WORKING WITH OP-AMPS

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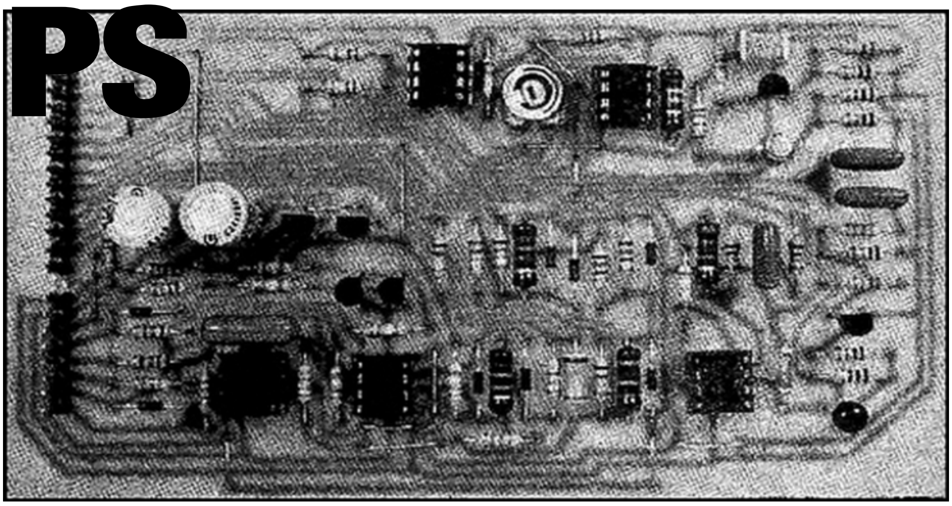

Not many years ago the OP-AMP was an expensive and specialised device. To give it its full title of 'operational amplifier' is to emphasise that its original role was to perform mathematical operations. If was the active component of the analogue computer, which largely appears to have taken a back seat these days.

The reason for the current popularity of the operational amplifier (or op-amp) is its cheapness and versatility in the form in which it is now to be found; that is as a monolithic integrated circuit. Of course, it can still be used for its original applications such as integration, differentiation, addition, subtraction, etc., but generally the field of application is much wider. It is used in purely linear fashion e.g. in audio amplifiers and instrumentation amplifiers, but it can also be used in pulse circuits and various other more exotic guises.

In this article, some of the op-amps uses in a variety of roles will be examined and will assume the reader has little previous knowledge of either the electronics or mathematics involved. Examples of circuit design will be presented along with the necessary theory.

The Ideal Op-Amp

In electronics it is frequently necessary to make sensible approximations in order to present a particular topic intelligibly. It is amazing how very complex and unwieldy formulae often become quite simple when some sort of approximation is made. This is certainly true of op-amps and the resulting formulae are then very readily applied to practical situations. Listing the main features of an ideal op-amp gives us:

a. infinite gain
b. infinite input impedance
c. zero output impedance
d. infinite bandwidth

This looks a very formidable specification at first sight. Of course, we cannot actually expect to realise these parameters, but the real values are relatively close enough to have little practical significance. For example, a typical voltage gain A might be 200000 which is a lot less than infinity, but if we compare A with A + 1 the difference is insignificant. It is this sort of comparison that allows us to make worthwhile simplifications.

Enter the 741

I decided to base this article on one particular chip, the 741, for several reasons; it is very cheap, easily obtainable and does not need a host of compensating components in order to make it work. It also has a short-circuit proof output. There are other op-amps that can outperform it in one way or another but it will serve well enough to introduce the basic principles of op-amps and their applications.

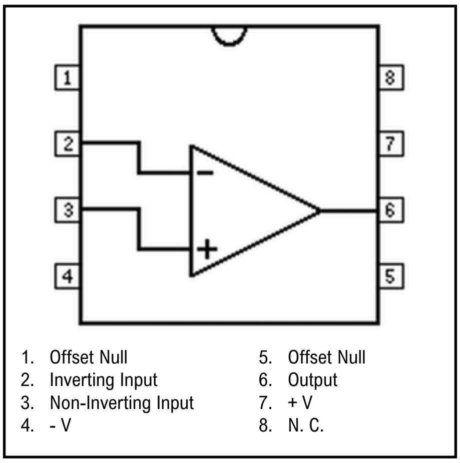

Figure 1. Pin-out diagram of the µA741CP op-amp.

Figure 1 shows the pin-out diagram for the 8-pin version (there is also a 14-pin version), from which we see that the connections fall into three groups, according to function:

a. power supplies +V and -V
b. offset-null terminals
c. inputs and output

Input and Output

There are two inputs and one output and the usual symbol showing these terminals appears in Figure 2. The input marked with a - sign is known as the 'inverting input' (180° phase-shift between this input and the output); the input marked with a + sign is known as the 'non-inverting input' (0° phase-shift between this input and the output). Figure 3 illustrates the action of each input considered separately, the other input then being taken to 0V.

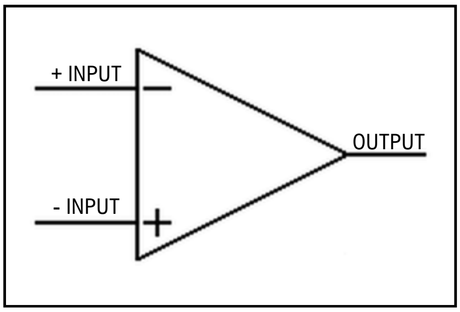

Figure 2. Basic op-amp symbol.

The arrows are used to represent signals in a general manner e.g. the 'up-arrow' can signify the positive half-cycle of a sine-wave, a positive DC level, a positive ramp etc. Similarly the 'down-arrow' signifies any negative waveform. So a positive signal applied to the inverting input produces a corresponding negative. Signal at the output and a positive signal applied to the non-inverting input produces a corresponding positive signal at the output.

Suppose now that the inputs are energised simultaneously and, to keep things simple, the signals are of equal amplitude. The two possible configurations are shown in Figure 4.

The question is, of course, what is the direction of the output in each case?

Consider the case of in-phase inputs shown in Figure 4(a). The output changes due to each input will be equal and opposite and the output will therefore remain unchanged.

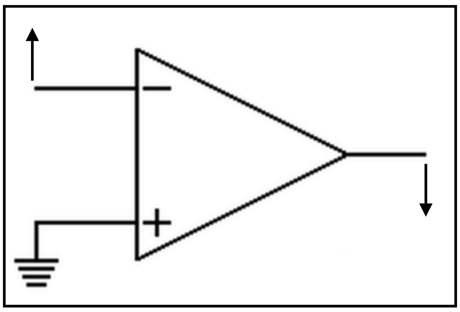

Figure 3(a). Action of inverting input

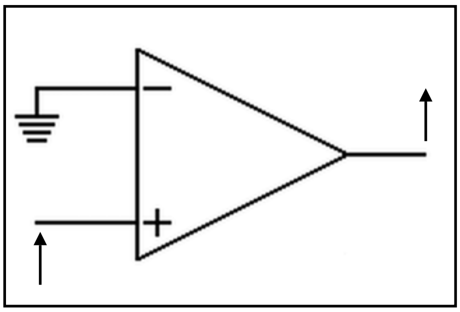

Figure 3(b). Action of non-inverting input

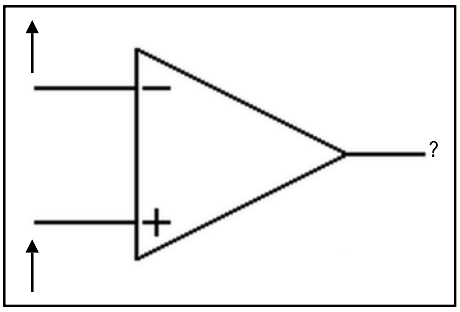

Figure 4(a). Equal in-phase inputs.

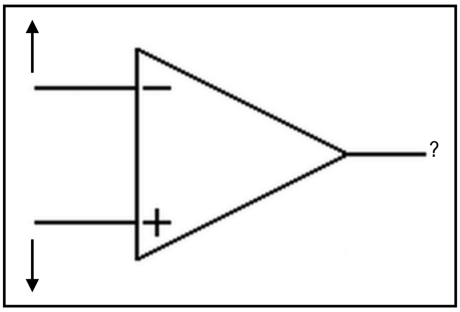

Figure 4(b). Equal anti-phase inputs.

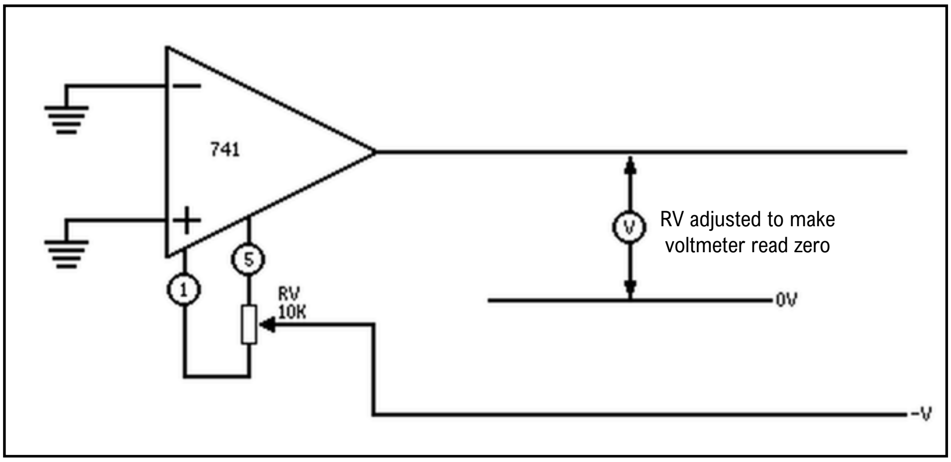

Figure 5. Using the 'offset null' facility.

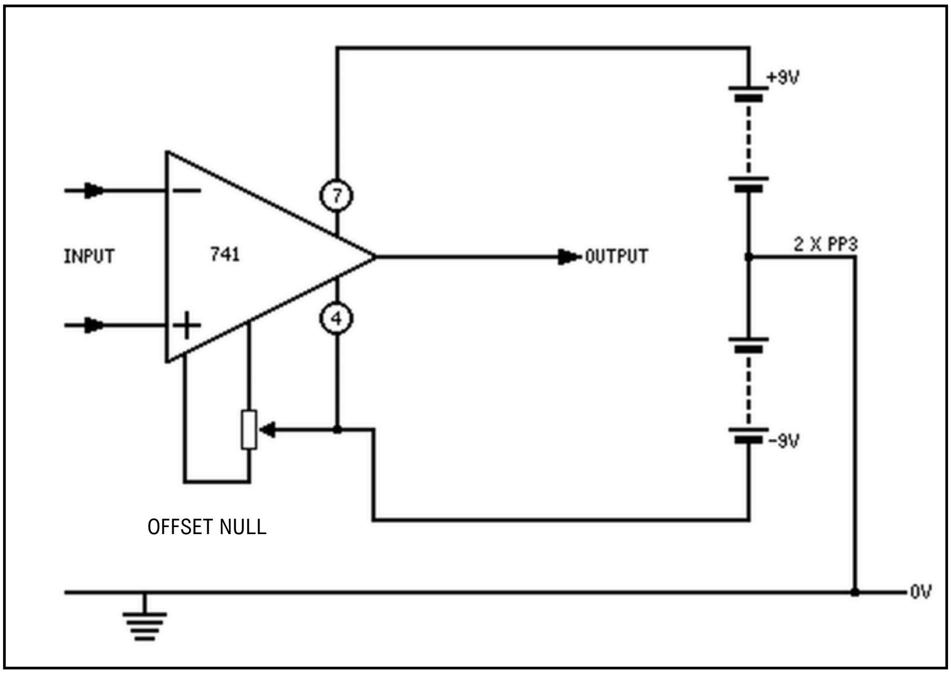

Figure 6. Power supply connections.

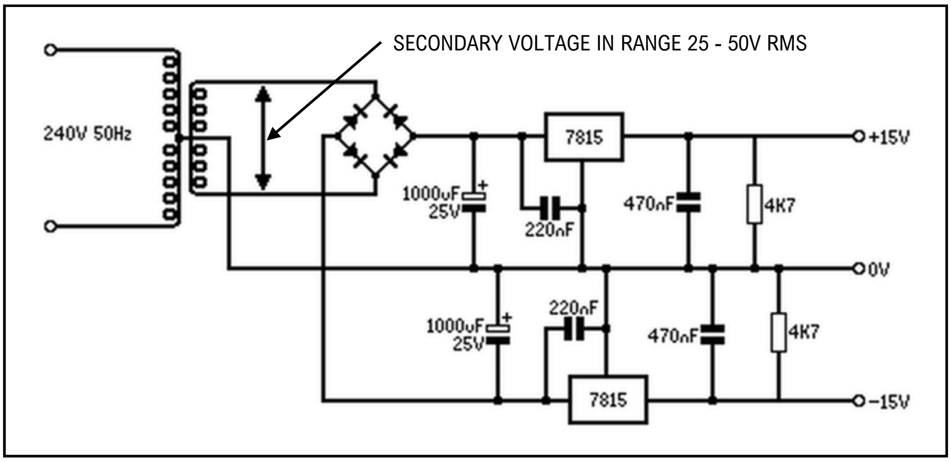

Figure 7. Mains operated dual 15V op-amp power supply.

In the case of anti-phase inputs, the positive signal at the - input will produce a negative output and the negative signal at the + input will also produce a negative output. So the two effects are additive, and a large output change occurs.

These two ways of driving the inputs are known as the differential-mode (anti-phase inputs) and common-mode (in-phase inputs) respectively. From this we can see that a principal characteristic of an op-amp is to amplify the former but reject the latter. This has great practical significance as we shall see in due course.

Offset Null

Having now discussed briefly the signal connections, we can consider the function of the two pins marked offset null.

Suppose we were to connect both inputs to 0V; we should expect the output to be also 0V, since there is nothing to amplify in order to produce an output. We might well be surprised, therefore, to find that the output was not in fact 0V at all but slightly offset from it, either above or below the 0V level. This arises because of the impossibility of manufacturing a perfectly symmetrical amplifier. However, the manufacturers allow for this by providing the 'offset null' facility. This is utilised in practice by connecting a potentiometer between the two offset null pins, with the wiper taken to -V. This would be a skeleton preset and is adjusted to bring the output to zero with both inputs also at zero. Figure 5 illustrates the technique.

Common-Mode Rejection Ratio

As stated previously there is a high gain in the differential mode of operation and zero gain in the common mode. However, the latter statement is not quite true; because of the imperfections already mentioned, the gain in common mode is small but it is not zero. This means that common-mode inputs will produce an output but it will be very small. In many practical situations, the signal is applied differentially but unwanted noise signals are picked up at both + and - inputs and present a common-mode input to the amplifier. Thus

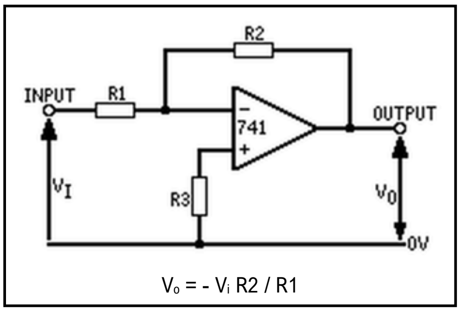

Figure 8. The inverting amplifier.

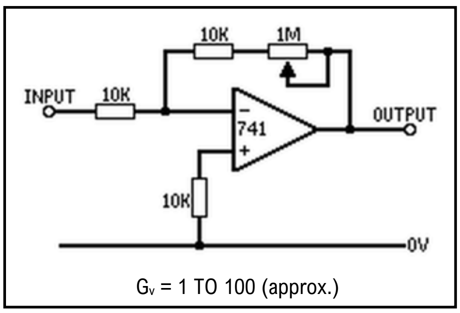

Figure 9. Inverting amplifier with variable gain.

the signal is subject to very high gain and produces a large output, while the unwanted noise voltages have very low gain and produce very little output. How well the amplifier is able to separate signal and noise in this way is expressed by a factor known as the 'Common-Mode Rejection Ratio' (CMRR).

The CMRR can be calculated as follows:

$$\text{CMRR} = 20 \log\left[\frac{\text{DIFFERENT MODE GAIN}}{\text{COMMON MODE GAIN}}\right] \text{dB}$$

So in practice the gain figures were 200000 and 4 respectively, the CMRR would equal 20 log (200000/4), which gives 94 dB; this would be a very good figure.

Power Supplies

The power supply pins are marked +V and -V since, in general, it is expected that the op-amp will develop outputs that swing either side of 0V. A typical pair of supplies would be ±15 volts, giving a possible output swing of 30 volts peak to peak. However, a convenient arrangement when experimenting consists of two PP3 batteries giving ±9 volts, as shown in Figure 6. PP3 batteries will give adequate current for our purposes; one op-amp takes very little current.

For those who prefer a mains power supply, I have given a low-cost design in Figure 7. It uses a couple of small regulator chips to give ±15 volts at up to 100 mA.

To explore the possibilities of the op-amp fully, access to some test equipment will be required. For example, an oscilloscope for examining waveforms, an audio sine/ square-wave generator for providing inputs, and a multimeter for measuring current and voltage levels. Also some form of breadboard will be required such as the 'solderless plug-in types', or just a piece of Veroboard with an 8-pin IC socket and a few terminal pins.

Amplifier Configurations
Inverting

Figure 8 shows an inverting amplifier. The term inverting amplifier implies a 180° phase-shift between input and output. To define the input/output relationship fully the voltage gain must be known as well.

This is given by Voltage gain = R2/R1, which shows that for a certain value of R1, the gain is determined by the choice of R2. Apart from using fixed resistor values, a potentiometer would give continuous control of gain or R2 could be switched to give gain changes in steps.

The unused + input is tied to 0V by R3. The value of this resistor is not usually particularly critical but it can be obtained from the formula R3 = R1 R2/(R1 + R2), which gives the value for best 'drift-free' performance. Unless this is a particular criterion, a good rule of thumb is to let R1 = R3 = 10K and select R2 for the required gain. Figure 9 shows an inverting amplifier in which the gain is continuously variable from 1 to 100 (approximately).

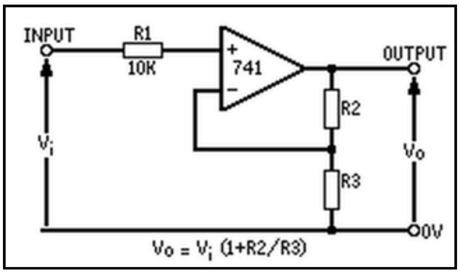

Figure 10. The non-inverting amplifier.

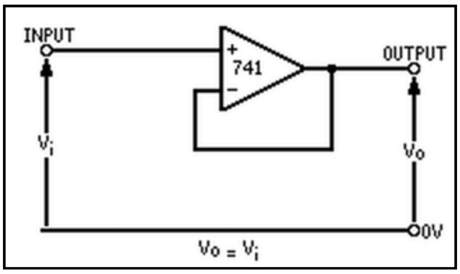

Figure 11. The voltage follower.

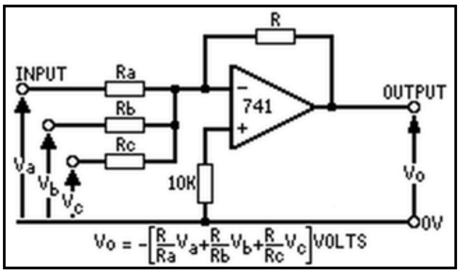

Figure 12. The summing amplifier.

Non-inverting

An amplifier may be needed whose gain can be just as easily defined but which has zero phase-shift. An amplifier of this type is shown in Figure 10.

The gain of the non-inverting amplifier is also defined by the ratio of two resistors, R2 and R3. However, the expression for gain is slightly different from the previous case; it is now given by 1 + R2/R3. A very wide range of gain is feasible. The minimum value is clearly 1, which occurs when R2 = 0. If, at the same time, R3 is made equal to infinity (i.e. removed entirely), the circuit becomes that of the voltage follower.

Voltage Follower

Figure 11 shows a voltage follower which is so-called because it has a voltage gain of one and zero phase-shift. A circuit in which the input and output are identical may not, at first, seem very useful. Its value derives from the fact that it has a very high input impedance and a very low output impedance. This means that it can be used as a matching device between points of high and low impedance.

Summing and Subtracting

Sometimes it is necessary to add two or more voltages together, or obtain the difference of two voltages. The summing amplifier (Figure 12) and the subtractor amplifier (Figure 13) meet these requirements.

In the case of the summing amplifier, the gain for each input separately is determined by the ratio R/Ra, R/Rb, etc. If these ratios are all equal to one, then the output voltage is equal, literally, to the sum of the input voltages. But it is obvious that the input voltages can be scaled up (or down) by some factor R/Rx, either equally for all inputs or preferentially.

The same facility for scaling the gains for each of the inputs is also available for the subtractor, as Figure 13 should illustrate.

Integrator

The last basic configuration to examine is the integrator, which is shown in Figure 14.

This circuit performs the mathematical operation of integration. However, there is no need to become involved in integral calculus. In practical terms, the circuit responds to a step input voltage by producing a ramp of opposite sign. The slope of the ramp depends upon the amplitude of the step and the 'integrator gain' 1/RC volts/sec per volt of input.

Figure 14 also shows a full cycle of the square-wave input; the integrator output consists of alternate negative and positive ramps, corresponding to the leading and trailing edges, respectively, of the input. If the input was a continuous square-wave, the output would be a triangular waveform.

Given the right data, it is a simple matter to calculate the amplitude of the output, as follows: if R = 100k and C = 100nF, the integrator gain is 10^7 / 10^5 = 100V/s per volt of input. This is more conveniently expressed as 0.1 V / ms per volt. If the input was a 100 Hz square-wave of 2 V amplitude, then the slope of the ramp would equal 0.1 V / ms x 2 = 0.2 V / ms. Since the time of a half-cycle at 100 Hz is 5 ms, the amplitude of the output is 0.2 V / ms x 5 ms, which equals 1 volt.

The integrator principle has many applications. One of them appears in Figure 15, the circuit shown performing a time to voltage conversion.

The amplitude of the ramp output is proportional to the duration of a negative input pulse. In the absence of such a pulse, both diodes conduct and hold the output at 0V. The arrival of a pulse reverse-biases both diodes and the ramp starts running. The rate at which it runs is set by RV1, which acts as a form of 'sensitivity control'. Since the ramp runs until the pulse finishes (if RV1 has been set correctly), the final amplitude of the output is proportional to the length of the input pulse.

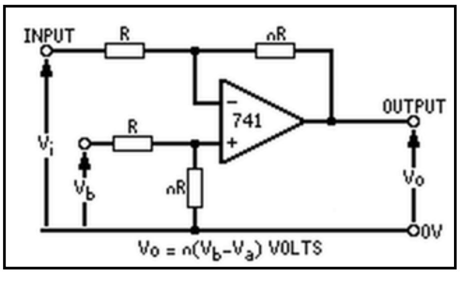

Figure 13. The subtractor amplifier.

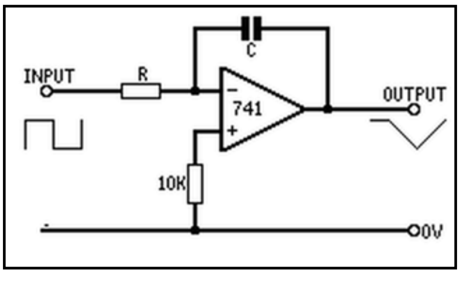

Figure 14. The integrator.

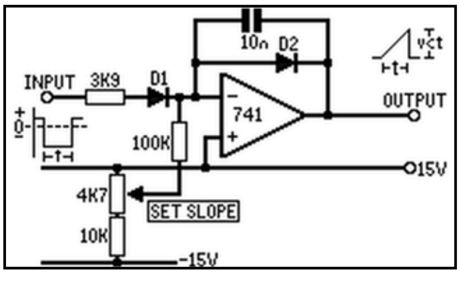

Figure 15. Circuit for time to voltage conversion.