CHAPTER 8

Operational Amplifiers

Operational amplifiers (op amps) are incredibly useful high-performance differential amplifiers that can be employed in a number of amazing ways. A typical op amp is an integrated device with a noninverting input, an inverting input, two dc power supply leads (positive and negative), an output terminal, and a few other specialized leads used for fine-tuning. The positive and negative supply leads, as well as the fine-tuning leads, are often omitted from circuit schematics. If you do not see any supply leads, assume that a dual supply is being used.

Note that we have labeled the supply voltages $+V_s$ and $-V_s$, as they are usually the same. However, they do not need to be, as you will see when we look at single-supply op amps in this chapter.

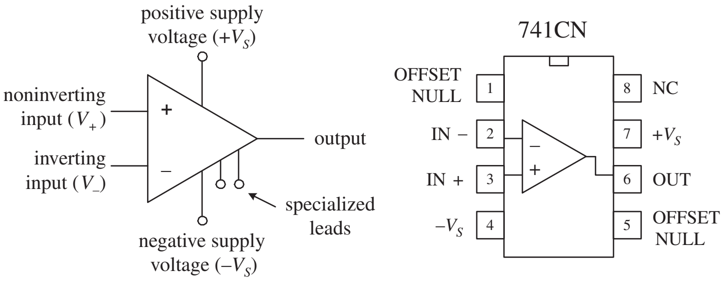


FIGURE 8.1

By itself, an op amp's operation is simple. If the voltage applied to the *inverting terminal* V_- is more positive than the voltage applied to the *noninverting terminal* V_+, the output saturates toward the *negative supply voltage* $-V_S$. Conversely, if $V_+ > V_-$, the output saturates toward the positive supply voltage $+V_S$ (see Fig. 8.2). This "maxing out" effect occurs with the slightest difference in voltage between the input terminals.

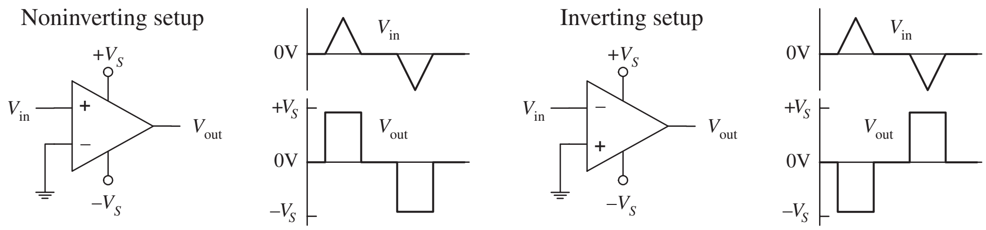


FIGURE 8.2

At first glance, it may appear that an op amp is not a very impressive device—it switches from one maximum output state to another whenever there's a voltage difference between its inputs. Big deal, right? By itself, it does indeed have limited applications. The trick to making op amps useful devices involves applying what is called *negative feedback.*

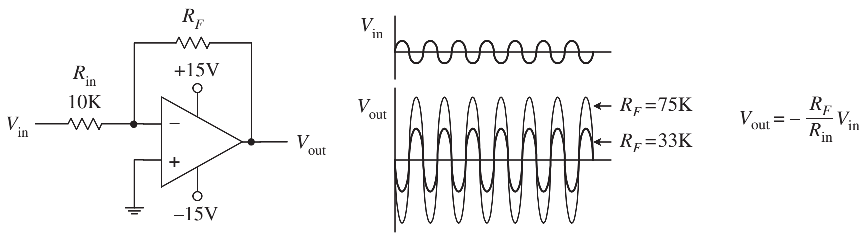


FIGURE 8.3

When voltage is "fed" back from the output terminal to the inverting terminal (this is referred to as *negative feedback*), the gain of an op amp can be controlled—the op amp's output is prevented from saturating. For example, a feedback resistor R_F placed between the output and the inverting input, as shown in Fig. 8.3, acts to convey the state of the output back to the op amp's input. This feedback information basically tells the op amp to readjust its output voltage to a value determined by the resistance of the feedback resistor. The circuit in Fig. 8.3, called an *inverting amplifier,* has an output equal to $-V_{in}(R_F/R_{in})$ (you will learn how to derive this formula later in this chapter). The negative sign means that the output is inverted relative to the input. The gain is then simply the output voltage divided by the input voltage, or $-R_F/R_{in}$ (the negative sign indicates that the output is inverted relative to the input). As you can see from this equation, if you increase the resistance of the feedback resistor, there is an increase in the voltage gain. On the other hand, if you decrease the resistance of the feedback resistor, there is a decrease in the voltage gain.

By adding other components to the negative-feedback circuit, an op amp can be made to do a number of interesting things besides pure amplification. Other interesting op amp circuits include voltage-regulator circuits, current-to-voltage converters, voltage-to-current converters, oscillator circuits, mathematical circuits (adders, subtractors, multipliers, differentiators, integrators, etc.), waveform generators, active filter circuits, active rectifiers, peak detectors, sample-and-hold circuits, etc. Most of these circuits will be covered in this chapter.

Besides negative feedback, there's positive feedback, where the output is linked through a network to the noninverting input. Positive feedback has the opposite effect as negative feedback; it drives the op amp harder toward saturation. Although positive feedback is seldom used, it finds applications in special comparator circuits that are often used in oscillator circuits. Positive feedback also will be discussed in detail in this chapter.

8.1 Operational Amplifier Water Analogy

This is the closest thing we could come up with in terms of a water analogy for an op amp. To make the analogy work, you have to pretend that water pressure is analogous to voltage and water flow is analogous to current flow.

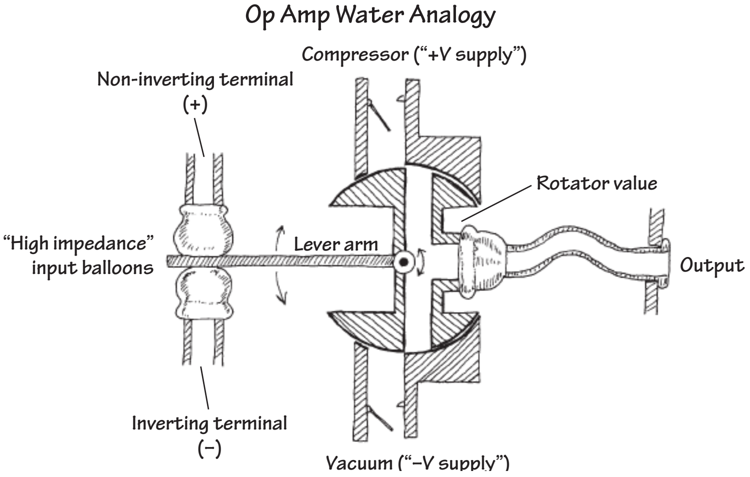


FIGURE 8.4

The inverting and noninverting terminals of the water op amp are represented by the two tubes with elastic balloon ends. When the water pressure applied to both input tubes is equal, the lever arm is centered. However, if the water pressure applied to the noninverting tube is made larger than the pressure applied to the inverting tube, the noninverting balloon expands and forces the lever arm downward. The lever arm then rotates the rotator valve counterclockwise, thus opening a canal from the compressor tube (analogous to the positive supply voltage) to the output tube. (This is analogous to an op amp saturating in the positive direction whenever the noninverting input is more positive in voltage than the inverting input.) Now, if the pressure applied at the noninverting tube becomes less than the pressure applied at the inverting tube, the lever arm is pushed upward by the inverting balloon. This causes the rotator valve to rotate clockwise, thus opening the canal from the vacuum tube (analogous to the negative supply voltage) to the output. (This is analogous to an op amp saturating in the negative direction whenever the inverting input is made more positive in voltage than the noninverting input.) See what you can do with the analogy in terms of explaining negative feedback. Also note that in the analogy there is an infinite "input water impedance" at the input tubes, while there is a zero "output water impedance" at the output tube. As you will see, ideal op amps also have similar input and output impedance. In real op amps, there are always some leakage currents.

8.2 How Op Amps Work (The "Cop-Out" Explanation)

An op amp is an integrated device that contains a large number of transistors, several resistors, and a few capacitors. Figure 8.5 shows a schematic diagram of a typical low-cost general-purpose bipolar operational amplifier.

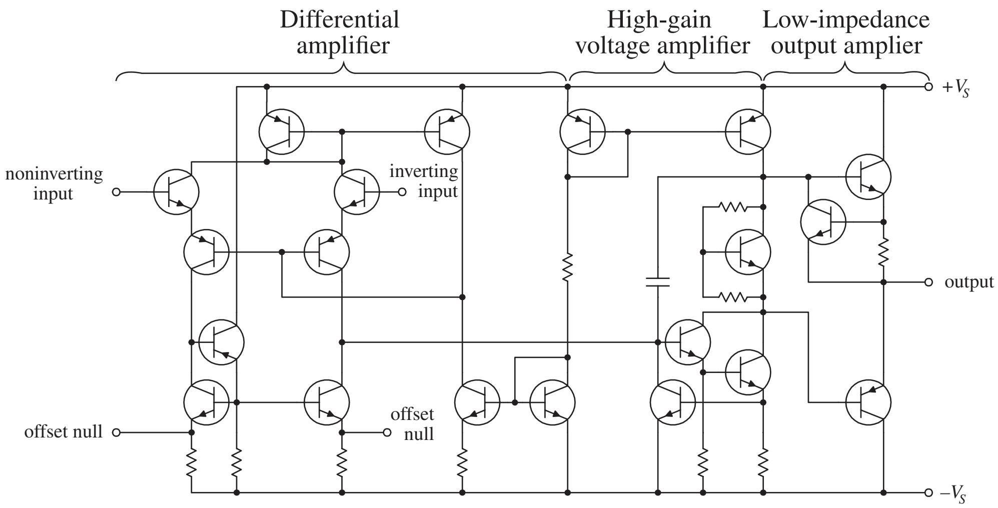


FIGURE 8.5

This op amp basically consists of three stages: a high-input-impedance differential amplifier, a high-gain voltage amplifier with a level shifter (permitting the output to swing positive and negative), and a low-impedance output amplifier. However, realizing that an op amp is composed of various stages does not help you much in terms of figuring out what will happen between the input and output leads. That is, if you attempt to figure out what the currents and voltages are doing within the complex system, you will be asking for trouble. It is just too difficult a task. What is important here is not to focus on understanding the op amp's internal circuitry but instead to focus on memorizing some rules that individuals came up with that require only working with the input and output leads. This approach seems like a "cop-out," but it works.

8.3 Theory

There is essentially only one formula you will need to know for solving op amp circuit problems. This formula is the foundation on which everything else rests. It is the expression for an op amp's output voltage as a function of its input voltages V_+ (noninverting) and V_- (inverting) and of its *open-loop voltage gain* A_o:

$$V_{out} = A_o(V_+ - V_-)$$

This expression says that an *ideal op amp* acts like an ideal voltage source that supplies an output voltage equal to $A_o(V_+ - V_-)$ (see Fig. 8.6). Things can get a little more complex when we start talking about *real op amps,* but generally, the open-loop voltage expression above pretty much remains the same, except now we have to make some slight modifications to our equivalent circuit. These modifications must take into account the nonideal features of an op amp, such as its input resistance R_{in} and output resistance R_{out}. Figure 8.6 *right* shows a more realistic equivalent circuit for an op amp.

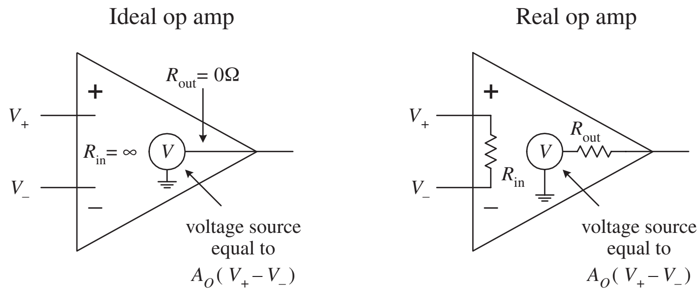


FIGURE 8.6

To give meaning to the open-loop voltage gain expression and to the ideal and real equivalent circuits, the values of A_o, R_{in}, and R_{out} are defined within the following rules:

Rule 1: For an ideal op amp, the open-loop voltage gain is infinite ($A_o = \infty$). For a real op amp, the gain is a finite value, typically between 10^4 to 10^6.

Rule 2: For an ideal op amp, the input impedance is infinite ($R_{in} = \infty$). For a real op amp, the input impedance is finite, typically between 10^6 (e.g., typical bipolar op amp) to $10^{12}\ \Omega$ (e.g., typical JFET op amp). The output impedance for an ideal op amp is zero ($R_{out} = 0$). For a real op amp, R_{out} is typically between 10 to 1000 Ω.

Rule 3: The input terminals of an ideal op amp draw no current. Practically speaking, this is true for a real op amp as well—the actual amount of input current is usually (but not always) insignificantly small, typically within the picoamps (e.g., typical JFET op amp) to nanoamps (e.g., typical bipolar op amp) range.

Now that you are armed with $V_{out} = A_o(V_+ - V_-)$ and rules 1 through 3, let's apply them to a few simple example problems.

EXAMPLE 1

Solve for the gain ($V_{\text{out}}/V_{\text{in}}$) of the circuit below.

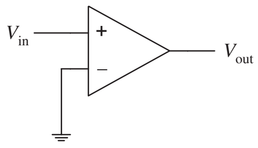


FIGURE 8.7

Since V_- is grounded (0 V) and V_+ is simply V_{in}, you can plug these values into the open-loop voltage gain expression:

$$V_{\text{out}} = A_o(V_+ - V_-) = A_o(V_{\text{in}} - 0\text{ V}) = A_oV_{\text{in}}$$

Rearranging this equation, you get the expression for the gain:

$$\text{Gain} = \frac{V_{\text{out}}}{V_{\text{in}}} = A_o$$

If you treat the op amp as ideal, A_o would be infinite. However, if you treat the op amp as real, A_o is finite (around 10^4 to 10^6). This circuit acts as a simple noninverting comparator that uses ground as a reference. If $V_{\text{in}} > 0$ V, the output ideally goes to $+\infty$ V; if $V_{\text{in}} < 0$V, the output ideally goes to $-\infty$ V. With a real op amp, the output is limited by the supply voltages (which are not shown in the drawing but assumed). The exact value of the output voltage is slightly below and above the positive and negative supply voltages, respectively. These maximum output voltages are called the *positive* and *negative saturation voltages*.

EXAMPLE 2

Solve for the gain ($V_{\text{out}}/V_{\text{in}}$) of the circuit below.

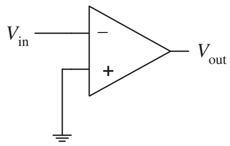


FIGURE 8.8

Since V_+ is grounded (0V) and V_- is simply V_{in}, you can substitute these values into the open-loop voltage gain expression:

$$V_{\text{out}} = A_o(V_+ - V_-) = A_o(0\text{ V} - V_{\text{in}}) = -A_oV_{\text{in}}$$

Rearranging this equation, you get the expression for the gain:

$$\text{Gain} = \frac{V_{\text{out}}}{V_{\text{in}}} = -A_o$$

If you treat the op amp as ideal, $-A_o$ is negatively infinite. However, if you treat the op amp as real, $-A_o$ is finite (around -10^4 to -10^6). This circuit acts as a simple inverting comparator that uses ground as a reference. If $V_{\text{in}} > 0$ V, the output ideally goes to $-\infty$ V; if $V_{\text{in}} < 0$ V, the output ideally goes to $+\infty$ V. With a real op amp, the output swings are limited to the saturation voltages.

8.4 Negative Feedback

Negative feedback is a wiring technique where some of the output voltage is sent back to the inverting terminal. This voltage can be "sent" back through a resistor, capacitor, or complex circuit or simply can be sent back through a wire. So exactly what kind of formulas do you use now? Well, that depends on the feedback circuit, but in reality, there is nothing all that new to learn. In fact, there is really only one formula you need to know for negative-feedback circuits (you still have to use the rules, however). This formula looks a lot like our old friend $V_{\text{out}} = A_o(V_+ - V_-)$. There is, however, the V_- in the formula—this you must reconsider. V_- in the formula changes because now the output voltage from the op amp is "giving" extra voltage (positive or negative) back to the inverting terminal. What this means is that you must replace V_- with fV_{out}, where f is a fraction of the voltage "sent" back from V_{out}. That's the trick!

There are two basic kinds of negative feedback, voltage feedback and operational feedback, as shown in Fig. 8.9.

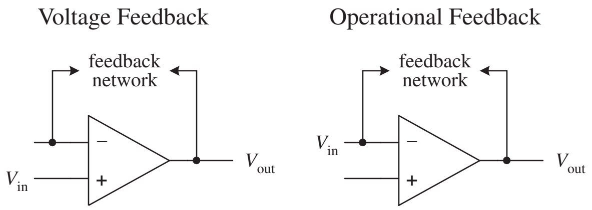


FIGURE 8.9

$$V_{out} = A_0(V_+ - fV_{out})$$

Now, in practice, figuring out what the fraction f should be is not important. That is, you do not have to calculate it explicitly. The reason why we have introduced it in the open-loop voltage expression is to provide you with a bit of basic understanding as to how negative feedback works in theory. As it turns out, there is a simple trick for making op amp circuits with negative feedback easy to calculate. The trick is as follows: If you treat an op amp as an ideal device, you will notice that if you rearrange the open-loop voltage expression into $V_{out}/A_o = (V_+ - V_-)$, the left side of the equation goes to zero—A_o is infinite for an ideal op amp. What you get in the end is then simply $V_+ - V_- = 0$. This result is incredibly important in terms of simplifying op amp circuits with negative feedback—so important that the result receives its own rule (the fourth and final rule).

Rule 4: Whenever an op amp senses a voltage difference between its inverting and noninverting inputs, it responds by feeding back as much current/voltage through the feedback network as is necessary to keep this difference equal to zero ($V_+ - V_- = 0$). This rule only applies for negative feedback.

The following sample problems are designed to show you how to apply rule 4 (and the other rules) to op amp circuit problems with negative feedback.

Negative Feedback Example Problems

BUFFER (UNITY GAIN AMPLIFIER)

Solve for the gain (V_{out}/V_{in}) of the circuit below.

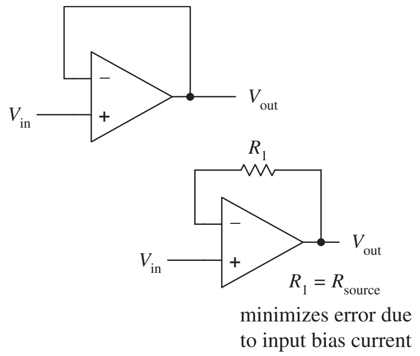


FIGURE 8.10

Since you are dealing with negative feedback, you can apply rule 4, which says that the output will attempt to make $V_+ - V_- = 0$. By examining the simple connections, notice that $V_{in} = V_+$ and $V_- = V_{out}$. This means that $V_{in} - V_{out} = 0$. Rearranging this expression, you get the gain:

$$\text{Gain} = \frac{V_{out}}{V_{in}} = 1$$

A gain of 1 means that there is no amplification; the op amp's output follows its input. At first glance, it may appear that this circuit is useless. However, it is important to recall that an op amp's input impedance is huge, while its output impedance is extremely small (rule 2). This feature makes this circuit useful for circuit-isolation applications. In other words, the circuit acts as a buffer. With real op amps, it may be necessary to throw in a resistor in the feedback loop (lower circuit). The resistor acts to minimize voltage offset errors caused by input bias currents (leakage). The resistance of the feedback resistor should be equal to the source resistance. We will discuss input bias currents later in this chapter.

INVERTING AMPLIFIER

Solve for the gain (V_{out}/V_{in}) of the circuit below.

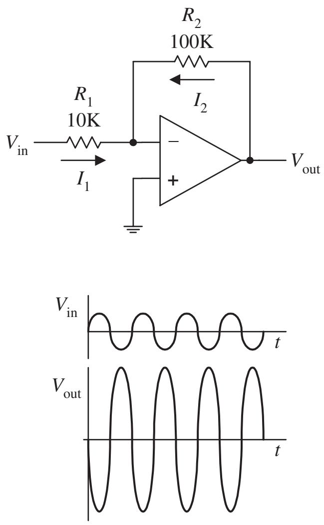


FIGURE 8.11

Because you have negative feedback, you know the output will attempt to make the difference between V_+ and V_- zero. Since V_+ is grounded (0 V), this means that V_- also will be 0 V (rule 4). To figure out the gain, you must find currents I_1 and I_2 so you can come up with an expression containing V_{out} in terms of V_{in}. Using Ohm's law, you find I_1 and I_2 to be

$$I_1 = \frac{V_{in} - V_-}{R_1} = \frac{V_{in} - 0\,V}{R_1} = \frac{V_{in}}{R_1}$$

$$I_2 = \frac{V_{out} - V_-}{R_2} = \frac{V_{out} - 0\,V}{R_2} = \frac{V_{out}}{R_2}$$

Because an ideal op amp has infinite input impedance, no current will enter its inverting terminal (rule 3). Therefore, you can apply Kirchhoff's junction rule to get $I_2 = -I_1$. Substituting the calculated values of I_1 and I_2 into this expression, you get $V_{out}/R_2 = -V_{in}/R_1$. Rearranging this expression, you find the gain:

$$\text{Gain} = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$$

The negative sign tells you that the signal that enters the input will be inverted (shifted 180°). Notice that if $R_1 = R_2$, the gain is −1 (the negative sign simply means the output is inverted). In this case you get what's called a *unity-gain inverter*, or an *inverting buffer*. When using real op amps that have relatively high input bias currents (e.g., bipolar op amps), it may be necessary to place a resistor with a resistance equal to $R_1 || R_2$ between the noninverting input and ground to minimize voltage offset errors.

NONINVERTING AMPLIFER

Solve for the gain (V_{out}/V_{in}) of the circuit below.

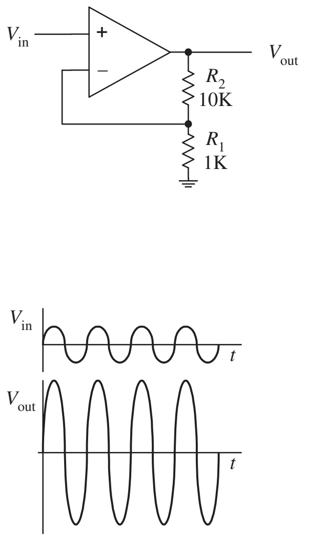


FIGURE 8.12

By inspection, you know that $V_+ = V_{in}$. By applying rule 4, you then can say that $V_- = V_+$. This means that $V_- = V_{in}$. To come up with an expression relating V_{in} and V_{out} (so that you can find the gain), the voltage divider relation is used:

$$V_- = \frac{R_1}{R_1 + R_2} V_{out} = V_{in}$$

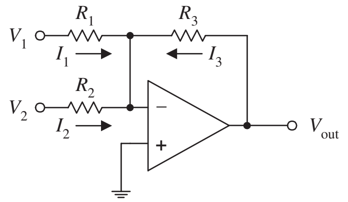
Rearranging this equation, you find the gain:

$$\text{Gain} = \frac{V_{out}}{V_{in}} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$$

Unlike the inverting amplifier, this circuit's output is in phase with its input—the output is "noninverted." With real op amps, to minimize voltage offset errors due to input bias current, set $R_1 || R_2 = R_{source}$.

SUMMING AMPLIFIER

Solve for V_{out} in terms of V_1 and V_2.



Since you know that V_+ is grounded (0 V), and since you have negative feedback in the circuit, you can say that $V_+ = V_- = 0\text{ V}$ (rule 4). Now that you know V_-, solve for I_1, I_2, and I_3 in order to come up with an expression relating V_{out} with V_1 and V_2. The currents are found by applying Ohm's law:

$$I_1 = \frac{V_1 - V_-}{R_1} = \frac{V_1 - 0\text{ V}}{R_1} = \frac{V_1}{R_1}$$

$$I_2 = \frac{V_2 - V_-}{R_2} = \frac{V_2 - 0\text{ V}}{R_2} = \frac{V_2}{R_2}$$

$$I_3 = \frac{V_{\text{out}} - V_-}{R_3} = \frac{V_{\text{out}} - 0\text{ V}}{R_3} = \frac{V_{\text{out}}}{R_3}$$

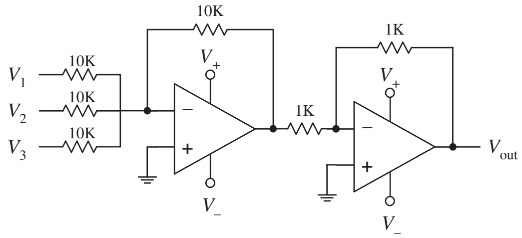


FIGURE 8.13

Like the last problem, assume that no current enters the op amp's inverting terminal (rule 3). This means that you can apply Kirchhoff's junction rule to combine I_1, I_2, and I_3 into one expression: $I_3 = -(I_1 + I_2) = -I_1 - I_2$. Plugging the results above into this expression gives the answer:

$$V_{\text{out}} = -\frac{R_3}{R_1}V_1 - \frac{R_3}{R_2}V_2 = -\left(\frac{R_3}{R_1}V_1 + \frac{R_3}{R_2}V_2\right)$$

If you make $R_1 = R_2 = R_3$, $V_{\text{out}} = -(V_1 + V_2)$. Notice that the sum is negative. To get a positive sum, you can add an inverting stage, as shown in the lower circuit. Here, three inputs are added together to yield the following output: $V_{\text{out}} = V_1 + V_2 + V_3$. Again, for some real op amps, an additional input-bias compensation resistor placed between the noninverting input and ground may be needed to avoid offset error caused by input bias current. Its value should be equal to the parallel resistance of all the input resistors.

DIFFERENCE AMPLIFIER

Determine V_{out}.

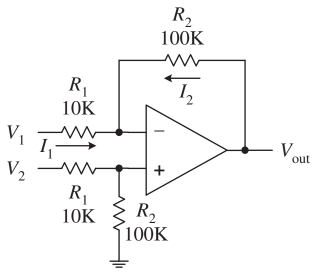


FIGURE 8.14

First, you determine the voltage at the noninverting input by using the voltage divider relation (again, assume that no current enters the inputs):

$$V_+ = \frac{R_2}{R_1 + R_2}V_2$$

Next, apply Kirchhoff's current junction law to the inverting input ($I_1 = I_2$):

$$\frac{V_1 - V_-}{R_1} = \frac{V_- - V_{\text{out}}}{R_2}$$

Using rule 4 ($V_+ = V_-$), substitute the V_+ term in for V_- in the last equation to get

$$V_{\text{out}} = \frac{R_2}{R_1}(V_2 - V_1)$$

If you set $R_1 = R_2$, then $V_{\text{out}} = V_2 - V_1$.

INTEGRATOR

Solve for V_{out} in terms of V_{in}.

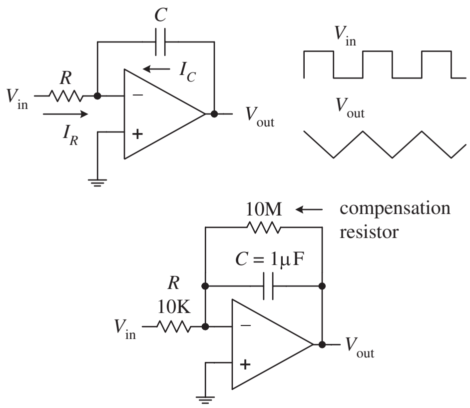


FIGURE 8.15

Because you have feedback, and because $V_+ = 0$ V, you can say that V_- is 0 V as well (rule 4). Now that you know V_-, solve for I_R and I_C so that you can come up with an expression relating V_{out} with V_{in}. Since no current enters the input of an op amp (rule 3), the displacement current I_C through the capacitor and the current I_R through the resistor must be related by $I_R + I_C = 0$. To find I_R, use Ohm's law:

$$I_R = \frac{V_{in} - V_-}{R} = \frac{V_{in} - 0\,\text{V}}{R} = \frac{V_{in}}{R}$$

I_C is found by using the displacement current relation:

$$I_C = C\frac{dV}{dt} = C\frac{d(V_{out} - V_-)}{dt} = C\frac{d(V_{out} - 0\,\text{V})}{dt} = C\frac{dV_{out}}{dt}$$

Placing these values of I_C and I_R into $I_R + I_C = 0$ and rearranging, you get the answer:

$$dV_{out} = -\frac{1}{RC}V_{in}\,dt$$

$$V_{out} = -\frac{1}{RC}V_{in}t$$

Such a circuit is called an *integrator*; the input signal is integrated at the output. Now, one problem with the first circuit is that the output tends to drift, even with the input grounded, due to nonideal characteristics of real op amps such as voltage offsets and bias current. A large resistor placed across the capacitor can provide dc feedback for stable biasing. Also, a compensation resistor may be needed between the noninverting terminal and ground to correct voltage offset errors caused by input bias currents. The size of this resistor should be equal to the parallel resistance of the input resistor and the feedback compensation resistor.

DIFFERENTIATOR

Solve for V_{out} in terms of V_{in}.

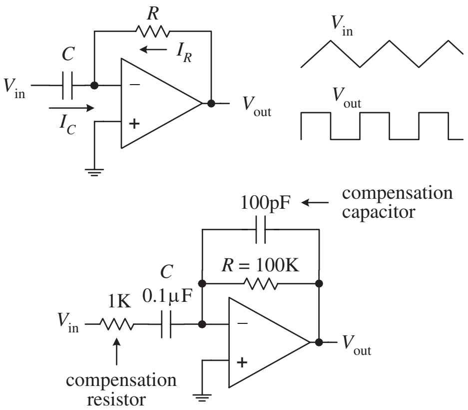


FIGURE 8.16

Since you know that V_+ is grounded (0 V), and since you have feedback in the circuit, you can say that $V_- = V_+ = 0$ V (rule 4). Now that you know V_-, solve for I_R and I_C so that you can come up with an expression relating V_{out} with V_{in}. Since no current enters the input of an op amp (rule 3), the displacement current I_C through the capacitor and the current I_R through the resistor must be related by $I_R + I_C = 0$. To find I_C, use the displacement current equation:

$$I_C = C\frac{dV}{dt} = C\frac{d(V_{in} - V_-)}{dt} = C\frac{d(V_{in} - 0\,V)}{dt} = C\frac{dV_{in}}{dt}$$

The current I_R is found using Ohm's law:

$$I_R = \frac{V_{out} - V_-}{R} = \frac{V_{out} - 0\,\text{V}}{R} = \frac{V_{out}}{R}$$

Placing these values of I_C and I_R into $I_R + I_C = 0$ and rearranging, you get the answer:

$$V_{out} = -RC\frac{dV_{in}}{dt}$$

Such a circuit is called a *differentiator*; the input signal is differentiated at the output. The first differentiator circuit shown is not in practical form. It is extremely susceptible to noise due to the op amp's high ac gain. Also, the feedback network of the differentiator acts as an *RC* low-pass filter that contributes a 90° phase lag within the loop and may cause stability problems. A more practical differentiator is shown below the first circuit. Here, both stability and noise problems are corrected

with the addition of a feedback capacitor and input resistor. The additional components provide high-frequency rolloff to reduce high-frequency noise. These components also introduce a 90° lead to cancel the 90° phase lag. The effect of the additional components, however, limits the maximum frequency of operation—at very high frequencies, the differentiator becomes an integrator. Finally, an additional input-bias compensation resistor placed between the noninverting input and ground may be needed to avoid offset error caused by input bias current. Its value should be equal to the resistance of the feedback resistor.

8.5 Positive Feedback

Positive feedback involves sending output voltage back to the noninverting input. In terms of the theory, if you look at our old friend $V_{out} = A_o(V_+ - V_-)$, the V_+ term changes to fV_{out} (f is a fraction of the voltage sent back), so you get $V_{out} = A_o(fV_{out} - V_-)$. Now, an important thing to notice about this equation (and about positive feedback in general) is that the voltage fed back to the noninverting input will act to drive the op amp "harder" in the direction the output is going (toward saturation). This makes sense in terms of the equation; fV_{out} adds to the expression. Recall that negative feedback acted in the opposite way; the fV_{out} (= V_-) term subtracted from the expression, preventing the output from "maxing out." In electronics, positive feedback is usually a bad thing, whereas negative feedback is a good thing. For most applications, it is desirable to control the gain (negative feedback), while it is undesirable to go to the extremes (positive feedback).

There is, however, an important use for positive feedback. When using an op amp to make a comparator, positive feedback can make output swings more pronounced. Also, by adjusting the size of the feedback resistor, a comparator can be made to experience what is called *hysteresis.* In effect, hysteresis gives the comparator two thresholds. The voltage between the two thresholds is called the *hysteresis voltage.* By obtaining two thresholds (instead of merely one), the comparator circuit becomes more immune to noise that can trigger unwanted output swings. To better understand hysteresis, let's take a look at the following comparator circuit that incorporates positive feedback.

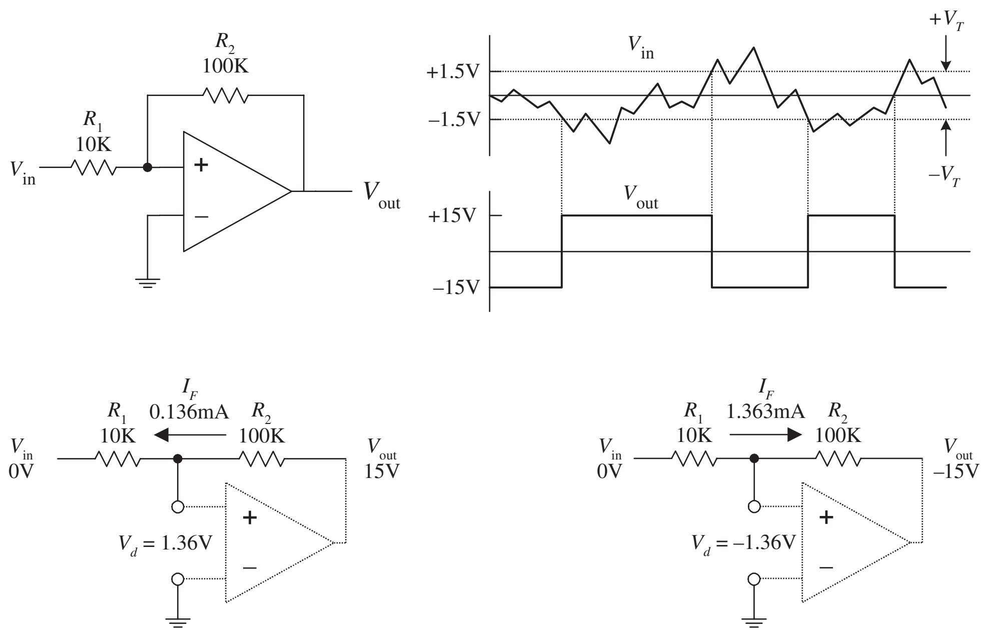


FIGURE 8.17

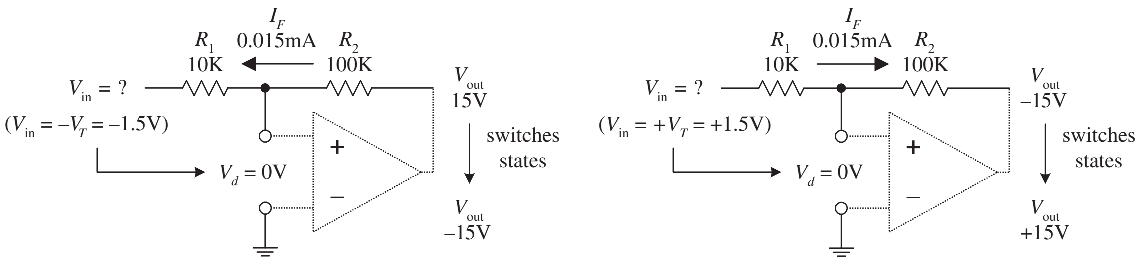


FIGURE 8.17 (*Continued*)

Assume that the op amp's output is at positive saturation, say, +15 V. If V_{in} is 0 V, the voltage difference between the inverting input and noninverting input (V_d) will be 1.36 V. You get this by using Ohm's law:

$$I_F = (V_{out} - V_{in})/(R_1 + R_2)$$
$$V_d = I_F R_1$$

This does not do anything to the output; it remains at +15 V. However, if you reduce V_{in}, there is a point when V_d goes to 0 V, at which time the output switches states. This voltage is called the *negative threshold voltage* ($-V_T$). The negative threshold voltage can be determined by using the previous two equations—the end result being $-V_T = -V_{out}/(R_2/R_1)$. In the example, $-V_T = -1.5$ V. Now, if the output is at negative saturation (–15 V) and 0 V is applied to the input, $V_d = -1.36$ V. The output remains at –15 V. However, if the input voltage is increased, there is a point where V_d goes to zero and the output switches states. This point is called the *positive threshold voltage* ($+V_T$), which is equal to $+V_{out}/(R_2/R_1)$. In the example, $+V_T = +1.5$ V. Now the difference between the two saturation voltages is the hysteresis voltage: $V_h = +V_T - (-V_T)$. In the example, $V_h = 3$ V.

8.6 Real Kinds of Op Amps

General Purpose

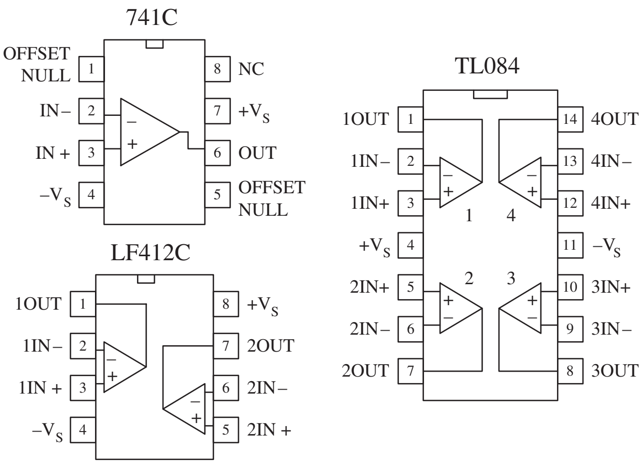


FIGURE 8.18

There is a huge selection of general-purpose and precision op amps to choose from. Precision op amps are specifically designed for high stability, low offset voltages, low bias currents, and low drift parameters. Because the selection of op amps is so incredibly large, we will leave it to you to check out the electronics catalogs to see what devices are available. When checking out these catalogs, you will find that op amps (not just general-purpose and precision) fall into one of the following categories (based on input circuitry): bipolar, JFET, MOSFET, or some hybrid thereof (e.g., BiFET). In general, bipolar op amps, like the 741 (industry standard), have higher input bias currents than either JFET or MOSFET types. This means that their input terminals have a greater tendency to "leak in" current. Input bias current results in voltage drops across resistors of feedback networks, biasing networks, or source impedances, which in turn can offset the output voltage. The amount of offset a circuit can tolerate ultimately depends on the application. Now, as we briefly mentioned earlier in this chapter, a compensation resistor placed between the noninverting terminal and ground (e.g., bipolar inverting amplifier circuit) can reduce these offset errors. (More on this in a minute.)

Precision

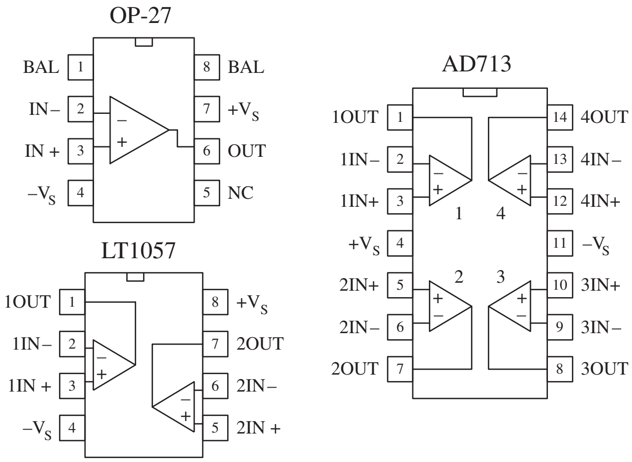


FIGURE 8.19

A simple way to avoid problems associated with input bias current is to use a FET op amp. A typical JFET op amp has a very low input bias current, typically within the lower picoamp range as compared with the nanoamp range for a typical bipolar op amp. Some MOSFET op amps come with even lower input bias currents, often as low as a few tenths of a picoamp. Though FET op amps have lower input bias current than bipolar op amps, there are other features they have that are not quite as desirable. For example, JFET op amps often experience an undesired effect called *phase inversion*. If the input common-mode voltage of the JFET approaches the negative supply too closely, the inverting and noninverting input terminals may reverse directions—negative feedback becomes positive feedback, causing the op amp to latch up. This problem can be avoided by using a bipolar op amp or by restricting the common-mode range of the signal. Here are some other general comments about bipolar and FET op amps: offset voltage (low for bipolar, medium for JFET, medium to high for MOSFET), offset drift (low for bipolar, medium for FET), bias matching (excellent for bipolar, fair for FET), bias/temperature variation (low for bipolar, fair for FET).

To avoid getting confused by the differences between the various op amp technologies, it is often easier to simply concentrate on the specifications listed in the electronics catalogs. Characteristics to look for include speed/slew rate, noise, input offset voltages and their drift, bias currents and their drift, common-mode range, gain, bandwidth, input impedance, output impedance, maximum supply voltages, supply current, power dissipation, and temperature range. Another feature to look for when purchasing an op amp is whether the op amp is internally or externally frequency compensated. An externally compensated op amp requires external components to prevent the gain from dropping too quickly at high frequencies, which can lead to phase inversions and oscillations. Internally compensated op amps take care of these problems with internal circuitry. All the terms listed in this paragraph will be explained in greater detail in a minute.

Programmable Op Amp

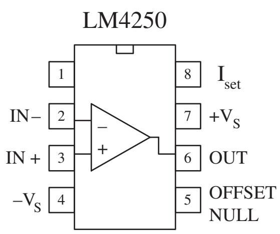
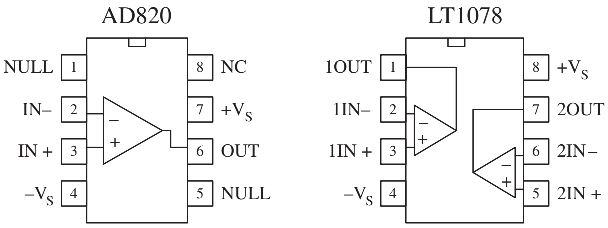


FIGURE 8.20

A programmable op amp is a versatile device that is used primarily in low-power applications (e.g., battery-powered circuits). These devices can be programmed with an external current for desired characteristics. Some of the characteristics that can be altered by applying a programming current include quiescent power dissipation, input offset and bias currents, slew rate, gain-bandwidth product, and input noise characteristics—all of which are roughly proportional to the programming current. The programming current is typically drawn from the programming pin (e.g., pin 8 of the LM4250) through a resistor and into ground. The programming current allows the op amp to be operated over a wide range of supply currents, typically from around a few microamps to a few millamps. Because a programmable op amp can be altered so as to appear as a completely different op amp for different programming currents, it is possible to use a single device for a variety of circuit functions within a system. These devices typically can operate with very low supply voltages (e.g., 1 V for the LM4250). A number of different manufacturers make programmable op amps, so check the catalogs. To learn more about how to use these devices, check out the manufacturers' literature (e.g., for National Semiconductor's LM4250, go to *www.national.com*).

Single-Supply Op Amps



These op amps are designed to be operated from a single positive supply (e.g., +12 V) and allow input voltages all the way down to the negative rail (normally tied to ground). Figure 8.21 shows a simple dc amplifier that uses a single-supply op amp. It is important to note that the output of the amplifier shown cannot go negative; thus it cannot be used for, say, ac-coupled audio signals. These op amps are frequently used in battery-operated devices.

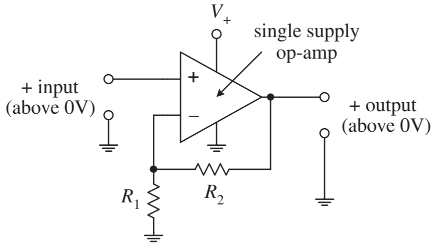


FIGURE 8.21

Audio Amplifiers

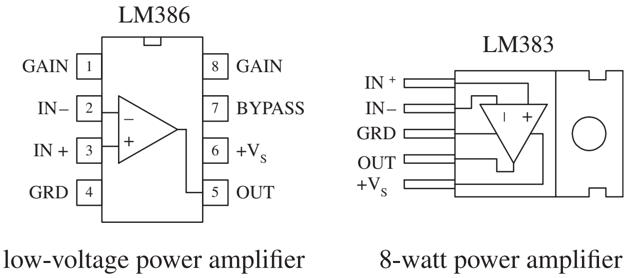


FIGURE 8.22

These are closely related to conventional op amps but designed specifically to operate best (low audio band noise, crossover distortion, etc.) within the audio-frequency spectrum (20 to 20,000 Hz). These devices are used mainly in sensitive preamplifiers, audio systems, AM-FM radio receivers, servo amplifiers, and intercom and automotive circuits. There are a number of audio amplifiers to choose from. Some of these devices contain unique features that differ when compared with those of conventional op amps. For example, the popular LM386 low-voltage audio amplifier has a gain that is internally fixed at 20 but which can be increased to up to 200 with an external capacitor and resistor placed across its gain leads (pins 1 and 8). This device is also designed to drive low-impedance loads, such as an 8-Ω speaker, and runs off a single supply from +4 to +12 V—an ideal range for battery-powered applications. The LM383 is another audio amplifier designed as a power amplifier. It is a high-current device (3.5 A) designed to drive a 4-Ω load (e.g., one 4-Ω speaker or two 8-Ω speakers in parallel). This device also comes with thermal shutdown circuitry and a heat sink. We'll take a closer look at audio amplifiers in Chap. 15.

8.7 Op Amp Specifications

Common-mode rejection ratio (CMRR). The input to a difference amplifier, in general, contains two components: a common-mode and a difference-mode signal. The common-mode signal voltage is the average of the two inputs, whereas the difference-mode signal is the difference between the two inputs. Ideally, an amplifier affects the difference-mode signals only. However, the common-mode signal is also amplified to some degree. The common-mode rejection ratio (CMRR), which is defined as the ratio of the difference signal voltage gain to the common-mode signal voltage gain provides an indication of how well an op amp does at rejecting a signal applied simultaneously to both inputs. The greater the value of the CMRR, the better is the performance of the op amp.

Differential-input voltage range. Range of voltage that may be applied between input terminals without forcing the op amp to operate outside its specifications. If the inputs go beyond this range, the gain of the op amp may change drastically.

Differential input impedance. Impedance measured between the noninverting and inverting input terminals.

Input offset voltage. In theory, the output voltage of an op amp should be zero when both inputs are zero. In reality, however, a slight circuit imbalance within the internal circuitry can result in an output voltage. The input offset voltage is the amount of voltage that must be applied to one of the inputs to zero the output.

Input bias current. Theoretically, an op amp should have an infinite input impedance and therefore no input current. In reality, however, small currents, typically within the nanoamp to picoamp range, may be drawn by the inputs. The average of the two input currents is referred to as the *input bias current.* This current can result in a voltage drop across resistors in the feedback network, the bias network, or source impedance, which in turn can lead to error in the output voltage. Input bias currents depend on the input circuitry of an op amp. With FET op amps, input bias currents are usually small enough not to cause serious offset voltages. Bipolar op amps, on the other hand, may cause problems. With bipolar op amps, a compensation resistor is often required to center the output. We will discuss how this is done in a minute.

Input offset current. This represents the difference in the input currents into the two input terminals when the output is zero. What does this mean? Well, the input terminals of a real op amp tend to draw in different amounts of leakage current, even when the same voltage is applied to them. This occurs because there is always a slight difference in resistance within the input circuitry for the two terminals that originates during the manufacturing process. Therefore, if an op amp's two terminals are both connected to the same input voltage, different amounts of input current will result, causing the output to be offset. Op amps typically come with offset terminals that can be wired to a potentiometer to correct the offset current. We will discuss how this is done in a minute.

Voltage gain (A_V). A typical op amp has a voltage gain of 10^4 to 10^6 (or 80 to 120 dB; gain in dB = 20 $\log_{10} A_0$[11]) at dc. However, the gain drops to 1 at a frequency called the *unity-gain frequency* f_T, typically from 1 to 10 MHz—a result of high-frequency limitations in the op amp's internal circuitry. We will talk more about high-frequency behavior in op amps in a minute.

Output voltage swing. This is the peak output voltage swing, referenced to zero, that can be obtained without clipping.

Slew rate. This represents the maximum rate of change of an op amp's output voltage with time. The limitation of output change with time results from internal or external frequency compensation capacitors slowing things down, which in turn results in delayed output changes with input changes (propagation delay). At high frequencies, the magnitude of an op amp's slew rate becomes more critical. A general-purpose op amp like the 741 has a 0.5 V/μs slew rate—a relatively small value when compared with the high-speed HA2539's slew rate of 600 V/μs.

Supply current. This represents the current that is required from the power supply to operate the op amp with no load present and with an output voltage of zero.

Table 8.1 is a sample op amp specifications table.

TABLE 8.1 Sample Op Amp Specifications

TYPE	TOTAL SUPPLY VOLTAGE MIN (V)	TOTAL SUPPLY VOLTAGE MAX (V)	SUPPLY CURRENT (mA)	OFFSET VOLTAGE TYPICAL (mV)	OFFSET VOLTAGE MAX (mV)	CURRENT BIAS MAX (nA)	CURRENT OFFSET MAX (nA)	SLEW RATE TYPICAL (V/μS)	f_T TYPICAL (MHz)	CMRR MIN (dB)	GAIN MIN (mA)	OUTPUT CURRENT MAX (mA)
Bipolar 741C	10	36	2.8	2	6	500	200	0.5	1.2	70	86	20
MOSFET CA3420A	2	22	1	2	5	0.005	0.004	0.5	0.5	60	86	2
JFET LF411	10	36	3.4	0.8	2	0.2	0.1	15	4	70	88	30
Bipolar, precision LM10	1	45	0.4	0.3	2	20	0.7	0.12	0.1	93	102	20

8.8 Powering Op Amps

Most op amp applications require a dual-polarity power supply. A simple split ±15-V supply that uses a tapped transformer is presented in Chap. 11. If you are using batteries to power an op amp, one of the following arrangements can be used.

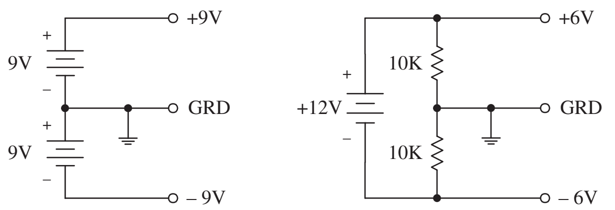


FIGURE 8.23

Now, it is often desirable to avoid split-supplies, especially with small battery-powered applications. One option in such a case is to use a single-supply op amp. However, as we pointed out a second ago, these devices will clip the output if the input attempts to go negative, making them unsuitable for ac-coupled applications. To avoid clipping while still using a single supply, it is possible to take a conventional op amp and apply a dc level to one of the inputs using a voltage-divider network. This, in turn, provides a dc offset level at the output. Both input and output offset levels are referenced to ground (the negative terminal of the battery). With the input offset voltage in place, when an input signal goes negative, the voltage applied to the input of the op amp will dip below the offset voltage but will not go below ground (provided you have set the bias voltage large enough, and provided the input signal is not too large; otherwise, clipping occurs). The output, in turn, will fluctuate about its offset level. To allow for input and output coupling, input and output capacitors are needed. The two circuits in Fig. 8.24 show noninverting and