

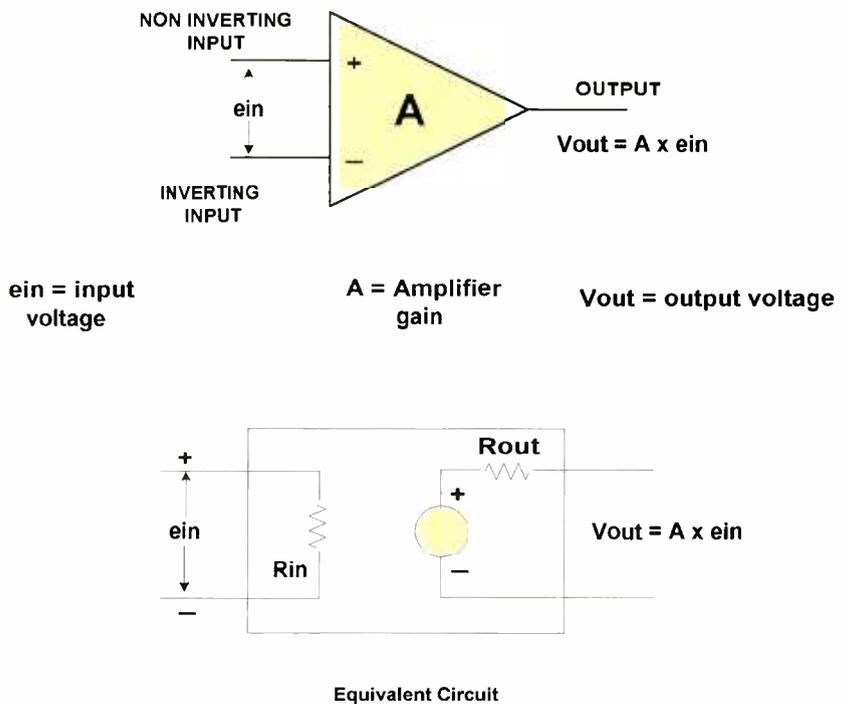
## Basic Op-Amps

The operational-amplifier (op-amp) is a staple item in electronic circuits and is a building block that is often one of the main components in linear, audio, and video circuitry. This device is basically a high-gain amplifier that is used in conjunction with feedback networks to make up a circuit whose properties are determined by linear-passive components, such as resistors, capacitors, inductors, as well as nonlinear components (diodes, varistors, thermistors, etc). The term “operational-amplifier” comes from the use of these devices in analog computers that were used decades ago to perform mathematical operations (addition, multiplication, differentiation, integration, summation, etc) on input quantities. The term has stuck and is still used, even though analog computers have largely departed the scene, having been replaced by digital computers long ago. Today’s operational-amplifier is a sophisticated device, composed of many transistors, diodes, and resistors, all in a chip and packaged in various configurations.

There are thousands of types of op-amps available, from flea-powered microwatt units to units capable of handling a few hundred watts of power—from a few cents to many dollars in cost. As you may imagine, the specs and performance requirements, as well as reliability, temperature range, and packaging, all affect cost. Op-amps that can do many ordinary jobs very well are available for under 50 cents, owing to low-cost plastic packages, large-scale integration, and high-volume production. Technologies commonly used are bipolar, FET, CMOS, and combinations. Some large or high-power op-amps are made using monolithic fabrication methods.

### An Ideal Amplifier

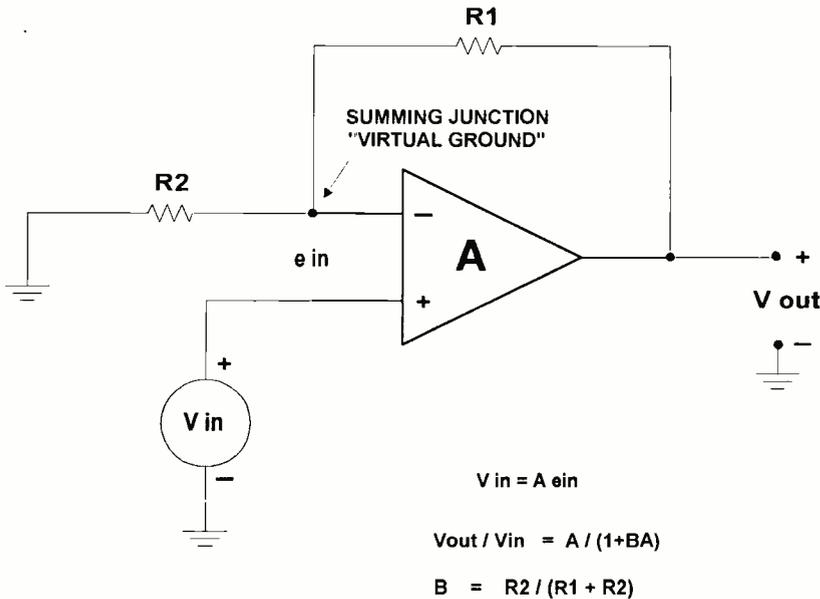
From a circuit viewpoint, for the purposes of explanation, an ideal amplifier is



used to represent an op-amp. An ideal amplifier has the following properties: infinite forward gain, bandwidth and input impedance with zero output impedance, noise voltage, DC offset, bias currents, and reverse gain. (See Fig. 1.) In practice, all op-amps have some bias current that flows in the inputs—almost negligible for JFET and CMOS types, but more significant in bipolar types. This current must be considered in high-impedance circuits, in DC and instrumentation amplifiers, and in circuits that must operate over a wide temperature range. In addition, even if you were to short the op-amp inputs together, you may not get zero output voltage, but some random DC level.

This DC voltage can be considered as

an equivalent DC input offset voltage present at the input. DC offset can also be produced from equal input bias currents flowing through unequal resistance in the inverting and non-inverting input circuits. This will produce a DC input voltage differential at the input. Some op-amps have external pins to which a potentiometer can be connected to balance out or otherwise cancel this voltage, bringing the DC output to zero under zero-signal input conditions. These are widely used in instrumentation amplifiers and related applications where nulling or zero adjustments are required. All amplifiers generate some noise, which is due to thermal and semiconductor junction effects, and can be considered as an equivalent input noise



**FIG 2**  
**BASIC OP AMP VOLTAGE AMPLIFIER**  
**NONINVERTING CONFIGURATION**

voltage. Amplifiers are available with low-noise characteristics for those applications where noise must be kept to a minimum.

A real-world op-amp has a lot of gain (>1000X voltage gain) and a fairly high input impedance (>100K). Generally there are two inputs shown, an inverting and a non-inverting input, and one output referenced to ground (but not always, differential outputs are sometimes used in certain applications). One of the inputs may be grounded in many common applications where a single-ended signal source is present. This is a common situation. There are limitations on the DC levels allowable on the inputs and limitations on the available output voltage swing.

Op-amps are available that allow a full output voltage swing between the positive ( $V_{cc}$ ) supply and negative ( $V_{dd}$ ) supply. These are sometimes referred to as rail-to-rail capable. In addition, if the exact same voltage is present on the inverting and non-inverting inputs, ideally the output voltage should be zero. This is not always so, and the degree of imperfection is called the common-mode rejection ratio. This is usually 60 dB or better, with 70–80 dB as a minimum. Note that this may vary with input voltage levels to some degree. Also, variations of power supply voltage

may show up as equivalent input signals. The degree to which the op-amp rejects this is called the supply-voltage rejection ratio. It is usually better than 60 dB and typically 70–80 dB or better. After all, nothing is perfect in life.

**What's To Gain?**

Op-amp power supply connections are sometimes shown in diagrams, especially if decoupling capacitors and resistors are necessary, but more often shown elsewhere in the schematic, as they play no part in the primary circuit function

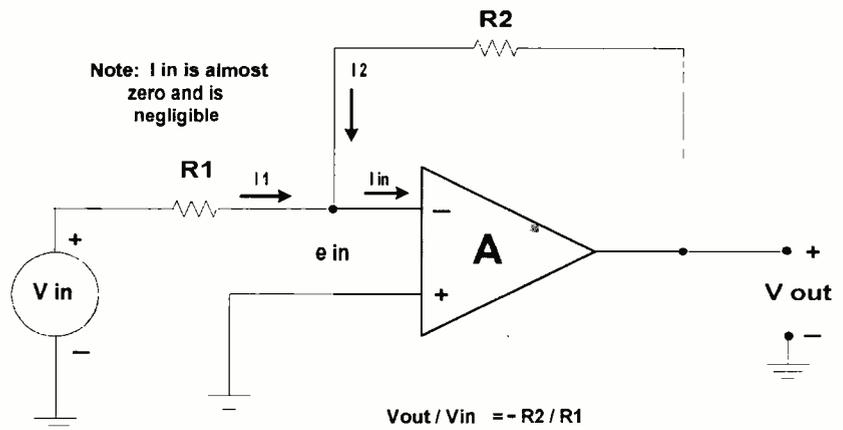
other than to power the amplifier. Many general-purpose op-amp chips have two or four separate operational-amplifiers in one package, with common power-supply connections. In practice the ideal amplifier criteria requirements are met only approximately, but as will be shown, close enough for most purposes.

Practically, an op-amp will have a gain of 10,000 or more, an input impedance of megohms, and a 3 dB bandwidth of several tens of hertz or more. If an amplifier has a 3 dB bandwidth of 40 Hz and a gain of 100,000 times, this is a gain bandwidth product of 4 million hertz, or 4 MHz. ( $40 \times 100,000$ ). It is advantageous in many feedback applications to have the gain falling at 6 dB per octave or 20 dB per decade at frequencies beyond the corner frequency (that frequency at which the amplifier gain has fallen 3 dB or 70.7 percent of its DC value).

Since the op-amp is used mainly in feedback circuits having much lower closed-loop gain, these performance figures are good enough in many cases. In fact, even a single high-gain (100X) common emitter transistor amplifier stage can be treated as an op-amp if feedback is employed, with surprisingly little error. In many cases, a single transistor will work almost as well as a more expensive op-amp device. One example is a simple audio amplifier stage from which a moderate gain (5–20X) is required. This will be shown in an example later.

**Op-Amp Families**

One of the most popular op-amps of all time is the venerable LM741, its dual



**FIG 3**  
**BASIC OP AMP VOLTAGE AMPLIFIER**  
**INVERTING CONFIGURATION**

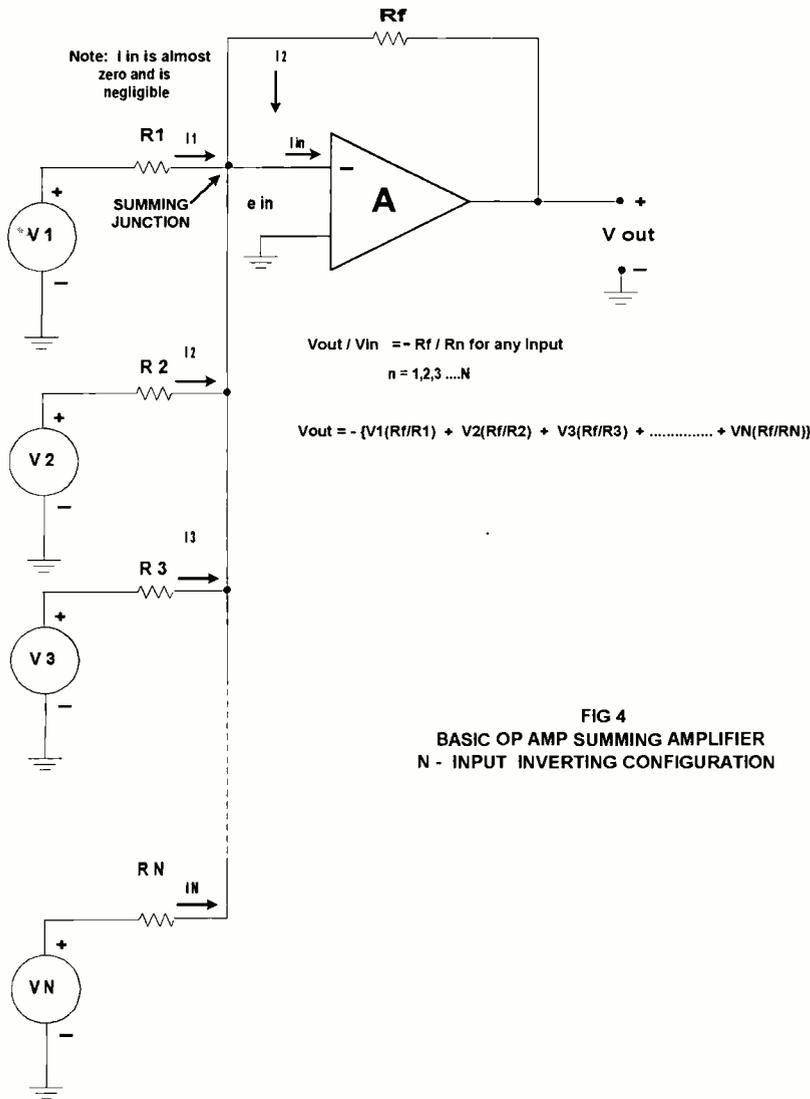


FIG 4  
BASIC OP AMP SUMMING AMPLIFIER  
N - INPUT INVERTING CONFIGURATION

that, while not difficult, can contain several terms and fractional expressions, leading to rather messy algebraic manipulation of these terms. This can confuse, intimidate, and scare away many readers. It is easy to get wrapped up in the math and then spend way too much time trying to figure out what is being done or what is meant. If you have ever studied algebra or calculus, you will surely have been through this. You also lose sight of the intended goal and the subject being discussed. What was to be a discussion of circuits turns into a time-wasting digression, usually a tedious and frustrating algebra exercise. This proves little except that you might be a complete bonehead because you do not immediately see the "obvious" meaning of these complex expressions. (Often the authors needed several hours correctly deriving them the first time or else just copied them from elsewhere so as to impress readers and look like geniuses). This will be avoided. We are going to make some simplifying approximations to get rid of the second and higher order stuff, which can be studied later after some basics are covered. Simplified approximations will still yield results accurate to a percent or so and avoid confusing trivial details which, while interesting, have dubious practical consequences for things the experimenter will get involved with. Even five or ten percent accuracy is good enough in many cases, if you are not doing instrumentation work.

### Feedback And Formulas

Figure 2 is a basic op-amp application, a simple gain stage. Amplifier A is a basic op-amp with a very high-input resistance. Resistors R1 and R2 make up a feedback network, a simple voltage divider. The voltage at the junction of R1 and R2 is  $R2/(R1 + R2)$ . In feedback amplifier work, the gain of the feedback network is commonly designated by the Greek letter  $\beta$  (beta). This gain is the ratio of output voltage to input voltage and is usually less than one—in many cases, much smaller than one. It may often be a complex number, having both real and imaginary components. Since practical feedback networks consist of resistors, capacitors, and sometimes inductors, they therefore have defined magnitude and phase characteristics. It may also be nonlinear, using diodes, varistors, and other nonlinear devices.

For the following discussions we will limit  $\beta$  to being linear and a purely real

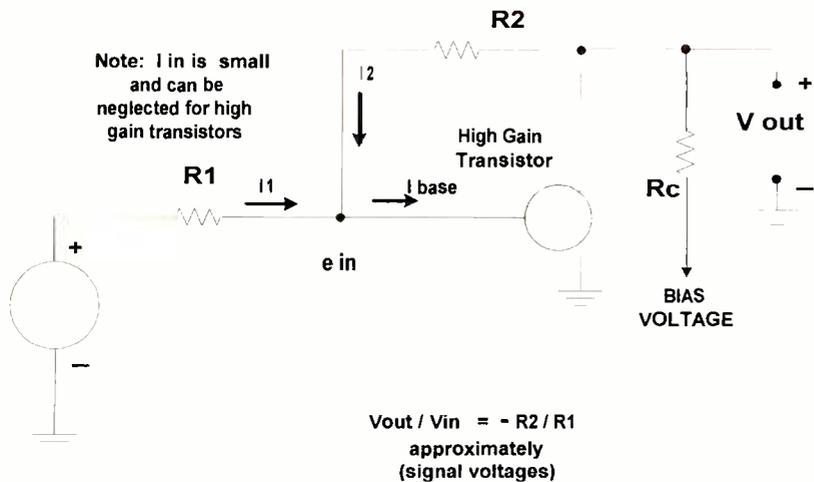
version LM747 and their many descendants. The JFET input TLO8X series is also very popular, coming in single (TLO81), double (TLO82), and quadruple (TLO84) units. The TLO81 and TLO82 come in 8-pin DIP packages, while the TLO84 comes in a 14-pin DIP package. These op-amps operate well from 5–12-volt experimenter supplies and require both a plus and minus supply. These are also cheap and widely available. Other general-purpose types are the LM324, LM1458 (bipolar), and LM3900, along with all their variations and flavors. There are many others, but those mentioned are easily obtained by the hobbyist wishing to experiment with them, cheap, and in plentiful supply. Many manufacturers make them, so obsolescence should not be a problem for a long time.

We will use the TLO8X series for circuit examples, as they are general-pur-

pose JFET types. The TLO8X series allows the use of higher resistance values and therefore smaller capacitor values, which is often more convenient from a design standpoint. The TLO8X series has an open-loop (no feedback used, the full gain the amp can deliver) voltage gain of over 10,000 and having JFET inputs, an input impedance of a million megohms. The gain bandwidth product (obtained by measuring frequency where gain falls to unity) is rated at 4 MHz for the TLO8X series. Op-amps are available with gain bandwidth products to several hundred MHz and even higher, and these are used in video and RF applications.

### Keeping It Simple

A word first to the nitpickers. (You know who you are). The exact explanation of op-amp and feedback principles requires the use of network equations



Note: DC Biasing for transistor not shown

**FIG 5**  
**BASIC TRANSISTOR VOLTAGE AMPLIFIER**  
**INVERTING CONFIGURATION**

number, as this simplifies the math. Most experimenter circuits will not involve complex feedback networks, but the reader should be made aware that this is not always the case.

In Fig. 2, the output voltage from the op-amp is  $V_{out} = A \times e_{in}$ .  $A$  is the gain of the amplifier (generally 10,000X or more). In a practical op-amp circuit powered by 5–15 volt supplies,  $V_{out}$  will be at most  $\pm 5$  to  $\pm 15$  volts. Therefore,  $e_{in}$  will be this voltage,  $V_{out}$  divided by the gain of the op-amp (10,000 or more). This says that  $e_{in}$  is very, very small, in the millivolt or microvolt range. However,  $V_{in}$  from the outside world is the input voltage we are applying to the circuit and could be a volt or more, such as a line-level audio signal, etc., while  $e_{in}$  is very much smaller. The circuit adjusts itself so that the ratio of  $V_{out}$  to  $e_{in}$  equals the gain of the amplifier, which we will take as 10,000. This requires  $V_{out}$  to be such that the portion of  $V_{out}$  at the junction of feedback network  $R1$  and  $R2$  exactly equals  $V_{in}$  minus  $e_{in}$ , so the total voltage difference across the inverting and non-inverting outputs is  $e_{in}$ . This occurs when:

$$V_{out} \{R2/(R1+R2)\} = V_{in} - e_{in}$$

But,  $V_{out} = A \times e_{in}$ , where  $A$  is the gain of the amplifier. Define  $R2/(R1+R2)$  as  $\beta$ , the feedback factor equal to the ratio of  $R2$  to  $R1$  and  $R2$ . For example, if  $R1 = 9K$  and  $R2 = 1K$  then  $\beta$  equals

$1/(9+1)$  or  $1/10$ , or  $0.1$ . This means that one tenth the output voltage is being fed back via the feedback network. By substituting the previously mentioned equalities in the first equation:

$$A \times e_{in} \{\beta\} = V_{in} - e_{in}$$

If you add like quantities to both sides of the equation, it still is valid. Therefore, if you add  $e_{in}$  to both sides of the equation:

$$A \times e_{in} \{\beta\} + e_{in} = V_{in}$$

Noting that  $e_{in}$  is common to both terms in the left side of the equation, it can be factored out:

$$e_{in} \times [A \times \beta + 1] = V_{in}$$

But  $e_{in}$  must equal  $V_{out}$  divided by  $A$ , the gain of the op-amp, so that:

$$(V_{out} / A) \{A \times \beta + 1\} = V_{in}$$

The effective circuit gain is what we want, i.e. the ratio of  $V_{out}$  to  $V_{in}$ . We are inputting a signal represented by  $V_{in}$  and would like to know the magnitude of  $V_{out}$  that will result. If both sides of the equation are first multiplied by  $A$ , then divided by  $V_{in}$ , and then finally by the entire quantity in brackets  $\{A \times \beta + 1\}$ , we get an equation that expresses the ratio of  $V_{out}$  to  $V_{in}$  as a function of  $A$ , the op-amp gain, and  $\beta$ , the feedback factor:

$$\text{Gain} = (V_{out} / V_{in}) = A / (A \times \beta + 1)$$

$A \times \beta$  means the product of these two quantities. Since the order of multiplication does not change the product,  $A \times \beta = \beta \times A = \beta A$  (realizing the  $\times$  stands for multiplication we can get rid of it). Also, the order of addition of two quantities does not affect the sum. Then the equation appears as:

$$\text{Gain} = A / (1 + \beta A)$$

This is a very important equation when working with op-amps or most any feedback amplifier. It applies to a lot of things. The ratio of  $A$  to  $(1 + \beta A)$  yields not only the gain, but affects other circuit-performance factors, as well. In a real-world case, if  $A$  is 10,000 and if  $\beta$  is 0.01 or more (it generally is), note that the product of  $\beta$  and  $A$  will be greater than 100. Then, a very nice simplifying approximation can be made. It is true that for any quantity  $X$  much larger than 1 (10 times or more would qualify),  $1$  plus  $X$  approximately equals  $X$  with an error of around  $1/X$  times 100 percent. As an example if  $X$  were 10 then  $10 \approx 11$  approximately with an error of  $1/10 \times 100$  percent, or ten percent, which is obviously true. If  $X$  were 100, then  $(1 + 100) \approx 100$  with an error of  $1/100 \times 100$  percent, or 1 percent. Note that in our case where  $A$  is 10,000 and  $\beta$  is 0.01, the product  $\beta A$  is 100 and  $1 + \beta A \approx \beta A$  within one percent. Therefore, if in any case  $\beta A > 1$ , we can rewrite the equation as:

$$\text{Gain} = A / (1 + \beta A) \approx A / (\beta A) = 1/\beta$$

(Note that  $A$  is common to numerator and denominator and can be cancelled out.)

In other words, if the product of the op-amp gain ( $A$ ) and the feedback factor ( $\beta$ ) is much larger than one, the value of  $\beta$  determines the overall gain of the op-amp circuit. The product of  $\beta A$  is called the open-loop gain. The overall circuit gain with the feedback loop in place is called the closed-loop gain. The beauty of this concept is that, given a large enough value of  $A$ , the gain and other parameters of a feedback amplifier or any other system employing feedback can be closely controlled by a network of components that can be specified to any degree of accuracy needed. The value of  $A$ , component tolerances, drift, noise, temperature effects, and all things

(Continued on page 41)

## ALL ABOUT

(continued from page 23)

affecting  $A$  become less and less relevant to the circuit performance as the value of  $\beta A$  increases.

We do not mean to pull a snow job here, but you should spend whatever time is needed to understand these concepts, as they are the heart of the theory. Once understood, op-amp circuits will be a breeze to work with.

### Virtual Ground

In a practical op-amp circuit  $e_{in}$  is very small, since the value of  $A$  is at least several thousand. Since  $e_{in}$  is that voltage appearing across the input of the op-amp (see Fig. 3), if one input terminal of the op-amp is connected to ground or has zero signal on it, the other input will also be very close to ground. Note again that  $e_{in}$  is at most a few millivolts in practical circuits. Under all signal levels this will be true, provided the op-amp is not driven into saturation or another region where the gain falls to a low value. This gives rise to the term virtual ground, since the op-amp input is always very close in voltage to ground. The input terminal in many applications is the inverting input, with the non-inverting input grounded or connected to a source of zero signal. Additionally, the amplifier itself has a high-input impedance, often measured in megohms. The input current to the op-amp itself is negligible and zero for all practical purposes. Therefore, in Fig. 3, the input current  $I$  in  $R_1$ , equal to  $V_{in}/R_1$ , has to equal the feedback current in  $R_2$ , equaling  $V_{out}/R_2$ . Since these currents entering and leaving any junction must equal

Graf and Sheets are no strangers to the pages of Gernsback. Their educational projects, such as the *RF-Field Strength Meter* and the *MPX2000 FM Transmitter*, can be found at **North Country Radio**. Established in 1986, this company offers projects related to amateur TV transmitters/receivers, AM and FM transmitters/ receivers, video cameras, and numerous other subjects. Visit the Web site at [www.northcountryradio.com](http://www.northcountryradio.com) for more information.

**Ordering Information:** PO Box 53, Wykagyl Station, New Rochelle, NY 10804-0053; Voice: 914-235-6611; Fax: 914-576-6051; e-mail: [Rgraf30832@aol.com](mailto:Rgraf30832@aol.com).

### Engineering and Technical Support

PO Box 200, Hartford, NY 12838

Voice/Fax: 518-854-9280

e-mail: [support@northcountryradio.com](mailto:support@northcountryradio.com)

zero (Kirchoff's current law, the law of continuity—and plain common sense), it follows that the positive current flowing in  $R_1$  must be cancelled by a current flowing in  $R_2$ , except for a tiny current flowing into the op-amp, which is zero for all practical purposes. The only way this can happen is if  $V_{out}$  equals  $-V_{in}$  in  $(R_2/R_1)$ .

Note that there is an inversion in phase, since the currents must cancel. The voltage gain is simply the ratio of  $R_2$  to  $R_1$ . The two resistors set the gain. If multiple inputs are desired, extra input resistors and input sources can be added as in Fig. 4. The output voltage is given as:

$$V_{out} = -[V_{in1} \times R_f / R_1 + V_{in2} \times R_f / R_2 + V_{in3} \times R_f / R_3 + V_{inN} \times R_f / R_N]$$

This is called a summing amplifier (see Fig. 4) and the junction of all the resistors at the input is called the summing junction. Since the input of the amplifier is a virtual ground, there is almost complete isolation

between all the input sources. This circuit makes an excellent audio mixer with virtually no cross-talk effects. By varying the values of the input resistors,  $R_1$ – $R_N$ , different gains can be obtained for the various inputs.

As far as AC signals are concerned, a high-gain single-transistor amplifier circuit can approximate the behavior of an op-amp in these circuits if the collector is considered the output, the base the inverting input, and the emitter the non-inverting input. Naturally DC biasing arrangements are needed and there are DC level considerations, but the principles of feedback still apply. (see Fig. 5).

Several op-amp circuits will be discussed in the next part of this article. **P**



## Basic Op-Amps, Part 2

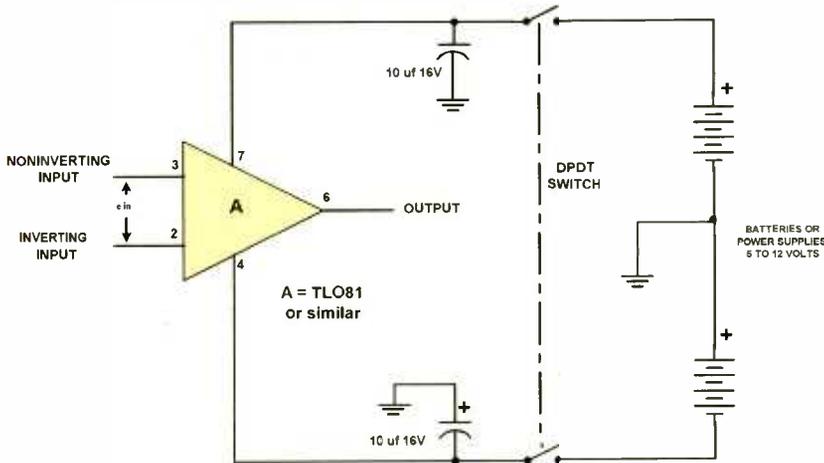


FIG 1  
BASIC OP AMP BREADBOARD

The operational-amplifier (op-amp) is useful for a wide variety of applications. Last month, we discussed basic theory and a few elementary circuits. For further understanding of how op-amps, (or most anything else), work, some hands-on experience is essential. So let's get working.

We suggest that a simple breadboard circuit, as shown in Fig. 1, be constructed, as a basic functioning op-amp circuit for experimentation. An 8-pin DIP op-amp can be used, such as a 741 or TLO81, as only one amplifier section will be needed. The TLO81 is cheap and readily available, and it's a JFET type that is an excellent general-purpose amplifier for experimentation and hobby circuits. Of course, other types can be used if you have them handy, but JFET types are probably preferable since they allow the use of more reasonable component values (capacitors, especially).

### Supply Voltages

The op-amp should be rated to work with the supply voltages you will use. Anything from 5 to 12 volts will be okay. You will need two supplies of equal voltage, one delivering a positive (plus) voltage and one delivering a negative (minus) voltage. Ideally a laboratory-type AC-powered adjustable DC supply delivering plus and minus voltages would be desirable. However, several AA batteries with two suitable battery holders, two 9-volt transistor radio batteries, or two 6-volt lantern batteries will work just as well.

AA-battery holders that hold four to eight AA cells are widely available, and two such holders can be used to make up a suitable supply. The batteries should last a very long time in

this application. Dedicated "universal" experimenter breadboard setups are available (approx. \$20 to \$40) that feature connectors and sockets suitable for plugging in most components and jumpers to configure almost any circuit. These breadboard setups will prove to be time-savers and will eliminate much, if not all, soldering.

Some source of signal should be handy—a function generator, an audio oscillator, or even audio from a CD or tape player. Access to an oscilloscope is desirable, but not necessary.

A few op-amp circuits will be discussed. These circuits are for demonstration and teaching purposes to illustrate the principles of op-amps, and they are not claimed to be optimized for any specific application.

There are refinements that can be added in some cases, but were omitted for simplicity. There are literally millions of op-amp circuits, and in a short column we cannot cover very much.

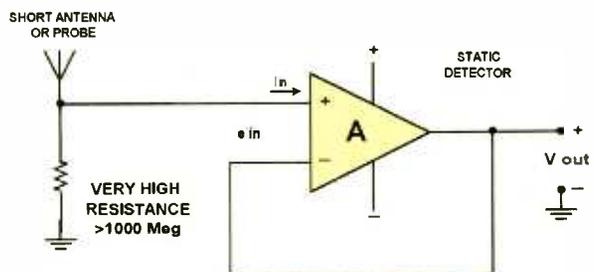
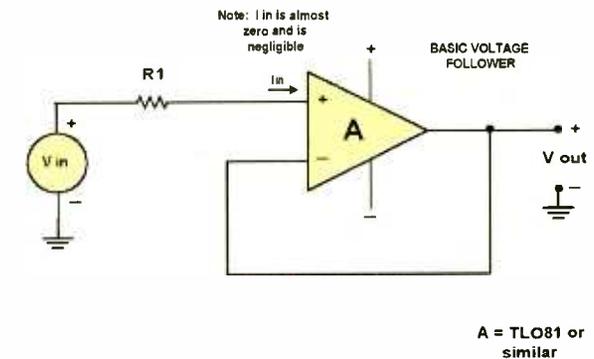


FIG 2  
VOLTAGE FOLLOWER

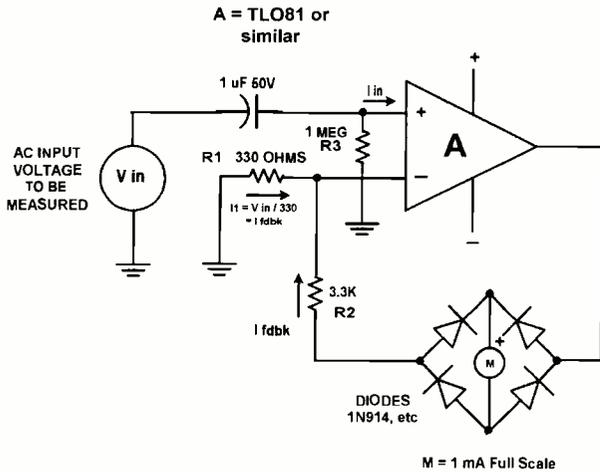


FIG 3  
LINEAR AC VOLTMETER CIRCUIT

The reader is strongly advised to consult the literature and manufacturer's application notes. Several years ago National Semiconductor offered a publication titled "Linear Applications Handbook" (our copy is dated 1994), which is an excellent reference text, full of ideas and applications, using op-amps. The devices referenced in older literature may be out of production and no longer available, but the circuit principles and ideas are relatively timeless and can be applied to currently available devices.

### The Voltage Follower

The circuit in Fig. 2 is a voltage follower. This unity-gain amplifier uses a TLO81 or similar JFET op-amp as a buffer and driver. A very high-impedance source (microphone, sample-and-hold circuit, transducer, etc.) can be interfaced to a lower impedance load with no loss in voltage. The gain here is all current gain. Since the feedback factor is unity, the output voltage will equal the input voltage minus  $e_{in}$ . Since  $e_{in}$  is very small and the gain of the amplifier is high (10,000), the output voltage will equal the input voltage within 0.01 percent.

This circuit can be used as a simple, high-impedance meter amplifier. If a DVM is connected to the op-amp output and a single 1.5-volt AA cell is connected to the input through a 22-meg resistor (highest commonly available resistor value), the resistor will have practically no effect on the voltage reading of the battery. This demonstrates the high-input impedance—in

the thousands of megohms—available with this circuit. By using a voltage-divider network and appropriate switching, you can make a high-impedance voltmeter that will have input impedance of hundreds of megohms or more. By using CMOS type op-amps, you can construct a simple electrometer able to read currents as low as 1 trillionth of an ampere (or 1 picoampere, if you prefer).

If the input of the amplifier is connected to a short (3-inch) wire, a body charged with electricity (hard rubber comb rubbed on flannel, or a glass rod rubbed with silk, etc.) brought near this wire will produce a change in the op-amp output voltage. Now we have a static-charge detector circuit. However, practically, a high resistance should be connected between the noninverting input and ground to establish a stable operating point. This resistor could be several thousand megohms in practice.

### Overcoming Diode Drops

Another useful circuit (Fig. 3) is an AC-voltmeter. The meter rectifier is in the feedback circuit, compensating for the diode forward drop. A conventional meter rectifier using a diode-bridge rectifier is compressed at the low end of the meter scale since small AC voltages may not overcome the diode forward voltage drop of 0.6 volt. This causes nonlinearity at the low end of the scale. When the bridge is placed in the feedback loop, the AC-signal current in the feedback loop

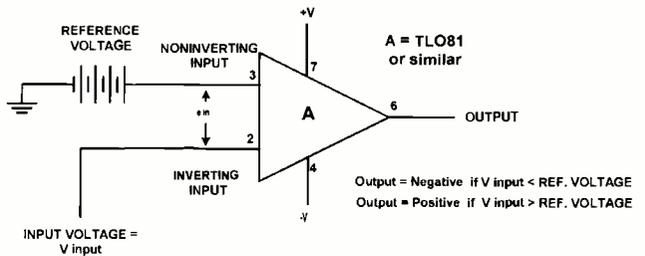


FIG 5  
BASIC OP AMP COMPARATOR

must equal the input current through R1. This equilibrium forces the op-amp to produce sufficient voltage to overcome the 0.6-volt diode drop, irrespective of the input level. Therefore, the meter will read linearly. It is easy to make an AC voltmeter with a full-scale deflection of 100 millivolts or less with this circuit with a perfectly linear scale. This AC-voltmeter circuit works well and will be fairly accurate in the audio-frequency range and into the low-frequency RF range (100 kHz) or higher with fast diodes and a wideband op-amp.

A voltage follower can be used as a peak detector (Fig. 4) to give the peak voltage of a waveform. The signal is applied to the noninverting input as shown. Capacitor C1 will charge to the peak voltage of the input signal. Since the diode is in series with the amplifier output, it will compensate for the diode drop. The output voltage will equal the peak value of the input voltage.

### Op-Amps Make Waves

Op-amps can also be used as comparators to compare two voltages. Figure 5 shows a typical circuit. The reference voltage is applied to the inverting input. Any voltage greater than this reference voltage will drive the op-amp output in a positive direction. Since the gain of the op-amp is several thou-

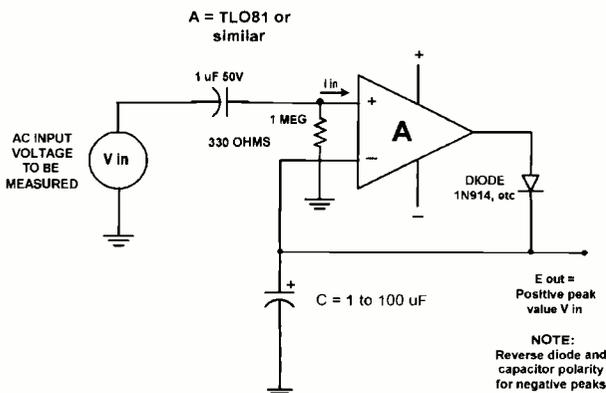


FIG 4  
PEAK DETECTOR CIRCUIT

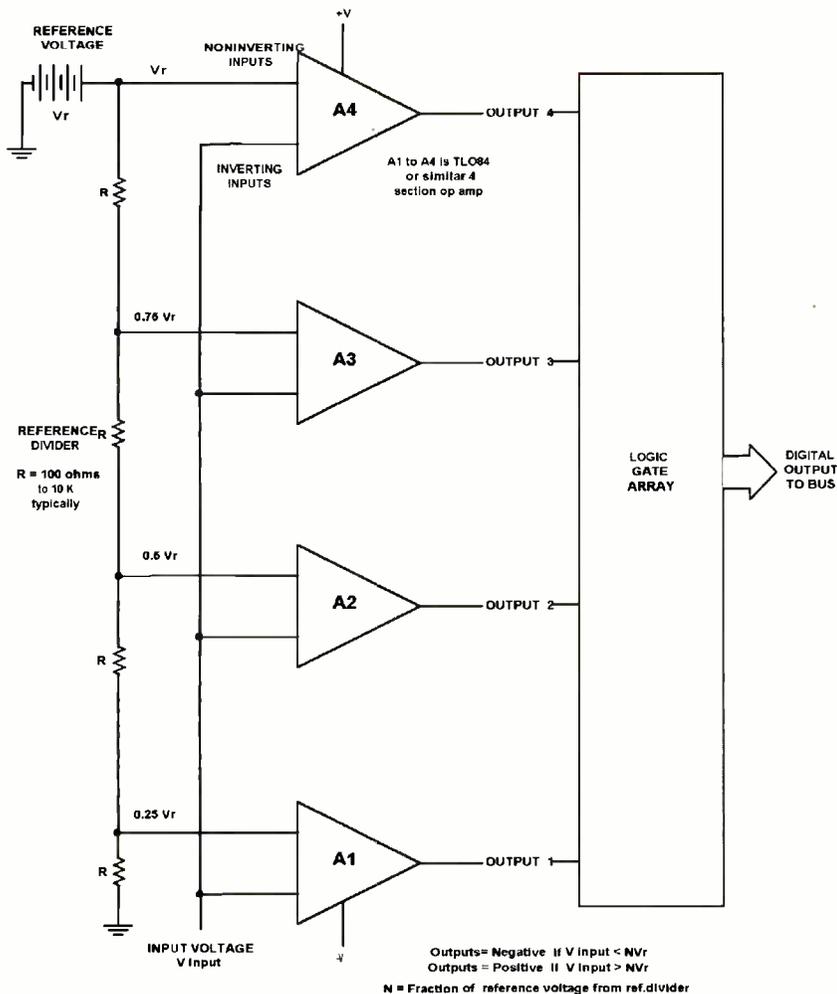


FIG 6  
BASIC FLASH A-D CONVERTER

sand, this transition is very sharp. Voltages less than this amount will cause the output to go in a negative direction. Output can be fed to an LED indicator or logic circuit as an indicator or used to drive another circuit.

Several op-amps can be connected to a resistive divider and can have their inputs connected to a common input. (See Fig. 6). The outputs can be fed to a system of logic gates that will produce a binary pattern that is a function of how many comparators are ON or OFF. The output can be made to be a binary value representing the number of ON or OFF comparators. The idea is to make a “flash” analog to digital (A-D) converter, since the output is an instantaneous function of input. The flash A-D converter is useful for digitizing fast waveforms and is widely used in digitization of video signals. By summing the comparator outputs, a staircase wave can be generated from a ramp-waveform input.

By using both positive and negative feedback, it is possible to make oscillators with different output waveforms. Figure 7 shows a square-wave oscillator. Capacitor C1 charges toward the positive supply rail through R1. After it reaches the reference voltage derived from R2 and R3, the comparator output goes low. This result also changes the reference voltage to a lower (more negative) level, which forces the comparator to a negative output.

Now the capacitor discharges towards the negative supply rail. This sequence will continue until the voltage at the inverting input reaches the new reference voltage. At this point the comparator switches to high (positive) output. The cycle is repeated. A square-wave output results. By using diodes and two separate feedback resistors, you can make dissimilar charge and discharge paths, allowing two different time constants. This setup allows generation of a variable duty-cycle waveform. A potentiometer can be used along with, or in place of, R1 and R2 to adjust this duty cycle, as shown in Fig. 8.

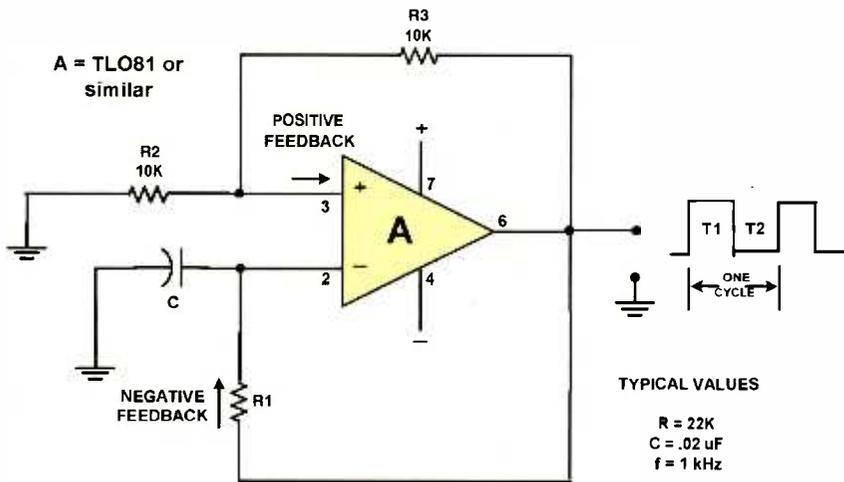
### Generating A Sine Wave

It is possible to generate a sine wave using a circuit known as a Wein Bridge. At a frequency  $f = 1/(2\pi RC)$ , the network shown in Fig. 9 will have a transfer function of 1/3 with zero phaseshift between input and output—permitting its use as a frequency-determining network. The Wein bridge is connected between the output and noninverting input as shown in Fig. 9, allowing positive feedback and oscillation.

However, the amplifier would generate a poor waveform, since limiting the output can only be accomplished by driving the amplifier to its positive and negative limits, resulting in severe clipping of any generated sine wave. Another feedback network is used to introduce negative feedback. A resistive divider with a division ratio of slightly more than 1/3 is used. This ratio reduces the gain to a little

over 3, which is enough to sustain oscillation. Limiting would still be obtained by clipping in the output, although the waveform would be somewhat improved.

Using a voltage-dependent resistor for R4 allows automatic gain control. Resistor R4 is selected to have a resistance that increases with applied voltage. A thermistor can be used for this purpose, but a more common approach is to use an ordinary tungsten-filament lamp. This kind of lamp has the exact characteristic we need. As more voltage is applied across the lamp, the filament heats up, its resistance increases, and the negative feedback increases, and lowers the gain of the op-amp. This sequence tends to reduce the amplitude of oscillation to a level that will not drive the op-amp into limiting. Very pure sine waves can be generated in this manner, and less than 1 percent distortion is easy to achieve. By making R1 and R2 a ganged potentiometer, you can obtain variable frequency operation. This circuit was widely used in the vacuum-tube days, and a 120-volt, 3-watt tungsten lamp was used for R4. For an op-amp version, one of the 5-volt, 10 mA subminiature lamps will work well. The lamp is typically operated at 10 to 20 percent of rated voltage, and the filament should barely glow. Resistor R3 is a pot to adjust the amplitude of oscillation at that level that yields satisfactory operation.



FOR THIS CIRCUIT:  
 $T1 = T2 = 1.1 RC$  APPROX  
 $T1 + T2 = \text{ONE CYCLE}$   
 $F = 1 / 2.2 RC$  APPROX

FIG 7  
 SQUARE WAVE OSCILLATOR CIRCUIT

### Creating A Tuned Amplifier

Finally, the use of both positive and negative feedback enables one to make a tuned amplifier having the desired given center frequency and bandwidth. A simple bandpass stage is shown in Fig. 10. We will not go into the design details except to present the design equations for one simple type of stage. Combining several of these stages allows one to derive a filter network of desired characteristics. These are called active filter networks. There are a number of circuit configurations, yielding low-pass, bandpass, and high-pass types of filters. Refer to a book on active filters for more detailed information. In addition, software programs are available from manufacturers that allow a PC to be used for the design of almost any active filter.

For the filter shown (suitable for bandpass audio use) with

bandwidth B and center frequency f and gain A:

$$\omega = 2\pi f \quad Q = f/B \quad a = 1/Q \quad H = \alpha |A| \quad \text{and } Q > \sqrt{(A/2)}$$

$$R1 = 1 / (H \times \omega \times C1)$$

$$Req = 1/Q (C1 + C2)\omega$$

$$R2 = R1 \times Req / (R1 - Req)$$

$$R3 = A \times R1(1 + C1/C2)$$

In practice, suitable values are chosen for C1 and C2 (generally, they are equal) and the resistors calculated. At audio frequencies, a suitable range of values may be around .001 to 0.1  $\mu$ F. Note that the exact type of op-amp is not specified; an ideal op-amp is assumed. The TLO81 comes close enough.

As an example, design a filter for 1 kHz with a bandwidth of 100 Hz. We will try to use capacitors of 0.01  $\mu$ f at C1 and C2. The filter should have a gain A of 10X (or 20 dB).

First check:

$$Q \text{ required} = f/B = 1000/100 = 10$$

$$a = 1/Q = 0.1 \text{ and } H = 1$$

$$\omega = 2\pi f = 6.28 \times 1000 = 6280$$

$$\text{Then check to see if } Q > \sqrt{A/2} \quad 10 > \sqrt{10/2} \quad \sqrt{10/2} = \sqrt{5} = 2.23$$

Since  $10 > 2.23$ , this condition is satisfied. Then:

$$R1 = 1 / (1)(6280)(10 \exp -8) = 15.9 \text{ K (16K)}$$

$$Req = 1/10 (2 \times 10 \exp -8)6280 = 796 \Omega (820\Omega)$$

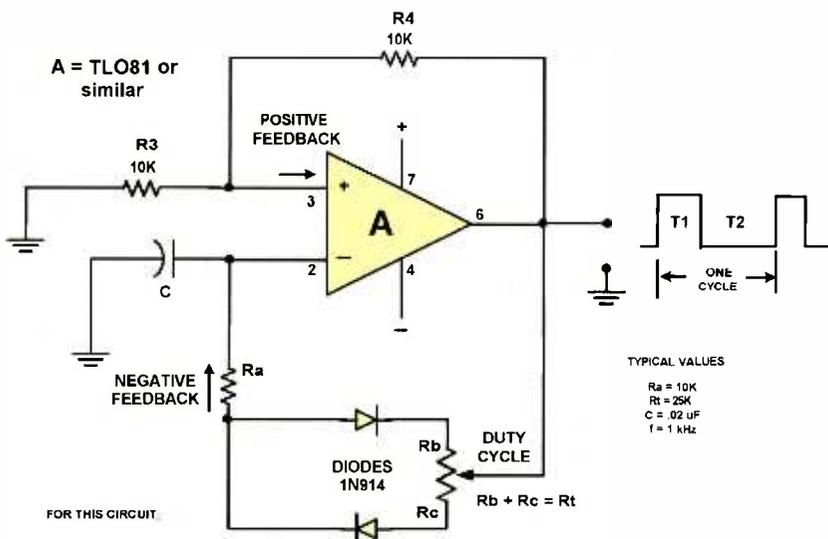
$$R2 = 15.9 \times 796 / (15.9 - 7.96) = 838 \Omega (820 \Omega)$$

$$R3 = 10 \times 15.9 (2) = 318 \text{ K (330 K)}$$

Values in parentheses are nearest standard 5% resistor values.

This circuit was built and tested, and results agreed with theory, as did a SPICE simulation. This circuit in itself is useful, as a 1-kHz tuned amplifier is useful for testing and in ham radio work as a CW filter. The design of this filter is rather simple, and the reader should try other frequencies and bandwidths as an exercise.

We have presented a number of circuits that should give a novice some



FOR THIS CIRCUIT:  
 $T1 = 1.1 (Ra + Rb) C$  APPROX  
 $T2 = 1.1 (Ra + Rc) C$  APPROX  
 $T1 + T2 = \text{ONE CYCLE}$   
 $F = 1 / 2.2 (Ra + 1.1 Rb) C$  APPROX

FIG 8  
 SQUARE WAVE OSCILLATOR CIRCUIT  
 VARIABLE DUTY CYCLE

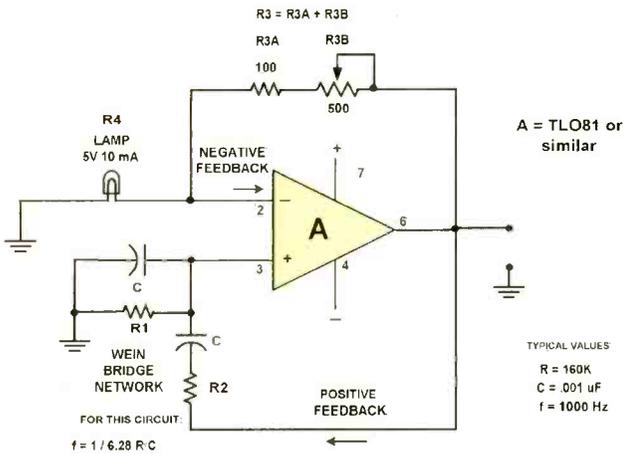


FIG 9  
WIEN BRIDGE OSCILLATOR CIRCUIT  
SINE WAVE OUTPUT

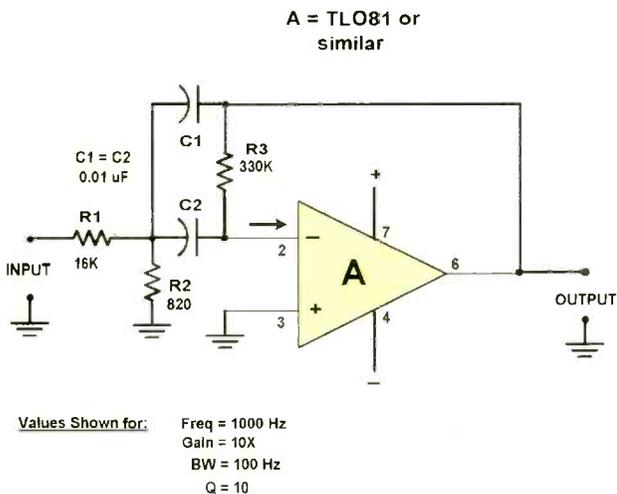
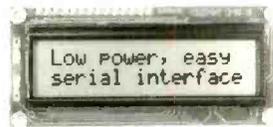


FIG 10  
BANDPASS ACTIVE FILTER

starting experience with op-amps. It would be a good idea to try some of these circuits and others that you can find, as well. There is no substitute for experience, and undoubtedly you will come up with some circuits of your own that can be tailored for your applications.

## SERIAL LCDs

Serial LCDs work great with BASIC Stamps® and other microcontrollers. One-wire interface • simple serial protocol • low cost • high quality • in stock

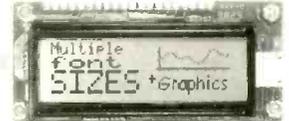


### BPI-216N

- 2x16 text LCD
- 2400/9600 bps
- \$45 (non-backlit)

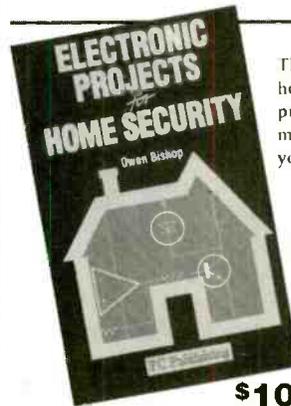
### SGX-120L

- Mini graphics LCD
- 2400/9600 bps
- just \$99



Many other models available—see [www.seetron.com/](http://www.seetron.com/)

Scott Edwards Electronics, Inc.  
[www.seetron.com](http://www.seetron.com) • 520-459-4802



This book deals with many aspects of home security – intruder, fire and flood protection – with the emphasis on how to make the best of electronic devices that you can build yourself.

## Electronic Projects for HOME SECURITY

- Projects to help secure your home •
- Principles of operation explained •
- Constructional details given •
- Suitable for beginners •

**\$10.99**

There are 25 constructional projects, ranging in complexity from a single-door protection circuit, that can be built in an hour or two, to a sophisticated multi-channel security system, that most intruders will find very difficult to beat.

ELECTRONICS TECHNOLOGY TODAY INC.  
PO Box 240, Massapequa Park, NY 11762-0240

Yes, send my copy of PCP115 ELECTRONIC PROJECTS FOR HOME SECURITY by Owen Bishop to the address at right. I am enclosing \$10.99 plus \$4.00 shipping charges in USA and Canada. All payments must be made in US funds. Sorry, no orders accepted outside of USA and Canada. New York State residents add local sales tax. Allow 6-8 weeks for delivery.

Please charge my  Visa  MasterCard

Signature \_\_\_\_\_

Card # \_\_\_\_\_ Exp. Date \_\_\_\_\_

Name \_\_\_\_\_

Address \_\_\_\_\_

City \_\_\_\_\_ State \_\_\_\_\_ ZIP \_\_\_\_\_

MA10

hope

If you know a child with a life-threatening illness, call 1-800-722-WISH or visit [www.wish.org](http://www.wish.org)

MAKE A WISH