

INTRODUCTION

Feedback has become such a well-known concept that the word has entered the general vocabulary. In control systems, feedback consists in comparing the output of the system with the desired output and making a correction accordingly. The "system" can be almost anything: for instance, the process of driving a car down the road, in which the output (the position and velocity of the car) is sensed by the driver, who compares it with expectations and makes corrections to the input (steering wheel, throttle, brake). In amplifier circuits the output should be a multiple of the input, so in a feedback amplifier the input is compared with an attenuated version of the output.

4.01 Introduction to feedback

Negative feedback is the process of coupling the output back in such a way as to cancel some of the input. You might think that this would only have the effect of reducing the amplifier's gain and would

be a pretty stupid thing to do. Harold S. Black, who attempted to patent negative feedback in 1928, was greeted with the same response. In his words, "Our patent application was treated in the same manner as one for a perpetual-motion machine." (See the fascinating article in *IEEE Spectrum*, December 1977.) True, it does lower the gain, but in exchange it also improves other characteristics, most notably freedom from distortion and nonlinearity, flatness of response (or conformity to some desired frequency response), and predictability. In fact, as more negative feedback is used, the resultant amplifier characteristics become less dependent on the characteristics of the open-loop (no-feedback) amplifier and finally depend only on the properties of the feedback network itself. Operational amplifiers are typically used in this *high-loop-gain* limit, with *open-loop* voltage gain (no feedback) of a million or so.

A feedback network can be frequency-dependent, to produce an equalization amplifier (with specific gain-versus-frequency characteristics, an example being the famous RIAA phono amplifier

characteristic), or it can be amplitude-dependent, producing a nonlinear amplifier (a popular example is a logarithmic amplifier, built with feedback that exploits the logarithmic V_{BE} versus I_C of a diode or transistor). It can be arranged to produce a current source (near-infinite output impedance) or a voltage source (near-zero output impedance), and it can be connected to generate very high or very low input impedance. Speaking in general terms, the property that is sampled to produce feedback is the property that is improved. Thus, if you feed back a signal proportional to the output current, you will generate a good current source.

Feedback can also be *positive*; that's how you make an oscillator, for instance. As much fun as that may sound, it simply isn't as important as negative feedback. More often it's a nuisance, since a negative-feedback circuit may have large enough phase shifts at some high frequency to produce positive feedback and oscillations. It is surprisingly easy to have this happen, and the prevention of unwanted oscillations is the object of what is called *compensation*, a subject we will treat briefly at the end of the chapter.

Having made these general comments, we will now look at a few feedback examples with operational amplifiers.

4.02 Operational amplifiers

Most of our work with feedback will involve operational amplifiers, very high gain dc-coupled differential amplifiers with single-ended outputs. You can think of the classic long-tailed pair (Section 2.18) with its two inputs and single output as a prototype, although real op-amps have much higher gain (typically 10^5 to 10^6) and lower output impedance and allow the output to swing through most of the supply range (you usually use a split supply, most often $\pm 15V$). Operational amplifiers are now available in literally hundreds of

types, with the universal symbol shown in Figure 4.1, where the (+) and (-) inputs do as expected: The output goes positive when the noninverting input (+) goes more positive than the inverting input (-), and vice versa. The (+) and (-) symbols don't mean that you have to keep one positive with respect to the other, or anything like that; they just tell you the relative phase of the output (which is important to keep negative feedback negative). Using the words "noninverting" and "inverting," rather than "plus" and "minus," will help avoid confusion. Power-supply connections are frequently not displayed, and there is no ground terminal. Operational amplifiers have enormous voltage gain, and they are *never* (well, hardly ever) used without feedback. Think of an op-amp as fodder for feedback. The open-loop gain is so high that for any reasonable closed-loop gain, the characteristics depend only on the feedback network. Of course, at some level of scrutiny this generalization must fail. We will start with a naive view of op-amp behavior and fill in some of the finer points later, when we need to.

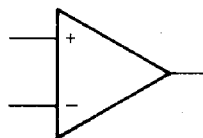


Figure 4.1

There are literally hundreds of different op-amps available, offering various performance trade-offs that we will explain later (look ahead to Table 4.1 if you want to be overwhelmed by what's available). A very good all-around performer is the popular LF411 ("411" for short), originally introduced by National Semiconductor. Like all op-amps, it is a wee beastie packaged in the so-called mini-DIP (dual in-line package), and it looks

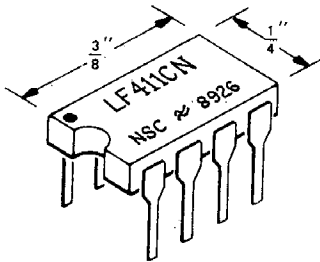


Figure 4.2. Mini-DIP integrated circuit.

as shown in Figure 4.2. It is inexpensive (about 60 cents) and easy to use; it comes in an improved grade (LF411A) and also in a mini-DIP containing two independent op-amps (LF412, called a “dual” op-amp). We will adopt the LF411 throughout this chapter as our “standard” op-amp, and we recommend it as a good starting point for your circuit designs.

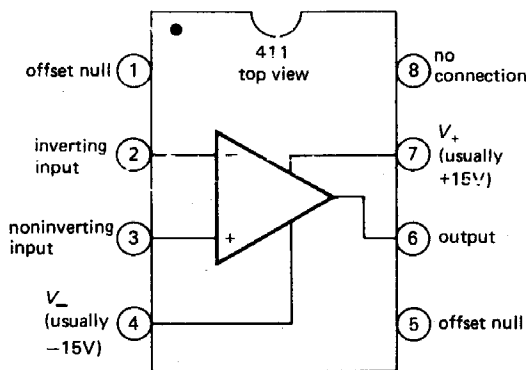


Figure 4.3

Inside the 411 is a piece of silicon containing 24 transistors (21 BJTs, 3 FETs), 11 resistors, and 1 capacitor. The pin connections are shown in Figure 4.3. The dot in the corner, or notch at the end of the package, identifies the end from which to begin counting the pin numbers. As with most electronic packages, you count pins counterclockwise, viewing from the top. The “offset null” terminals (also known as “balance” or “trim”) have to do with correcting (externally) the small asymmetries

that are unavoidable when making the op-amp. You will learn about this later in the chapter.

4.03 The golden rules

Here are the simple rules for working out op-amp behavior with external feedback. They’re good enough for almost everything you’ll ever do.

First, the op-amp voltage gain is so high that a fraction of a millivolt between the input terminals will swing the output over its full range, so we ignore that small voltage and state golden rule I:

I. The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.

Second, op-amps draw very little input current (0.2nA for the LF411; picoamps for FET-input types); we round this off, stating golden rule II:

II. The inputs draw no current.

One important note of explanation: Golden rule I doesn’t mean that the op-amp actually changes the voltage at its *inputs*. It can’t do that. (How could it, and be consistent with golden rule II?) What it does is “look” at its input terminals and swing its output terminal around so that the external feedback network brings the input differential to zero (if possible).

These two rules get you quite far. We will illustrate with some basic and important op-amp circuits, and these will prompt a few cautions listed in Section 4.08.

BASIC OP-AMP CIRCUITS

4.04 Inverting amplifier

Let’s begin with the circuit shown in Figure 4.4. The analysis is simple, if you remember your golden rules:

I. Point *B* is at ground, so rule I implies that point *A* is also.

2. This means that (a) the voltage across R_2 is V_{out} and (b) the voltage across R_1 is V_{in} .

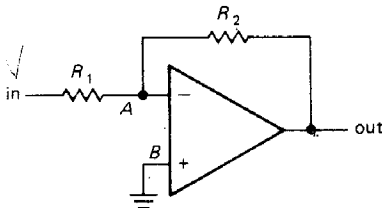


Figure 4.4. Inverting amplifier.

3. So, using rule II, we have

$$V_{out}/R_2 = -V_{in}/R_1$$

In other words,

$$\text{voltage gain} = V_{out}/V_{in} = -R_2/R_1$$

Later you will see that it's often better not to ground B directly, but through a resistor. However, don't worry about that now.

Our analysis seems almost too easy! In some ways it obscures what is actually happening. To understand how feedback works, just imagine some input level, say +1 volt. For concreteness, imagine that R_1 is 10k and R_2 is 100k. Now, suppose the output decides to be uncooperative, and sits at zero volts. What happens? R_1 and R_2 form a voltage divider, holding the inverting input at +0.91 volt. The op-amp sees an enormous input unbalance, forcing the output to go negative. This action continues until the output is at the required -10.0 volts, at which point both op-amp inputs are at the same voltage, namely ground. Similarly, any tendency for the output to go more negative than -10.0 volts will pull the inverting input below ground, forcing the output voltage to rise.

What is the input impedance? Simple. Point A is always at zero volts (it's called a *virtual ground*). So $Z_{in} = R_1$. At this point you don't yet know how to figure the

output impedance; for this circuit, it's a fraction of an ohm.

Note that this analysis is true even for dc - it's a dc amplifier. So if you have a signal source offset from ground (collector of a previous stage, for instance), you may want to use a coupling capacitor (sometimes called a blocking capacitor, since it blocks dc but couples the signal). For reasons you will see later (having to do with departures of op-amp behavior from the ideal), it is usually a good idea to use a blocking capacitor if you're only interested in ac signals anyway.

This circuit is known as an *inverting amplifier*. Its one undesirable feature is the low input impedance, particularly for amplifiers with large (closed-loop) voltage gain, where R_1 tends to be rather small. That is remedied in the next circuit (Fig. 4.5).

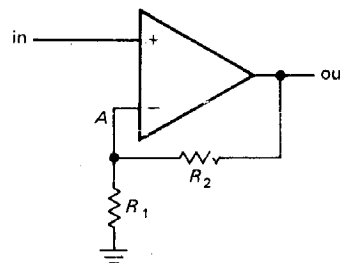


Figure 4.5. Noninverting amplifier.

4.05 Noninverting amplifier

Consider Figure 4.5. Again, the analysis is simplicity itself:

$$V_A = V_{in}$$

But V_A comes from a voltage divider:

$$V_A = V_{out}R_1/(R_1 + R_2)$$

Set $V_A = V_{in}$, and you get

$$\text{gain} = V_{out}/V_{in} = 1 + R_2/R_1$$

This is a *noninverting amplifier*. In the approximation we are using, the input impedance is infinite (with the 411 it would be $10^{12}\Omega$ or more; a bipolar op-amp

will typically exceed $10^8\Omega$). The output impedance is still a fraction of an ohm. As with the inverting amplifier, a detailed look at the voltages at the inputs will persuade you that it works as advertised.

Once again we have a dc amplifier. If the signal source is ac-coupled, you must provide a return to ground for the (very small) input current, as in Figure 4.6. The component values shown give a voltage gain of 10 and a low-frequency 3dB point of 16Hz.

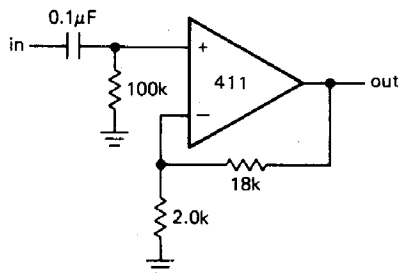


Figure 4.6

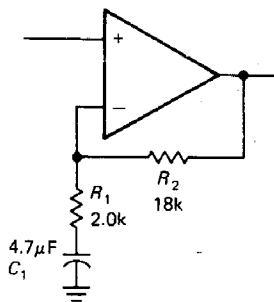


Figure 4.7

An ac amplifier

Again, if only ac signals are being amplified, it is often a good idea to “roll off” the gain to unity at dc, especially if the amplifier has large voltage gain, in order to reduce the effects of finite “input offset voltage.” The circuit in Figure 4.7 has a low-frequency 3dB point of 17Hz, the frequency at which the impedance of the

capacitor equals 2.0k. Note the large capacitor value required. For noninverting amplifiers with high gain, the capacitor in this ac amplifier configuration may be undesirably large. In that case it may be preferable to omit the capacitor and trim the offset voltage to zero, as we will discuss later (Section 4.12). An alternative is to raise R_1 and R_2 , perhaps using a T network for the latter (Section 4.18).

In spite of its desirable high input impedance, the noninverting amplifier configuration is not necessarily to be preferred over the inverting amplifier configuration in all circumstances. As we will see later, the inverting amplifier puts less demand on the op-amp and therefore gives somewhat better performance. In addition, its virtual ground provides a handy way to combine several signals without interaction. Finally, if the circuit in question is driven from the (stiff) output of another op-amp, it makes no difference whether the input impedance is 10k (say) or infinity, because the previous stage has no trouble driving it in either case.

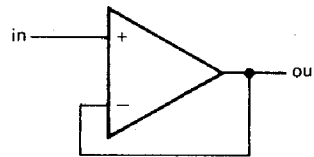


Figure 4.8. Follower.

4.06 Follower

Figure 4.8 shows the op-amp version of an emitter follower. It is simply a noninverting amplifier with R_1 infinite and R_2 zero (gain = 1). There are special op-amps, usable only as followers, with improved characteristics (mainly higher speed), e.g., the LM310 and the OPA633, or with simplified connections, e.g., the TL068 (which comes in a 3-pin transistor package).

An amplifier of unity gain is sometimes called a *buffer* because of its isolating

properties (high input impedance, low output impedance).

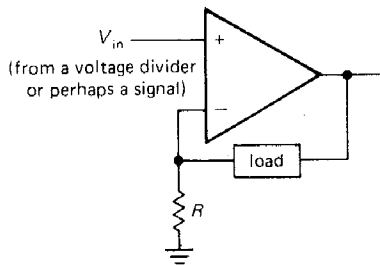


Figure 4.9

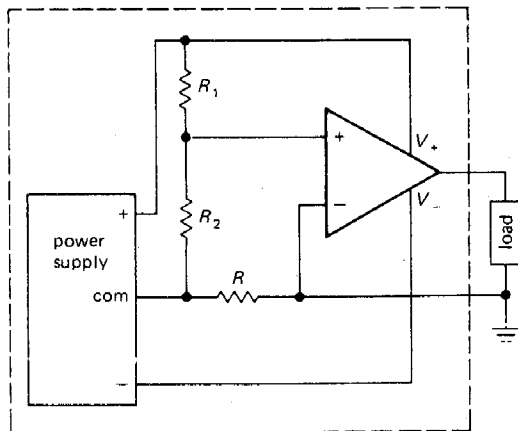


Figure 4.10. Current source with grounded load and floating power supply.

4.07 Current sources

The circuit in Figure 4.9 approximates an ideal current source, without the V_{BE} offset of a transistor current source. Negative feedback results in V_{in} at the inverting input, producing a current $I = V_{in}/R$ through the load. The major disadvantage of this circuit is the “floating” load (neither side grounded). You couldn’t generate a usable sawtooth wave with respect to ground with this current source, for instance. One solution is to float the whole circuit (power supplies and all) so that you can ground one side of the load (Fig. 4.10).

The circuit in the box is the previous current source, with its power supplies shown explicitly. R_1 and R_2 form a voltage divider to set the current. If this circuit seems confusing, it may help to remind yourself that “ground” is a relative concept. Any one point in a circuit could be called ground. This circuit is useful for generating currents into a load that is returned to ground, but it has the disadvantage that the control input is now floating, so you cannot program the output current with an input voltage referenced to ground. Some solutions to this problem are presented in Chapter 6 in the discussion of constant-current power supplies.

Current sources for loads returned to ground

With an op-amp and external transistor it is possible to make a simple high-quality current source for a load returned to ground; a little additional circuitry makes it possible to use a programming input referenced to ground (Fig. 4.11). In the first circuit, feedback forces a voltage $V_{CC} - V_{in}$ across R , giving an emitter current (and therefore an output current) $I_E = (V_{CC} - V_{in})/R$. There are no V_{BE} offsets, or their variations with temperature, I_C , V_{CE} , etc., to worry about. The current source is imperfect (ignoring op-amp errors: I_b , V_{os}) only insofar as the small base current may vary somewhat with V_{CE} (assuming the op-amp draws no input current), not too high a price to pay for the convenience of a grounded load; a Darlington for Q_1 would reduce this error considerably. This error comes about, of course, because the op-amp stabilizes the emitter current, whereas the load sees the collector current. A variation of this circuit, using a FET instead of a bipolar transistor, avoids this problem altogether, since FETs draw no gate current.

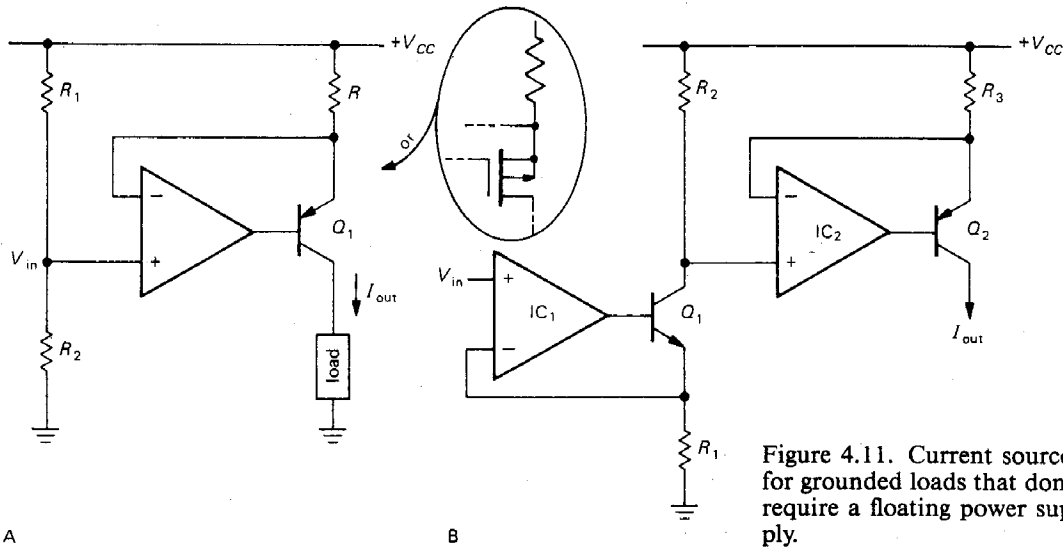


Figure 4.11. Current sources for grounded loads that don't require a floating power supply.

With this circuit the output current is proportional to the voltage drop below V_{CC} applied to the op-amp's noninverting input; in other words, the programming voltage is referenced to V_{CC} , which is fine if V_{in} is a fixed voltage generated by a voltage divider, but an awkward situation if an external input is to be used. This is remedied in the second circuit, in which a similar current source with *npn* transistor is used to convert an input voltage (referenced to ground) to a V_{CC} -referenced input to the final current source. Op-amps and transistors are inexpensive. Don't hesitate to use a few extra components to improve performance or convenience in circuit design.

One important note about the last circuit: The op-amp must be able to operate with its inputs near or at the positive supply voltage. An op-amp like the 307, 355, or OP-41 is good here. Alternatively, the op-amp could be powered from a separate V_+ voltage higher than V_{CC} .

EXERCISE 4.1

What is the output current in the last circuit for a given input voltage V_{in} ?

Figure 4.12 shows an interesting variation on the op-amp/transistor current

source. It has the advantage of zero base current error, which you get with FETs, without being restricted to output currents less than $I_{DS(ON)}$. In this circuit (actually a current sink), Q_2 begins to

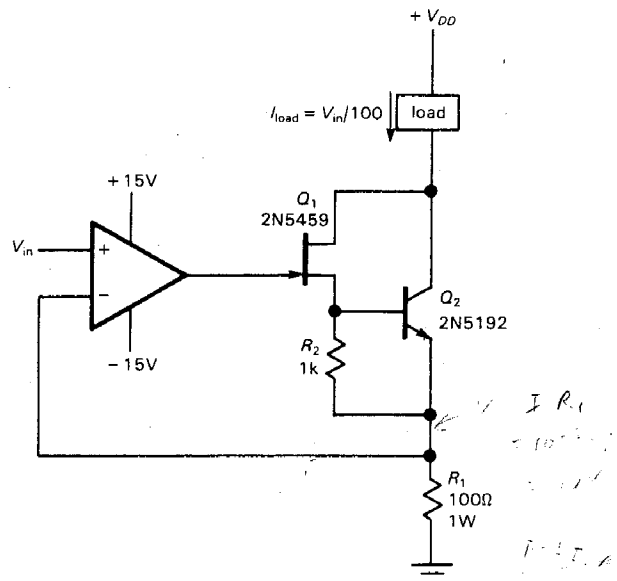


Figure 4.12. FET/bipolar current source suitable for high currents.

conduct when Q_1 is drawing about 0.6mA drain current. With Q_1 's minimum I_{DSS}

of 4mA and a reasonable value for Q_2 's beta, load currents of 100mA or more can be generated (Q_2 can be replaced by a Darlington for much higher currents, and in that case R_1 should be reduced accordingly). We've used a JFET in this particular circuit, although a MOSFET would be fine; in fact, it would be better, since with a JFET (which is a depletion-mode device) the op-amp must be run from split supplies to ensure a gate voltage range sufficient for pinch-off. It's worth noting that you can get plenty of current with a simple power MOSFET ("VMOS"); but the high interelectrode capacitances of power FETs may cause problems that you avoid with the hybrid circuit here.

Howland current source

Figure 4.13 shows a nice "textbook" current source. If the resistors are chosen so that $R_3/R_2 = R_4/R_1$, then it can be shown that $I_{load} = -V_{in}/R_2$.

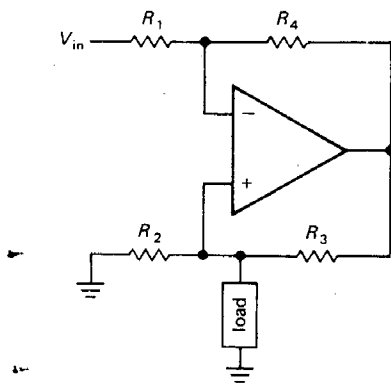


Figure 4.13. Howland current source.

EXERCISE 4.2

Show that the preceding result is correct.

This sounds great, but there's a hitch: The resistors must be matched exactly; otherwise it isn't a perfect current source.

Even so, its performance is limited by the CMRR of the op-amp. For large output currents, the resistors must be small, and the compliance is limited. Also, at high frequencies (where the loop gain is low, as we'll learn shortly) the output impedance can drop from the desired value of infinity to as little as a few hundred ohms (the op-amp's open-loop output impedance). As clever as it looks, the Howland current source is not widely used.

4.08 Basic cautions for op-amp circuits

1. In all op-amp circuits, golden rules I and II (Section 4.03) will be obeyed only if the op-amp is in the active region, i.e., inputs and outputs not saturated at one of the supply voltages.

For instance, overdriving one of the amplifier configurations will cause output clipping at output swings near V_{CC} or V_{EE} . During clipping, the inputs will no longer be maintained at the same voltage. The op-amp output cannot swing beyond the supply voltages (typically it can swing only to within 2V of the supplies, though certain op-amps are designed to swing all the way to one supply or the other). Likewise, the output compliance of an op-amp current source is set by the same limitation. The current source with floating load, for instance, can put a maximum of $V_{CC} - V_{in}$ across the load in the "normal" direction (current in the same direction as applied voltage) and $V_{in} - V_{EE}$ in the reverse direction (the load could be rather strange, e.g., it might contain batteries, requiring the reverse sense of voltage to get a forward current; the same thing might happen with an inductive load driven by changing currents).

2. The feedback must be arranged so that it is negative. This means (among other things) that you must not mix up the inverting and noninverting inputs.

3. There must always be feedback at dc in an op-amp circuit. Otherwise the op-amp is guaranteed to go into saturation.

For instance, we were able to put a capacitor from the feedback network to ground in the noninverting amplifier (to reduce gain at dc to 1, Fig. 4.7), but we could not similarly put a capacitor in series between the output and the inverting input.

4. Many op-amps have a relatively small maximum differential input voltage limit. The maximum voltage difference between the inverting and noninverting inputs might be limited to as little as 5 volts in either polarity. Breaking this rule will cause large input currents to flow, with degradation or destruction of the op-amp.

We will take up some more issues of this type in Section 4.11 and again in Section 7.06 in connection with precision circuit design.

AN OP-AMP SMORGASBORD

In the following examples we will skip the detailed analysis, leaving that fun for you, the reader.

4.09 Linear circuits

Optional inverter

The circuits in Figure 4.14 let you invert, or amplify without inversion, by flipping a switch. The voltage gain is either +1 or -1, depending on the switch position.

EXERCISE 4.3

Show that the circuits in Figure 4.14 work as advertised.

Follower with bootstrap

As with transistor amplifiers, the bias path can compromise the high input impedance you would otherwise get with an op-amp,

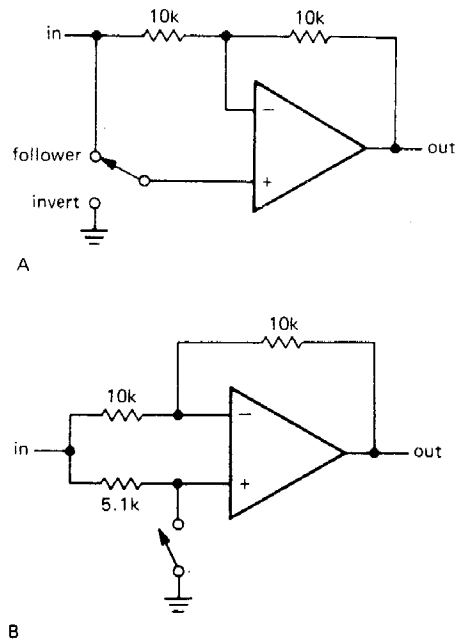


Figure 4.14

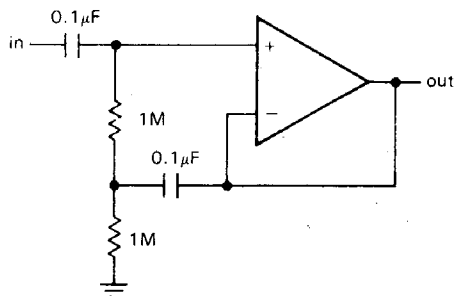


Figure 4.15

particularly with ac-coupled inputs, where a resistor to ground is mandatory. If that is a problem, the bootstrap circuit shown in Figure 4.15 is a possible solution. As in the transistor bootstrap circuit (Section 2.17), the $0.1\mu\text{F}$ capacitor makes the upper 1M resistor look like a high-impedance current source to input signals. The low-frequency rolloff for this circuit will begin at about 10Hz , dropping at 12dB per octave for frequencies somewhat below this. Note: You might be tempted to

reduce the input coupling capacitor, since its load has been bootstrapped to high impedance. However, this can generate a peak in the frequency response, in the manner of an active filter (see Section 5.06).

Ideal current-to-voltage converter

Remember that the humble resistor is the simplest *I*-to-*V* converter. However, it has the disadvantage of presenting a nonzero impedance to the source of input current; this can be fatal if the device providing the input current has very little compliance or does not produce a constant current as the output voltage changes. A good example is a *photovoltaic cell*, a fancy name for a sun battery. Even the garden-variety signal diodes you use in circuits have a small photovoltaic effect (there are amusing stories of bizarre circuit behavior finally traced to this effect). Figure 4.16 shows the good way to convert current

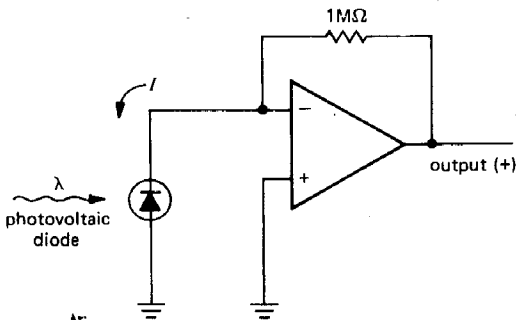


Figure 4.16

to voltage while holding the input strictly at ground. The inverting input is a virtual ground; this is fortunate, since a photovoltaic diode can generate only a few tenths of a volt. This particular circuit has an output of 1 volt per microamp of input current. (With BJT-input op-amps you sometimes see a resistor connected between the noninverting input and ground;

its function will be explained shortly in connection with op-amp shortcomings.)

Of course, this *transresistance* configuration can be used equally well for devices that source their current via some positive excitation voltage, such as V_{CC} . Photomultiplier tubes and phototransistors (both devices that source current from a positive supply when exposed to light) are often used this way (Fig. 4.17).

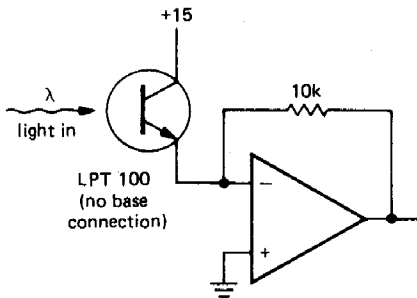


Figure 4.17

EXERCISE 4.4

Use a 411 and a 1mA (full scale) meter to construct a “perfect” current meter (i.e., one with zero input impedance) with 5mA full scale. Design the circuit so that the meter will never be driven more than $\pm 150\%$ full scale. Assume that the 411 output can swing to ± 13 volts (± 15 V supplies) and that the meter has 500 ohms internal resistance.

Differential amplifier

The circuit in Figure 4.18 is a differential amplifier with gain R_2/R_1 . As with the current source that used matched resistor ratios, this circuit requires precise resistor matching to achieve high common-mode rejection ratios. The best procedure is to stock up on a bunch of 100k 0.01% resistors next time you have a chance. All your differential amplifiers will have unity gain, but that’s easily remedied with further (single-ended) stages of gain. We will treat differential amplifiers in more detail in Chapter 7.

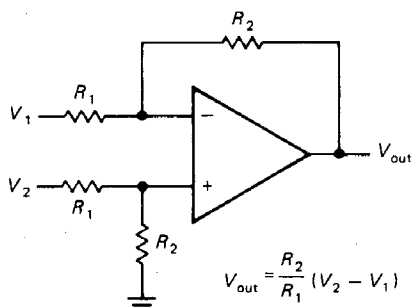


Figure 4.18. Classic differential amplifier.

Summing amplifier

The circuit shown in Figure 4.19 is just a variation of the inverting amplifier. Point *X* is a virtual ground, so the input current is $V_1/R + V_2/R + V_3/R$. That gives $V_{out} = -(V_1 + V_2 + V_3)$. Note that the inputs can be positive or negative. Also, the input resistors need not be equal; if they're unequal, you get a weighted sum. For instance, you could have four inputs, each of which is +1 volt or zero, representing binary values 1, 2, 4, and 8. By using input resistors of 10k, 5k, 2.5k, and 1.25k you will get an output in volts equal to the binary count input. This scheme can be easily expanded to several digits. It is the basis of digital-to-analog conversion, although a different input circuit (an $R - 2R$ ladder) is usually used.

EXERCISE 4.5

Show how to make a two-digit digital-to-analog converter by appropriately scaling the input resistors in a summing amplifier. The digital input represents two digits, each consisting of four lines that represent the values 1, 2, 4, and 8 for the respective digits. An input line is either at +1 volt or at ground, i.e., the eight input lines represent 1, 2, 4, 8, 10, 20, 40, and 80. Because op-amp outputs generally cannot swing beyond ± 13 volts, you will have to settle for an output in volts equal to one-tenth the value of the input number.

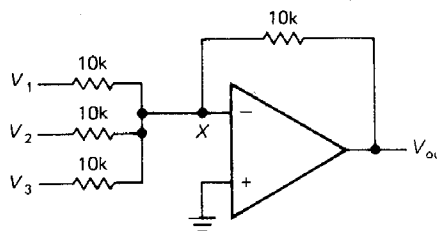


Figure 4.19

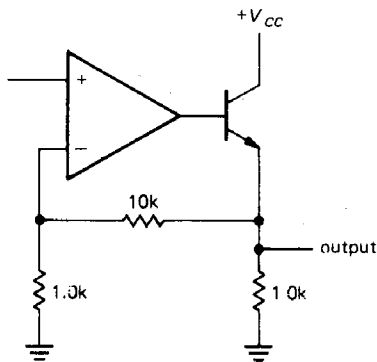


Figure 4.21

Power booster

For high output current, a power transistor follower can be hung on an op-amp output (Fig. 4.21). In this case a noninverting amplifier has been drawn; the follower can be added to any op-amp configuration. Notice that feedback is taken from the emitter; thus, feedback enforces the desired output voltage in spite of the V_{BE} drop. This circuit has the usual problem that the follower output can only source current. As with transistor circuits, the remedy is a push-pull booster (Fig. 4.22). You will see later that the limited speed with which the op-amp can move its output (slew rate) seriously limits the speed

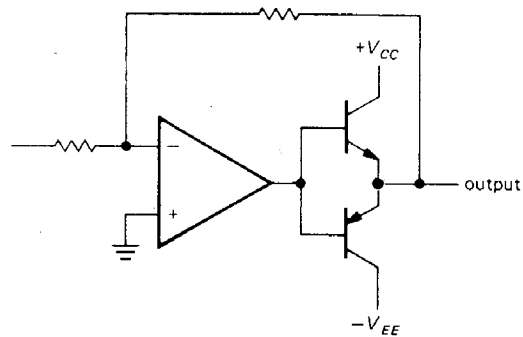


Figure 4.22

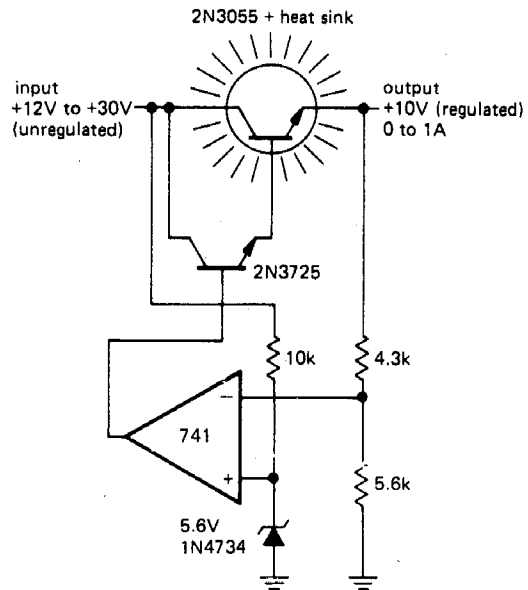


Figure 4.23

of this booster in the crossover region, creating distortion. For slow-speed applications you don't need to bias the push-pull pair into quiescent conduction, because feedback will take care of most of the crossover distortion. Commercial op-amp power boosters are available, e.g., the LT1010, OPA633, and 3553. These are unity-gain push-pull amplifiers capable of 200mA of output current and operation to 100MHz and above. You can include them inside the feedback loop without any worries (See Table 7.4).

Power supply

An op-amp can provide the gain for a feedback voltage regulator (Fig. 4.23). The op-amp compares a sample of the output with the zener reference, changing the drive to the Darlington "pass transistor" as needed. This circuit supplies 10 volts regulated, at up to 1 amp load current. Some notes about this circuit:

1. The voltage divider that samples the output could be a potentiometer, for adjustable output voltage.
2. For reduced ripple at the zener, the 10k resistor should be replaced by a current source. Another approach is to bias the zener from the output; that way you take advantage of the regulator you have built. Caution: When using this trick, you must analyze the circuit carefully to be sure it will start up when power is first applied.
3. The circuit as drawn could be damaged by a temporary short circuit across the output, because the op-amp would attempt to drive the Darlington pair into heavy conduction. Regulated power supplies should always have circuitry to limit "fault" current (see Section 6.05 for more details).
4. Integrated circuit voltage regulators are available in tremendous variety, from the time-honored 723 to the convenient 3-terminal adjustable regulators with internal current limit and thermal shutdown (see Tables 6.8–6.10). These devices, complete with temperature-compensated

internal zener reference and pass transistor, are so easy to use that you will almost never use a general-purpose op-amp as a regulator. The exception might be to generate a stable voltage within a circuit that already has a stable power-supply voltage available.

In Chapter 6 we will discuss voltage regulators and power supplies in detail, including special ICs intended for use as voltage regulators.

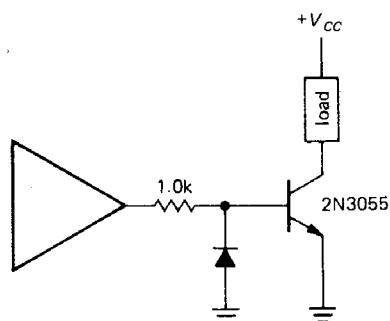


Figure 4.24