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COMPUTER CIRCUITS

FOR EXPERIMENTERS

Computer Circuits for Experimenters

by

Forrest M. Mims, III

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PREFACE

Practical digital computers have been in operation since the early 1950s, but recent advances in semiconductor technology have resulted in truly remarkable advances in the computer field. Now, all the electronic arithmetic circuitry for an electrical computer capable of addition, subtraction, multiplication, and division can be placed on a single silicon chip only a fraction of an inch square!

Only a few years ago experimenters who wished to build the electronic logic circuits which form the basis of digital computers were forced to assemble as many as a dozen or more components on individual circuit boards and then connect the various boards to one another to form the desired logic circuit. Now Radio Shack offers a line of low-cost integrated circuits which contain at least one and as many as six separate logic circuits and permit experimenters to design and assemble complex logic systems efficiently and economically.

This book contains complete instructions for assembling fifteen separate logic circuits ranging from simple gates to a complex decade counter. I assembled and tested all the circuits and each should operate as described if you follow the simple assembly instructions. I hope you enjoy building and operating each circuit.

First, though, read Chapter 1 to familiarize yourself with the basics of digital computer logic. If you are new to electronics, be sure to read Chapter 2. Then you will be prepared to try your hand at assembling the various projects—and going further by modifying the basic projects or even designing new ones on your own. By assembling the projects in this book, you will gain a good understanding of digital logic circuits, the basic building blocks of large scale digital computers.

Other Radio Shack books that could be helpful in understanding active and passive components are *Electronic Com-*

ponents Encyclopedia, Introduction to Transistors and Transistor Projects, and *Introduction to Integrated Circuits and IC Projects.*

FORREST M. MIMS, III

CONTENTS

CHAPTER 5

CHAPTER 6

CHAPTER 7

CHAPTER 8

CHAPTER 9

CHAPTER 10

CHAPTER 11

CHAPTER 1

INTRODUCTION TO COMPUTER ARITHMETIC

The entire field of mathematics is based upon the four basic arithmetic functions of addition, subtraction, multiplication, and division. Even more significant is that each of the four basic arithmetic functions can be performed by various kinds of addition. Subtraction is the inverse of addition, while multiplication is simply repeated addition. Division is the inverse of multiplication.

These basic facts are of immense importance since they mean the most complex arithmetic operations can be performed by addition alone. While you and I would find it inconvenient, to say the least, to add 32 18 times just to find the product of 32×18, an electronic digital computing circuit would perform this operation in *milliseconds.*

In this chapter we will discuss some of the basics of electronic arithmetic and the intriguing electronic circuits which have been developed to perform electronic arithmetic. In later chapters, we will actually build more than a dozen of these circuits and demonstrate how they can be used in a variety of electronic control systems. First, however, let's take a look at the number system electronic arithmetic circuits employ.

THE BINARY NUMBER SYSTEM

You and I are trained to perform arithmetic using the ten-digit decimal system. That happens to be fortunate, since the decimal system is far more convenient and efficient than most of the other number systems which have been tried over the years.

Unfortunately, electronic circuits which can use the decimal system are very difficult to design. Since most practical and economical electronic circuits operate in either of two states, that is they are either on or off, a number system with only two digits would be ideal for an electronic arithmetic circuit. Such a number system was devised even before the age of digital computers, and it was quickly adapted by the engineers who designed the first electronic logic circuits. It's called the **binary number system.**

At first glance a binary number seems completely unexplainable since it contains only the digits 1 and 0. Actually, the binary system is in principle simpler than any number system having more than two digits. To see why, let's establish three simple rules and then use them to count to ten in binary:

Rule 1. $0 + 0 = 0$
Rule 2. $0 + 1 = 1$
Rule 3. $1 + 1 = 10$

Rules 1 and 2 are simple enough, but Rule 3 might seem a little confusing since the result has the same appearance as the decimal number ten. Actually, the result corresponds to the binary equivalent of the decimal number two. Rule 3 is actually a carry rule and demonstrates that since 1 is the largest binary digit, a 1 plus 1 must equal a 0 carry 1 or 10. Ok, got that? If not, think it through before you go on—it's important that you understand.

Now let's use the three basic rules to count to the binary equivalent of the decimal number ten. To avoid confusion between the two number systems, I'll spell out the decimal numbers. Numbers 0 and 1, of course, correspond to zero and one, and we have already learned that the number 10 corresponds to two.

Three corresponds to $10 + 1$ or, from Rule 2, 11. Rule 3 must be used to find the binary number for four: $11 + 1 = 100$. And Rule 2 is used to find five: $100 + 1 = 101$.

Now that we have derived the first six binary numbers, let's just list the numbers from zero to ten:

DECIMAL	*BINARY*
0	0
1	1
2	10
3	11
4	100
5	101
6	110
7	111
8	1000
9	1001
10	1010

This list shows that binary numbers quickly become longer and more awkward than their decimal counterparts, but our derivation of these numbers shows how simple the system really is.

BINARY ARITHMETIC

Now that we have seen how the binary number system is formed, let's try some simple arithmetic. We have already added 1 to each of several binary numbers to find succeeding numbers, so let's try something a little more complex such as nine plus six:

$$\begin{array}{rl} & 1001 \text{ (nine)} \\ + & \underline{110} \text{ (six)} \end{array}$$

Just as in decimal addition, begin by adding the two *least* significant digits:

$$\begin{array}{rr} & 1001 \\ + & 110 \\ \hline & 1 \end{array}$$

Then continue adding toward the most significant digits:

$$\begin{array}{rr} & 1001 \\ + & 110 \\ \hline & 1111 \end{array}$$

The result is 1111 which is the binary equivalent for the decimal number fifteen. The sum was obtained rather easily since no carrying was required (Rule 3). Now let's add two binary numbers which require carrying.

$$\begin{array}{rl} 1011 & \text{(eleven)} \\ +\ \underline{1101} & \text{(thirteen)} \end{array}$$

Adding the two least significant digits gives 10:

$$\begin{array}{r} 1011 \\ +\ \underline{1101} \\ 0\text{, carry 1} \end{array}$$

Adding the next two digits also gives 10 since a 1 is carried:

$$\begin{array}{r} 1011 \\ +\ \underline{1101} \\ 00\text{, carry 1} \end{array}$$

The next two digits also give a 10 since a 1 is carried from the previous two. Finally, we arrive at the total by adding the two remaining digits plus the 1 carried from the previous two to get 11:

$$\begin{array}{r} 1011 \\ +\ \underline{1101} \\ 11000 \end{array}$$

The result is the binary equivalent for the decimal number twenty-four.

CONVERTING BINARY TO DECIMAL

It's quite simple to convert a binary number into its decimal equivalent. Just as in the decimal system, the position occupied by a binary digit determines the power by which the digit should be raised. Consider, for example, the decimal number 847:

$$\begin{array}{rrl} 847 = 8 \times 10^2 = & 800 & \\ 4 \times 10^1 = & 40 & \text{(add)} \\ 7 \times 10^0 = & \underline{\ \ 7} & \\ & 847 & \end{array}$$

This expansion of a decimal number can be applied to any other number system. Since the binary system has but two digits, the position occupied by binary digits determines to which power of the base two (instead of ten) the digit should be raised. Let's see how this works by breaking down the binary number 11000:

$$
\begin{aligned}
11000\ (\text{BINARY}) = {} & 1 \times 2^4 = 16 \\
& 1 \times 2^3 = 8 \\
& 0 \times 2^2 = 0 \\
& 0 \times 2^1 = 0 \\
& 0 \times 2^0 = \underline{0} \\
& \qquad\qquad \overline{24}\ (\text{DECIMAL})
\end{aligned}
$$

Since the result of the expansion is easily converted to decimal, it's quite convenient to convert binary to decimal using this simple technique.

ELECTRONIC LOGIC

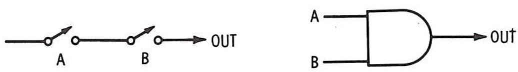
Earlier I said the binary system was well suited to electronic arithmetic since electronic circuits normally occupy one of two states. Some circuits can occupy many more states, and a resistor, for example, can have a value from a fraction of an ohm to many million ohms. But circuits which occupy just two states are far simpler, more reliable and easier to use.

The simplest kind of electronic logic element is an on-off switch. Since the switch has only two possible positions, we can call one position 0 and the other 1. If the open position is 0 and the closed position 1, a binary 1 is implemented when the switch is closed.

A single switch performs only the most basic logic function. However, two or more switches can be connected in parallel, in series, or both to perform more complex functions. These circuits are called *gates* since they can be used to pass or block an electrical current. The two most important gates are the AND and OR gates and each is described in the following sections.

AND GATE

A basic AND gate made by connecting two on-off switches in series is shown in Figure 1-1. If none or only one of the two switches is in the on position, the circuit is incomplete and current cannot flow. If switch A *and* switch B are both closed, the circuit is completed and current will flow. The AND gate can be expanded to include more than two switches, but few computer circuit AND gates have more than four switches. Figure 1-1 also shows the preferred logic symbol for the AND gate and a *truth table* which explains its operation. The truth table arranges all the various input and output conditions for the gate and permits logic designers to quickly determine the operation of the gate. Truth tables of increasing complexity can be used to explain almost all logic functions.



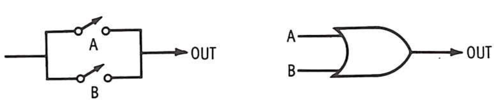
A	B	OUT
0	0	0
0	1	0
1	0	0
1	1	1

(*A*) *Basic* AND *gate.* (*B*) *Logic symbol.* (*C*) *Truth table.*

Figure 1-1. Basic switch AND gate, symbol, and truth table.

OR GATE

Figure 1-2A shows a basic OR gate made by connecting two switches in parallel. If only switch A *or* switch B is closed, the circuit is completed and current will flow. As with the basic two-switch AND gate, an OR gate can have more than two switches. Figure 1-2B shows the preferred logic symbol for the OR gate, and its truth table is given in Figure 1-2C.



A	B	OUT
0	0	0
0	1	1
1	0	1
1	1	1

(*A*) *Basic* OR *gate.* (*B*) *Logic symbol.* (*C*) *Truth table.*

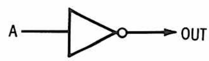
Figure 1-2. Basic switch OR gate, logic symbol, and truth table.

NOT CIRCUIT

The functions of the AND and OR gates can be greatly expanded by adding a circuit called an inverter. An inverter is simply a low-gain amplifier which reverses the function of an AND or OR gate. If the output of the OR gate shown in Figure

1-2 is fed into an inverter, the inverter will produce no output when switch A or switch B is closed. If both A and B are open, the inverter will permit current to flow. Since the inverter reverses the normal operation of AND and OR gates, it is often called a NOT circuit. Figure 1-3 shows the preferred logic symbol for a NOT circuit. Note the small circle at the right of the symbol. This denotes the inverter function.

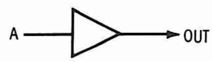
The NOT circuit can be implemented by simply reversing the on-off labels, and therefore functions, of the simple AND and OR gates shown in Figures 1-1 and 1-2. The result is the NAND and NOR gate, the first two logic circuits which combine two basic functions.



TRUTH TABLE

A	OUT
0	1
1	0

(*A*) NOT *circuit.*



TRUTH TABLE

A	OUT
0	0
1	1

(*B*) YES *circuit.*

Figure 1-3. NOT and YES circuit logic symbols and truth tables.

YES CIRCUIT

A special variety of the NOT circuit is the YES circuit. As its name implies, the YES circuit does not invert the polarity of the signal. While the NOT circuit is termed an *inverter,* a YES circuit is a *converter.*

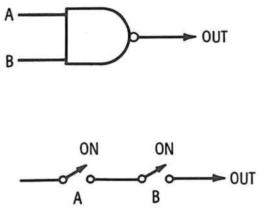
YES circuits are useful for isolating logic circuits from one another and providing amplification. For this reason they are frequently called *buffers* or *drivers.* Figure 1-3B shows the preferred logic symbol for the YES circuit. It is the same as the NOT symbol without the circle denoting the inverter.

Referring to the accompanying truth table for the NOT circuit, when a "0" is applied to the input, a "1" will be obtained at the output. For the YES circuit when a "0" is applied to the input, a "0" is present at the output.

NAND AND NOR GATES

Figure 1-4 shows how two switches can be connected to form a NAND and NOR gate. The circuits are identical to the AND and

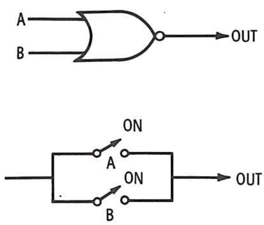
OR gates described earlier, but opposite operation is achieved. A NOT function has been implemented by reversing the on-off (1-0) role of the switches. The result is a NOT-AND or NAND gate and a NOT-OR or NOR gate. The preferred logic symbols for the NAND and NOR gates and their truth tables are shown in Figure 1-4.



TRUTH TABLE

A	B	OUT
0	0	1
0	1	1
1	0	1
1	1	0

(*A*) NAND *gate.*



TRUTH TABLE

A	B	OUT
0	0	1
0	1	0
1	0	0
1	1	0

(*B*) NOR *gate.*

Figure 1-4. NAND and NOR gates.

EXCLUSIVE OR AND NOR GATES

The elementary OR and NOR gates described thus far are considered *nonexclusive.* They will pass an electrical current if switch A or switch B or both A and B are open (NOR) or closed (OR). Some digital logic circuits require an OR or NOR gate which passes a current if one switch or the other is actuated—but not both. These specialized circuits are called **exclusive** OR and NOR gates. An exclusive OR circuit can be made by feeding the outputs from two AND gates into a NOR gate.

SOLID-STATE LOGIC CIRCUITS

The simple switching circuits used to explain the operation of the various gate circuits can be used in practical applications. It is interesting to realize that the first real digital computer, the Mark I Automatic Sequence Controlled Calculator, employed more than 3,000 relays to perform complex arithmetic operations. The relay is simply an electromagnetic switch consisting of a coil of fine wire wound around an iron core. When a current is passed through the coil, the core becomes magnetized and pulls a movable contact against a fixed contact to achieve switching. When the current is removed, the switch contacts resume an off position.

The Mark I, which was built in 1944, could multiply two 23-digit numbers in less than five seconds. But really impressive calculating abilities were made possible by using vacuum tubes and, later, solid-state circuits. The newer electronic switches were much smaller and faster than the relatively "slow" Mark I and its sluggish relays.

Vacuum tubes are no longer employed in practical logic circuits since solid-state circuits are far smaller, easier to operate, and require considerably less power. The simplest solid-state equivalent to the mechanical switch of the previous circuits is the *diode*. A diode is a simple semiconductor device consisting of a tiny chip of germanium or, more commonly, silicon which will pass an electrical current very well in one direction and very poorly in the other. A typical diode may have a forward resistance of a few hundred ohms or less and a reverse resistance of many millions of ohms. By simply reversing the direction of current flow, a diode can serve as a very simple and effective solid-state switch.

A more complex but far more effective solid-state switch is the transistor. Transistors are more flexible switches than diodes since a very small input signal can be used to control a much larger current passing through the transistor. This property is called *amplification*. Symbols for the diode and transistor are given in the next chapter.

Numerous other solid-state devices can be used to replace the mechanical switches of our basic logic circuits, and the list includes the silicon controlled rectifier (SCR), field effect transistor (FET), four-layer diode, tunnel diode, and various light-sensitive versions of the transistor and SCR.

MULTIVIBRATORS

A multivibrator is a symmetrical electronic circuit containing two sections, one of which controls the state of the other. If one half of the circuit is on, the other must be off and vice versa. A multivibrator can be easily made by cross-connecting the outputs of two gates with their inputs as shown in Fig. 1-5. When one gate turns on, the other turns off and vice versa.

Since multivibrators naturally operate in the on-off mode of the logic circuits described earlier, they are ideally suited for use in digital computer circuits. Indeed, they are indispensable for such operations as timing, pulse generation, temporary memories, and other important functions we'll discuss later. First, let's discuss the most important multivibrator configurations.

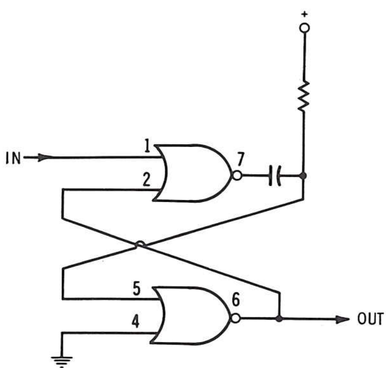


Figure 1-5. Multivibrator.

Astable Multivibrators

The *astable* or *free-running* multivibrator automatically changes the state of each of its two sections at rates ranging from less than once a second to millions of times a second. For this reason, astable multivibrators are frequently employed as *clocks* in digital logic circuits. In this role the multivibrator provides a continual stream of pulses which steps an input signal through the various logic elements.

Monostable Multivibrators

Unlike its astable cousin, the monostable multivibrator changes states only when instructed to do so by a single input signal. After a brief time interval, which can range from billionths of a second to a minute or more, it automatically resumes its normal state. In short, a monostable circuit issues a single output pulse for every input pulse. For this reason, monostable circuits are frequently called *single-shots* or *one-shots* by design engineers.

At first glance a circuit which emits a pulse each time it receives a pulse may not seem too useful, but single-shots are among the most versatile of logic circuits. By simply adjusting the output pulse width (*on* time), for example, a single-shot can be used to divide an incoming series of pulses by almost any number.

Interfacing is another valuable role for single-shots. Consider, for example, *switch bounce.* When almost any conventional switch is closed or opened, the contacts do not immediately make or break contact. Instead, a very rapid series of brief contact pulses is produced at the moment the switch is opened and closed. This does not affect most electronic circuits, but since most logic circuits are intentionally designed to detect brief pulses, a single switch closure may send up to five or more pulses into the system instead of the single desired pulse.

The single-shot can be conveniently used to eliminate the bounce problem. By making the output pulse much wider than any possible grouping of bounce pulses, a single pulse can be generated each time the switch is actuated.

Other uses for the single-shot include pulse stretching and threshold detection. We'll discuss these applications in more detail in a later chapter.

Bistable Multivibrators (Flip-Flops)

The most important class of multivibrator for digital logic purposes is the familiar flip-flop. This fascinating circuit resembles the single-shot monostable multivibrator since it changes state only when instructed to do so by an incoming pulse. But unlike the single-shot, the flip-flop does not automatically reset itself after a preset time interval. Instead, one side flips into the on state and flops back to the off state only when an input signal has been received. The other side flip-flops into opposite states. Unlike the single-shot, the flip-flop is stable in either its on or off state. Therefore it is also known as a bistable multivibrator.

By connecting a series of flip-flops together so that the output of the first controls the input of the second and so forth, binary addition *and* division can be performed. Even more significantly, since a flip-flop holds its state until the next control pulse is received, it can serve as a very effective memory circuit.

COMPLEX LOGIC CIRCUITS

The three basic logic circuits—AND gates, NOT gates, and inverters—can be used in an almost unlimited variety of complex logic circuits. We have already seen how two gates can be crisscrossed to make a multivibrator. Another important circuit made by interconnecting simple logic circuits is the *binary adder* shown in Figure 1-5. Until now, we've explained the logic circuits with 1s and 0s simply for convenience. A and B, yes and no, or any other designations could also be used to explain the operation of the basic logic circuits.

Now the 1 and 0 inputs and outputs of the various logic circuits will be used to indicate binary digits. Here's how: Note that the binary adder circuit in Figure 1-6 has two input terminals, A and B. If no input is present, AND gate 1 and OR gate 1 produce no output and a 0 is present on both the carry and sum output lines.

Assume a signal is placed on input A and that no signal is present at input B. This corresponds to a binary 1 and 0 being fed into the adder. AND gate 1 requires an input signal at both inputs before it will pass a signal so its output is zero. Therefore the carry output is also zero, but the output of NOT 1 is *not* zero which means it must be 1.

OR gate 1 requires only one input signal to issue an output signal. Therefore, since it is also connected to the input lines A and B, it is turned on by the single 1 input at A. It then sends an output signal (1) to AND gate 2. Since NOT 1 also presents an output (1) to AND gate 2, the gate passes an output signal and a binary 1 appears on the sum line. The adder has therefore added 1 and 0 and arrived at the correct total, 1.

This, of course, is a very elementary adder circuit, but by connecting the carry output to the input of a second adder and so forth, very complex binary additions can be performed. To

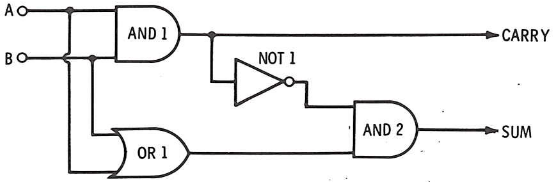


Figure 1-6. Binary adder logic diagram.

see how the carry function is implemented, try adding 1 and 1 with the adder circuit.

Flip-flops and other circuits can also be used to perform complex logic functions, and we will examine several of these in detail in later chapters.

LOGIC TERMINOLOGY

We have already covered many logic terms simply by describing the various logic circuits, but there are several additional terms which must be explained.

Logic Levels

Earlier I explained how the two binary digits 0 and 1 can be used to define the two logic states. Ideally, 0 corresponds to no output signal and 1 to an output signal. In practice, however, a 0 state may actually represent a signal of a fraction of a volt, while a 1 represents a signal of several volts. For this reason, logic engineers frequently say a logic signal is either low (0) or high (1). The fact a 0 signal is not actually zero is of no importance in a practical logic circuit, since each successive circuit requires the amount of voltage in the 1 state in order to be activated.

Positive and Negative Logic

Thus far, we have described logic systems employing *positive logic.* In positive logic a low voltage state is 0 and a high voltage state is 1. In negative logic, which is used less frequently, a low voltage state is 1 and a high voltage state is 0.

Logic Circuit Abbreviations

Numerous electronic techniques and circuits have been implemented to form various logic functions. Some are preferred for circuits employing individual components while others are best for integrated circuits. Three different types of logic circuits (DTL, RTL, and TTL) are employed in the projects in this book. These and other logic type abbreviations are explained below:

CML—Current Mode Logic
CTL—Complementary Transistor Logic

DCTL—Direct-Coupled Transistor Logic
DTL—Diode-Transistor Logic
ECL—Emitter-Coupled Logic
MOSL—Metal-Oxide-Semiconductor Logic
RTL—Resistor-Transistor Logic
TTL—Transistor-Transistor Logic (also T^2L)

There are various other types of logic circuits, but these are the most common. RTL was formerly the favored type, but most logic is now performed with TTL. ECL is used for very high-speed logic applications. MOSL is the logic type of the future, and is employed in many commercial applications (pocket calculators and watches, for example). Most experimenter projects use TTL, but RTL is ideal for some functions requiring very low-level logic signals and small operating voltages. Various forms of MOS logic will no doubt replace many TTL circuits in the future.

Still another form of logic terminology is the descriptions applied to various logic ICs. Names like "Hex Inverter," "Quad 2-Input Positive NAND Gate," "BCD to 7-Segment Decoder/ Driver," and "Dual J-K Master-Slave Flip-Flop" can be pretty confusing to the logic beginner. Actually, these strange sounding names are simply a kind of computer logic jargon with easily interpreted meanings. For example, "Hex Inverter" describes a single IC containing six (hex) separate inverters. And a "Quad 2-Input Positive NAND Gate" is an IC containing four (quad) 2—input NAND gates.

As you gain more experience in digital logic, you will learn additional logic terms. Those explained here, which you will meet again and again in the remainder of this book, are adequate for most applications.

DIGITAL CALCULATORS AND COMPUTERS

Earlier I mentioned that all four basic arithmetic functions can be achieved by conventional or inverse addition. This is a very important point since it means complex electronic arithmetic can be performed with nothing more than a binary adder. In fact, the heart of electronic calculators and digital computers is a binary adder called the Central Processing Unit (CPU). The simplest pocket calculator and the most advanced digital computer both have CPUs.

The difference between the immense calculating power of computers and the less sophisticated functions of calculators is *control*. A computer can be programmed to automatically execute immensely complex equations and make logical decisions during the course of solving a problem which may drastically affect the ultimate solution. Additionally, computers have enormous memory capability.

Calculators simply don't have room for the many varied operations and functions of computers, nor are they intended to. Instead, calculators offer rapid solutions to problems which are not so complex that a computer is required. Since no programming is required to instruct the CPU, the keyboard entry system of most calculators is a particularly attractive and helpful feature.

Thanks to solid-state electronics, modern calculators and computers are a fraction of their former size. In the early 1960s most computers were made by soldering individual transistors, diodes, resistors and capacitors to small circuit boards. Conductive foil patterns on the back side of the board served to connect the various components to one another. Hundreds and even thousands of these circuits were inserted into special racks and interconnected with one another to achieve complex logic functions. Generally, each circuit board contained only one or two logic functions.

While computers made in this fashion were much smaller than their vacuum tube predecessors, they were comparatively expensive since thousands of individual electronic components and solder connections were required.

In the late 1960s, integrated circuits began to be used on a large scale in digital computers and both size and cost began to shrink. As the name implies, an integrated circuit (or simply IC) combines several or even many electronic components on a single tiny "circuit board." Practical ICs are made by carefully processing, etching, coating, and metalizing tiny slabs of silicon to which very carefully controlled amounts of impurities have been added. The completed chip may have dozens of diodes, transistors, and resistors in a space smaller than this letter "O."

IC chips are packaged in a miniature ceramic, plastic, or metal housing to protect the chip from contamination and mechanical shock, and to provide a mounting point for the dozen or more electrical leads. While these packages are no larger than a paper clip, and many are much smaller, designers continue to miniaturize ICs. By employing the same technology used to make field-effect transistors, which are simpler in construction than conventional bipolar (PNP and NPN) transistors, literally hundreds and even thousands of individual components can now be placed on tiny silicon slabs.

The new generation of ICs is called MOS LSI which means *metal-oxide-semiconductor large scale integration.* MOS LSI ICs have made possible the pocket calculator, digital wristwatches and clocks, and other highly sophisticated electronic devices. The first miniature calculators required four separate ICs to pack in all the required logic circuitry, but within a few years all the components were crammed onto a single silicon chip! Now, almost all pocket calculators use a single chip—and more and more calculating power is being jammed onto the space that is available.

LEARNING DIGITAL LOGIC

The best way to learn a subject is to work with it rather than just read about. The remainder of this book contains more than a dozen logic circuits you can easily build and operate. I've built each of these circuits and tested them to verify their operation. With a little attention to the construction details provided with each circuit, you'll be able to build an operating version of each circuit with little or no trouble. And if you're like me, you'll have a great time experimenting with the circuits to demonstrate the various logic functions. I always prefer to personally verify operation of a circuit instead of just reading about it. And I invariably learn more by building the circuit!

For those readers who may have little or even no electronic-construction experience, the chapter has a number of electronic assembly hints. Then, the rest of the book describes the various computer logic circuits and how you can build each.

CHAPTER 2

ELECTRONIC-ASSEMBLY TIPS

Since all the projects in this book use low-voltage semiconductor components, assembly is completely safe and relatively straightforward. This chapter includes some basic assembly information which readers with little or no previous electronics experience will find helpful. Even those readers with more experience may find it helpful to review the chapter, particularly the section on *How to Solder*.

COMPONENT SELECTION

The components used in the projects in this book include integrated circuits (ICs), transistors, diodes, resistors, batteries, switches and potentiometers. If you have not built an electronic construction project before, some or even all of these components may seem strange or even hard to understand, but all of them are very easy to use in a project. This section will briefly describe each of these components and provide some hints on choosing components for a project.

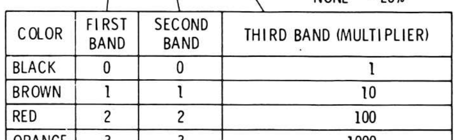
Resistors

Almost all electronic projects require resistors. As their name implies, resistors literally resist the flow of an electrical current. Therefore resistors are frequently used to limit the current to a component which might be destroyed by excessive current flow. Resistors are also used to supply a trickle of current to transistors in order to adjust the operating characteristics of the transistor to an optimum point. Finally, resistors are used to divide a large voltage into two or more smaller voltages and, in conjunction with a voltmeter, to permit current through a circuit to be conveniently measured.

Most resistors are made from powered carbon or high resistance wire, but semiconductor integrated circuits employ solid-state resistors made from carefully contaminated regions of silicon. Most discrete resistors are mounted in a protective ceramic or plastic cylinder. Low-power resistors may be as small as a short length of pencil lead, while high power resistors may be as big as a section of a pencil or even much bigger.

Resistors are specified in units of resistance called *ohms*. Three or more color bands around one end of the resistor permit the resistance to be quickly determined. This resistor color code is explained in Figure 2-1. To see how the code works, let's determine the value of a resistor with yellow, violet, and red bands. Always read the color bands beginning with the band closest to one end of the resistor. Yellow is the first band in our example, and Figure 2-1 shows that yellow corresponds to a value of 4.

Violet is the second band, and Figure 2-1 shows violet corresponds to a value of 7. The third band determines the factor



COLOR	FIRST BAND	SECOND BAND	THIRD BAND (MULTIPLIER)
BLACK	0	0	1
BROWN	1	1	10
RED	2	2	100
ORANGE	3	3	1000
YELLOW	4	4	10,000
GREEN	5	5	100,000
BLUE	6	6	1,000,000
VIOLET	7	7	10,000,000
GRAY	8	8	100,000,000
WHITE	9	9	

Figure 2-1. Resistor color code.

by which the first two numbers must be multiplied to find the total resistance. Red corresponds to a multiplication factor of 100, so the sample resistor is 47 × 100 or 4,700 ohms.

Often you will see a resistor value followed by a K or M. These letters are a kind of shorthand which indicate the value given should be multiplied by 1,000 or 1,000,000 respectively. For example, a 47K resistor has a value of 47,000 ohms and a 1.6 M resistor has a value of 1,600,000 ohms.

Many resistors have a fourth color band which specifies the component's tolerance. A gold band means the color code value is within 5 percent of the actual value, and a silver band means the color coded value is within 10 percent of the actual value. The resistor has a 20 percent tolerance if there is no band.

It is important to realize that most electronic circuits and all the projects described in this book will operate with resistors having a tolerance of 20 percent. This is important since it means you can substitute a resistor of similar value if the value specified is not available. For example, it's usually okay to substitute a 4,700-ohm resistor for a 5,000-ohm unit or a 1,200-ohm resistor for a 1,000-ohm unit. Since a specified resistor may be temporarily out of stock when you wish to purchase it, you can substitute a reasonably close value.

Potentiometers

The potentiometer is an adjustable resistor and is therefore quite useful in circuits which require frequent adjustments. Potentiometers come in a variety of configurations, but all perform the same function. I almost always use linear taper types in experimental circuits. These potentiometers provide a constant, linear change in resistance as the control is advanced. Audio taper types give a logarithmic change in resistance as the control is advanced and are therefore ideal for use as volume controls in amplifiers and other audio circuits.

You can use low cost printed-circuit or shaft-type potentiometers for experimental circuits. For permanent circuits, you may want to consider higher quality controls with a built-in power switch.

Capacitors

Capacitors have the unique ability to resist fluctuating voltage changes. By its ability to store an electrical charge, the capacitor acts as a reservoir of electrons which provides current during very brief voltage interruptions. This property of smoothing out an uneven voltage level makes capacitors very valuable for use as filters in power supplies which convert alternating current (AC) to direct current (DC).

Another very valuable property of the capacitor is its ability to block a direct current applied to it in series. An alternating current passes through a capacitor unimpeded so capacitors are frequently used as dc blocking devices in amplifiers and other circuits.

Capacitors require two conductive plates separated by an insulator called the *dielectric*. Very small capacitance values can be achieved by simply separating two small metal plates with a sheet of plastic. The completed assembly is coated with wax, ceramic or plastic to protect it. Larger values of capacitors require several interconnected layers of plates or other construction techniques. One of the most common techniques is to make a long thin sandwich from two strips of aluminum foil separated by a strip of insulator. The sandwich is rolled into a tight cylinder and coated with a protective layer of wax or plastic.

Like resistors, capacitors come in a wide range of tolerances. Frequently, the actual value of a capacitor will range from 20 to even 100 percent of the value printed on the device. This means capacitor substitutions are permissable in almost all electronic circuits. For example, a 0.025-μF capacitor can almost always be substituted for a 0.02-μF or even 0.01-μF unit with no difficulty.

Diodes

The diode is one of the simplest semiconductor components. A basic pn junction diode consists of a tiny chip of germanium or silicon to which controlled amounts of impurities have been added to form a region with a surplus of free electrons (n-type) directly adjacent to a region with a deficit of free electrons (p-type). If a negative current flow is introduced into the n side of the diode, the free electrons on that side will cross over the junction formed by the two regions and drop into the holes caused by the electron deficit on the p side of the junction. The result is a current flow, and the diode is said to be *forward biased.*

If, however, the negative current source is connected to the p side of the diode, the free electrons on the n side and holes on the p side will be attracted away from the junction. The result is a very tiny current flow, and the diode is said to be *reverse biased.*

As we saw in Chapter 1, the property of passing a current flow in only one direction means diodes are very useful as simple solid-state logic switches. Diodes are also used for numerous other applications. Certain special-purpose diodes can even be used to regulate voltages and provide very rapid and automatic switching.

The circuits described in this book are all powered by low-voltage batteries, so almost any general-purpose diodes can be used. I've found it helpful to keep a supply of such diodes on hand for use in experimental circuits. Radio Shack supplies assortments of tested glass-encased diodes for less than 10¢ each (276-821) and assortments of untested diodes for less than 4¢ each (276-114). Untested diodes may not meet manufacturer's specifications but most work well in experimental circuits.

You can easly check a diode by connecting it in series with a small flashlight bulb and a 1½ volt battery. The lamp should be illuminated with the diode in one position but not be illuminated when the diode leads are reversed.

Light-Emitting Diodes (LEDs)

A very interesting diode is the light-emitting diode (LED). The LED acts like a conventional diode when reverse biased, but when forward biased it emits light. Some kinds of infrared-emitting diodes are very efficient and emit up to hundreds of milliwatts of invisible infrared radiation. These diodes are used in infrared communication systems and object-detection devices.

Other less efficient LEDs emit visible green, yellow, amber, or red light. Red emitters are easier to manufacture and they are also the most economical.

Radio Shack markets several visible red-emitting LEDs which are ideally suited for use as indicators in digital logic circuits. When the LED is *on* it represents the binary 1 and when the LED is turned *off* it represents the binary 0 (positive logic).

LEDs can be substituted for one another in many applications. Since some LEDs can withstand far more current than others, be sure to select one which is rated for the expected current. Too much current will damage or even destroy an LED.

Always make sure the LED is connected in the proper direction or it will not operate properly. A special marking is always provided on the LED package which identifies the positive (anode) or negative (cathode) lead. Data supplied with the LED explains the marking.

Transistors

The transistor is a semiconductor device which electronically resembles two diodes connected back-to-back. The result is a device which has two pn junctions. While diodes are simple pn devices, transistors are pnp or npn devices.

The center region of a transistor has the unique ability of controlling a current flow through the device. With no current connected to the center region, current cannot flow and the transistor is considered off. When a small current is injected into the center region, the transistor is turned on and a current flows.

Since a transistor uses a very small current to control a much larger current, it has gain and can be used as an amplifier. By applying a relatively large input signal, the transistor can be turned completely on so that it acts very much like a switch. This combination of amplification and switching makes transistors extremely valuable in digital logic circuits.

Thus far we have described junction *bipolar* transistors. Another class of transistor which has recently become very important in digital logic is the *field-effect transistor* (FET). Conventional bipolar transistors are normally off, but FETs are normally on. A very small voltage placed at the center terminal of a FET causes an electrical field which restricts some of the current flow, and as the voltage increases the field eventually squeezes off the current flow entirely. This condition is called *pinch-off*.

FETs are exceptionally sensitive devices and will change from the on state to the off state with only a tiny input signal. Chapter 3 describes a simple FET logic probe which you can build and use to demonstrate this sensitivity.

Though thousands of transistor types are available, substitutions can usually be made. Radio Shack, for example, carries a line of over 35 ARCHER (TM) transistors which can be used as direct replacements for more than 20,000 different transistors.

Most of the transistors used in this book are general-purpose devices. If a specified type is temporarily out of stock, you can substitute another device intended for a similar application so long as both the original and replacement have the same polarity (PNP or NPN). For example, I prefer to use the very versatile 2N2222 transistor in many projects and have specified it for several of the projects in this book. If a 2N2222 is not available, you can substitute an A5T3904 or 2N2484 and obtain identical results.

Integrated Circuits (ICs)

As we noted in Chapter 1, ICs are high density "packages" of transistors, resistors, and other diodes on tiny silicon chips. Literally hundreds of different ICs are available and each is designed to perform a particular function. Radio Shack markets more than 30 different ICs ranging from digital logic circuits to high performance voltage regulators, operational amplifiers and audio amplifiers.

Most ICs are housed in metal cans similar to those used for transistors, in ceramic or plastic rectangular-shaped dual-in-line packages (DIPs), or in small flat packs. Some are packaged in small plastic transistorlike packages. A single IC may have from 8 to 64 or more leads, but most have no more than 16.

Some fundamental digital circuits, such as the flip-flop, require a dozen or more individual components, and a single low cost IC may contain four flip-flops on a single silicon chip. Obviously it's much simpler—and cheaper—to use an IC in a logic circuit than to use dozens of individual transistors, diodes, resistors and capacitors.

All the components described thus far can frequently be substituted or replaced by components of similar value. Since ICs are made for a specific purpose, however, direct substitutions are not always possible. Pin positions, for example, vary from IC to IC, to say nothing of the variations in internal circuitry.

One instance where substitutions are possible is when you are building up your own logic circuits. If the circuit calls for two AND gates and all you have available is a type 7400 quad 2-input NAND gate and a type 7404 hex inverter, you can add two of the six inverters from the 7404 to the output of two of the four NAND gates of the 7400 to get two AND gates. We'll discuss digital logic ICs more in later chapters.

Batteries

All of the circuits described in this book will operate from battery power. Some simple circuits require only 3 volts, and I suggest that you use two "C" or "D" size cells connected in series for these projects. You can use Radio Shack catalog number 270-1437 or 270-1439 two-cell holders to hold these cells.

The projects which use TTL ICs require 5.5 volts. Since four dry cells in series supply approximately this voltage, I suggest you use two of the holders described above connected in series to obtain the proper voltage for the TTL projects.

Radio Shack markets conventional carbon-zinc, mercury and alkaline cells. Carbon-zinc and alkaline cells are ideal for all the projects. While the former cells are much cheaper, the latter have a much longer life. Therefore, I usually prefer to use alkaline cells to power construction projects.

Switches

You can eliminate the need for an on-off power switch by simply removing a battery from the circuit being powered. But if you prefer to use a power switch for convenience, choose a slide or toggle switch. Slide switches are very inexpensive, but toggle switches are easier to install, last longer and are easier to actuate.

Radio Shack markets more than 50 different switches, so take your time before settling on a final choice. Inexpensive switches are fine for experimental projects, but you may wish to purchase a more attractive switch for permanent projects.

Most switches are classed according to their positions and poles. For example, a double pole (DP) switch is actually two separate switches in one housing actuated by a single lever or toggle. A double throw (DT) switch has two on positions, while a single throw (ST) switch has only one position. The abbreviations can be combined to give a complete designation about a particular switch. For example, a DPDT switch consists of two side-by-side SPDT switches with two on positions.

READING CIRCUIT DIAGRAMS

Simple symbols have been devised to help circuit designers draw an electronic circuit diagram or schematic. Figure 2-2

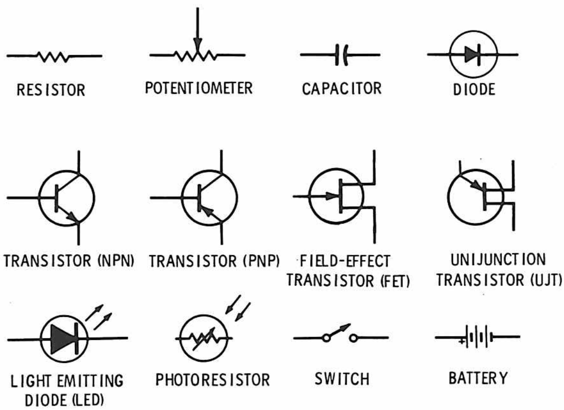


Figure 2-2. Some common schematic symbols.

shows most of the circuit diagram symbols used in this book. Logic symbols are a form of circuit diagram also, and several of the most common types were presented in Chapter 1. Since several basic logic circuits may be used dozens or even hundreds of times in a single logic circuit, logic symbols provide simpler and more legible circuit diagrams than diagrams which show all the components within each logic circuit. Also, logic symbols permit the operation of a circuit to be quickly determined.

CIRCUIT BOARDS

Some of the circuits in this book use so few components that a circuit mounting board is not a necessity. However, operation of both simple and more complex circuits is considerably enhanced by using a circuit board to mount all the components.

I built all of the circuits described in this book on alternate grid perforated board available from Radio Shack (catalog number 276-1392). Before mounting the components on the board, I tested the circuit on a special spring board used by design engineers which permits various parts to be rapidly inserted and removed from the circuit. When the circuit was operating properly, I transferred the components to a "perf" board in a configuration which you can easily duplicate.

Perforated boards are ideal for experimental circuits since modifications and component changes can be quickly made. Also, since all the component leads are exposed it's easy to check operation of the circuit at various test points with a volt meter.

For more permanent projects, you may want to use etched-circuitry construction. Etched-circuit projects are professional in appearance and sturdier and more reliable than perforated board construction. Radio Shack markets an etched circuit kit with complete instructions which is ideal for custom circuit board fabrication. The catalog number is 276-1576.

SOLDERING

Whatever circuit-board technique is employed, good soldering practices are essential for reliable operation. If you have had prior soldering experience, read the following procedures over just for a review. If you are a soldering novice, read the procedures very carefully and practice soldering some lengths of scrap wire together before attempting to solder actual components to one another.

1. Avoid using a soldering gun or high-wattage iron when assembling transistorized circuits since the high heat may damage semiconductors and other components. Instead, obtain a "pencil" soldering iron rated from 25 to 40 watts and tin the tip in accordance with the manufacturer's instructions.
2. Never use acid-core solder for soldering electronic components since it is corrosive and may damage electronic parts. Always use rosin-core solder—the type sold by Radio Shack.
3. To ensure a low-resistance, permanent bond, always remove all grease, oil, paint and other foreign matter cover-

ing parts to be soldered together. If necessary, use an abrasive, such as sandpaper or a solvent.

4. Begin soldering a connection by first heating the joint where solder is to be applied. When the connection has been heated for a few seconds, leave the iron in place and apply solder to the connection (not the iron).
5. Allow the solder to flow through and around the connection for a second or so before removing the iron. Don't apply excessive solder or physically move the connection before it has cooled.
6. Keep the tip of the iron clean. Wipe off accumulations of debris with a damp sponge or cloth.

If these six steps are followed, a good solder connection is easily made. A good connection will appear smooth and shiny, while a poor one will be dull and rough.

MOUNTING INTEGRATED CIRCUITS

Most electronic components are easy to mount on a perforated board, but the close spacing of their many leads makes ICs more difficult to mount directly on a board. *"Integrated Circuit Projects, Volume 1,"* a Radio Shack publication, describes several ways to mount ICs to a perforated board by

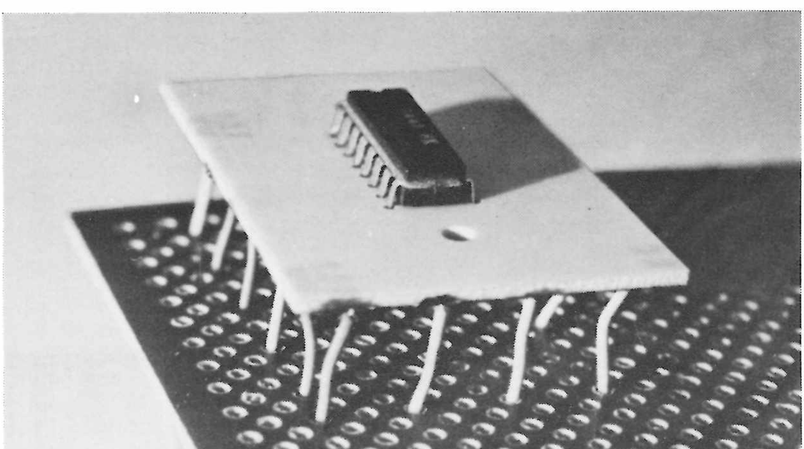


Figure 2-3. IC adapter installed on a perfboard.

using either a special IC socket, socket adapter board, or both (see pages 10-15). I prefer to solder ICs directly to small adapter boards available from Radio Shack (catalog numbers 276-024 and 276-028). If you prefer, you can solder a socket to the adapter board and use one socket-board for many different projects. Or you can solder several commonly used ICs to their own boards without using a socket.

Whichever technique you employ, always mark the IC pin numbers on the back of the adapter board adjacent to the foil pattern solder pads which make contact with the IC. Then solder lengths of insulated hookup wire to each pad. Figure 2-3 shows how a completed IC adapter appears when mounted on a perforated board with its connection leads. For more IC installation and mounting details, see *"Integrated Circuit Projects, Volume 1."*

CHAPTER 3

LOGIC-STATUS INDICATORS

The only way to determine if a logic current is operating properly is to apply a control signal and observe the device controlled by the output. Frequently the controlled device is a light-emitting diode (LED) or a numeric display. If the display fails to operate when a control signal is applied to the logic, how do you troubleshoot the problem?

You could use a voltmeter or oscilloscope to trace the various voltage levels through the logic circuit, but a much simpler and economical technique is to employ a *logic probe,* a simple circuit which lights an LED when a logic "1" is present, and extinguishes the LED when a logic 0 is present. Besides being used for troubleshooting, such a circuit is ideal for use as a permanent status indicator in demonstration and experimental logic circuits.

This chapter describes the construction of two simple logic-status indicators. Both give a positive logic output by turning on an LED when a logic 1 is present and extinguishing the LED when a logic 0 is present. Each circuit can be assembled for less than $3.00, and both are ideal for use as permanent logic probes. I will use one of the logic-status indicators as a built-in display in many of the following projects.

HOW THEY WORK

You could use an LED in series with a small current-limiting resistor as a logic-status indicator. The LED would glow when connected from a logic 1 to ground, and the resistor would protect the LED by limiting the current to a safe value.

Unfortunately, this simple status indicator tends to "load" the circuit it is monitoring by literally absorbing most of the logic output signal if one is present. Therefore, operation of the logic circuit may be impaired during the measurement, and the resultant readings may be erroneous. Worse yet, some ICs may be damaged by the excessive current flow caused by the LED. Many ICs are designed to operate LEDs directly, but since all are not, a logic-status indicator can be very handy.

The solution to the problem is to borrow a tiny quantity of the logic signal and amplify it with one or more transistors. When a logic 1 is present at the amplifier input, an LED connected in series with the collector-emitter leads of the transistor will glow.

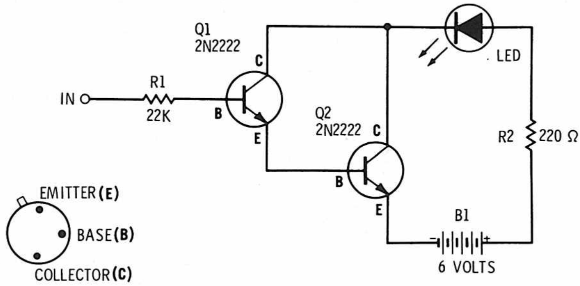


Figure 3-1. A Darlington transistor logic-status indicator.

Figure 3-1 shows one kind of simple logic-status indicator. The circuit contains only two transistors, two resistors, and a LED. The two transistors are connected in what is called a *Darlington pair*. This configuration provides very high amplification (gain) with a very high input impedance. The latter feature means the circuit does not load down the logic circuit it is monitoring.

Resistor R1 is placed between the input of the Darlington pair and the status-indicator input to increase the isolation between the logic circuit undergoing monitoring and the status indicator. The resistor can be eliminated, but the status indicator would have less impedance. For more impedance, the resistor can be increased in value.

Resistor R2, in series with the LED, limits the current through the LED to a safe value. This resistor serves an important function and should not be omitted.

A second kind of logic status indicator is shown in Figure 3-2. This circuit is simpler and has a much higher input impedance than the previous circuit. Like the previous circuit, this one is so sensitive and has such a high input impedance that it will respond when the input lead is merely touched with a finger.

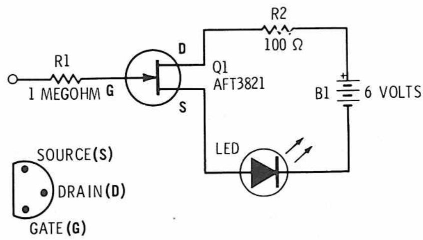


Figure 3-2. A FET logic-status indicator.

The secret to the circuit in Figure 3-2 is transistor Q1, a field-effect transistor (FET). A small negative voltage at very low current will create an electrical field inside the FET which prevents current from following through the LED. A small positive voltage will eliminate the field and permit current to pass through the FET and the LED. Therefore, a positive logical 1 at the input connection will cause the LED to glow.

The value of input resistor R1 in the FET logic-status circuit is much higher (1,000,000 ohms) than R1 in the Darlington circuit, since the FET circuit has a higher input impedance. In fact, the circuit will operate if R1 is increased to 100 million ohms. Discounting the resistance of the FET, this means the FET draws only 60 billionths of an ampere (60 nanoamps). Resistor R2 is placed in series with the FET and LED to limit current through the LED to a safe value.

To better understand the operation of these logic-status indicators, I suggest that you assemble one or even both of them. Besides being simple to assemble, you can use one or both circuits in almost all the following projects. Construction details are included in the following section.

CIRCUIT ASSEMBLY

I assembled both prototype logic-status indicators on alternate grid perforated boards. You can construct each circuit on a separate board, or you can assemble both circuits on the same board.

Darlington Transistor Logic-Status Indicator

Figure 3-3 shows a pictorial view of the completed Darlington transistor probe. This is one of the simplest circuits in this book, and assembly is straightforward. The parts list is given in Table 3-1. Begin assembly by comparing the bottom of the two transistors to the pin diagram shown in Figure 3-1. Note that the emitter lead is closest to the small metal tab. It is important that all three leads of both transistors be connected properly or one or both transistors may be damaged.

Gently bend the center base lead of each transistor between the other two leads and insert the transistors in the board as shown in Figure 3-3. Bend the collector lead of Q1 toward the collector lead of Q2 and solder the leads to one another. Be sure to review the section on soldering in Chapter 2 if you have had little or no soldering experience.

Next, bend the emitter lead of Q1 toward the base lead of Q2 and solder the two leads to one another. Insert the LED into the board with its cathode lead nearest the collector-collec-

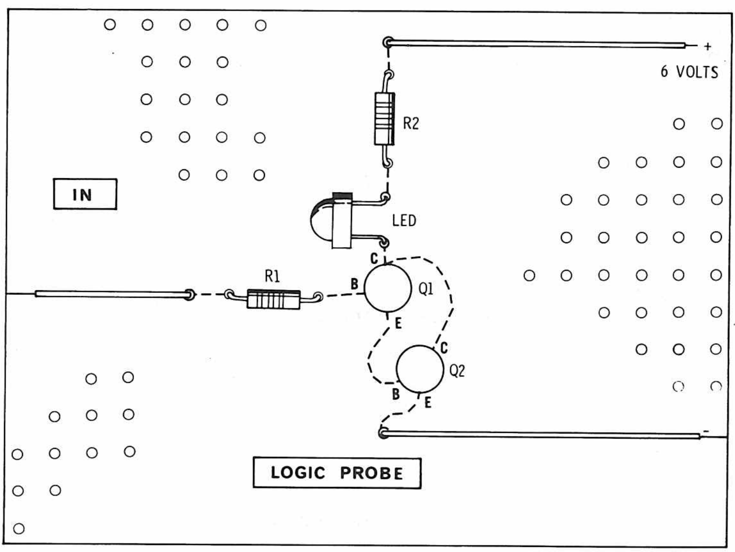


Figure 3-3. Pictorial wiring diagram of the Darlington transistor logic-status indicator.

tor connection between Q1 and Q2 and solder the cathode lead to the two collector leads. R2 is a 220 ohm resistor (red-red-brown). Bend its leads at right angles to the resistor and insert them in the board as shown in Figure 3-3. The remaining lead is the connection to the positive battery terminal.

Table 3-1. Darlington Logic-Status Indicator Parts List

Item	Description
B1	Battery, 3-6 volts (see (text)
LED	Light-emitting diode (276-041 or 276-026)
Q1, Q2	2N2222 transistor (276-2009)
R1	Resistor, 22,000 ohm, ½-watt
R2	Resistor, 220 ohm, ½-watt
Misc.	Perforated board (276-1392), hookup wire, solder

(Radio Shack catalog numbers shown in parentheses.)

R1 is a 22,000 ohm resistor (red-red-orange). Bend its leads at right angles and insert them into the board as shown in Figure 3-3. Solder one lead to the base of Q1. The remaining lead becomes the input connection to the circuit. The negative battery connection point is the emitter of Q2.

The completed circuit should resemble the logic-status indicator portion of the basic logic circuits in Chapters 4 and 5. See, for example, the photograph in Fig. 4-3. Note that these circuits do not include R2, the current limiting resistor incorporated to reduce the LED current to a safe value, since only 3 volts is used to power each circuit.

FET-Logic Status Indicator

The FET logic-status indicator is even simpler to assemble than the Darlington version since only one transistor is required. The parts list is given in Table 3-2. Figure 3-4 is a pictorial view of the circuit. Begin assembly by comparing the leads of FET Q1 with the pin diagram provided in Figure 3-2. Then insert Q1 into the board as shown in Figure 3-4 and bend its leads slightly outward.

Next, bend the leads of R1, a one million ohm resistor (brown-black-green), at right angles and insert them into the board as shown in Figure 3-4. Solder one end of R1 to the gate lead of Q1. Bend the leads of R2, a 100 ohm resistor (brown-

Table 3-2. FET Logic Status Indicator Parts List

Item	Description
B1	Battery, 3-6 volts (see text)
LED	Light-emitting diodes (276-041 or 276-026)
Q1	AFT3821 FET (276-2028)
R1	Resistor, 1 megohm, ½-watt
R2	Resistor, 100 ohms, ½-watt
Misc.	Perforated board (276-1392), hookup wire, solder

(Radio Shack catalog numbers shown in parentheses.)

black-brown), at right angles and insert them into the board also. Solder one lead to Q1's drain. The remaining leads of R1 and R2 become the input and positive battery connections, respectively.

Complete assembly of the circuit by installing the LED, with the anode lead pointing toward Q1. Make sure the lead polarities on the LED are correct and insert the LED into the board as shown in Figure 3-4. Then solder the source lead of Q1 to the anode lead of the LED. The remaining LED lead serves as the negative battery terminal.

The completed FET logic-status indicator should resemble the photograph of the prototype circuit in Figure 3-5. Note

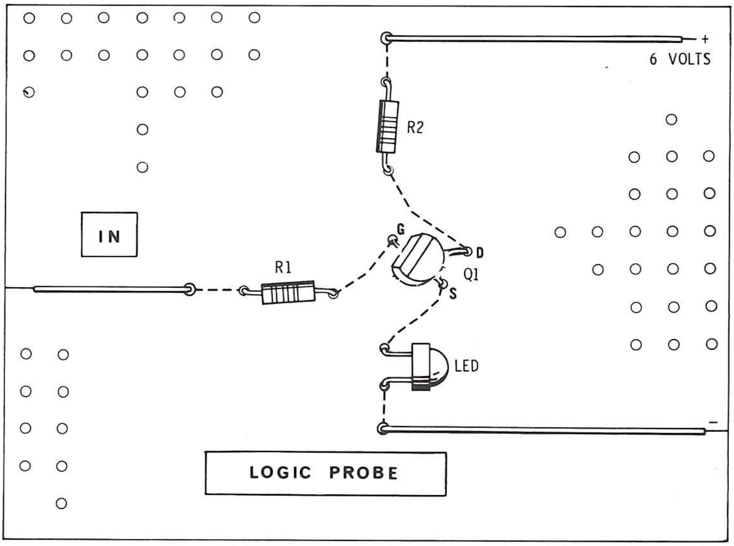


Figure 3-4. Pictorial wiring diagram of the FET logic-status indicator.

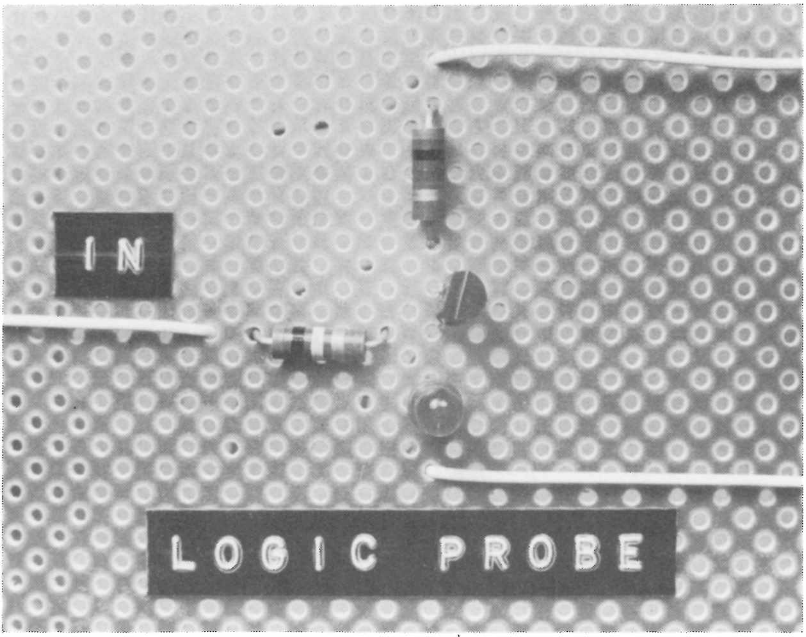


Figure 3-5. Assembled FET logic-status indicator.

how connection wires have been added to the input and battery connection points to facilitate the proper operation of the circuit.

TESTING AND OPERATION

Before connecting a power source to the logic-status indicators, inspect all the connections to make sure there are no wiring errors. Also, make sure no exposed wires are shorted against other wires.

After you have inspected each circuit, connect a 6-volt battery (made from four 1½ volt batteries in series) to the Darlington circuit. You can use clip leads (Radio Shack catalog number 278-1156) to connect the battery to the circuit if the cells are mounted in a holder. Use a Radio Shack catalog number 270-1437 holder for two "C" cells and a 270-1439 holder for two "D" cells. Make sure that the alligator clips on the clip leads do not touch the frame of the holder, or the battery will be shorted.

When the battery is connected, the LED will be extinguished. Now, connect a clip lead between the input lead on R1 to the positive battery terminal. This positive input signal should cause the LED to glow, and when it is removed the LED should again turn off. If the LED does not glow when the input signal is applied, recheck the wiring. Make sure the battery is connected properly. Also, make sure Q1, Q2 and the LED are properly connected.

Now, test the FET circuit by connecting the 6-volt battery used to power the Darlington circuit. The LED may flicker on when the power is first connected since this circuit is very sensitive to stray body or lead capacitance. Now touch the exposed input lead with a finger. The LED should flicker on and possibly stay on so long as the input lead is touched.

Next, touch the input lead to the negative battery terminal. The LED should immediately be extinguished. When the input lead is touched to the positive battery terminal, the LED should immediately turn on.

GOING FURTHER

Future chapters will describe dozens of applications for either of these very useful logic-status indicators. The circuits are so useful that I used the Darlington version in the circuits described in the next two chapters and in others also.

Since a logic-status indicator is such a valuable circuit, you may wish to assemble one or both circuits described here as a miniature logic probe. You can build the circuit on a small rectangle of circuit board which fits inside a small plastic container along with two AA penlight cells in series. The LED should be mounted in a readily visible location. Solder a length of stranded hookup wire to the negative battery terminal and solder an alligator clip to its free end. This clip lead will be connected to the ground connection of the logic circuit being tested. A standard probe such as the Radio Shack catalog number 274-720 or an insulated phone tip (274-723) can be used for an input probe. The probe can be connected to a length of hookup wire or mounted directly to the small plastic case which houses the probe circuitry.

You can omit the internal battery in the probe by borrowing power from the logic circuit being tested. Simply connect an additional clip lead to the positive terminal of the indicator circuit and clip the lead to the positive power line of the circuit under test. You can omit resistor R2 in both circuits if the power supply voltage is only about 3 volts. But do not leave R2 out if higher voltages are used or the LED may be damaged by excessive current flow.

Since logic probes are very useful devices for both troubleshooting *and* understanding the operation of digital logic circuits, I hope you will at least assemble one or both perforated board versions. If you find the circuits as useful and interesting as I have, you will probably want to consider building at least one permanent version.

CHAPTER 4

COMBINATION AND-OR GATE

An ideal way to understand the operation of both positive and negative logic, as well as AND and OR gates is to assemble the combination AND-OR gate described in this chapter. This simple gate requires only two diodes, two switches, a resistor and a couple of "C" cells. You can use one of the logic-status indicator circuits described in the previous chapter to observe the output status of the gate in any of its operating modes.

HOW IT WORKS

The circuit diagram for the combination AND-OR gate is shown in Figure 4-1. The circuit operates as both a positive-logic OR gate and a negative-logic AND gate. In the positive-logic mode, both switches must initially be in the 2 position (open). If either switch A *or* B is moved to the 1 position (closed), the circuit functions as an OR gate and a positive logic 1 will appear at the output of the two diodes. If a logic probe is connected to the output, its LED will glow.

In the negative logic mode the circuit functions as an AND gate. In the initial condition, both switches A and B must be in the 1 position. If only one switch is placed in the 2 position, the output of the circuit will be a negative logic 0 (positive logic 1) and an LED logic probe connected to the gate output will glow. But if both switches A *and* B are placed in the 2 positions, the gate output will become a negative logic 1 and the LED logic indicator will be extinguished.

I included a Darlington transistor-logic-status indicator directly on the circuit board of the prototype combination AND-OR gate for convenience. Since the power supply consists of only two 1½ volt "C" cells, a current-limiting resistor is not

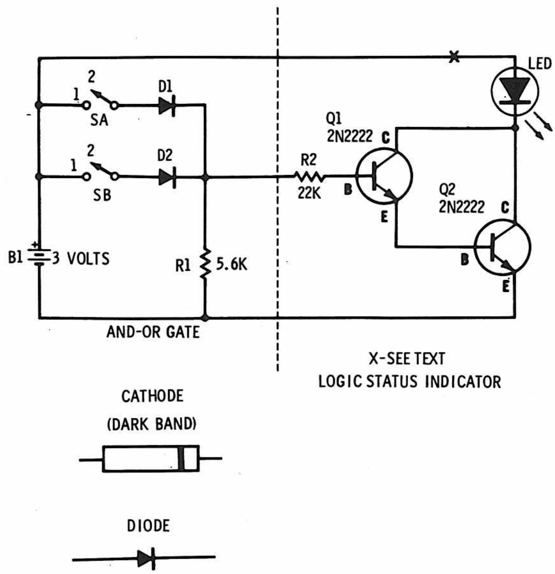


Figure 4-1. Combination AND-OR gate.

included. If you operate the circuit with a 6-volt power supply, insert a 220 ohm resistor at point "X" in Figure 4-1. If the resistor is not included, excessive current will flow through the LED and it may be degraded or even destroyed.

CIRCUIT ASSEMBLY

The pictorial in Figure 4-2 shows a suggested parts layout for the combination AND-OR gate. The parts list is given in Table 4-1. Begin assembly by drilling two holes in one end of the board to accept the two input switches. Toggle switches are easier to mount, but slide switches are more economical.

Next, examine the two diodes and note that each has a bar or other marking around one end. This is the cathode end of

Table 4-1. AND-OR Gate Parts List

Item	Description
B1	Battery, 3 volt
D1, D2	Glass Diode (276-821)
R1	Resistor, 5,600 ohms, ½-watt
SA, SB	SPST switches (275-612 or similar)
Misc.	Logic-status indicator (see text), perforated board (276-1392), labels, hookup wire, solder

(Radio Shack catalog numbers shown in parentheses.)

the diode and should face *away* from the switch it is connected to. Bend the leads of both diodes at right angles and insert them in the board as shown in Figure 4-2. Solder the cathode leads of each diode to one another, and solder the anode lead of D1 to the center terminal of switch A and the anode lead of D2 to the center terminal of switch B. Complete assembly of the gate circuit by bending the leads of R1, a 5,600 ohm resistor (green-blue-red), at right angles and inserting them into the board as shown in Figure 4-2. Solder one end of R1 to the junction of D1 and D2.

The gate circuit is now complete and the logic-status indi-

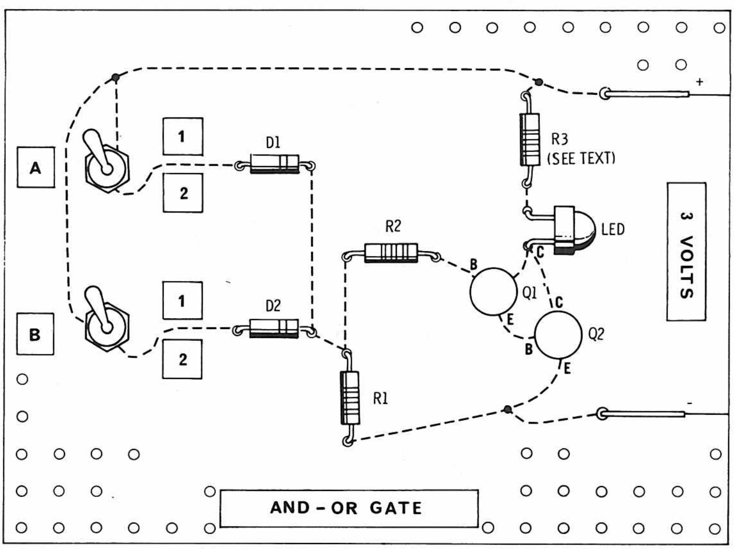


Figure 4-2. Pictorial wiring diagram of the AND-OR gate.

cator can be mounted on the board. If you assembled one or both indicators in Chapter 3, simply connect either circuit to the combination gate by referring to Fig. 4-1. If not, build the Darlington or FET circuit described in Chapter 3 directly on the circuit board as shown in the pictorial in Figure 4-2. Detailed assembly instructions for the indicator circuit are given in Chapter 3.

For best results, use short lengths of insulated hookup wire to connect the positive connection on the indicator circuit (LED anode) to the remaining terminal on each switch. Use a third length of wire to connect R1's free lead to the negative connection of the logic indicator (Q2's emitter). The circuit should now resemble the photograph of the prototype in Figure 4-3.

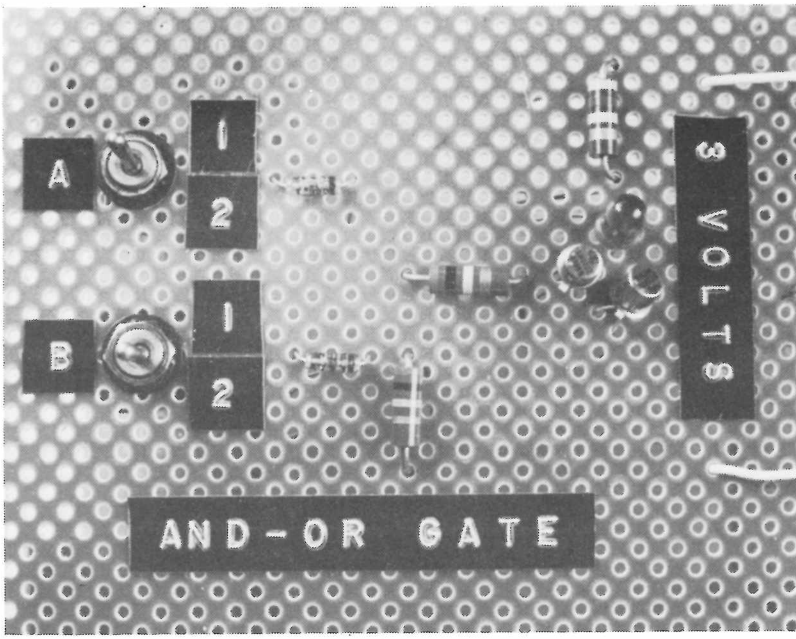


Figure 4-3. Assembled combination AND-OR gate.

Note that the indicator circuit shown in Figures 4-1 and 4-2 does not include a resistor to limit current through the LED. This is because the recommended power supply voltage is only

3 volts. If a 6-volt supply is used, insert a 220 ohm current limiting resistor (R3) at point "X" in Figure 4-1.

Complete assembly of the gate by connecting a 3-volt battery made by connecting two "C" or "D" cells in series. For best results, place the cells in a battery holder (Radio Shack catalog number 270-1437 or 270-1439) and use clip leads (Radio Shack 278-1156) to connect the battery to the gate.

TESTING AND OPERATION

Inspect the circuit to make sure all the connections are correct, and then connect the battery to the circuit as shown in Figure 4-2. Test the positive-logic OR gate by placing both switches in the 2 position. If switch A *or* switch B is moved to the 1 position, the LED should immediately glow. Since this is a nonexclusive OR gate, the LED will continue to glow if both switches are placed in the 1 position.

If the operation of the gate is opposite that described here, the switches are installed backwards and the position numbers should be reversed. Alternatively, you can rotate each switch 180 degrees.

Test the negative logic AND gate by placing both switches in the 1 positions. When only one switch is moved to the 2 position, the LED remains on (negative logic 0). But if both switch A *and* switch B are moved to the 2 position, the LED will be extinguished (negative logic 1).

GOING FURTHER

This combination AND-OR gate makes an ideal demonstration device for teaching the two most basic logic functions. It also illustrates the concept of both positive and negative logic. Therefore, it is an excellent candidate for installation in a permanent housing as a demonstration device.

Radio Shack stocks several housings which are well suited for this project. If you would like the various components to be visible, choose a Perfbox (TM) (catalog number 270-097) or a "P-Box" (270-105). The circuit can be mounted on the perforated cover of the box just as shown in Figure 4-2. Mount the battery holder to the back of the housing with appropriate hardware.

For a really interesting and educational logic demonstrator, you may want to add one or more additional logic circuits to the basic AND-OR gate described here. Good candidates are the NOR gate described in Chapter 5 and the NOT circuit described in Chapter 6.

CHAPTER 5

DIODE-TRANSISTOR NOR GATE

In Chapter 1 we learned that the three basic logic circuits are the AND gate, OR gate and NOT circuit. We also learned that the NOT circuit or inverter can be added to either gate circuit to form, respectively, a NAND and NOR gate.

In this chapter we will use the basic diode AND-OR gate described in the previous chapter and a simple inverter consisting of a single transistor and a single resistor to form a NOR gate. Since this NOR gate employs positive logic, its operation is more quickly understood than a combination gate employing both positive and negative logic.

HOW IT WORKS

Refer to the circuit diagram in Figure 5-1 to see how the NOR gate operates. In Chapter 4 we saw how a positive signal at either input of the simple diode OR circuit used there and in this chapter would place a logic 1 at the output of the gate and cause the LED in a logic indicator connected to the output to glow.

The same operation occurs in this circuit, except that a one-transistor NOT circuit inverts the output of the OR gate. Therefore, with no input signal at either diode, the output of the diode OR gate is a logic 0 which is inverted by Q1 to give a logic 1 at its output. When an input signal is placed either at

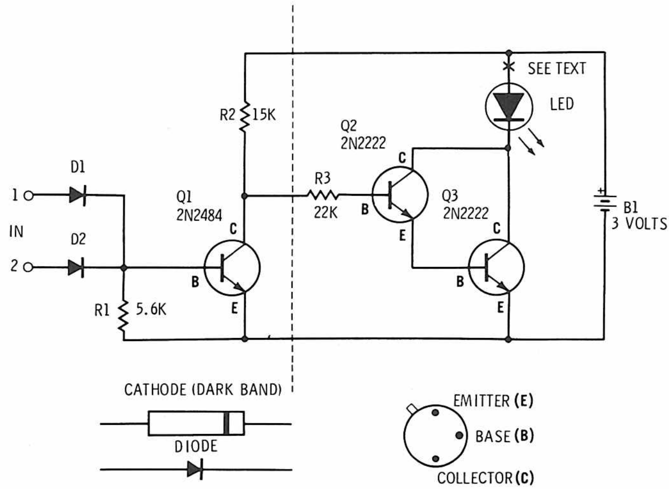


Figure 5-1. Schematic diagram of a positive-logic NOR gate.

input 1 or input 2, the diode OR gate goes to a logical 1 state and the inverter output goes to a logical 0. The result is implementation of the NOR function.

CIRCUIT ASSEMBLY

Figure 5-2 is a pictorial view of the assembled NOR gate. The parts list is given in Table 5-1. Begin assembly by installing the two diodes as shown in the pictorial. Be sure the cathode ends face in the same direction (the cathode is marked by a band around one end of the diode). Solder a short length of hookup wire to the anode of each diode. These two wires will be used as input leads. Then solder the two diode cathodes to one another.

Continue assembly by installing Q1 and R1, a 5,600 ohm resistor (green-blue-red), as shown in Figure 5-2. Solder one end of R1 to the junction of D1, D2, and Q1 base. Q1 is a 2N2484 transistor, but you can also use a 2N2222 or other NPN general purpose transistor. Next, solder the remaining end of R1 to the emitter of Q1. Then install R2, a 15,000 ohm resistor (brown-green-orange) and solder one end to the collector of Q1.

The NOR gate is now complete and ready for testing if you built one or both logic probes described in Chapter 3. All that

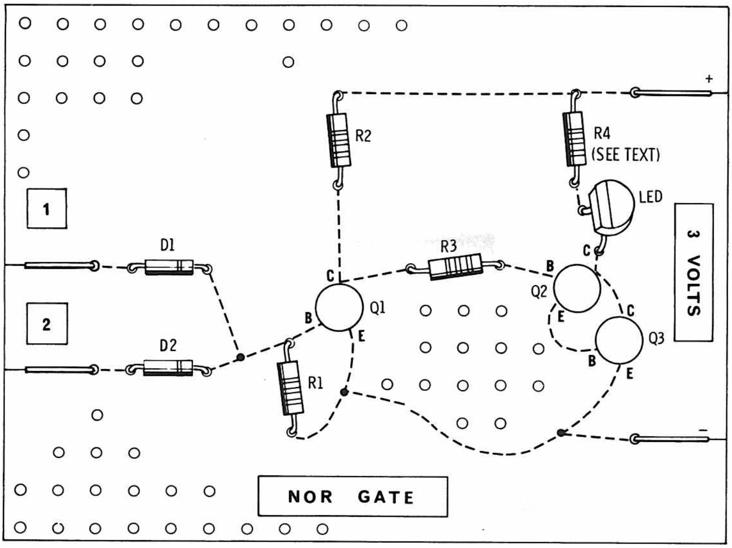


Figure 5-2. Pictorial wiring diagram of a NOR gate.

is necessary is to connect the input of the logic-status indicator to the NOR gate output (Q1's collector). If your probe has a self-contained battery, connect the negative side of the battery to the negative connection point on the NOR gate. If not, borrow power from the NOR gate by connecting the positive and negative leads of each circuit to one another.

Table 5-1. NOR Gate Parts List

Item	Description
B1	Battery, 3 volt
D1, D2	Glass diode (276-821)
Q1	2N2484 transistor (276-2010)
R1	Resistor, 5,600 ohms, ½-watt
R2	Resistor, 15,000 ohms, ½-watt
Misc.	Logic-status indicator (see text), perforated board (276-1392), labels, hookup wire, solder

(Radio Shack catalog numbers shown in parentheses.)

The completed prototype NOR gate is shown in Figure 5-3. I installed a logic status indicator directly on the circuit board and connected it as shown in Figure 5-2.

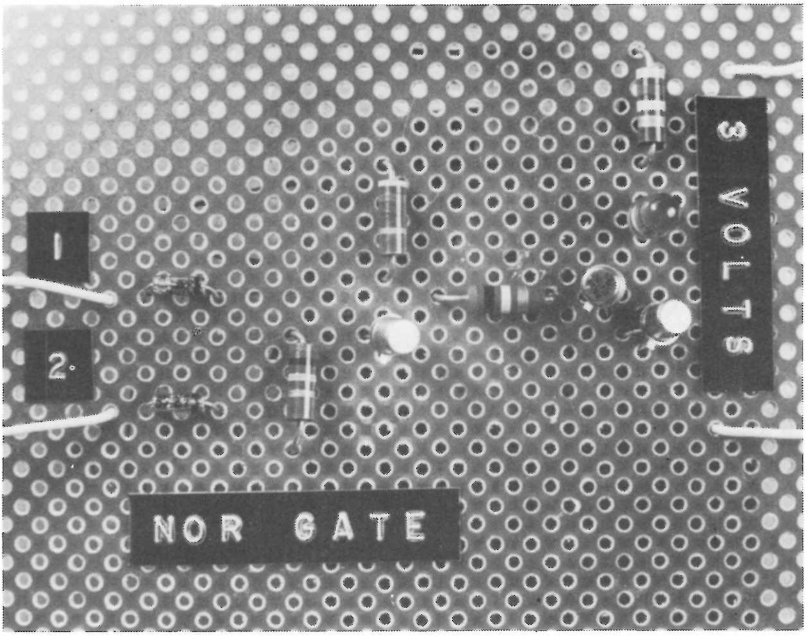


Figure 5-3. The assembled NOR gate.

TESTING AND OPERATION

Check all connections on the circuit to make sure there are no wiring errors. Then connect a 3-volt battery made from two 1½-volt "C" or "D" cells to the circuit. The LED on the logic status indicator should immediately turn on. This illustrates the NOR operation of the gate since both inputs are low (logical 0) and the output is high (logical 1).

Now, touch input A or input B to the positive battery connection to place a logical 1 into the gate. The LED should be immediately extinguished. Repeat the test with the other input lead and a similar action will occur. This very simple check graphically demonstrates the NOT-OR function of the NOR gate.

GOING FURTHER

Like the combination AND-OR gate in Chapter 4, the NOR gate is an ideal logic-demonstration circuit. For best results, build the circuit on the perforated cover of a Radio Shack

Perfbox or P-Box and install the battery holder inside the case. Install two input switches by soldering the two input leads to the center terminal of two SPST toggle switches and the remaining two terminals to the positive battery connection.

To illustrate the operation of the circuit as both a diode-transistor logic (DTL) gate and a resistor-transistor logic (RTL) gate install a 4,700 ohm resistor (yellow-violet-red) between the two diode cathodes and a third input lead or switch. This input lead will give the same logic operation as the two diode inputs.

Still another interesting addition to the basic NOR gate is a second logic-status indicator. By connecting the input of this indicator to the base of Q1, the circuit will illustrate both the OR and NOR function simultaneously. When one of the inputs is activated with a logical 1, the diode outputs will go high and the logic indicator LED connected to Q1's base will glow. Simultaneously, Q1 will invert the high signal at its base to a low output (logical 0) at its collector and extinguish the logic indicator LED connected to this point. When the input signal is removed, the first LED will go low and the second will go high.

CHAPTER 6

YES AND NO CIRCUITS

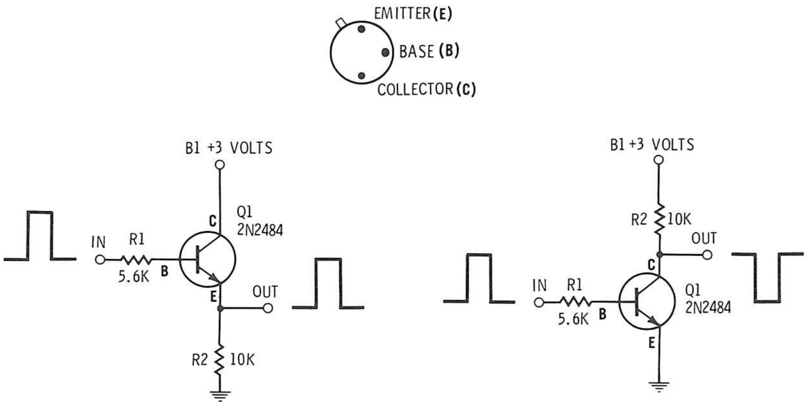
Simple transistor circuits resembling amplifiers are not used in many logic circuits. The two most basic circuits in this category are the *converter* and *inverter*. Converters are YES circuits. They accept an input signal and pass it on to another stage without reversing its polarity. YES circuits are usually called *buffers* by logic design engineers. They are very useful for connecting a low-output logic circuit to a following circuit or indicator which may tend to load down the original circuit. For this reason, buffers are sometimes called *drivers*.

The inverter is a NOT circuit since it reverses the phase or polarity of an incoming signal. Inverters are very useful for converting AND and OR gates into NAND and NOR gates. They can also convert the latter two gates back to the former.

In this chapter I'll show you how to assemble both an inverter and a converter and use each circuit to demonstrate its function. You can assemble both circuits on a single board or use separate boards. If you only wish to assemble the circuits for a temporary demonstration, you can use a single board and merely change one resistor position to turn the converter into an inverter.

HOW THEY WORK

The circuit diagram for the basic converter circuit is shown in Figure 6-1A. If you are familiar with simple transistor am-



(*A*) *Logic converter* (YES *circuit*). (*B*) *Logic inverter* (NOT *circuit*).

Figure 6-1. Logic converter and inverter circuits.

plifiers, you will recognize this configuration as the *emitter follower*. Sometimes this circuit is called a *common-collector* circuit.

The converter has a high input impedance and a low output impedance and is therefore useful for coupling high-impedance circuits (e.g., a logic gate) to low-impedance circuits (e.g., an LED).

Figure 6-1B shows the circuit diagram for the inverter circuit. Again, those of you familiar with basic transistor amplifiers will recognize this circuit as a *common-emitter* configuration. The common-emitter circuit has higher gain than the common collector, but only medium input and output impedances.

The most important property of the common-emitter circuit is inversion. The circuit reverses the phase of an incoming alternating-current signal and the polarity of a direct-current signal.

Both circuits described here can be demonstrated with the same logic-status indicators described in Chapter 3 and employed in Chapters 4 and 5.

CIRCUIT ASSEMBLY

You can install both circuits on a single perforated board, on separate boards, or use one circuit as a basis for the other. Q1 in both circuits is a 2N2484 transistor, but you can use a 2N2222 or any other general purpose NPN transistor. The parts list is given in Table 6-1.

Table 6-1. Converter and Inverter Parts List

Item	Description
B1	Battery, 3 volt
Q1	2N2484 transistor (276-2010)
R1	Resistor, 5,600 ohms, ½-watt
R2	Resistor, 10,000 ohms, ½-watt
Misc.	Logic-status indicator (see text), perforated board (276-1392), labels, hookup wire, solder

(Radio Shack catalog numbers shown in parentheses.)

Figure 6-2 is a pictorial representation of the converter (YES) circuit. Construction is straightforward since the circuit uses only two resistors and a single transistor. Install R1 and Q1 first. R1 is a 5,600 ohm resistor (green-blue-red). Solder one of its leads to the base of Q1. The remaining lead becomes the input connection. Next, install R2, a 10,000 ohm resistor (brown-black-orange), and solder one of its leads to the emitter of Q1. This becomes the output connection. Solder

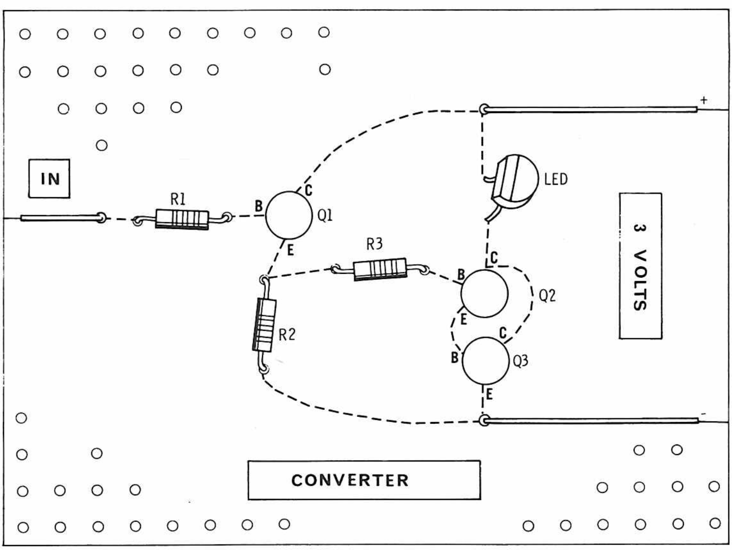


Figure 6-2. Pictorial wiring diagram of the logic converter circuit.

a positive battery-connection lead to Q1's collector and a negative battery-connection lead to the remaining lead of R2.

I installed a Darlington logic-status indicator directly on the prototype converter's perforated board, but this step is not necessary if you have already assembled one of the logic-status indicators described in Chapter 3. Chapter 3 provides construction details for the indicator circuit used here. If you install the indicator on the circuit board, your completed circuit should resemble the prototype circuit which is shown in Figure 6-3.

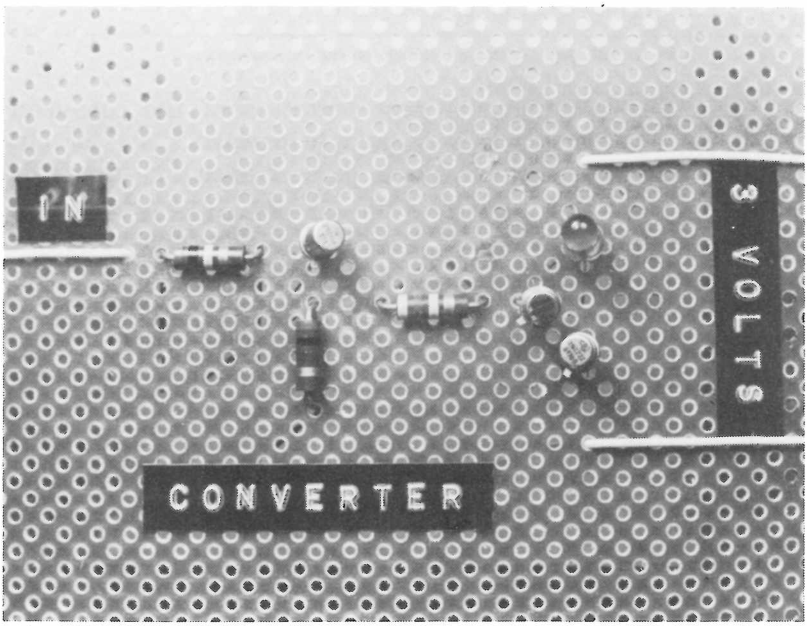


Figure 6-3. The assembled converter.

Construction of the inverter circuit is similar to the converter except R2 is connected to Q1's collector instead of its emitter. Also, the output is taken from the collector instead of the emitter. Figure 6-4 is a pictorial view of the completed circuit. You can observe operation of the inverter with a separate or self-contained logic-status indicator. I used a self-contained indicator on the same board as the inverter and the completed circuit is shown in Figure 6-5.

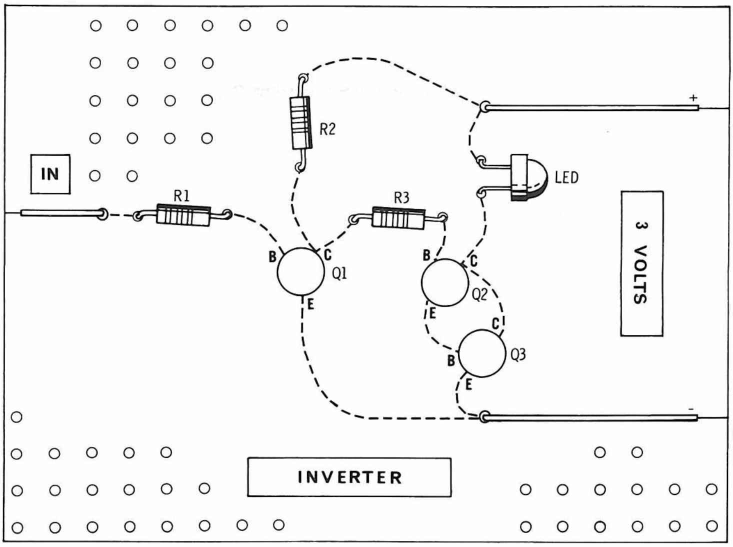


Figure 6-4. Pictorial wiring diagram of the logic inverter circuit.

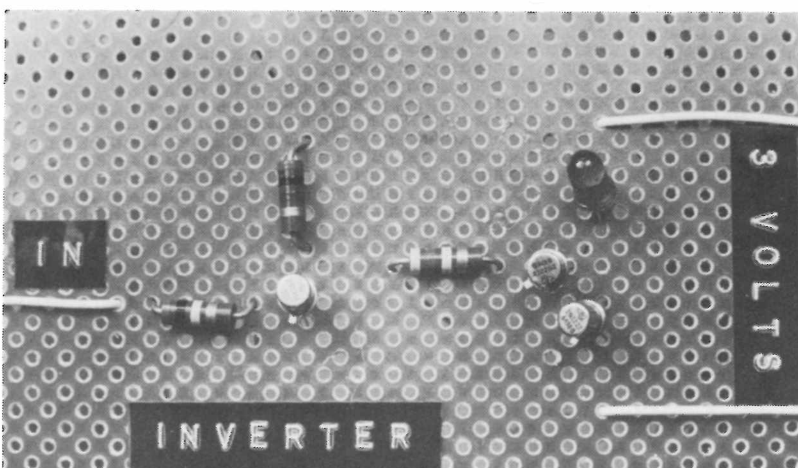


Figure 6-5. The assembled inverter.

TESTING AND OPERATION

Power for both circuits is provided by a 3-volt battery made from two 1½ volt "C" or "D" cells inserted in a holder. Test the converter first by connecting the battery to the positive and negative leads. The LED logic-status indicator circuit should be off. Now, place a logic 1 on the lead by touching it to the positive battery-connection point. The LED should immediately glow and stay on until the lead is removed. Removing the lead corresponds to placing a logical 0 on the input, so the LED is extinguished.

Now test the inverter circuit by connecting it to the 3-volt battery. The LED should immediately glow even though there is no input signal. This is because the circuit has inverted the logic 0 at its input to a logic 1 at its output. Now place a logic 1 at the input by touching the input lead to the positive battery terminal. The circuit will invert this signal to a logic 0 and the LED will be immediately extinguished.

GOING FURTHER

As with the previous basic logic circuits, the converter and inverter circuits are well suited for use as permanent demonstration logic circuits. One construction possibility is to assemble both circuits, one below the other, on the perforated panel of a Radio Shack Perfbox or P-Box. Use a separate indicator for each circuit and replace each input lead with a single normally open SPST push-button switch. Connect one terminal of each switch to each circuit input. Both of the remaining terminals go to the positive battery-connection point.

Now you can place a logic 1 into either circuit by simply pressing its respective push button. Use appropriate labels to explain the operation of each circuit. Be sure to include a power switch between the negative battery terminal and the circuit to improve battery life.

CHAPTER 7

RTL ASTABLE MULTIVIBRATOR

The circuits described thus far have illustrated only the basic logic functions. Now, we will combine two logic gates in a crisscross configuration to obtain a more complex logic circuit, the *multivibrator*.

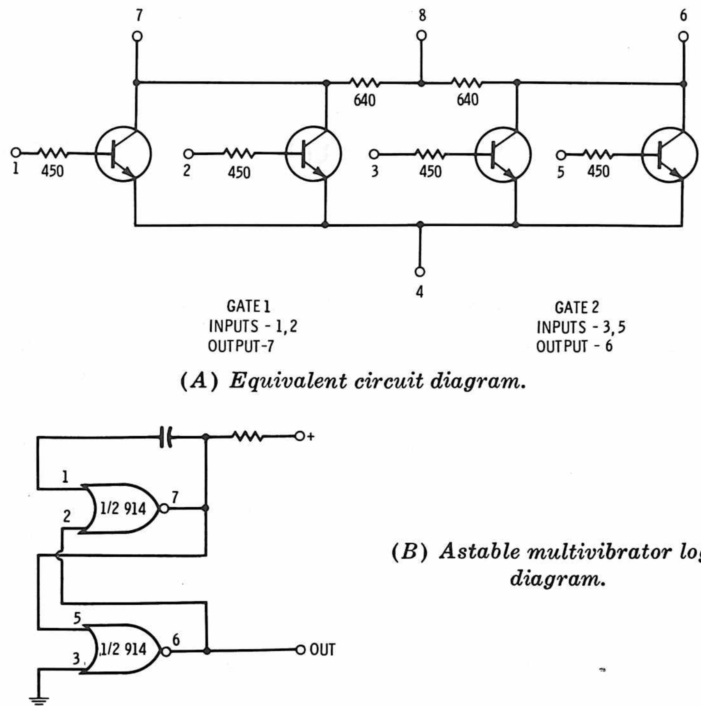
By definition, a multivibrator is a two-stage amplifier with positive feedback. As Chapter 1 noted, multivibrators play a very important role in digital logic, and for that reason most of the remaining circuits employ some form of multivibrator.

The astable or free-running multivibrator automatically switches from one state to another without the need for an input signal. The circuit usually contains two nearly symmetrical sections, each of which contains one or more transistors. When the circuit is operating, one transistor is always conducting (on) while the other is not conducting (off) and vice versa. Monostable and bi-stable (flip-flops) multivibrators are modified versions of the astable multivibrator and will be described in detail in subsequent chapters.

HOW IT WORKS

It's possible to construct an astable multivibrator from individual transistors, resistors, diodes, and capacitors, but it's much easier and economical to use an integrated circuit which already contains most of the necessary components. Earlier I said that a multivibrator can be made by connecting two gates together. So let's employ a standard RTL dual 2-input gate to make an astable multivibrator.

The gate we're going to use is one of the most popular RTL ICs, the 914. The circuitry of this IC, along with the logic diagram for converting the two gates to an astable multivibrator is shown in Figure 7-1.



(A) Equivalent circuit diagram.

(B) Astable multivibrator logic diagram.

Figure 7-1. The 914 equivalent circuit and astable multivibrator logic diagram.

The 914 contains two positive logic NOR gates. You can easily verify the NOR operation of the device by connecting one of the gates to a 3-volt battery and, while using a logic-status indicator to monitor the output state, alternately connect each input lead to the battery's positive terminal. The output will be high (logic 1) but when an input signal is present (logical 1) on either or both inputs the output goes low.

By connecting the output of each gate to one input of its partner, each gate can be made to control the state of the other. The result is a multivibrator. A capacitor and resistor can be used to control the rate at which the two logic gates switch back and forth. A small value capacitor gives a fast switching rate and a larger one a slow rate. The result is a series of back and forth switching actions whose frequency can be easily altered by means of the capacitor and resistor.

A practical 914 astable multivibrator circuit is shown in Figure 7-2. Since the various connection pins on the 914's package are not arranged in the same manner as the logic diagram in Figure 7-1, the circuit does not resemble the logic diagram at first glance. But both circuits are identical.

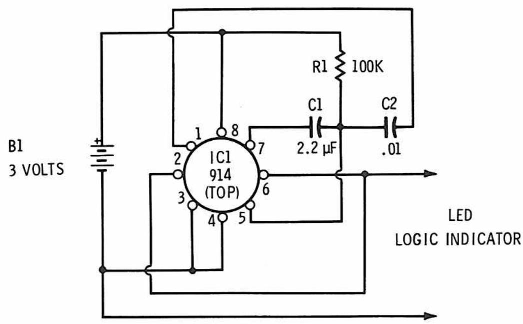


Figure 7-2. A practical dual-gate astable multivibrator.

CIRCUIT ASSEMBLY

Figure 7-3 is a pictorial which will aid you in constructing a working version of the 914 astable multivibrator. The parts list is given in table 7-1. For visual clarity in the illustrations, I began construction by soldering the leads of the 914 to a

Table 7-1. Dual Gate Astable Multivibrator Parts List

Item	Description
B1	Battery, 3-6 volt
C1	Capacitor, 2.2 μF (272-997)
C2	Capacitor, 0.01 μF (272-1065)
IC1	RTL 914 dual 2-input gate (276-015)
R1	Resistor, 100,000 ohms, ½-watt
Misc.	Logic-status indicator (see text), perforated board (276-1392), IC adapter (276-028), hookup wire, solder

(Radio Shack catalog numbers shown in parentheses.)

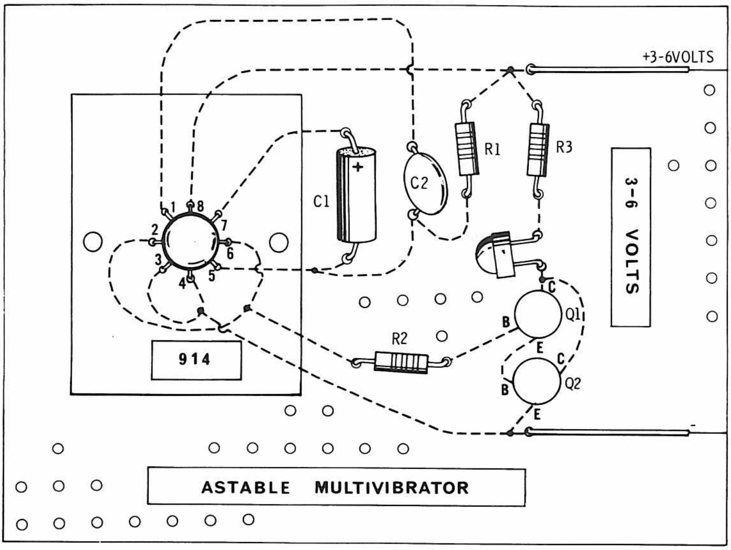


Figure 7-3. A pictorial wiring diagram of the astable multivibrator.

Radio Shack IC adapter (catalog number 276-028). However, you can install the IC in a socket if you prefer.

I mounted the 914 and its adapter board on a perforated board with leads soldered to each of the adapter board's solder pads which made contact with the eight IC pins. Again, this was to provide a more attractive and easily understood layout. Since so few additional components are used you may wish to solder them directly to the solder pads on the adapter board instead of using a perforated board.

Whichever construction technique you employ, mark each IC pin number next to its adjacent solder pad to prevent wiring errors and save time. Double check the pin diagram in Figure 7-2 and remember it shows the IC *from the top.*

Continue construction by installing C1, C2 and R1 in the circuit board as shown in Figure 7-3. Secure these parts in place by bending their leads outward and then solder one lead from each of these three parts to one another. This junction is then soldered to the connection lead from pin 5 of the IC.

Next, solder the remaining lead from C1 to the connection lead from pin 7 of the IC and the remaining lead from C2 to the connection lead from pin 1 of the IC. Then solder R1's remaining lead to the connection lead from pin 8 of the IC.

Complete the assembly of the basic multivibrator by soldering the IC pin connection leads to one another as shown in Figure 7-3. Pin 2 goes to pin 6 and pin 3 goes to pin 4. Then connect power leads to the circuit. The positive lead is soldered to pin 8 of the IC and the negative lead to pins 3 and 4. Figure 7-4 shows the completed unit.

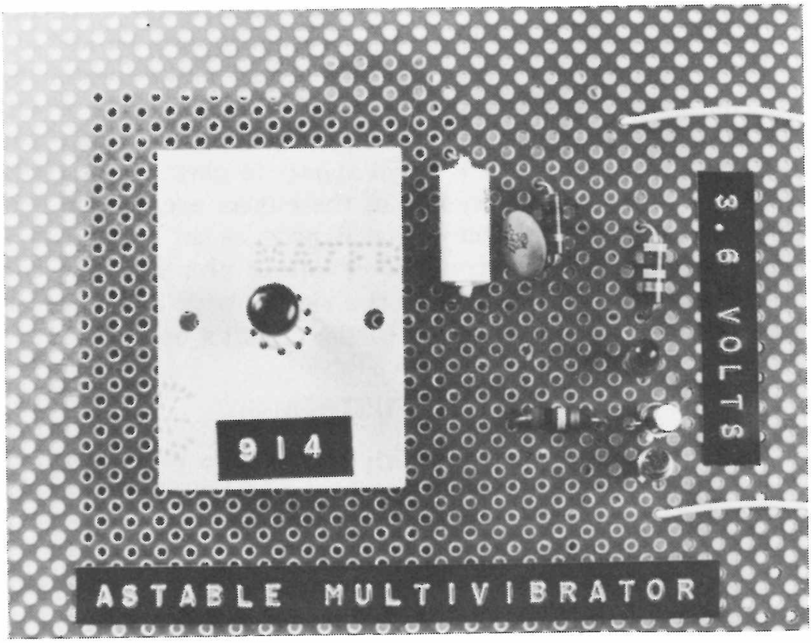


Figure 7-4. Assembled dual-gate astable multivibrator.

You can monitor the operation of the circuit with a small earphone connected between the output connection (pin 6) and the negative battery connection lead. When the circuit is operating, a series of clicks or a musical tone (depending on its frequency) will be heard from the earphone. A logic-status indicator can also be used to monitor the output of the circuit if the switching rate is slow enough to permit the eye to respond to its on-off action. A 2.2 μF capacitor for C1 will give a switching rate of about 1 Hz (cycle per second).

I installed a complete Darlington logic-status indicator on the perforated board but you can also connect an LED directly between pin 6 of the IC and the negative battery terminal. The latter technique is simpler, but the LED doesn't glow nearly as brightly as in the Darlington circuit.

TESTING AND OPERATION

Before applying power to the circuit, inspect all wiring connections to make sure no errors have been made, and then connect a 3-volt battery to the two power leads. If the circuit is correctly assembled, the LED should begin to flash on and off.

You can vary the switching rate of the multivibrator by altering the values of C1 and R1. Reducing the value of C1, for example, will speed the rate up to thousands of cycles per second. At this rate the LED will appear to glow continuously due to the slow visual response of the human eye, but an earphone connected to the circuit will produce an audible tone which reveals that the circuit is operating properly. You can better verify the operation of the circuit with any general-purpose oscilloscope connected to the circuit's output.

GOING FURTHER

You can use this simple multivibrator as a practical light flasher, a logic clock, or as a logic demonstrator. Each of these applications will be enhanced if you house the circuit in a permanent enclosure such as the Radio Shack Perfbox.

A particularly interesting modification of the basic circuit is addition of a second LED logic-status indicator to monitor the status of the second gate which helps form the multivibrator. Leave the original indicator connected to pin 6 of the 914, and connect a second indicator to pin 7 and the negative battery terminal. Now when one LED flashes on, the other turns off. After an interval determined by C2 and R1, the first LED will turn off, the second will flash on, and the process will continue. This on-off switching action graphically demonstrates the operation of the multivibrator.

This is the first in a series of multivibrator circuits, and several others will be presented in subsequent chapters. Since several of these additional circuits require a digital logic clock circuit for proper operation, I'm going to interrupt our multivibrator projects with a brief chapter on a simple and very useful digital logic clock.

CHAPTER 8

SIMPLE DIGITAL LOGIC CLOCK

Many digital logic circuits require a series of control pulses to step a logic problem through the various logic elements. Sometimes the input signal provides the control pulses, particularly if it is a naturally pulsating signal. Other circuits require a separate external pulsing circuit; since this circuit provides timing for the logic circuit it is usually called a *clock*.

The simple astable multivibrator described in Chapter 6 makes a good digital logic clock for many applications, and similar clocks are frequently employed by digital-equipment designers. An even simpler clock, however, can be made with a special kind of transistor called a unijunction transistor (UJT). This clock requires at least five components, one more than the criss-crossed dual-gate multivibrator clock described in Chapter 6, but it offers somewhat better operating flexibility.

HOW IT WORKS

Figure 8-1 shows the circuit diagram of the UJT digital logic clock. In operation, capacitor C1 is charged through resistor R1 and potentiometer R2 until Q1's emitter becomes forward biased. At this point, the UJT (Q1) conducts and permits C1 to discharge through Q1 and R4. When C1 discharges, the UJT's emitter is no longer forward biased and it is again turned off. C1 then begins charging again until the cycle repeats.

The circuit provides two output pulses. The gradual charging of the capacitor provides a slow rise time positive sawtooth wave at the emitter of Q1. And the rapid discharge of C1 through the UJT provides a fast spike across R4. The latter pulse is ideal for triggering a digital logic circuit.

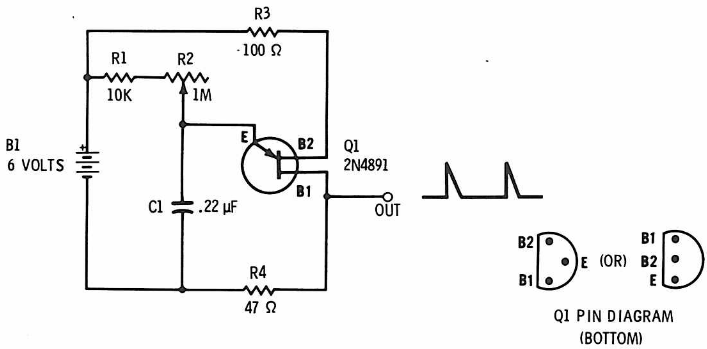


Figure 8-1. Unijunction transistor clock circuit.

The repetition rate of the UJT clock can be varied by adjusting potentiometer R2, altering the value of C1, or both. Potentiometer R2 provides a fast, convenient adjustment and is ideal for typical use.

CIRCUIT ASSEMBLY

Assembly of the UJT clock is straightforward. Since the clock can be used with several of the following projects, I suggest you build it on a perforated board as shown in the pictorial in Figure 8-2. Later, you may wish to assemble a UJT clock circuit directly on the circuit board of some of the other projects.

The parts list is given in Table 8-1. Begin construction by installing R3, the UJT, and R4 as shown in the pictorial. Solder one end of R3, a 100 ohm resistor (brown-black-brown) to the UJT's base 2 lead. Solder one end of R4, a 47 ohm resistor (yellow-violet-black), to the UJT's base 1 lead. This junction will become the clock output connection so solder a short length of insulated hookup wire to it.

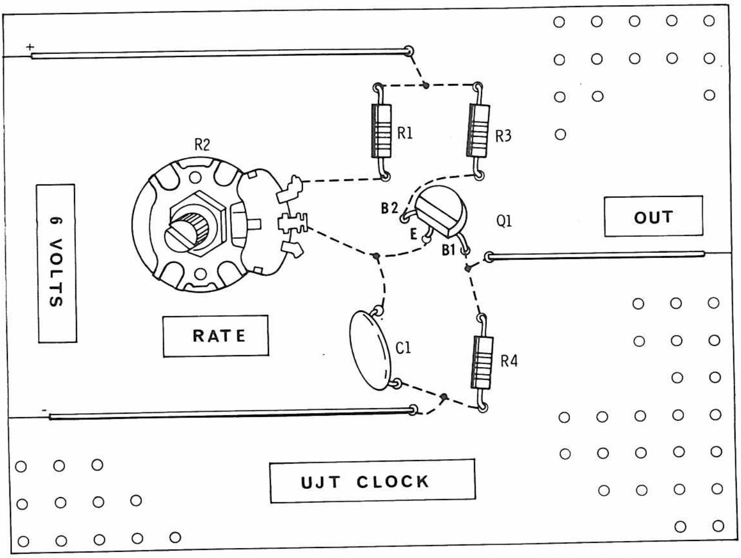


Figure 8-2. Pictorial wiring diagram of the UJT clock.

Next, install C1 and solder one lead to the UJT emitter lead and the other to the free lead of R4. Then solder a short length of hookup wire to the center terminal and another short wire to one outer terminal of potentiometer R2. Insert the wires into the perforated board and solder one to the C1-UJT emitter connection. R1 is a 10,000 ohm resistor (brown-black-orange). Solder the second wire from R2 to one of R1's leads. R1's remaining lead is soldered to R3's remaining lead.

The circuit is completed by soldering a positive battery connection lead to the junction of R1 and R3 and a negative con-

Table 8-1. UJT Clock Parts List

Item	Description
B1	Battery, 6 volt
C1	Capacitor, 0.22 μF (272-1070)
Q1	2N4891 unijunction transistor (276-2029)
R1	Resistor, 10,000 ohms, ½-watt
R2	Potentiometer, 1 megohm (271-211)
R3	Resistor, 100 ohms, ½-watt
R4	Resistor, 47 ohms, ½-watt
Misc.	Perforated board (276-1392), hookup wire, solder

(Radio Shack catalog numbers shown in parentheses.)

nection lead to the junction of C1 and Q1's base 1. Be sure to inspect the final circuit for wiring errors before connecting a battery.

The completed circuit should resemble the prototype pictured in Figure 8-3. You may wish to drill a mounting hole for potentiometer R2, but for experimental purposes the mounting technique employed here is adequate.

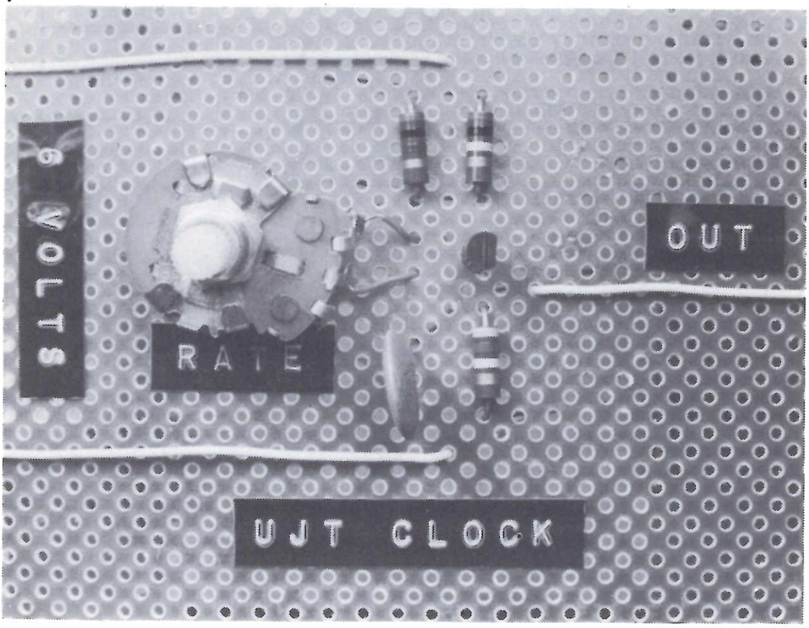


Figure 8-3. Assmbled unijunction transistor clock.

TESTING AND OPERATION

Test the completed UJT clock by connecting a logic status indicator to the C1-UJT emitter junction. The normal output point is not used since the pulses are too fast too see. Connect a 6-volt battery (four 1½ volt "C" or "D" cells in series) to the circuit and observe the LED. If it appears to stay on but has a slight flicker, the circuit is operating properly. It may be necessary to dim the room lights and adjust potentiometer R2 before the flicker becomes visible.

Another test is to temporarily connect a small 8-ohm speaker across R4. If the UJT circuit is oscillating, a series of clicks will be heard from the speaker. The rate of the clicks can be varied by adjusting R2.

GOING FURTHER

We'll use this basic clock circuit in several subsequent projects. After you have seen how versatile it is, you may want to install it in a permanent housing. A speaker connected across R4 will provide an audible indication of the clock's operation, and LED logic-status indicators on the circuits being operated will provide a visual indication of operation.

CHAPTER 9

RTL MONOSTABLE MULTIVIBRATOR

In Chapter 7 we saw how criss-crossing the outputs of two gates with one of each gate's inputs creates a simple, reliable astable multivibrator. This same concept can be slightly modified to produce a monostable multivibrator. Recall from Chapter 1 that an astable multivibrator is free-running and switches back and forth between its two sections spontaneously. The monostable multivibrator is stable only when one of its two sections is on and the other off. An incoming pulse will cause the on-off status of the two sections to be reversed, but only for a temporary time determined by the RC time constant of an external resistor and capacitor. For this reason the monostable multivibrator is often called the *one-shot* or *single-shot.*

The single-shot circuit described here uses the same RTL IC used in Chapter 7, a 914 dual 2-input gate. In the next chapter we will assemble another single-shot, which employs a TTL monostable expressly designed for single-shot operation.

HOW IT WORKS

Figure 9-1 shows the logic diagram for the RTL single-shot. In Chapter 7, the two NOR gates within the 914 were made to switch spontaneously by the interconnection network shown

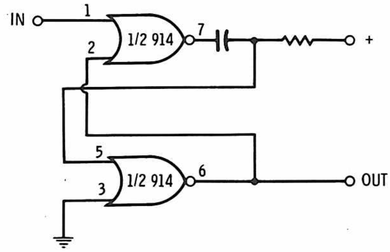


Figure 9-1. Logic diagram for a monostable multivibrator.

in Figure 7-1. By leaving one of the gate input leads unconnected, the multivibrator can be made to switch only when triggered by an external pulse.

The logic diagram for the single-shot in Figure 9-1 is virtually identical to the astable circuit in Figure 7-1, with the exception of the pin 1 (input to gate 1) and capacitor connections. Pin 1 is left unconnected and becomes the input lead. The capacitor is moved to between the output of gate 1 and one input of gate 2.

The width of the output pulse of the single shot is dependent on the RC time constant of the external capacitor and resistor. A very small time constant will give output pulses only nanoseconds or microseconds in duration, but a larger time constant can give much larger output pulses. This means the single-shot is very useful as a pulse-forming circuit. Incoming pulses of various durations and amplitudes can be standardized into identical pulses of any desired width and amplitude.

This also means the single-shot can be used to divide an incoming stream of pulses by practically any number. All that's necessary is to make the time constant of the single-shot *longer* than the interval between the number of pulses by which you wish to divide the pulse stream. For example, if the single-shot output pulse is five times as long as the interval between two pulses, five pulses will occur during a single output pulse and the single-shot will divide the pulse stream by five. That is it will generate a series of pulses having a frequency one-fifth that of the incoming pulse stream.

Figure 9-2 is a timing diagram which shows how frequency division occurs when a single-shot's output pulse width is increased. Notice that the single-shot always triggers on the input pulse which occurs immediately after the end of the output pulse.

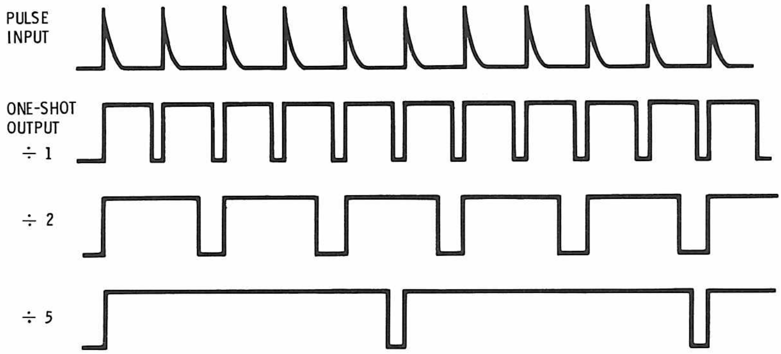


Figure 9-2. Frequency division with a one-shot multivibrator.

Single shots can be used for other applications as well and we will discuss some of them in both this and the next chapters. First, let's put one together.

CIRCUIT ASSEMBLY

Assembly of the RTL single-shot is straightforward, particularly if you built the RTL astable multivibrator in Chapter 6. The circuit for a practical single-shot is shown in Figure 9-3 and a pictorial of the completed circuit in Figure 9-4. The parts list is given in Table 9-1.

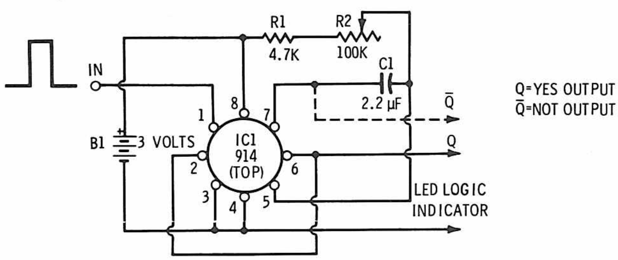


Figure 9-3. A practical dual-gate monostable multivibrator.

Begin construction by soldering a 914 IC to a socket adapter as described in Chapter 7. If you assembled the circuit in that chapter, you may prefer to use the 914 employed in that circuit. Solder connection leads to each of the eight solder pads connected to the IC and mount the adapter on a perforated board by inserting the connection leads through appropriate holes in the board.

Table 9-1. Dual-Gate Monostable Multivibrator Parts List

Item	Description
B1	Battery, 3-6 volt
C1	Capacitor, 2.2-μF (272-997)
IC1	RTL 914 dual 2-input gate (276-015)
R1	Resistor, 4,700 ohms, ½-watt
R2	Potentiometer, 100,000 ohms (271-092)
Misc.	Logic-status indicator (see text), perforated board (276-2392), IC adapter (276-028), hookup wire, solder

(Radio Shack catalog numbers shown in parentheses.)

Pin 1 of the IC is the input connection and should be threaded back through the board as shown in the pictorial. Solder the lead from pin 2 to the lead from pin 6. This function

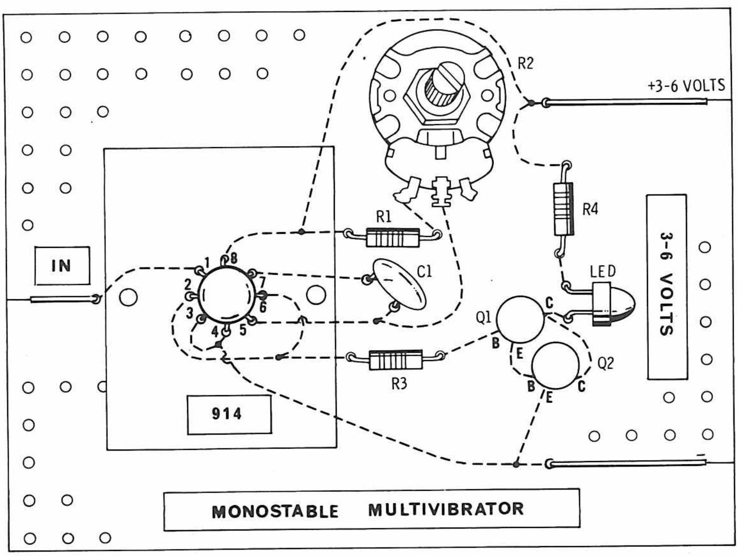


Figure 9-4. Pictorial wiring diagram of the monostable multivibrator.

is the output connection and we will return to it later. Solder the pin 3 lead and pin 4 lead together. This is the negative battery connection so solder a short length of insulated hookup wire to the connection and run it through one of the holes in the perforated board.

Next, insert C1 and R1 in the board. R1 is a 4,700-ohm resistor (yellow-violet-red). Solder one of its leads to the IC pin 8 connection lead. This junction becomes the positive battery terminal, so solder a short length of insulated hookup wire to the connection and run it through one of the holes in the perforated board. Then solder one lead from C1 to the IC pin 7 connection lead.

Prepare R2, a 100,000 ohm potentiometer, by soldering a length of hookup wire to the center and another length to one outer terminal. Insert these leads into the perforated board and solder one to C1's remaining lead *and* the IC pin 5 connection lead. Solder the other lead to the free end of R1.

To observe the operation of the single-shot you need at least one logic-indicator circuit. I assembled a Darlington indicator circuit directly on the same board as the single-shot, but you can use a separate circuit if you prefer. Connect the logic indicator input to the IC pin 6 connection lead, and the negative lead from the indicator to the single-shot's negative lead. If you want to borrow power from the single-shot to operate the

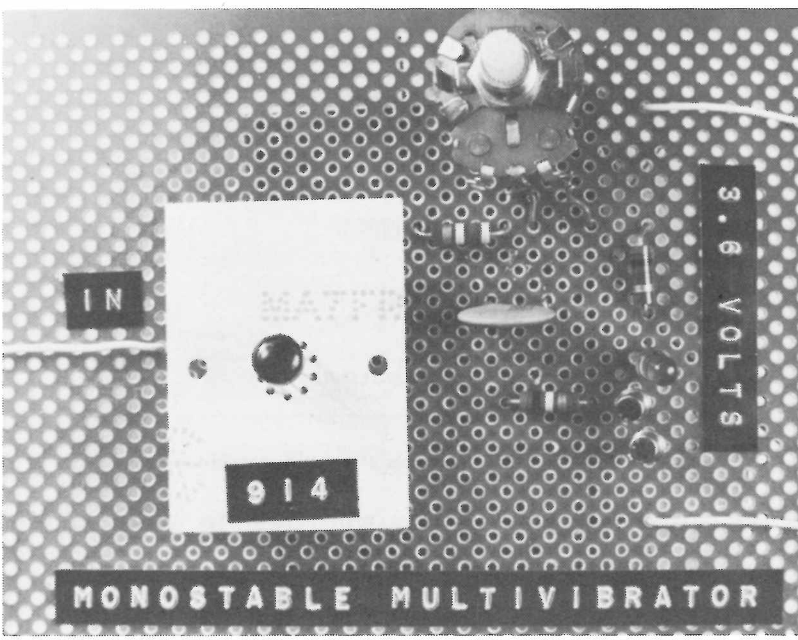


Figure 9-5. Assembled dual-gate monostable multivibrator.

indicator circuit, connect the positive leads from each circuit together.

The circuit is now complete and should resemble the prototype pictured in Figure 9-5. Check all the connection points to make sure there are no wiring errors, and then you can test the circuit.

TESTING AND OPERATION

Activate the single-shot by connecting a 3-volt battery to the input leads. You can use up to 6 volts, but if you do be sure to include current-limiting resistor R4 to protect the LED. Touch the input lead to the positive battery terminal, and the LED should flash on momentarily. The LED should then stay off until a positive signal (logical 1) is again placed at the input. If the LED flickers on and off, the single-shot may be responding to your body capacity. RTL gates are very sensitive and may trigger on less than a ½-volt input signal. For this reason they are very sensitive to false triggering and in many applications are less desirable than TTL ICs and their relatively high trigger-level requirements.

You can vary the width of the output pulse by varying R2. When R2 is set to a low resistance, the output pulses will be very fast, and when R2 is set to a high value, the pulses will be very long.

GOING FURTHER

The best way to observe operation of the single-shot is to connect an external clock to the input. The UJT clock described in the previous chapter is ideal for this purpose. All you need to do is connect the clock output from the UJT circuit (Q2's base 1 in Figure 8-1) to pin 1 of the single-shot circuit. You can borrow power from the single-shot circuit if you are employing 6 volts. If you are using 3 volts, power the UJT clock with a separate 6-volt battery and connect the two negative leads (but not the two positive leads) together.

By setting the UJT clock to a relatively slow pulse rate of a few cycles or less per second, the LED logic-status indicator should flash on once for each pulse. You can verify this by simply connecting an 8-ohm speaker directly across the leads of

R4 in Figure 8-1. The speaker should click each time the LED flashes.

When the clock and single-shot are operating properly, experiment with frequency division by adjusting R2 of the single-shot to produce a long output pulse, and adjusting R2 of the clock to produce a relatively fast pulse rate (perhaps ten per second). With the speaker connected to the clock, notice how the LED flashes only once for a constant series of clicks from the speaker. Since the LED flashes only after a preset number of input pulses to the single-shot, frequency division has occurred. By experimenting with the settings of both the clock and the single-shot, you can observe a wide range of frequency division. This experiment is particularly interesting if an oscilloscope is available to monitor both the output pulses from the clock and the output pulses from the single-shot.

You can better observe frequency division by connecting the logic-status indicator to the IC pin 7 connection lead. This is the output lead of the 914's first gate and is normally high (*logic 1*) since the other gate output is normally low (*logic 0*).

When the incoming pulse stream is relatively fast and the single-shot output is relatively long, the LED connected to the output of gate 2 will be on most of the time. Since the incoming pulses are spaced at short intervals, the single-shot will be retriggered almost as soon as the single-shot pulse is over. Therefore, the LED will appear to be on almost continuously, with a subtle flicker indicating the rate of frequency division.

By moving the LED logic indicator to the other output, the LED will normally be off and flash on at the rate of frequency division. This operating mode is much more noticeable than the other.

Still another application for the single-shot is a bounceless push button. As noted in Chapter 1, mechanical switches do not open and close immediately. Instead, a rapid series of brief on-off spikes occur when the switch is opened and closed. When a "bouncy" switch is connected to a logic circuit, several input signals may be fed into the circuit when only one was intended.

The single-shot can be used to eliminate the adverse effects of switch bounce by providing a wide, well-shaped pulse each time the switch is actuated. All that's necessary to convert the circuit described here for this mode of operation is to connect a switch between the input and the positive battery terminal, and eliminate R2 by connecting R1 directly to C1. For wider pulses, increase C1 to about 10 μF. But remember that the width of the output pulse should not be too wide or the single-shot may still be in a triggered state when a second switch signal occurs. Similarly, the width should not be too brief or the switch may be turned off, especially if it is a push-button type, *after* the single-shot pulse is over. If this occurs, the bounce which occurs when the switch opens may false-trigger the single-shot.

Single-shots have still other applications, and a particularly interesting one is as an electronic music-frequency generator and tone stepper. All that's required to convert the circuit described here for this mode of operation is to speed up the clock, decrease the pulse width from the single-shot, and replace the logic-status indicator with a small earphone connected from pin 6 of the IC to ground. Complete construction details for this project are provided in "Integrated Circuit Projects, Vol. 1," a Radio Shack publication (pp. 69-77).

CHAPTER 10

TTL MONOSTABLE MULTIVIBRATOR

Simple RTL single-shots (monostable multivibrators) such as the one made from a dual 2-input NOR gate are useful for many digital logic circuits and other applications. But since RTL circuits require relatively small trigger signals, they have only fair noise immunity. TTL circuits have much better noise immunity since they require larger trigger signals. Also, TTL circuits are faster than RTL circuits.

The single-shot described here is the versatile TTL 74121. This IC is available from Radio Shack in a dual in-line package for slightly more than a dollar. By suitable selection of the external timing capacitor and resistor, the output pulse width of the 74121 can be varied from 40 nanoseconds to 40 seconds. The 74121 includes several sophisticated features not available with the simple single-shot described in the previous chapter. For example, it has better temperature immunity, higher duty-cycle capability, and better pulse-width control.

HOW IT WORKS

Although the 74121 incorporates far more components than the RTL version described earlier, its operation is fundamentally identical. The circuit diagram for a practical single-shot employing the 74121 is shown in Figure 10-1. Pins 3 and 4 are connected to the inputs of a 2-input NOR gate. When a *negative* pulse is connected to either or both pins the single-shot will trigger. External timing is provided by a capacitor (C1) connected between pins 10 and 11, and a resistor (R1) connected from pin 9 to pin 14 (the positive voltage pin).

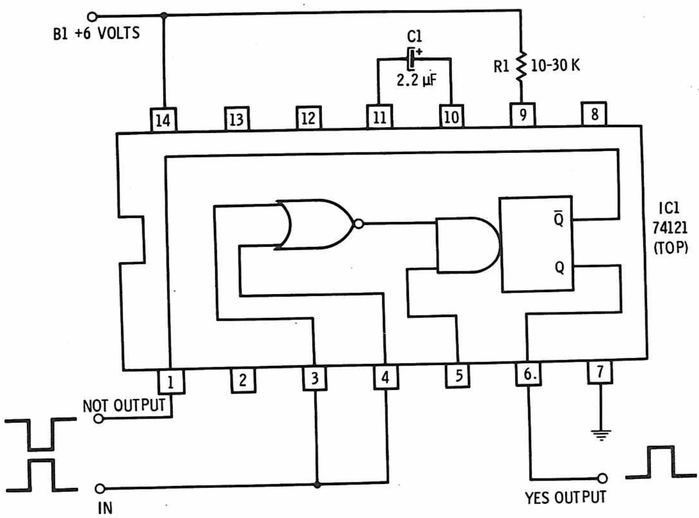


Figure 10-1. A TTL single-shot circuit.

The 74121 supplies a positive output at pin 6 and an inverted output at pin 1. Pin 1 is normally high (logical 1) until the single-shot is triggered. Pin 6 then goes high for an interval determined by C1 and R1. Pin 6 then resumes its low condition and pin 1 again goes high.

CIRCUIT ASSEMBLY

The parts list is given in Table 10-1. Begin assembly by soldering the 74121 to a Radio Shack IC adapter. Be sure to use care when soldering the IC to the adapter to avoid the possibility of damage. I prefer to warm the pin-foil pattern joint by placing the tip of the iron in contact with one side of the joint. After a second or two, touch the solder to the other side of the joint. Be sure to clean the foil side of the adapter board with fine sand paper or steel wool before soldering, if it is tarnished.

Table 10-1. TTL 74121 Single-Shot Parts List

Item	Description
B1	Battery, 6 volt
C1	Capacitor, 2.2 μF (272-997)
IC1	TTL 74121 monostable multivibrator (276-1814)
R1	Resistor, 10,000 to 30,000 ohms, ½-watt (see text)
Misc.	Logic-status indicator (see text), perforated board (276-1392), IC adapter (276-024), hookup wire, solder

(Radio Shack catalog numbers shown in parentheses.)

Solder insulated connection leads to the pads on the adapter connected to pins 1, 3, 4, 6, 7, 9, 10, 11, and 14. Then install the IC on a perforated board by threading the leads through appropriate holes in a perforated board.

Figure 10-2 is a pictorial view of the circuit. Using this figure as a guide, solder the connection leads of pins 3 and 4 together and solder an input lead to the resulting junction. Pins 7 and 14 become the power supply leads, so thread them through holes in the board as shown in Figure 10-2.

Next, install R1, which can have a value of from 10,000 to 30,000 ohms, and solder its leads to the IC pins 9 and 14 con-

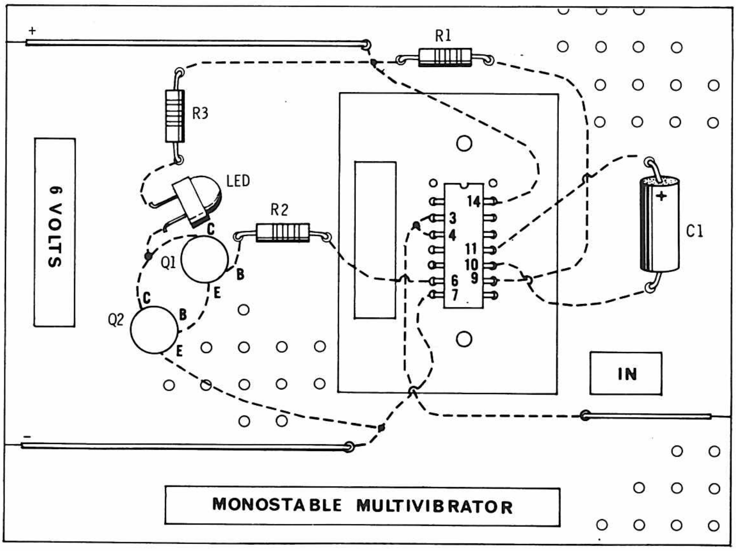


Figure 10-2. Pictorial wiring diagram of the TTL single-shot multivibrator.

nection leads. Then install C1 and solder its leads to the IC pins 10 and 11 connection leads.

I installed a LED logic-status indicator directly on the single-shot circuit board to monitor operation of the circuit. Assembly details are shown in Figure 3-2. Since a 6-volt power supply is used, be sure to include a 220 ohm resistor between the LED and the positive battery connection to prevent possible damage to the LED. Connect the input of the indicator to the IC pin 6 connection lead.

TESTING AND OPERATION

The completed circuit should resemble the photograph of the prototype shown in Figure 10-3. Check all wiring connections

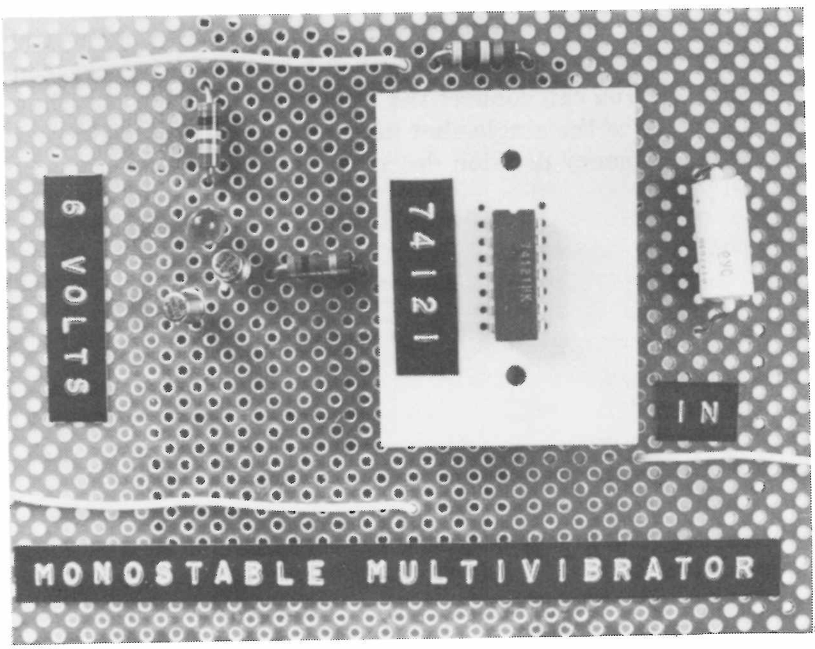


Figure 10-3. Assembled TTL single-shot circuit.

to the IC pin orientation, and connect a 6-volt battery to the power leads. Do not use a higher voltage since the IC may be damaged.

The logic-status indicator LED should be off when power is first connected. Apply a negative signal to the input by touching the input lead to the battery's negative terminal. The LED should flash on for a moment as the single-shot output goes high for an interval determined by R1 and C1. Just as with the RTL single-shot, you can vary the pulse width by altering the value of R1 and C1.

GOING FURTHER

The 74121 single-shot is a good candidate for a permanent logic-demonstration circuit, and the complete circuit can be easily housed in a Radio Shack Perfbox or P-Box. For best results, connect LED logic indicators to both of the single-shot outputs (pins 1 and 6). Pin 1 is normally high while pin 6 is normally low. The LEDs will alternately flash on and off when the input is triggered.

You can use the circuit as a bounceless switch by connecting a switch from pins 3 and 4 to ground (negative battery connection). Or you can connect the UJT clock described in Chapter 8 directly to the single-shot input and duplicate the experiments in frequency division described in Chapter 9.

CHAPTER 11

FLIP-FLOP COUNTING CIRCUITS

One of the most important logic circuits is the bistable multivibrator or flip-flop. The flip-flop is not free-running like the astable multivibrator or monostable like the single-shot. Instead, the flip-flop has two stable states and can be triggered from one to the other by a single control pulse.

The bistable nature of the flip-flop gives it a memory capability. It also provides a means for division and binary counting. In this chapter I'll show you how to demonstrate basic flip-flop action with the 7473, a popular TTL IC containing two separate flip-flops. Then we'll assemble a fascinating flip-flop circuit called a decade counter which counts an incoming stream of pulses and provides a running total in binary up to nine. The cycle then repeats itself until the pulses stop.

FLIP-FLOP OPERATION

The complete name for the dual flip-flop used here is "Dual JB Master/Slave Flip-Flop." The "Master/Slave" terminology is used since one section of each flip-flop transfers logic information to the other section. The second section is then said to be slaved to the first. Except for common voltage pins, the two flip-flops in the 7473 package are completely independent.

The J and K refer to two control inputs which can be used to set and reset the flip-flop. Each flip-flop has individual JK inputs plus a clock input. The clock input is used to cycle the flip-flop with an external pulse train.

Figure 11-1 shows the circuit diagram for a practical 7473 flip-flop demonstration circuit. Pin connections and the 7473 internal logic connections are also shown. Notice that only one of the two flip-flops is used.

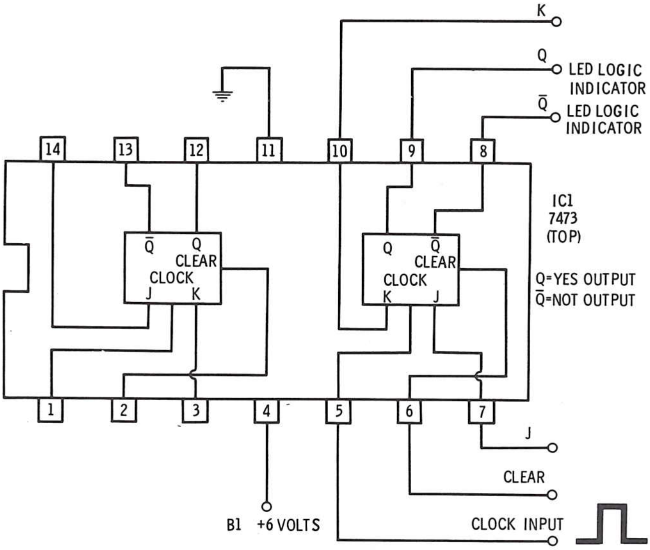


Figure 11-1. A TTL flip-flop circuit.

FLIP-FLOP ASSEMBLY

The parts list is given in Table 11-1. Begin assembly of the flip-flop circuit by soldering the 7473 IC to a Radio Shack IC adapter. Chapter 10 describes how to solder IC pins to an adapter's solder pads. Then solder insulated hookup wire to

Table 11-1. TTL 7473 Flip-Flop Parts List

Item	Description
B1	Battery, 6 volt
IC1	TTL 7473 J-K Master/Slave Flip-Flop (276-1803)
Misc.	Logic-status indicator (see text), perforated board (276-1392), IC adapter (276-024), hookup wire, solder

(Radio Shack catalog numbers shown in parentheses.)

the solder pads which make contact with pins 4, 5, 6, 7, 8, 9, 10, and 11 on the IC. Mount the IC on a perforated board as shown in the photograph in Figure 11-2 by inserting the connection leads through holes in the perforated board. No pictorial view of the flip-flop is necessary since other than the logic-status indicators no external components are used. Then thread the connection leads to pins 4 (+6 volts), 11 (ground), 5 (CLOCK input), 6 (CLEAR), 7 (J), and 10 (K) through holes in the board as shown in the photograph of the prototype. Identify each lead with a tape labeler to prevent confusion.

For best results, connect a LED logic-status indicator to both outputs of the flip-flop. When the flip-flop is reset, pin 9 is high (logic 1) and pin 8 low (logic 0).

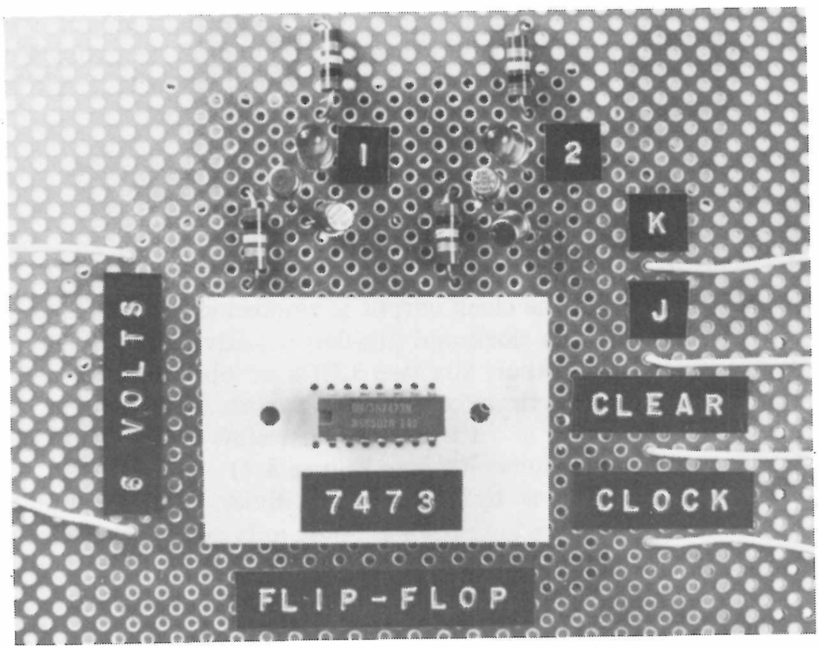


Figure 11-2. Assembled TTL flip-flop.

TESTING THE FLIP-FLOP

Test the flip-flop by connecting a 6-volt battery to the power leads. TTL ICs should normally be operated at 5.5 volts, but most 6-volt batteries provide less than their rated value. When power is applied, one of the LEDs should glow, and when the CLOCK lead is momentarily touched to the battery's negative terminal the first LED should turn off and the second one should turn on.

Since it is nearly impossible to touch a wire to a contact without obtaining contact bounce, the flip-flop circuit provides a good demonstration of switch bounce. It is likely that each time you apply a negative pulse to the CLOCK input that the two LEDs will flip-flop back and forth one or more times when the contact is first made *and* when it is broken. The flip-flop action may be so fast that one LED will appear to stay on continuously when in fact it flip-flopped one or more times!

Test the J, K, and CLEAR inputs by touching each in turn to the battery negative terminal (ground). When J is grounded, the LED connected to pin 8 should turn on and the LED at pin 9 should be extinguished. When K is grounded pin 8 should go low and pin 9 high. Finally, when CLEAR is grounded, pin 8 should again go high and pin 9 low.

GOING FURTHER WITH THE FLIP-FLOP

An interesting and entertaining experiment is to connect the UJT clock described in Chapter 8 to the CLOCK input of the flip-flop. When the clock output is connected to the flip-flop CLOCK lead and the clock and flip-flop negative battery terminals connected together, the two LEDs at pins 8 and 9 will flip-flop back and forth automatically. If both LEDs appear to be on, the clock rate is set too high. Just slow down the clock by rotating potentiometer R2 (see Figure 8-2).

A single flip-flop is by definition a divide-by-two counter since either of the two outputs is high on only every other clock pulse. By connecting one output of the unused flip-flop to the CLOCK input of the second flip-flop, a simple divide-by-four counter can be made. Connect the UJT clock to the CLOCK input of the unused flip-flop at pin 1. Then connect output pin 12 to the clock input of the other flip-flop at pin 5. Leave the LED status indicator connected to pin 9 in place, and connect the other LED to pin 12.

Now, one flip-flop receives pulses from the UJT and flip-flops in step with each pulse (pulse 1: flip; pulse 2: flop; pulse

3: flip; etc.). Every other flip-flop sends a "clock" pulse from the first flip-flop to the second and it flip-flops at half the rate of the first unit. The result is a divide-by-four counter. You can verify this operation by simply watching the LEDs flash on and off as the flip-flops do their thing. You already know that the LED connected to the first flip-flop flashes on every other clock pulse (divide-by-two). Since the LED connected to the second flip-flop flashes at half this rate, it shows division of the original clock signal by four.

To observe the memory capability of a flip-flop chain, simply disconnect the UJT clock from pin 1 of the first flip-flop. The LEDs will stop flashing and will hold their status as long as battery power is supplied. When the clock pulses are again supplied to pin 1, the LEDs will continue flashing as if there had been no interruption.

Try some experiments of your own by grounding the various CLEAR, J, and K inputs of each flip-flop while the circuits are counting. You may be surprised at the results. Also try disconnecting the flip-flop power supply momentarily to see if the counter is reset to its original status. Finally, try connecting a bounceless push-button single-shot to the clock input of the first flip-flop (pin 1) to manually enter data into the counter. See Chapters 9 and 10 for details on single-shot construction.

Flip-flop chains such as this simple two-unit circuit described here are called *registers* or simply *counters*. In the next section we will see how versatile and useful a four flip-flop register can be.

FLIP-FLOP DECADE COUNTER

Four separate flip-flops can be interconnected to make a *binary coded decimal* (BCD) *decade counter*. Don't be confused by the terminology, because a BCD decade counter simply counts incoming pulses and supplies a running total of the sum in binary. One decade counter counts from 0 to 9 and repeats, two count from 0 to 99 and repeat, and so forth.

While you can make a decade counter from four flip-flops and a pair of NAND gates, it is much easier to use the 7490, a TTL decade counter IC. This versatile IC contains all four flip-flops and both gates in a single dual in-line package (DIP),

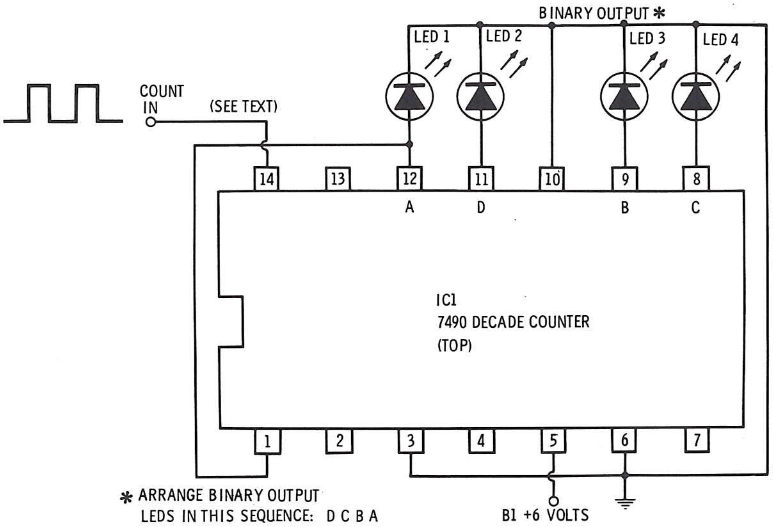


Figure 11-3. The BCD counter circuit.

and can be used as a decade counter, divide-by-two counter, divide-by-five counter, and divide-by-ten counter.

Normally four flip-flops will count to sixteen and then recycle, but the gates are connected so that when a count of ten is reached the counter is automatically reset. For this reason, a decade counter is a *preset* counter. Other kinds of preset counters are also available.

Table 11-2. TTL 7490 Decade Counter Parts List

Item	Description
B1	Battery, 6 volt
IC1	TTL 7490 decade counter (276-1808)
LED 1	Light-emitting diode (276-042)
LED 1-4	Clock circuit (see text), perforated board (276-1392),
Misc.	IC adapter (276-024), hookup wire, solder

(Radio Shack catalog numbers shown in parentheses.)

A practical decade counter circuit using the 7490 is shown in Figure 11-3 and a pictorial view of a working prototype in Figure 11-4. The parts list is given in Table 11-2. Since the decade counter illustrates so many functions of digital logic and teaches binary as well, I think it's the most important

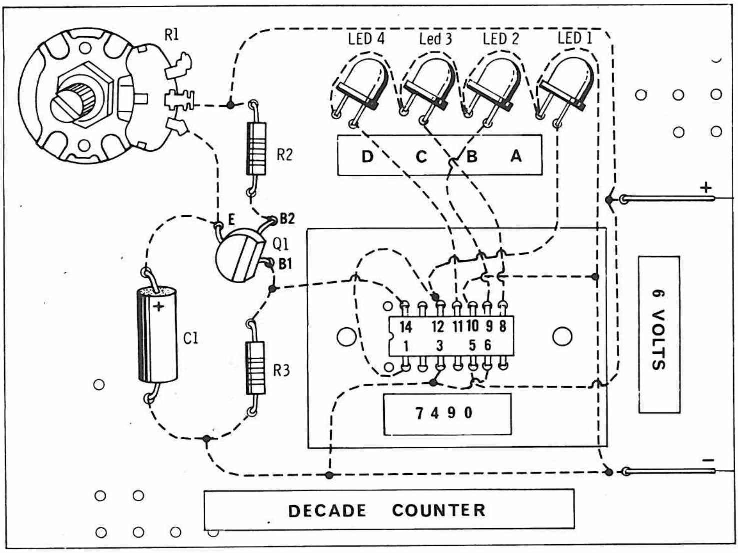


Figure 11-4. Pictorial wiring diagram of the BCD counter.

project in this book. If you don't build any other project at least try the decade counter.

DECADE COUNTER ASSEMBLY

Solder the 7490 IC to a Radio Shack IC adapter as described in Chapter 10 and solder connection wires to the solder pads connected to the IC pins 1, 3, 5, 6, 8, 9, 10, 11, 12, and 14. Then install the IC on a perforated board with its connection leads.

Next, solder the connection leads from IC pins 3, 6, and 10 to one another. This connection becomes the negative battery lead. The positive battery connection lead is made by threading pin 5 connection lead through the board as shown in the pictorial. The input lead is made by threading the IC pin 14 connection lead through the board.

Continue assembly by soldering the connection leads from the IC pins 1 and 12 to one another. Then install four LEDs in the board as shown in Figure 11-4 and use a length of bare hookup wire to solder all their cathodes together. Solder one end of this wire to the negative battery-connection lead.

Finally, solder each LED to the four output pins of the IC. The output pins are 8, 9, 11, and 12 and they are not arranged in the proper binary order, so be sure to arrange the LEDs as shown in Figure 11-4 (pins 11, 8, 9, and 12).

The decade counter is now complete and should resemble the prototype unit pictured in Figure 11-5. Be sure to recheck the wiring before connecting a source of power.

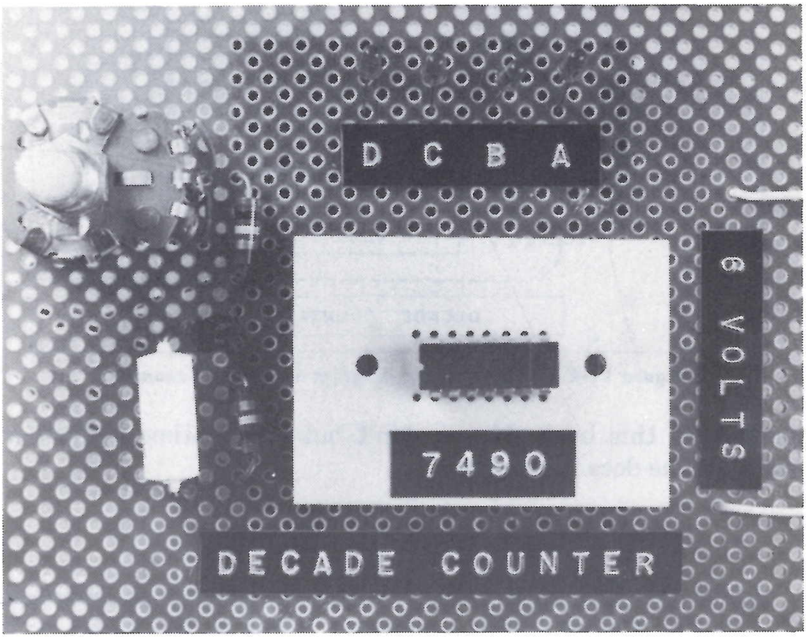


Figure 11-5. Assembled TTL decade counter.

TESTING THE DECADE COUNTER

You can test the counter by manually applying count pulses to the input connection lead (pin 14), but much better results will be had by using the UJT clock circuit described in Chapter 8 to automatically generate the count pulses. Connect the UJT output to pin 14 and connect the positive and negative leads of each circuit to one another so the UJT clock can borrow power from the decade counter battery (which should supply no more than 6 volts).

When the UJT clock is adjusted to a reasonably slow pulse rate (perhaps one pulse per second), the four LEDs will count from 0 to 9 in binary and automatically repeat the sequence.

GOING FURTHER

The decade counter is ideal for a permanent logic-demonstration project. Assemble the circuit along with the UJT clock on the perforated cover of a Radio Shack Perfbox or P-Box. Install a 6-volt battery made from four AA penlight cells and a battery holder (Radio Shack catalog number 270-1435) in the back of the box. Be sure to connect a power switch between the battery positive terminal and pin 5.

Mount the UJT clock's potentiometer in a hole bored in the perforated panel. This will permit convenient adjustment of the count rate.

To see how the binary output of the decade counter can be converted to decimal digits, see Chapters 4 and 5 of "Integrated Circuit Projects, Volume 1," a Radio Shack publication. The circuit described there utilizes a 7447 BCD to 7-segment decoder/driver to convert the BCD output of a 7490 decade counter into the appropriate format for a 7-segment display tube. The 7447 contains some 32 gates and 12 inverters and illustrates the use of logic circuits in converting a binary signal or output into a more convenient decimal format.

INDEX

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