

# Designing with Linear IC's

This month we inaugurate our new back-to-school series. This time around we'll be looking at linear IC's, and how you can use them in your own designs.

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INTEGRATED-CIRCUIT TECHNOLOGY HAS made the job of circuit design much simpler. That's because those devices have progressed to the point that very few external components are needed to form a fully functional circuit. Consider, for instance, an operational amplifier: when setting the gain of those devices, the design simply entails picking the *ratio* of two resistors.

That's not to say, however, that working with linear IC's does not present its own unique problems. The purpose of this article, and the ones that will follow, is to introduce you to the various types of linear IC's. In the coming months we'll be looking at how those devices work, and how to use them successfully in your circuit designs.

## IC construction

As you can see in Fig. 1-a, an IC is made up of layers of p-type and n-type semiconductor material. The bottom-most layer of the IC is called the substrate. The substrate is about 6 mils thick and its area can measure from  $50 \times 50$  to  $160 \times 160$ . In our example, the substrate is p-type material. In other IC's it could just as easily be n-type; it all depends on the design of the particular device.

The IC is fashioned by stacking alternating layers of p-type and n-type semiconductor material on the substrate as shown in Fig. 1-a. Each layer measures about 5- to 30-micrometers thick.

That brings us to one of the most basic design considerations that must be remembered when designing IC circuits. The p-type substrate and n-type next layer

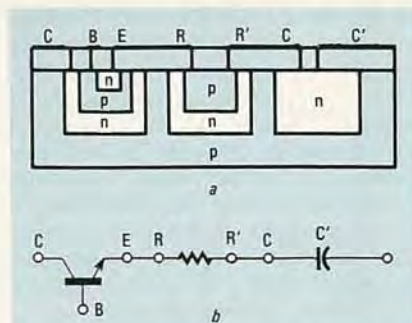


FIG. 1—ALL THE COMPONENTS in an IC are formed from layers of p-type and n-type semiconductor material. The circuit for the device shown in a is shown in b.

form a PN "diode" junction that must be reverse biased under normal conditions. The circuit designer must keep that constraint in mind. Although some clever designers are able to use forward bias for that junction, accidental reverse bias can destroy the device. In general, then, the substrate should be connected to either ground or to the case if it is made of metal.

Incidentally, the circuit formed by the IC is shown in Fig. 1-b.

## Differential amplifiers

The heart of most linear IC amplifiers is the transistor differential amplifier shown in Fig. 2. A differential amplifier is designed to produce an output signal that is proportional to the difference between two input signals.

Transistors Q1 and Q2 form a differential pair because their emitters are tied together and their emitter currents are determined by a common constant-current source. Since the current,  $I_3$ , from the constant-current source can not vary, it can neither increase nor decrease in response to changes in load. Since the sum of the transistor's emitter currents,  $I_1 + I_2$ , is equal to  $I_3$ , we may conclude that keeping the sum constant, because  $I_3$  is

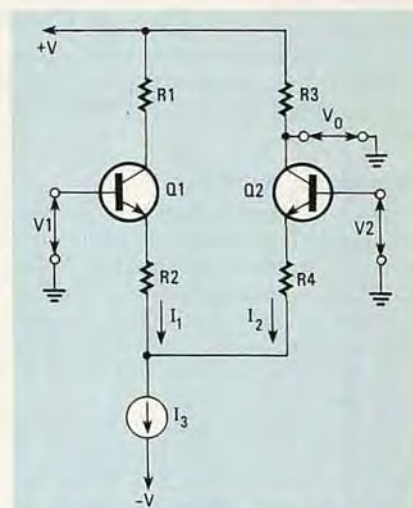


FIG. 2—THE DIFFERENTIAL AMPLIFIER, shown here, is the circuit on which the operational amplifier is based.

constant, requires one of the currents to decrease if the other increases. In other words: If  $I_1$  increases, then  $I_2$  will decrease, and if  $I_1$  decreases, then  $I_2$  will increase. Those relationships are critical to understanding the operation of the differential amplifier circuit.

For purposes of this discussion, we will assume that the collector and emitter currents of the transistors are identical. (In fact, however, those currents differ by the amount of the base current.) We will therefore assume further: that  $I_1$  and  $I_2$  are also the collector currents of Q1 and Q2 respectively.

The voltage appearing at the collector of Q2 is our output signal  $V_O$ . The base of Q2 is designated the inverting input (symbolized by a  $-$  sign), while the base of Q1 is the noninverting input (symbolized by a  $+$  sign). By definition, those two inputs produce equal but opposite effects on the output signal. That means the two inputs will produce out-of-phase outputs. The output signal produced by the noninverting input is in phase with the input signal; the output signal produced by the inverting input is out of phase with the input signal. A consequence of that action is that identical voltages applied to both inputs will cancel each other and produce zero output.

Let's first examine the operation of the inverting input—the base of Q2. When both  $V_1$  and  $V_2$  are zero, then  $V_O$  is at a quiescent value, or zero. If  $V_2$  is made positive, current  $I_2$  will increase (Q2 is

NPN). The voltage drop across R3 will also increase, so  $V_O$  will go down. In other words, a positive-going input signal produces a negative-going output; the input is an inverting input.

The noninverting input is the base of Q2. When V1 is made positive, current  $I_1$  will increase. Since the sum  $I_1 + I_2$  is constant, current  $I_2$  must therefore decrease. With  $I_2$  decreased, the voltage across R3 is less, so  $V_O$  increases. In that case, then, a positive-going input signal creates a positive-going output signal; thus the base of Q1 is truly a noninverting input.

### Operational amplifiers

By far the most popular IC linear amplifier is the operational amplifier, whose schematic symbol is shown in Fig. 3. The typical IC op-amp consists of a differential input amplifier followed by a high-gain amplifier chain. The output stage must be bipolar, meaning that it can go either positive or negative.

Let's examine the pinout of an op-amp for a moment. First, what is not present in the device shown in Fig. 3-a? The answer to that is that no ground or common terminal is used! There are two power-supply terminals ( $V+$  and  $V-$ ), but no ground. Rest with that mystery for a bit; we'll explain it shortly.

Finishing up with the pinout, the two inputs, inverting and noninverting, are the same as discussed previously. The output terminal is self-explanatory.

The ideal op-amp has the following properties: Infinite open-loop gain, infinite input impedance, zero output impedance, zero noise contribution, infinite bandwidth, and, finally, inputs that "stick together."

Open-loop gain means the gain with no feedback, and for the ideal op-amp it is infinite. The open-loop gain for real op-amps is not infinite, but it is very, very high (20,000 for inexpensive devices, over 1,000,000 for premium-grade ones).

Infinite input impedance implies that the ideal op-amp input will neither sink nor source current. Again, real op-amps differ from the ideal. The input impedance is not infinite, but is very, very high (1 megohm to over  $10^{12}$  ohms).

The output impedance of real op-amps is not zero, but is very low (usually under 100 ohms). That property makes it a nearly ideal voltage source to drive any following stages.

Zero noise contribution means the op-amp supplies no noise of its own to the output signal. That ideal is rarely met, however, and one must use premium-grade "low noise" devices if noise is a factor.

What about infinite bandwidth? Few op-amps have gain-bandwidth products over 2-3 MHz, and frequency-compensated types (e.g. 741) will provide sub-

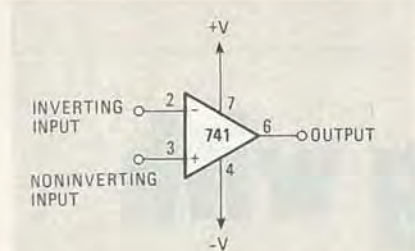


FIG. 3—SCHEMATIC SYMBOL for an op-amp. Note that there is provision for positive and negative supplies, but no ground terminal.

stantial gain only to 10 kHz.

What does "inputs that stick together" mean? It means we must treat both inputs the same. If we apply a voltage to one input, then we must treat the other as if the same voltage were applied to it also! And that is not just some theoretician's mumbo-jumbo. If you apply 2 volts to the inverting input, you will measure 2 volts on the noninverting one as well! That property will be very important when we analyze op-amp circuits in the months to come. In fact, you may have already been exposed to that concept, but under the confusing heading of "virtual ground." A virtual ground occurs when the noninverting input is grounded. In that case, we must treat the inverting input as if it were also grounded! Hence, the inverting input is said to be at "virtual" ground.

Designing circuits around the operational amplifier is made a lot easier by the fact that gain is set simply by the ratio of feedback and input resistors. We can tailor frequency response with simple R-C networks, or even just a capacitor in parallel with the feedback resistor.

The operational amplifier also simplifies the design of electronic integrators, differentiators, and logarithmic amplifiers. In fact, it was in those kinds of circuits that the op-amp was first used. The name "operational" amplifier came about because that type of amplifier could perform mathematical operations in analog computer circuits.

The power supply for operational amplifiers, and many other linear IC's, is shown in Fig. 4. Although batteries are shown here, electronic regulated power supplies may be substituted. The typical op-amp will operate at any potentials between  $\pm 4.5$  volts and  $\pm 18$  volts, with some operating at  $\pm 22$  volts.

There are actually two separate supplies used:  $+V$  and  $-V$ . The  $+V$  power supply is positive with respect to ground, while  $-V$  is negative with respect to ground. There is no ground terminal on the op-amp. The signal common is the ground terminal of the power supply. The inverting and non-inverting input signals, and the output signal, are referenced to the power-supply common!

Power-supply decoupling capacitors are not always needed, but it is a good idea

to include them. Generally those decoupling capacitors are placed close to the body of the op-amp, rather than at the power supply. For frequency-compensated devices such as the 741, you might be able to get away with no decoupling at all. But for all uncompensated types use 0.1- $\mu$ F capacitors to ground both the  $+V$  and  $-V$  inputs. It is also wise to use 1- $\mu$ F tantalum capacitors in parallel with the 0.1- $\mu$ F units in order to take care of low frequency decoupling.

Power-supply specifications for op-amps can be a little confusing. We have two basic problems: supply-rail limit and maximum allowable voltages.

The supply-rail limit refers to the minimum difference between the power-supply potential and the maximum output signal voltage. For common 741-type devices, that potential is about 3.5 volts. The maximum signal output potential, therefore, is 3.5 volts below the power-supply voltage.

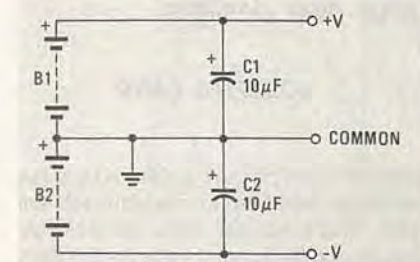


FIG. 4—POWER SOURCE for an op-amp. Note that regulated voltage sources could be used in place of the batteries.

How does that affect the designer? Suppose you are designing the input signal amplifier for a 10-volt A/D converter. You want the maximum signal amplitude to be 10-volts, obviously. The DC power-supply potential must be  $10 + 3.5$ , or 13.5-volts DC. If you had planned to use  $\pm 12$ -volt DC supplies, then your signal would clip on peaks! For 12-volt DC supplies, the maximum output signal would be  $12 - 3.5$ , or 8.5 volts!

Some op-amps have small supply-rail limits. The BiMOS devices, for example, can come within 0.5 volt of the supply rail. The usual way of guessing that limit (if it isn't published) is to count the number of PN junctions (base-emitter or base-collector) in the transistors between the output terminal and either power supply terminal, then multiply by 0.6 volt. The positive ( $+V$ ) and negative ( $-V$ ) supply-rail limits may be different on some op-amps.

The problem of maximum supply potential comes about only when trying to operate the device at maximum, and not thoroughly reading the spec sheet. The  $V_{MAX}$  ratings might be  $\pm 18$ -volts DC, leading one to believe that  $+V$  and  $-V$  may both be 18-volts DC. That's not always true! Look for the specified termi-

nal-to-terminal maximum voltage; that is, the maximum voltage that may safely be applied between  $+V$  and  $-V$  terminals of the op-amp.

Let's look at a "for instance!" The 741 device has maximums for  $-V$  and  $+V$  of  $\pm 18$ -volts DC, but a terminal-to-terminal maximum of only 30 volts. If we applied 18-volts DC to both  $+V$  and  $-V$ , the potential would be  $+V - -V = 18 - (-18) = 36$  volts. That potential exceeds the 30-volt limit. If we apply maximum potential to one terminal, then the other must be derated to stay within the specification. For example, in the case above let's assume  $+V$  is 18-volts DC. The maximum allowable for  $-V$  is  $30 - 18$ , or 12 volts DC. In that case, we would set  $+V = 18$  volts DC and  $-V = 12$  volts DC.

We also sometimes see a related problem that causes op-amp burn-out at strange times. If the supply voltages rise unevenly at turn-on, or decay unevenly at turn-off, it is possible that some op-amps will burn out. Such problems occur mostly when one supply has a lot more capacitance than the other, or when one supply is a lot more heavily loaded than the other.

A similar problem occurs if the input voltage is allowed to rise higher than a supply voltage. The result can be an incorrectly biased substrate and burn-out of the device. That problem usually occurs only when there is some energy-storage device, such as a large capacitor, at the input

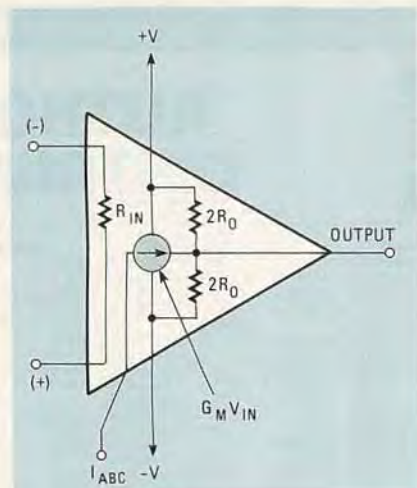


FIG. 5—AS THIS MODEL of the operational transconductance amplifier shows, the input of that device acts as a simple resistance while the output acts as a current source.

terminal. In that case, the input voltage may decay at a slow enough rate that some voltage remains at the inputs after power to the device has been removed.

### Current-difference amplifiers

The operational amplifier is only one form of linear IC. There are, of course, dozens of others. Many of them are special-function devices (e.g. cassette-tape recorder pre-amplifiers, etc), but at least two devices have quite a bit in common with the op-amp.

One of those devices is the current-difference amplifier (CDA); that device is also called the Norton amplifier. In essence, the CDA is a current-input/voltage-output device, so it can be called a trans-resistance amplifier.

The CDA is particularly useful in automotive applications, or other cases where a single monopolar power supply is used. Although the CDA never caught on like the op-amp, it is nonetheless very useful. We will examine the CDA in detail in a future article.

### The OTA

The other device that has a lot in common with an op-amp is the OTA (Operational Transconductance Amplifier). Figure 5 is a circuit model for that device. The input is modeled as a simple resistance much like an ordinary operational amplifier. The output, however, is modeled as a current source, where the magnitude of the current is equal to  $G_M V_{IN}$ ; the "gain," therefore is the transconductance ( $G_M$ ).

The transconductance operational amplifier will also be discussed in full in a future article.

In the next part of this series we will get down to brass tracks with the op-amp. Discussed will be the inverting-follower circuit configuration, how to set gain, and how to determine minimum input resistances. We will also introduce you to certain op-amp problems—and their solutions.