Feature

Basic Electronics #5

by Ron C. Johnson

Here's a riddle for you: What area of electronics knowledge is most rapidly becoming obsolete? (Besides copies of Steve Rimmer's old editorials, I mean...)

Transistor design, of course.

Why?

Because, unless you are one of those individuals who likes to inflict pain on yourself, (hmm... in which case you possibly do read Steve's old stuff as well...), you will, whenever possible circumvent the whole issue of discrete components and use op amps or other dedicated integrated circuit devices.

Operational amplifiers, which have been around for quite a few years now, are one type of integrated circuit which provide a simple, inexpensive way to build circuits where amplification is required.

More on that in a moment.

For those of you who are new to electronics, a quick explanation of integrated circuits is in order.

You probably know, from previous segments of this series, that a transistor is made out of silicon, layers of which have been doped with impurities. Leads are connected to the appropriate layers and when properly biased, the amplification of a signal can be achieved. Often several transistor amplifier stages must be cascaded together to get enough gain with the required input and output impedance, etcetera. This all requires space on a printed circuit board and significant amounts of time, expertise, cost, (luck?!) to get the thing working properly and reliably.

Op Amps

Enter the integrated circuit. By using precision photographic techniques, whole circuits, including many resistors, transistors, capacitors, (made out of layers of doped silicon), can be deposited on tiny 'chips'. Fine wires are connected to appropriate spots on the chip and extend out to pins arranged around the perimeter of the device. Obviously, with a whole circuit on the chip, circuit design should be simplified while the complexity is increased. This reduces cost, size, and so on.

Most of you are well aware of this already. The integrated circuit, of course, is the building block of the electronic calculator, personal computer, and so on. In the last twenty-five years we have gone from the simplest amplifier on a chip, to the incredibly powerful circuits used in microcomputers, such as the 80486 and 68000 series microprocessors chips, application specific integrated circuits (ASIC's), etcetera. (And bigger, better models are arriving every day. So come on down to Honest Ron's used chip emporium today for low, low 4.9% financing... oops, sorry. I get carried away...)

Where was I?

Operational amplifiers. Yes... One type of integrated circuit is an operational amplifier. An op amp is a building block, an amplifier with certain known specifications, which can, with a minimum of external components, be used to obtain a given amount of gain over a given bandwidth with known input and output impedance specifications. This is very useful since most circuits use gain in some way or another to achieve their purposes.

There are lots of different models of op amps with variations as to the number of devices per package, their specifications, package type and number of pins. Some are general purpose while others have been designed for use in specific applications.

So in this segment of Basic Electronics I'll be talking about the

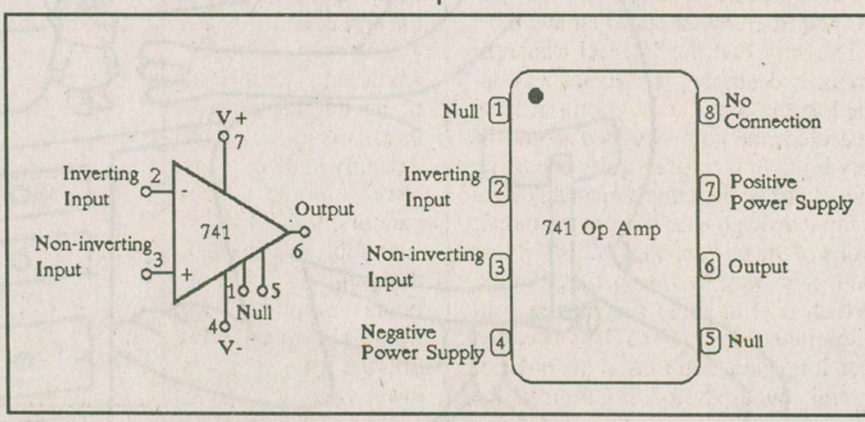

Fig. 1. Schematic Symbol and Pin Diagram of an Op Amp

theory of op amps and some applications they can be used in. As usual I'll try to keep it simple but there is a bit of math necessary so that you can design an op amp stage for yourself. Next month we'll build one or two of the actual circuits talked about here.

Here we go...

An op amp is a high gain DC amplifier that has a high input impedance and a low output impedance, as mentioned previously, built into a single device with several leads. Figure One shows the schematic symbol and pin diagram for a typical (if somewhat older), op amp, the 741 general purpose op amp. Figure 2A shows the internal circuitry. Of course, we can only access the input and output pins of the device so the internal schematic has limited usefulness to us.

I said that an op amp is a high gain DC amplifier. What does that mean?

The way that the internal transistor circuit is designed, if a signal was applied to the input and the output level measured, the gain obtained would be very high. In fact, practically speaking, it would be so high that almost any level of input voltage would drive the output to one of the power supply rails if it was used this way in an actual circuit. (Which it is in some specialized configurations. More later.) This is called open loop gain, and runs in the order of several hundreds of thousands: for design purposes we can consider it to be infinite.

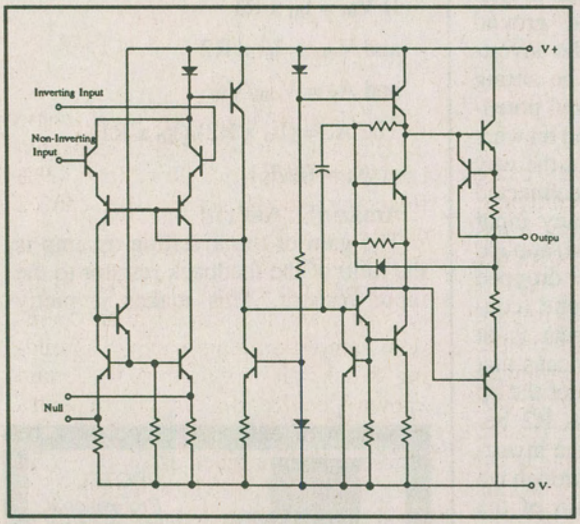

Fig. 2A. Internal Schematic of a 741 Op Amp

In addition to its high gain an op amp is a DC amplifier because the internal circuit is direct coupled (no capacitive coupling between stages). This means it will amplify from DC (zero cycles per second) and up. This is important because it enables the op amp not only to amplify AC signals such as audio or radio frequencies, but it can amplify DC levels, useful in applications such as comparators, servo controls, etcetera.

I also said that the op amp has a high input impedance and low output impedance. If you remember some of the considerations used when we designed a transistor amp a few segments ago you will know that a high input impedance is desirable; it means that the input of the amplifier does not load down the previous stage. Low output impedance is also desirable; it means that the amplifier can drive fairly low impedance loads efficiently.

All of these specifications make the op amp superior to designing with transistors. Again, looking back at our transistor amplifier, (which we ultimately used to build a phase shift oscillator), gain, input impedance and output impedance were important and interrelated considerations which made the design difficult. With the op amp we start with almost ideal conditions and design from there, sometimes compromising them in the process.

You're probably wondering what kind of an amplifier needs an almost infinite gain. Actually there are some, called comparators, which I'll discuss shortly, but when designing a conventional amplifier we want to be able to control the gain to some lower value.

How do we do it?

Feedback is the answer. Negative, that is. When we discussed oscillators we considered positive feedback which meant feeding the output back to the input in phase, or with zero phase shift, (a positive output is added to a positive input increasing the signal). If the gain was high enough oscillation occurred. Negative feedback means feeding back the output 180 degrees out of phase, (a negative output is added to a positive input decreasing the total which decreases the gain).

Op amps are purposely designed with inverting and non-inverting inputs to facilitate controlling the way signals are fed into them. This makes it easy to add a few external components to obtain a predictable amount of negative feedback and thus a predictable gain. Usually op amps a powered from a split power supply (positive and negative voltages with respect to ground) to facilitate the output fluctuating around zero volts. This is necessary to obtain a true AC waveform at the output.

Actually determining the resistor values and configuration needed for a desired gain requires a bit better understanding of how the device operates and its specifications. Let take a little deeper look...

As I mentioned, op amps have both inverting and non-inverting inputs, labelled negative (-) and positive (+) respectively. The non-inverting input causes the output to change proportional to the input by a factor of whatever

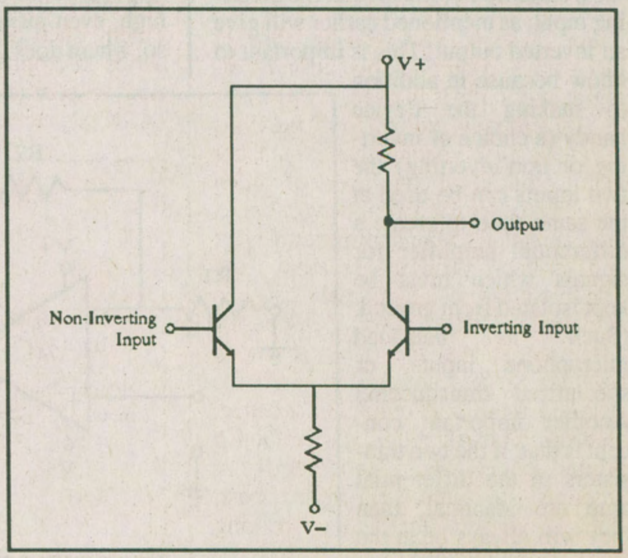

Fig. 2B. The Differential Amp Input Circuit

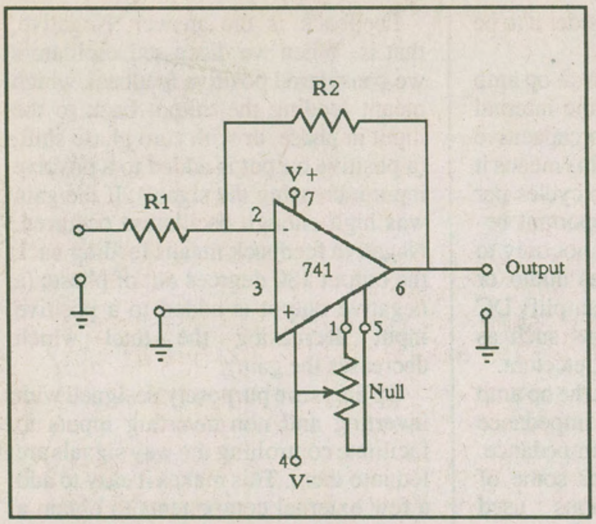

Fig. 3. An Inverting Op Amp Configuration

the gain of the circuit is. If the input goes positive, the output will go positive as well. The inverting input does the opposite. When the input goes positive the output will swing negative. This is the same as saying that a signal applied to the inverting input would be given a phase shift of 180 degrees through the amplifier. A signal applied to the non-inverting input would have a zero degree, or no shift at all, through the amplifier.

Figure 2B shows a simplified schematic of the input circuitry inside the chip. This is a typical differential transistor amplifier which provides the two inputs mentioned. Signals to either of the bases of the transistors will be amplified by the same amount (under ideal conditions), except that the inverting input, as mentioned earlier will give an inverted output. This is important to know because in addition to making the device handy (a choice of inverting or non-inverting) the two inputs can be used at the same time to create a differential amplifier for signals which must be kept isolated from ground. (Such as balanced microphone inputs, or specialized transducers.) Another important concept is that, if the two transistors in the differential amp are identical, then they will always be at the same potential, because their emitters are tied together and both bases will be 0.7 volts higher.

Well, how do we use these inputs to obtain what we want?

Figure 3 shows a typical inverting op amp configuration where negative feedback is applied using two resistors, R1 and R2. Notice that the non-inverting input has been tied to ground. If the non-inverting input is at ground potential then the inverting input must be sitting virtually at ground potential as well (based on what I said earlier about the way the internal transistors are connected together). That means that any input voltage (with respect to ground) applied to the resistor, R1, will be dropped across R1 because its other end (connected to the inverting input) is at ground potential. That also means that any voltage on the output pin of the op amp must be dropped across R2 because it also is connected to the inverting input. If we think that all through we can then believe that the gain of the amplifier, which is the voltage out divided by the voltage in, will be:

Gain $(A_v) = V_{R2}/V_{R1}$

Are you still with me? Okay, here's where I pull a rabbit out of a hat...

Remember that I said that the input impedance of the op amp was very high, even infinite for our purposes. If so, where does the current go that flows through R1 creating the voltage across R1? The only other path it has is through the feedback resistor, R2. R1 and R2 are effectively in series if the input impedance is infinite. That means that the same amount of current flows through both resistors.

Stay with me here, folks... It isn't as bad as it looks. Remember that when the input voltage is going positive the output, being inverted, is going negative, so the current will flow as I have said. But what does this all mean?

If $V_{in} = I_{in} \times R1$

and $V_{out} = I_{in} \times R2$

and $A_v = V_{out}/V_{in}$

The $A_v = (I_{in} \times R2)/(I_{in} \times R1)$

or $A_v = R2/R1$

Amazin'... Ain't it!

The gain of the inverting op amp is the ratio of the feedback resistor to the input resistor. This makes it pretty

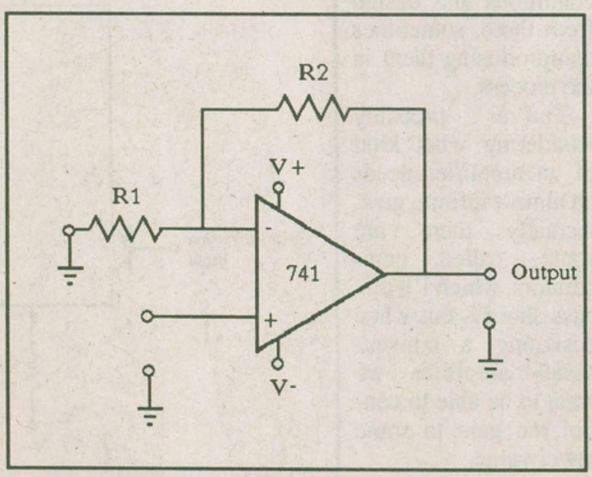

Fig. 3. A Non-Inverting Op Amp Configuration

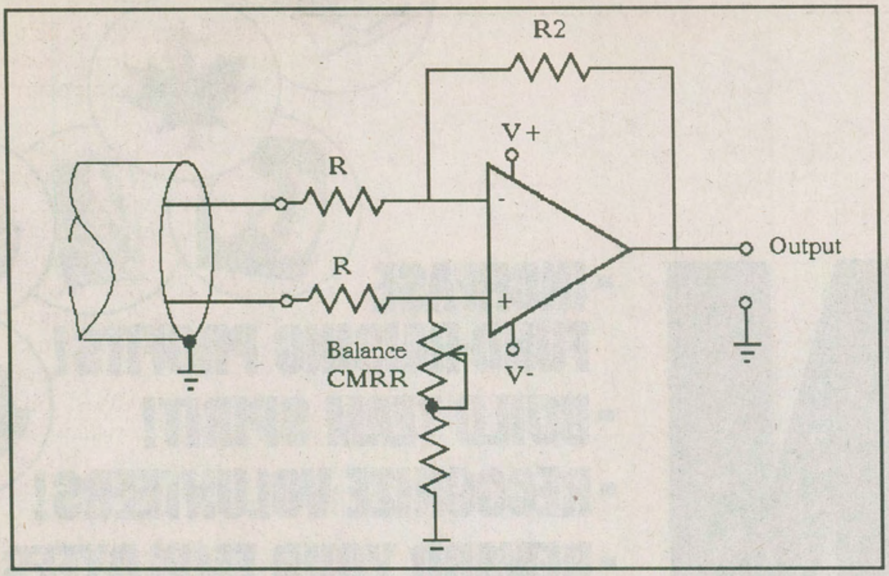

Fig. 4B. A Balanced Differential Amplifier

simple to design a gain stage which has good input impedance and output impedance with an op amp and two resistors.

Well, what if you want to build a non-inverting amplifier?

Figure 4A shows a variation on the previous circuit which allows you to put the input on the non-inverting input and ground the inverting input. The output will then be in phase with the input. I won't go through the derivation of the gain formula. Let me just tell you that the closed loop gain for the non-inverting amp is:

$$A_v = (R2/R1) + 1$$

I said before that both inputs could be used at the same time to create a differential amplifier for balanced microphone inputs, etcetera. Figure 4B shows a typical configuration of this sort. This has a definite advantage in that the usual balancing transformer can be eliminated and improve performance at the same time. This is due to the Common Mode Rejection provided by the differential input. Because the inputs drive the output in opposite directions, any signal that is present on both inputs will be cancelled out, one input causing the output to go one way while the other causes it to go the other. The Common Mode Rejection Ratio is a specification of the device which indicates how well it accomplishes this. In the circuit shown the CMRR is further enhanced by including a potentiometer to adjust for best CMR performance.

What's next?

Voltage followers.

A voltage follower is a non-inverting configuration in which the output is coupled back to the inverting input directly and the input signal is connected directly to the non-inverting input. If you look at the gain formula for a non-inverting amplifier and plug in zero ohms for both R1 and R2 you will find the answer is a value of one. The gain of a voltage follower is one; but what good is that? (And why do they call it a voltage follower anyway?)

The answer is in the input and output impedances. Sometimes we don't need any voltage gain through a stage but we need to match impedances. We need a high input impedances so as not to load down the previous stage and a low output impedance in order to drive the load with sufficient current. The voltage follower does that for us. (And I don't know why they call it a voltage follower... Actually, not entirely true. Usually this stage follows a stage of voltage gain to achieve the purposes I just mentioned.)

Onward!

Comparators

Actually comparators are a device unto themselves but are really just op amps with specs and features particularly suited to switching applications. Regular op amps can be used as comparators in most applications too. A comparator is a device which compares the levels of the signals on its inputs and switches its output depending on which is at a higher level. As shown in Figure 6 a comparator configuration uses no feedback which means that the gain of the circuit is very high. If the voltage on the non-inverting input is more positive than the voltage on the inverting input the op amp amplifies the differential voltage by this large gain causing the output to quickly reach the positive power supply rail. If the signal level on the inverting input is larger, the opposite happens, sending the output to the negative power supply rail. All this amounts to a switching action depending on the input levels.

In the circuit shown in Figure 6 the non-inverting input has a sine wave applied to it while a reference voltage is connected to the inverting input. The waveforms show that as long as the sine wave is below the reference level the output of the op amp is sitting at the negative power supply. When the instantaneous value of the sine wave exceeds the reference voltage the op amp output switches to a level equal to the positive power supply.

Figure 6 also shows how a reference voltage would be practically obtained, using a voltage divider consisting of two resistors in series.

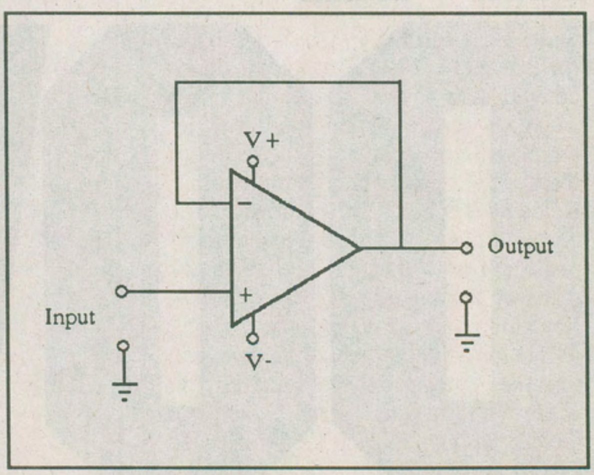

Fig. 5. A Voltage Follower Configuration

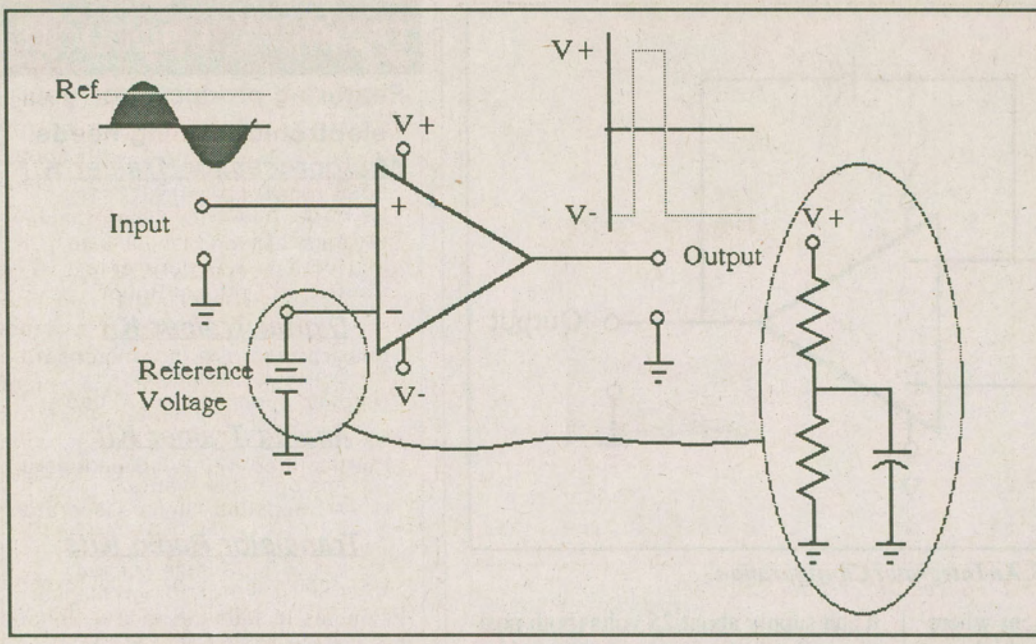

Fig. 6. A Comparitor Configuration

They'd be glad to help.) But here's a clue anyway: Gain of One and Positive Feedback.

The Wien Bridge Oscillator makes use of both of the op amp's inputs to accomplish this with both positive and negative feedback. The positive feedback loop couples the output of the op amp back to the non-inverting input through a bandpass filter using two resistors and two capacitors. This allows a narrow band of frequencies to be coupled, in phase, to the input of the amp but in so doing, that band is attenuated by about a factor of 1/3. To make this up the amp must have a gain of about three so the negative feedback to the inverting input is set to obtain that gain. All of this fulfils the requirements for oscillation.

Next, we look at the summing amp in Figure 7. This is really just an inverting amplifier with additional inputs but is a useful configuration for many applications. By tying several resistors together at the inverting input several signals can be mixed together (like in an audio mixer or some instrumentation applications). The gain associated with each input is determined as before and, by choosing the value of the input resistor the gain associated with each input can be made different.

The integrator shown in Figure 8 is an interesting and useful, if somewhat specialized, circuit. If you remember your high school calculus you will know that integration is a mathematical operation which determines the area under a curve (or any other waveshape, for that matter). An example of this is converting a square wave input into a triangle wave at the output. The integrator uses a capacitor in the feedback loop of the op amp to accomplish this. Remember when I said that the same current that flows through the input resistor flows through the feedback resistor? In this case that same current flows into the feedback capacitor, and, if the input voltage is held constant, then the input current is constant. If you were with me 'way back when we talked about capacitors in Basic Electricity you will remember that the voltage across a capacitor will increase linearly if the current into it is kept constant. In this case the capacitor will charge at a constant rate which amounts to the same thing as integrating the signal applied to the input. We know that the voltage across the capacitor is the voltage at the output because the op amp input is at virtual ground.

Scary ain't it?

Okay... and finally, Figure 9 and the Wien Bridge Oscillator. I don't have to go into how an oscillator oscillates. You already know from reading the segment on transistor oscillators. (And if you didn't, just ask E&TT for a back issue.

Wow, what a list. And, of course this is not really complete. There are endless variations on the configurations I have shown you here, and a few more that I didn't have room for.

The problem with all of this is that it sounds good on paper. What about the practical end of op amps? Are they really as easy to work with as I have suggested? Actually, they are, as you will

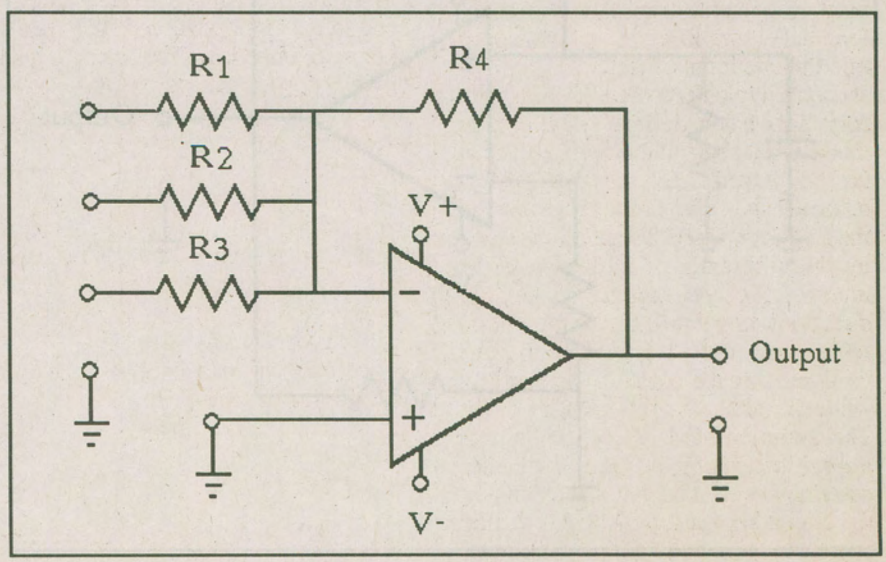

Fig. 7. A Summing Amplifier Configuration

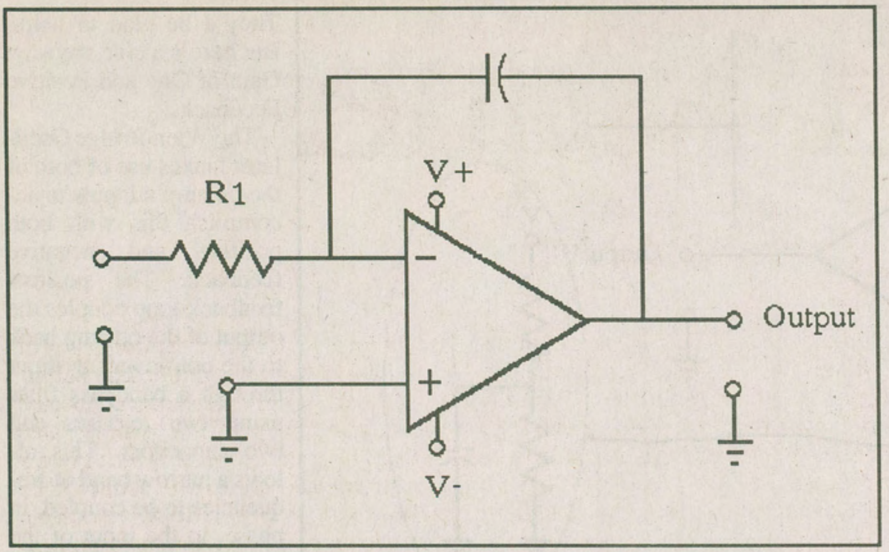

Fig. 8. An Integrator Configuration

see from next month's segment where I'll have a small project in which we throw a few of these circuits together on a breadboard and from there onto a printed circuit board. One thing you will need in order to breadboard and test op amp circuits is a dual power supply so if you were thinking of building or buying a DC power supply, make sure it can supply about 25 volts (both positive and negative) and at least a half an amp.

Must sign off for this month. Gotta get back to reading Steve's old editorials. See you next time... ❐

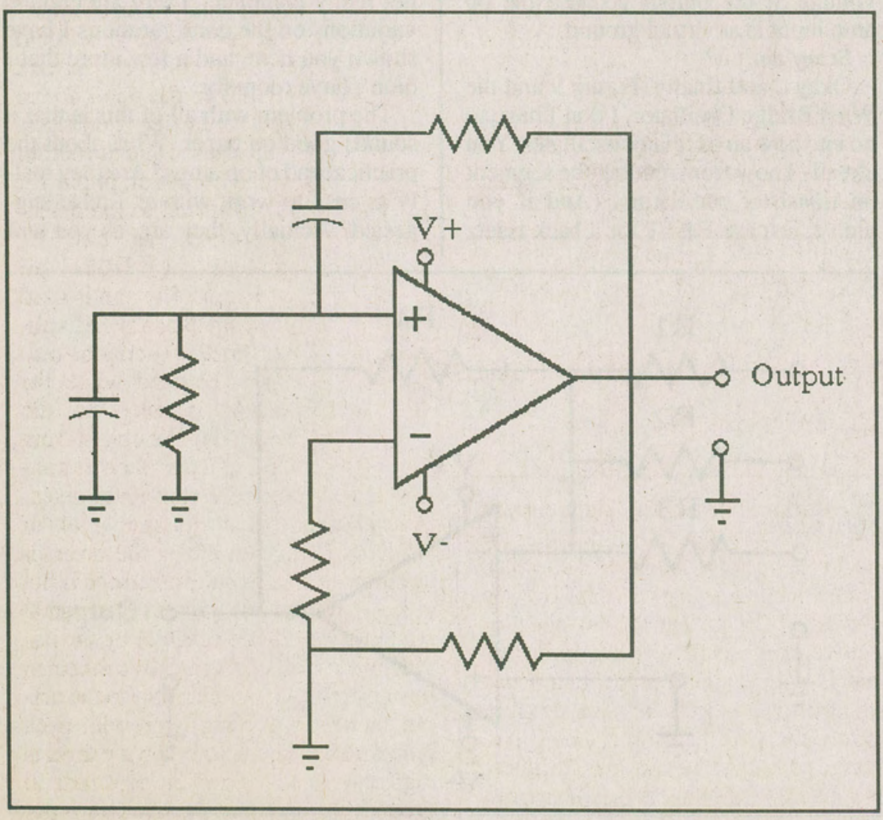

Fig. 9. A Wien Bridge Oscillator