Chapter 19
Operational Amplifiers

The operational amplifier, or op-amp, is a basic building block of modern electronics. Op-amps date back to the early days of vacuum tubes, but they only became common with the invention of the integrated circuit.

Probably the most common op-amp — perhaps the most common integrated circuit ever — is the 741 op-amp. There are many other types of IC op-amps, but the 741 is still the classic device.

The 741 circuit in Fig. 19-1 consists of some 20 transistors, eleven resistors, and one capacitor, all combined together into one tiny integrated circuit that costs just a few pennies. There are a few things worth pointing out about that circuit (and we will do so shortly), but fortunately most of the time we don't need to look at the circuit at all. We usually just think of it as an 8-pin integrated circuit, some of whose pins aren't even always used, and we draw it as a triangular block as shown in Fig. 19-2. The triangle is a generic symbol used to denote an amplifier, and the small numbers (such as 2, 3, and 6) denote the pin numbers for the integrated circuit; these pin numbers also appear in Fig. 19-1. Not all IC op-amps use these same pin numbers, but this is a fairly common pattern.

Notice that Fig. 19-1 shows two pins labelled Null, pins 1 and 5. These are usually called *Null Offset*, but they are seldom used. They don't generally appear in block diagrams such as Fig. 19-2 unless you specifically need to connect to them.

Let's look at these op-amps from several different viewpoints.

Power Connections

Fig. 19-1 and Fig. 19-2 both show a pair of pins called V+ (pin 7) and V– (pin 4). These power pins are often not shown in more advanced circuit diagrams, since engineers simply assume that op-amps need power supplies or batteries, and that you know enough to connect them without being shown how. Notice also that there is no pin explicitly labelled "ground".

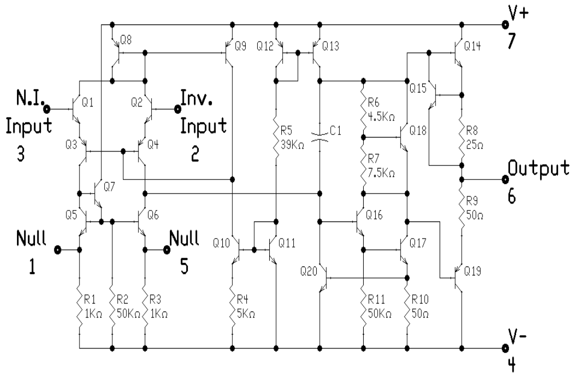

Fig. 19-1. Schematic diagram of the 741 op-amp

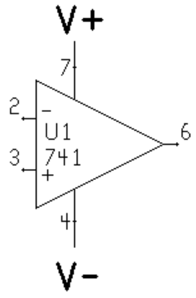

Fig. 19-2. 741 op-amp block

Most IC op-amps require a total power supply voltage somewhere between about 10 and about 40 volts, applied between the V+ and V– pins. Fig. 19-3 shows several ways to do that.

The most common way is to apply a positive voltage, such as perhaps +10 volts, to pin 7, and an equal, but negative –10 volts to pin 4, as in the top left diagram. The total voltage between the two pins is therefore 20 volts, which is fine for most op-amps. The op-amp doesn't care what the actual voltages are, as long as the difference between the two pins is in the right range.

But there are many other ways to achieve this. For example, the bottom left shows pin 7 at +20 volts, while pin 4 is grounded. The top right shows the opposite — pin 7 is grounded, while pin 4 is at –20 volts. The bottom right even shows a rather far out, but still OK, solution: +350 volts on pin 7, and +330 volts on pin 4. Each of these circuits places 20 volts between the two pins, so the IC is happy.

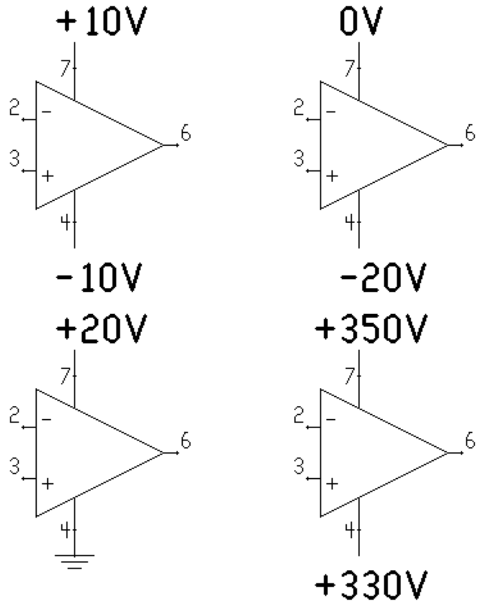

Fig. 19-3. Various 741 op-amp power connections

In Fig. 19-1, you can see that the V+ line is a long line along the top of the diagram, while the V– line is a long line at the bottom. These two lines (and the voltages that go with them) are usually called the *positive rail* and *negative rail*, respectively.

These two rails limit the other voltages we are allowed to use. To prevent damage to the op-amp, we must watch how we connect the input and output pins.

Input pins

Op-amps have two signal input pins. In the 741 circuit, these are pins 2 and 3.

- Pin 2 is called the *Inv*. or *inverting* input in Fig. 19-1, but is labelled with a minus sign in Figs. 19-2 and 19-3. Both of these names are used. What they mean is that any input to this pin will be amplified, but will come out inverted at the output. A positive-going signal at the inverting input will come out negative going at the output, pin 6.
- Pin 3 is called *N.I.* in Fig. 19-1, which stands for *Not Inverted*. It is labelled + in the remaining figures. A signal coming in here is *not* inverted at the output.

The *Null* pins in Fig. 19-1 (they are actually called *null offset*) are also inputs of sorts, but only used for special purposes. We will only briefly mention them below.

In general, the voltage on the input must be somewhere between the positive and negative rail voltages. For example, if the positive rail is at +350 volts and the negative rail is at +330 volts (this is a *very* unusual connection, but possible), the input pins should not go below +330 volts or above +350 volts. Some op-amps do allow the inputs to go slightly above or below the rails, but not by much.

In many cases, the input voltage will be midway between the two rails. For example, if the two rails are +350 and +330 volts, the inputs would often be held at +340 volts.

If the rail voltages are equal and opposite (for example, if they are +15 volts and –15 volts) then the midpoint voltage is 0 volts or ground. It is then very easy to keep the inputs near the midpoint.

Even though the rail voltages are often not shown, you can usually get a rough idea of what they are by looking at the input connections. For example, at the left of Fig. 19-4 we see a resistor connecting an input lead to ground. If ground is the midpoint, then clearly the two rails must be plus and minus, and are probably the same voltages. On the other hand, the right circuit in Fig. 19-4 shows a resistor going from an input to some point labelled +V/2. If +V/2 is the midpoint, then most likely the positive rail is at some voltage +V, and the negative rail is at 0 volts or ground.

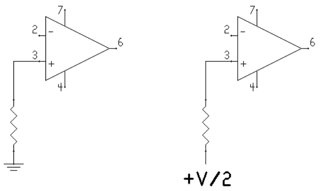

Fig. 19-4. Op-amp inputs

Looking back at Fig. 19-1, we see that the circuitry at both inputs is identical. They both go directly into the base of transistors Q_1 and Q_2. These transistors are both connected as emitter followers (or common cathode amplifiers), and they feed another pair of identical transistors, Q_3 and Q_4. This tells us two things:

1. Since emitter followers have a high input resistance, the op-amp inputs have a high input resistance also. They draw very little current from whatever feeds them. So little, in fact, that for some calculations we can assume that the input current is zero. (Some op-amps are made with FET input transistor, in which case their input current really *is* zero.)

2. Even if the input current is not quite zero, at least the two inputs are symmetrical; that is, they use the same internal circuitry. So their input currents should at least be very close to each other, if not really zero.

2. The voltage on the output must also be somewhere between the positive and negative rails, but it is slightly more limited. In most circuits, the output is close to the midpoint voltage, and it often can't even get closer than a volt or two to either rail. For example, the output pin of a 741 op-amp connected between ground (0 volts) and +20 volts will generally be between +2 and +18 volts, and will probably be close to +10 volts a lot of the time.

Output pin

The output from the 741 op-amp is on pin 6. Fig. 19-1 shows that the output comes through a pair of fairly small resistors from two transistors, Q_{14} and Q_{19}.

Q_{14} can pull the output voltage up toward the positive rail (but not past it), while Q_{19} can pull it down to the negative rail (but not past it). In other words, the output voltage cannot go more positive than the positive rail, or more negative than the negative rail. In fact, most op-amps can't even get all the way *to* the rails. For example, the 741 output can only get within about 2 volts of the rails. If, for instance, the power voltages are ±10 volts, the output can only go up to about +8 or down to –8 volts.

The op-amp output circuit resembles what audio or communications people call a *push-pull* circuit; digital people would call it a *totem-pole* circuit. This means that the output transistors can do a fairly decent job forcing the output voltage up or down. That is, the output can provide some reasonable currents to a load. Some circuits add an external pair of transistors to provide even more output current.

Just as the purpose of biasing in transistor amplifiers is to make the output voltage equal to about half of V_{CC}, so op-amps are usually biased to make their output voltage half-way between the rails. As before, using a pair of equal power voltages, one positive and the other negative, makes the output sit near 0 volts or ground.

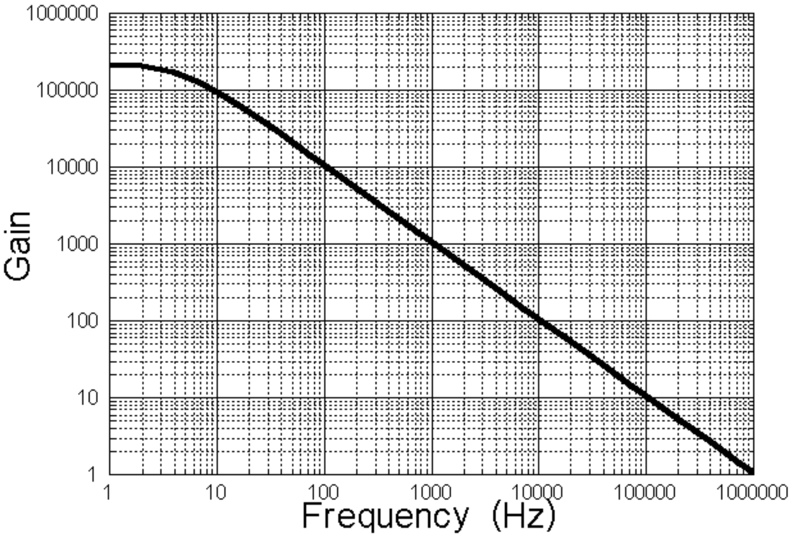

Fig. 19-5. 741 Op-amp frequency response

Op-amp gain

As usual, we define the gain as

$$V_{out} = \text{Gain} \times V_{in}$$

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

but V_{in} and V_{out} are defined slightly differently from the plain transistor amplifier circuit.

V_{in} is defined as

$$V_{in} = V_{N.I.} - V_{Inv}$$

where $V_{N.I.}$ is the voltage on the non-inverting input, and V_{Inv} is the voltage on the inverting input. In other words, the input voltage is the difference between the two input pins. If the voltages on the two input pins are the same — even if they are fairly large — the op-amp sees no input. Only the difference between the two pins is recognized.

V_{out} is defined as

$$V_{out} = V_{\text{of output pin}} - \frac{V_+ + V_-}{2}$$

This is actually simpler than it looks. The last term on the right, $(V_+ + V_-)/2$, is just the average of the positive and negative rail voltages, so V_{out} is the difference between the actual voltage on the output pin (pin 6 in the 741) and the midpoint between the two rails. Thus the equation

$$V_{out} = \text{Gain} \times V_{in}$$

says that if V_{in} is zero (meaning that the two input pins have the same voltage and their difference is therefore zero), the output should be midway between the two rails (i.e., the difference between the actual output voltage and the midpoint is also zero.)

(This is what the theory says. In practice, though, there is always a little unbalance in the circuit — called input offset — which causes the output voltage to be different. If that's a problem, then the two Null offset pins can be used to adjust the output to be midway.)

Looking at Fig. 19-1 again, we see that there are quite a few transistors between the input and the output. Although the gain of a single stage might be fairly small, gains of cascaded stages multiply, so the gain of an op-amp is much higher.

Fig. 19-5 shows the gain vs. frequency of a typical 741 op-amp (741 op-amps made by different manufacturers may be slightly different, as are other types of op-amps). We can see that the gain at low frequencies — below a few Hertz — is more than 100,000. But at just 5 or 6 Hz, the gain starts to drop. It gets lower and lower as we go to higher frequencies, and by the time we get to 1 MHz the gain is down to 1. Since the gain varies from very big to very small, it's difficult to specify exactly what the gain is. So we simply say that

- An op-amp is not very useful at the higher frequencies where the gain is small, and
- At the lower frequencies where the op-amp *is* useful, the gain is large enough that we just call it "huge".

This completely avoids the problem of specifying an exact value. For those applications where the op-amp can be used, the gain is simply called huge. And if we need an op-amp at a frequency where the gain isn't large enough, we have to look at some other type of op-amp which will have enough gain at high frequencies to be useful.

Input and output voltages

From the gain equation

$$V_{out} = \text{Gain} \times V_{in}$$

we can see that multiplying even a significant fraction of a volt input times a huge gain could give us a huge output voltage. But that can't be! As mentioned earlier, the output from an op-amp is limited; it has to lie somewhere between the positive and negative rail voltages. In other words, the output voltage can't be very big. The only way to achieve that is to keep V_{in} tiny — so tiny that, even after it is multiplied by a huge gain, the product is still a reasonably small number.

How tiny? Suppose we have 741 op-amp using ±10-volt power supplies; The output is thus limited to a maximum of about ±8 volts. Assuming a gain of, say, 10,000 or so, we would then have as a maximum

$$V_{in} = \frac{V_{out}}{\text{Gain}} = \frac{8}{10{,}000} = 0.0008 \text{ volt}$$

This is small enough that an ordinary voltmeter would have trouble measuring it. So let's just say that the input voltage for normal operation of an op-amp is small enough that we can call it zero volts.

But since V_{in} is defined as

$$V_{in} = V_{N.I.} - V_{Inv}$$

that means that the voltage between the inverting and non-inverting inputs has to be zero or very close to zero during normal operation.

Negative feedback

But, as usual, theory is just a bit different from the real world. We earlier mentioned that there is something called offset — when the input voltage is zero, the output should theoretically also be zero, but it may not be. In fact, the op-amp might even push the output all the up or down to the rail voltage. While this could be corrected by using the null offset pins, that doesn't always work because there is some slight drift with time — whatever adjustment you make today may not work tomorrow or next week.

The solution is to let the op-amp adjust its own input voltage to bring the output voltage back to the correct (or at least reasonable) value. This is done by using negative feedback.

The word *feedback* describes a connection where part (or all) of the output of a system is sent back to the input. If the feedback is such that it opposes an action or corrects errors, then it is called *negative*. If it is such that it increases errors or aids an action, then it is called *positive*. If there is no feedback, then we say the system is *open loop*.

Fig. 19-6 shows a simple example of negative feedback in an amplifier. The negative feedback is provided by the resistor path from the output back to the inverting (–) input. In fact, we can make a general rule as follows:

In an amplifier using an op-amp, there will always be some circuit connecting the output back to the inverting or – input.

Always.

That circuit will usually contain resistors, though in a simple case it might just be a single wire (which represents a zero-ohm resistance). It may also contain capacitors or other components.

The non-inverting amplifier

Fig. 19-6 shows a basic non-inverting amplifier. Since the input is applied to the + (N.I.) input, the output is not inverted.

Although the gain of the op-amp itself is some huge number (see Fig. 19-5), the gain of the complete circuit is not. In fact, it depends only on the resistor values. We can find the circuit gain as follows:

1. Assume that the circuit output is some value we will call V_o.

2. Calculate the voltage at the junction of the two resistors. We would usually use the voltage divider formula, but since in this particular case the two resistors are equal, the voltage at the midpoint of the resistors is $V_o/2$.

3. This voltage is sent back to the – input of the op-amp. Since we know (!) that the two op-amp inputs must be at the same voltage, the voltage at the + input is also $V_o/2$.

4. Hence the input voltage V_i is half of the output voltage. This means that the output voltage is twice the input voltage, and so the gain is 2.

Regardless of the resistor values, we can always go through these steps using the voltage divider equation to

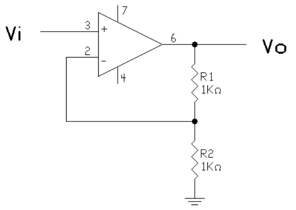

Fig. 19-6. Non-inverting amplifier

calculate the input voltage. But if you prefer an actual equation that solves for the gain in one step, it is

$$\text{Gain} = \frac{V_0}{V_i} = \frac{R_1 + R_2}{R_2}$$

The gain of the entire amplifier is actually the reciprocal of the loss in the voltage divider, which is

$$\frac{R_2}{R_1 + R_2}$$

For example, if the voltage divider sends $\frac{1}{100}$ of the output back to the input, then the gain is 100.

Note that the V_i and V_o in the gain equation are not the same as the V_{in} and V_{out} that we had earlier. V_{in} and V_{out} are the voltages at the input and output of the *op-amp*, whereas V_i and V_o are the voltages at the input and output of the entire *circuit*. The op-amp may still have a huge gain, but the complete *circuit* has a gain of just 2.

Depending on the feedback circuit, we can have higher gain or lower gain. To have a higher gain, we reduce the amount of signal being fed back. To have a lower gain, we increase the amount of feedback. One common non-inverting amplifier, called a *voltage follower*, is shown in Fig. 19-7. This circuit sends 100% of the output signal back to the input, and its gain is 1. Although it therefore has no voltage gain, it is still useful to isolate circuits, or to provide a current or power gain.

To see that the circuit provides negative feedback, let's look at what actually happens. Suppose that we start with input and output voltages all zero, but then the input voltage rises slightly. As Fig. 19-7 shows, the input voltage V_i is connected to the + (non-inverting) input. As this signal rises, the output starts to rise as well, but much faster because of the huge gain of the op-amp. The increased output causes the – (inverting) input voltage to rise as well. As soon as the voltage on the – input rises to the level of the + input, the op-amp stops raising its output voltage and the circuit settles down again. In other words, as soon as the voltage difference between the + and – inputs rises, the signal fed back from the output rises to match, reducing the voltage V_{in} that the op-amp sees between the two inputs. Thus the feedback signal fights the input signal, causing negative feedback.

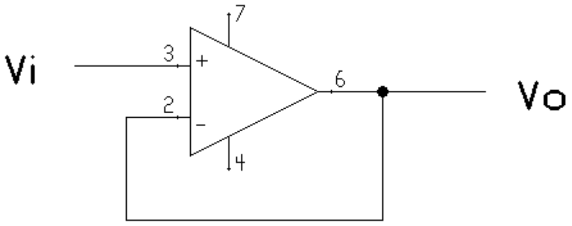

Fig. 19-7. Voltage follower has a gain of 1

Amplifier frequency response

As we saw in Fig. 19-5, the frequency response of a 741 op-amp is quite poor; only at the very lowest frequencies does it have the full gain. The gain plotted in Fig. 19-5 is called the *open-loop gain* — that is the gain without any feedback. The open loop response is also shown as the light curve in Fig. 19-7.

The heavy black curve in Fig. 19-7 shows what happens to the frequency response as soon as we add negative feedback.

This particular graph is plotted for a gain of 100. The huge gain of the op-amp at lower frequencies is cut down to 100. Although this doesn't increase the gain at very high frequencies, it does increase the *apparent* frequency response because the gain is now level from low frequencies up to near 10,000 Hz, and only starts to drop above that. The more feedback we apply, the lower the gain, but also the better is the apparent frequency response.

Negative feedback not only improves (flattens) the frequency response, but it also lowers the distortion that an amplifier produces. It also affects the input and output impedances of the circuit. Negative feedback is used in almost all high-quality amplifiers used for music because of its better frequency response and lower distortion.

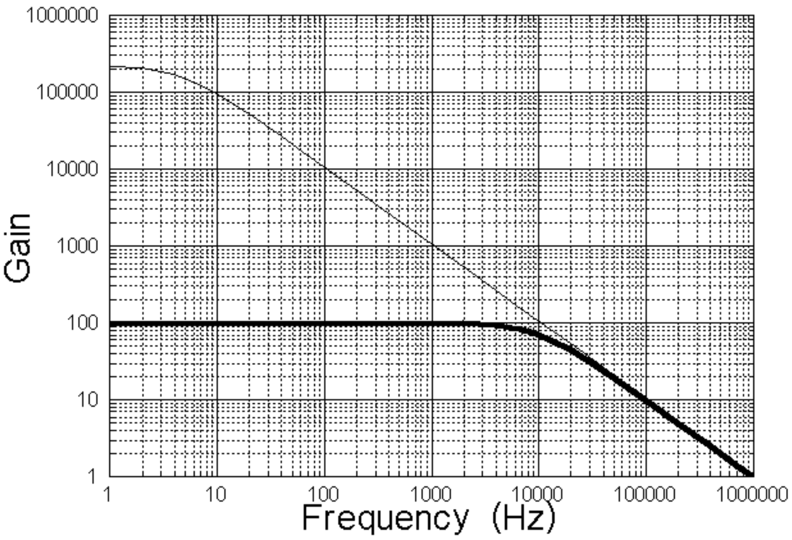

Fig. 19-8. Frequency response when the gain is 100

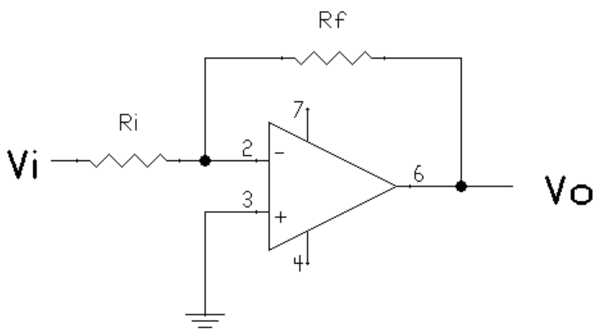

Fig. 19-9. Inverting amplifier circuit

The inverting op-amp amplifier

Fig. 19-9 shows the circuit of an inverting op-amp amplifier. It inverts the signal since the input signal is applied to the – (inverting) input. We figure out the circuit gain as follows:

1. Since the + input is grounded, it is at 0 volts.

2. Since in normal operation, the input voltage V_{in} to the op-amp is zero, then the – input (and the junction of the two resistors) is also at 0 volts.

3. The voltage across the input resistor R_i is equal to V_i, so the current through it is

$$I_{\text{through R}_1} = \frac{V_i}{R_i}$$

4. The voltage across the feedback resistor R_f is equal toV_o, so the current through it is

$$I_{\text{through R}_f} = \frac{-V_o}{R_f}$$

We put in a minus sign, since V_o is the opposite sign of V_i in an inverting amplifier.

5. The current into the op-amp inputs is essentially zero, so the currents in the two resistors must be equal:

$$\frac{V_i}{R_i} = \frac{-V_0}{R_f}$$

and therefore

$$\text{Gain} = \frac{V_o}{V_i} = -\frac{R_f}{R_i}$$

The minus sign tells us that the amplifier inverts; that is, if the input is plus, the output is minus, and vice versa.

Notice that, as before, there is a negative feedback path from the output back to the inverting input. Note too that sometimes we draw the inverting input on top, as in Fig. 19-9; other times we may draw it on the bottom, as in Fig. 19-7. We use whichever makes it more convenient to draw in the feedback path without crossing other connections. Be careful when wiring or troubleshooting the circuit.

The “Whole Story”

The circuits in Figures 19-6 and 19-9 work, but they need separate positive and negative power supplies. If we want to run them from a single positive supply, then the circuits become a bit more complicated. Fig. 19-10 shows an actual circuit showing two separate amplifier stages — a non-inverting stage with a gain of 10, followed by an inverting stage with a gain of 2.

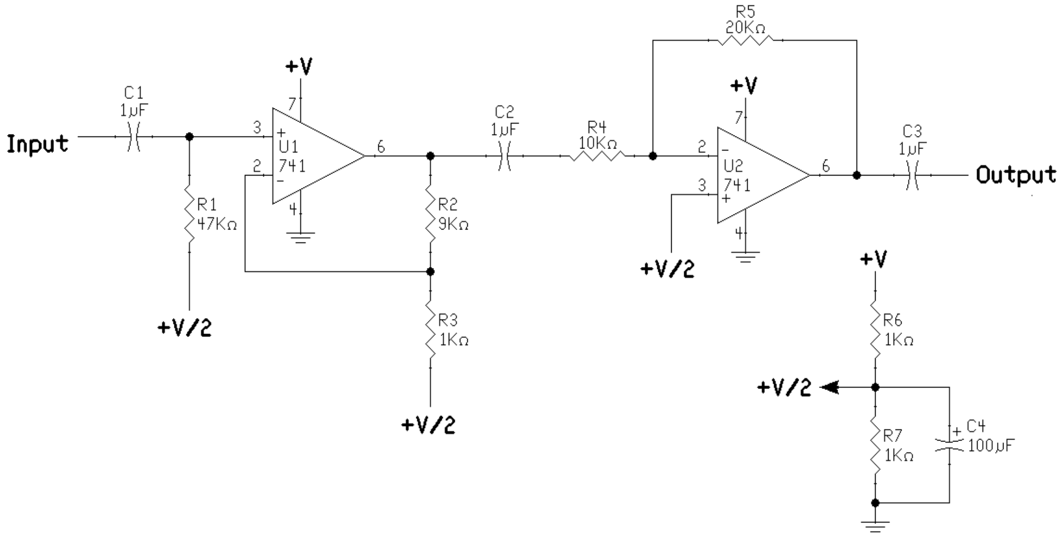

Fig. 19-10. Two amplifier stages using a single power supply

First of all, to run everything from a positive supply of +V volts, we need also a voltage of half of that — called +V/2 in the schematic. Resistors R_6 and R_7 are a voltage divider that provides that voltage. In addition, we must add capacitor C_4 to filter this signal so it is pure and contains no noise or ripple.

Next, since the inputs and outputs of the op-amps will have a voltage on them, we must provide isolation cap- acitors to keep these voltages from interfering with other, adjacent circuits. This is done by capacitors C_1, C_2, and C_3. In practice, we must make sure these are big enough that they let through all the frequencies of interest.

In the amplifiers themselves, all the points that used to be connected to ground in Figs. 19-6 and 19-9 are now connected to +V/2.

Finally, we must make sure that none of the op-amp inputs are left “floating” — that is, left unconnected from a dc circuit of some kind, which would let them float to some weird dc voltage. This means we must add resistor R1 to keep the + input of the first op-amp at the required +V/2 dc bias. None of the other inputs require a special resistor, since they are already held at +V/2 by some other circuit — a direct connection to +V/2 on the + input of the second op-amp, or by being connected to the output through a feedback circuit, as in the – inputs of both op-amps.