead, it "floats" and appears as a *very* high resistance. Standard and three-state buffers and inverters are summarized in (G).

Often, circuits made from gates exchange information in binary 1s and 0s that are encoded as high and low voltage levels. The information is usually sent over wires called *buses*. If the outputs of a number of gates are connected to the same bus, "traffic jams" can occur. Using three-state gates can put an end to this problem by placing data from a gate on the bus only when a slot for it exists.

Gates can be used individually or connected together to form a logic circuit. Almost all logic circuits can be placed in one of two categories—combinational or sequential.

Combinational Logic

Combinational logic circuits respond to incoming data almost immediately and without regard to earlier events. These circuits can be very simple or immensely complicated. Virtually any combinational circuit can be implemented with only NAND or NOR gates, or a combination of both. Two examples of combinational networks that use more than one kind of gate are illustrated in (H).

Sequential Logic

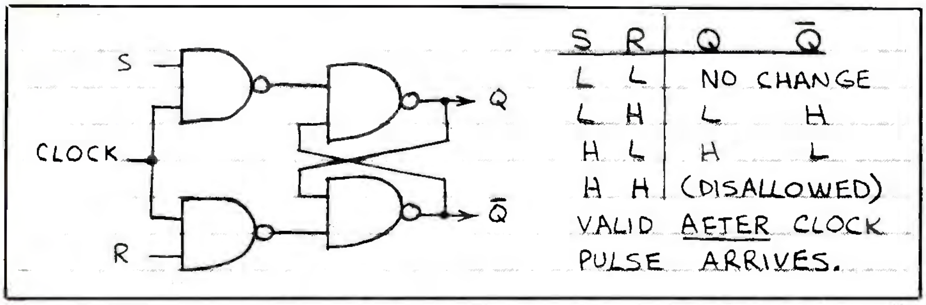
The output state of a sequential logic circuit is determined by the previous state of the input. In other words, bits of data move through sequential circuits step-by-step. Often, the data advances one step when a pulse is received from a "clock" (a circuit that emits a steady stream of pulses). The sequential logic building block is the common flip-flop.

Illustrated in (I) through (L) are five basic flip-flops. The basic RS (reset-set) flip-flop in (I) is also called a *latch*. Its Q and Q (the latter is pronounced "not-Q") are always in opposite states. The clocked RS flip-flop in (J) ignores data at S and R until a clock (or *enable*) pulse arrives at the clock input. Then it changes states.

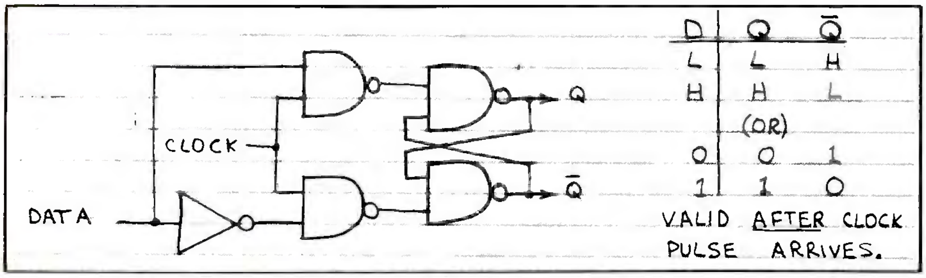
A D (data or delay) flip-flop, shown in (K), *stores* the current outputs between clock pulses. The JK flip-flop in (L) allows both inputs to be high, in which case, its outputs "toggle" or switch states with each clock pulse. The Q (or Q) output is low (or high) for every *other* input pulse to the T (toggle) flip-flop in (M). Therefore, the input pulses are divided by two.

Two or more flip-flops can be connected in various ways to make up different types of counters. Some arrangements yield binary counters that count in the binary format of 0s and 1s. Others can count in the decimal format and can be arranged to reset to 0 after a count of 9 or 5 or 1 for digital clocks, frequency counters, meters, etc. There are, of course, many types of IC counters, most of which include special features, such as count up, count down, reset, etc.

It's interesting to note that combinational and sequential logic ele-



(J)



(K)

ments can be mixed to fill the needs of specific applications. A typical example of this is the decimal counting circuit, shown in (N), that counts to 9 and on the next pulse resets to 0 to repeat counting up. The 7490 is a common BCD (binary-coded decimal) counter whose four output lines at A, B, C and D are decoded by the 7448 to turn on and off specific bars in the LED numeric display as the numbers cycle from 0 to 9 and repeat.

Linear ICs

Input and output voltages of linear ICs can vary over a wide range. Often, the output voltage is proportional to the input voltage such that if the two were graphed, the result would be a straight line (linear).

A single bipolar or field-effect transistor can function as a digital or a linear circuit. In both cases, the transistor can invert the signal at its input, as illustrated in (O). In the digital side of this circuit, transistor *Q1* is used as a switch. When the input is near +V (high), *Q1* turns on and *LED1* lights. When the input is near ground (low), *Q2* turns off. This turns off *LED1* and allows *LED2* to come on. This portion of the circuit is a combined buffer and inverter.

In the linear side of circuit (O), *Q2* is an amplifier that operates over the entire range from full off to full on. Resistors *R4* and *R5* form a voltage divider that applies a small voltage to *Q*'s base to keep the transistor slightly on even when no input is present. This allows *Q2* to operate in a linear mode. As input voltage rises, *LED3* brightens, *LED4* dims.

Op-Amps

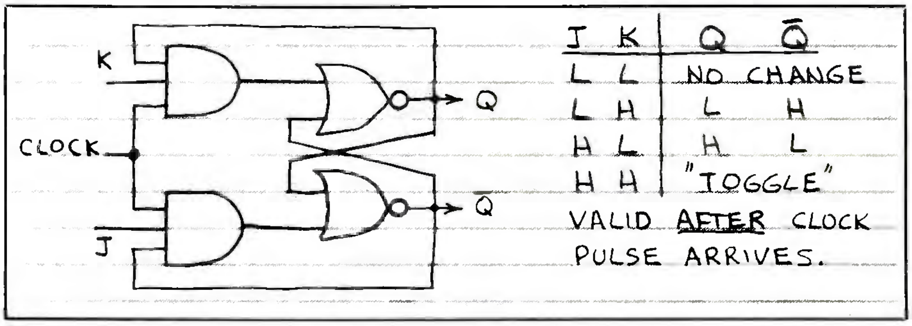
Operational amplifiers (or "op-amps") are by far the most versatile of linear ICs. They're called "operational" amplifiers because they were originally designed to do mathematical operations. Op-amps amplify the *difference* between voltages or signals (ac or dc) applied to their two inputs. The voltage applied to only one input will be amplified if the second input is grounded or maintained at some voltage level.

The op-amp has an inverting (−) and a noninverting (+) input. The polarity of a voltage applied to the inverting input is reversed at the output, while polarity at the noninverting input is the same as the output.

In some applications, the op-amp is used without feedback to provide maximum amplification (level). Usually, however, the gain is reduced to a more practical level by feeding back some of the output to the inverting input, as in circuit (P).

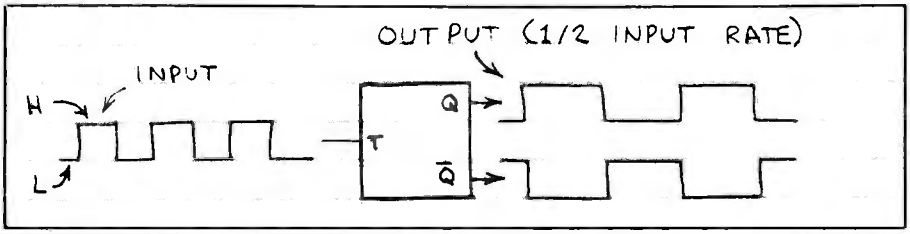
Without feedback resistor *R2* in the circuit, the output voltage will swing from full on to full off (or vice-versa) when the voltages applied to the inputs differ by only about 0.001 volt! This digital-like mode makes possible many useful applications.

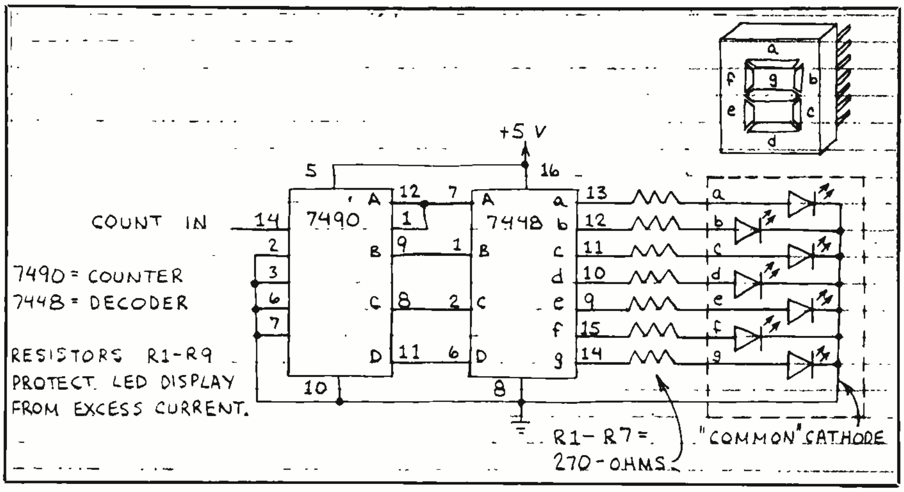
When operated as a comparator, the op-amp can be used as a timer. All that's needed is an RC (resistor-capacitor) network like the *R1/C1* combination shown in circuit (Q). In this circuit, *C1* graudally charges to +9 volts through *R1*. When the voltage on C1 exceeds the *reference voltage* supplied to the noninverting input of



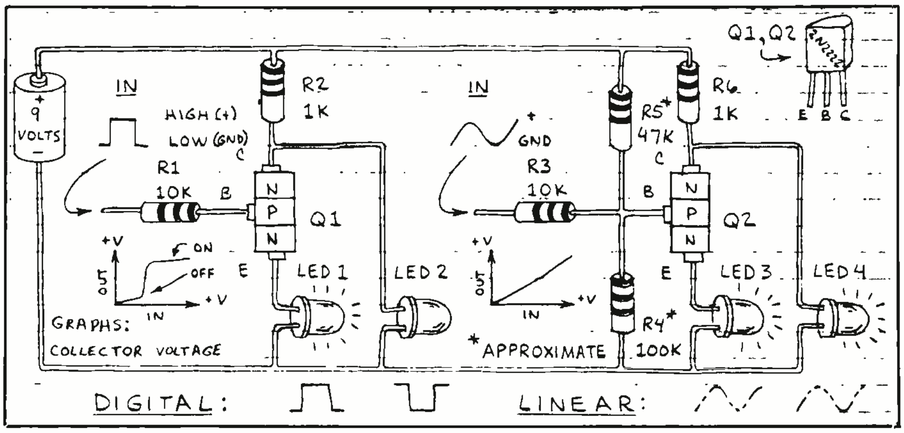
(L)

(M)





(N)



(O)

the op-amp, the output swings from high to low and the LED glows.

The time delay can be changed by altering the values of *R1* and *C1* or the setting of *R2*. To initiate a new cycle, *C1* must first be discharged. (Use a normally-open pushbutton switch connected between the top of *C1* and ground to do this.)

This simple timer circuit is the key ingredient of most IC timers. Most include an output flip-flop to give definite high or low output. Some include a binary counter that advances one count per delay period (or cycle). The timer is recycled each time the count advances. A decoder at the counter output permits total delays ranging from days to a year or more to be selected.

Voltage Regulators

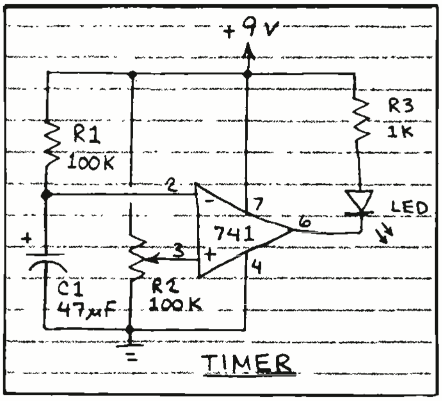
Voltage regulators convert a voltage applied to their inputs into a fixed or variable (usually lower) voltage. In most, a small fixed reference voltage (usually a volt or so) is applied to the noninverting input of an op-amp. The reference voltage (V_{ref}) is then amplified by the *ratio* of the feedback and input resistors. If one of the resistors is a potentiometer, the output voltage (V_{out}) can be varied from V_{ref} to +V (the supply voltage applied to the chip). Actual IC voltage regulators include extra transistors to provide V_{ref} and to allow the chip to drive loads that require more power than an op-amp alone can deliver.

Many types of fixed- and variable-output IC regulators are available. Most are installed in packages made of metal or having a metal tab to help radiate away excessive heat.

There are also many types of special-function linear ICs, many of which incorporate op-amps. Among these are audio amplifiers, phase-locked loops (PLLs), function generators, and telephone, radio, television, and computer communications devices. There are even many kinds that detect temperature, light, weight, and pressure!

In Parting

This concludes our serialization of Forrest Mims' book, *Getting Started In Electronics*. Though we've presented a lot of interesting information to get you started with a foundation in electronics, much more is covered in the book that's available at Radio Shack retail stores. **ME**



(Q)

(P)