

## Experiment 5: Operational Amplifiers or Op-amps, for short

### 1 Introduction

The Op-amp started its life in analogue computing applications back around 1950. Today the op-amp is found in a wide variety of applications from signal processing, control circuits to instrumentation. In short, op-amps employ differential amplifiers, which multiply two input signals by a differential gain and current sources on a silicon chip to produce an extremely high gain IC (integrated circuit) amplifier. For our purpose, we can suppose that it is all magic <sup>1</sup> inside the op-amp, while we will study its behaviour.

By itself, the gain of an op-amp (typically several hundred thousand) is too large to be useful and the op-amp is too unstable. To combat this, feedback is employed to reduce the gain of the amplifier and make the amplifier behave in a predictable fashion.

For precision work, many parameters of op-amp operation must be considered when designing circuits that employ them. For nearly all applications, we can pretend we have ideal op-amps (infinite gain, no input current). The schematic symbol for an op-amp is given below, figure 1:

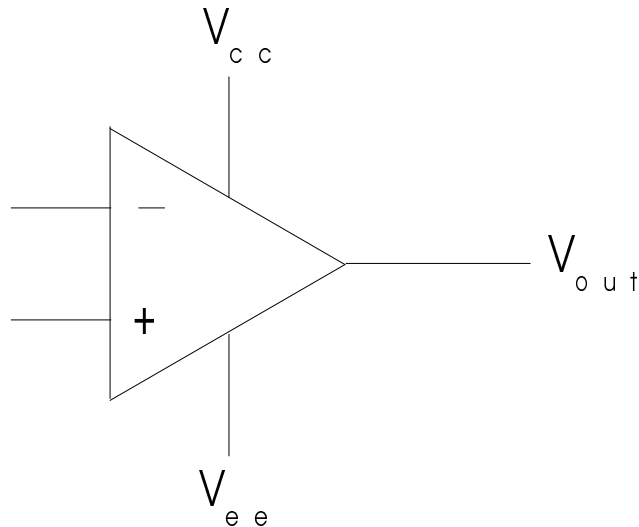


Figure 1: Schematic of an operational amplifier

The lead labelled with a ‘minus’ sign is the inverting input; the ‘plus’ is the non-inverting input.  $V_{cc}$  is the positive supply voltage and  $V_{ee}$  is the negative supply voltage. As its name suggests,  $V_{out}$  is the output of the amplifier. In this experiment, use  $Use V_{cc} = +15V$ ,  $V_{ee} = -15V$ , which are typical ratings.

#### 1.1 Key Features of Op-Amps

During the experiment it is important to keep the following facts in mind. Op-amps are designed to have infinite input impedance, zero bias voltage (that is between the two inputs) and zero output impedance. These facts in ideal op-amps leads to two rules central to designing circuits:

- (a) The inputs draw no current.
- (b) The output does whatever it can to keep the inputs at the same voltage.

These are often referred to as the “Golden Rules” of op-amp design. In addition, one should also keep in mind that when the inverting input is positive with respect to the non-inverting input, the output goes

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<sup>1</sup>see, for example, The Art of Electronics by Horowitz and Hill

negative. If it is negative with respect to the non-inverting input, then the output goes positive. This lab will concern itself with two common op-amp configurations: the inverting and non-inverting amplifier.

Of course, we are considering ideal op-amps, and nothing is ever ideal. However, for many applications there is no need to account for the real devices deviation from ideal. Nevertheless, some of the problems that one might have to account for are:

- (a) The inputs do draw a small current. For FET-input op-amps, this current is typically in picoamps. For very sensitive measuring instruments, this must be taken into account.
- (b) The output voltage is not necessarily zero when the inputs are at the same voltage. This is called the output-offset voltage and was a problem with older op-amps. To compensate for this, two of the pins that controlled the op-amp existed so that a variable resistor could be attached, permitting the output offset voltage to be ‘trimmed’ to zero. These pins are referred to on the data sheets as the ‘offset null’ pins.
- (c) The ‘open loop gain’ of the amplifier is not infinity. Unless you are designing an extremely high gain amplifier, the real gain of the amplifier (several hundred to several million) is never a problem.

There are other things, which one might have to consider, such as temperature coefficients, but they are beyond the scope of this lab. For a more detailed account of designing with real world op amps, see *The Art of Electronics* by Horowitz and Hill.

## 2 Non-Inverting Amplifier

Non-Inverting amplifiers do just as their name implies: they amplify a signal with zero phase shift. Meaning, if a sine wave is the input, then a sine wave with zero phase shift is the output, simply amplified. Recalling, the role of the inverting and non-inverting inputs of the op-amp, described above, it is clear that a non-inverting op-amp should be wired as shown in figure 2.

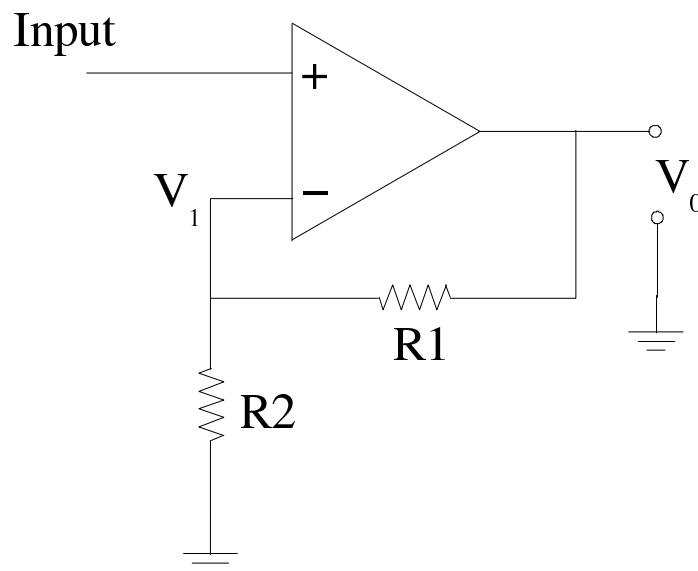


Figure 2: Non-inverting Amplifier

### 2.1 Wiring of the Non-inverting Amplifier

You can now wire up the non-inverting amplifier, but before doing so let us think about how to pick the appropriate resistance values. Suppose a small positive voltage ( $V_{in}$ ) is placed on the non-inverting ('+') input. Since the voltage is on the non-inverting input, the output will swing positive. It will do so until

the voltage on the inverting (‘-’) input is the same as that on the ‘+’ input. The output voltage is  $V_0$  and the voltage on the ‘-’ input is  $V_1$ . Recall the golden rules, with the current at the input equal to zero and the two inputs at the same voltage (i.e no potential difference), Kirchoff’s junction rule at the input node yields:

$$\begin{aligned} \frac{V_1}{R_2} + \frac{V_1 - V_0}{R_1} &= 0 \\ \Rightarrow V_1 &= \frac{R_2}{R_1 + R_2} V_0 \end{aligned} \quad (1)$$

But, we already pointed out that  $V_1$  is the same as the input voltage,  $V_{in}$ ! This fact and Eq. 1; therefore, yield an expression for the gain,  $G$ , of the op-amp:

$$G \equiv \frac{V_0}{V_{in}} = 1 + \frac{R_1}{R_2} \quad (2)$$

*Use this information to construct the circuit in shown in figure 2 choosing  $R_1$  and  $R_2$  (from your “parts box”) such that the gain of the amplifier is approximately 10.*

## 2.2 Input Offset

Now that you have constructed the circuit, *apply zero volts to the input*, put another way, ground the input. One might expect that the output should also be 0V; however, due to the internal transistors and resistors of the op-amp this expectation is not the case. *Measure the output voltage.* This value is your input offset. With 0V applied to the op-amp it can be considered as either a non-inverting or inverting (described below) amplifier; therefore, we can apply the analysis of the non-inverting amplifier with out loss of generality. Recall Eq.1, if we call the offset voltage,  $V_{off}$ , and the error voltage,  $V_{0_{error}}$ , which arises because we do not have the correct bias voltage applied, then:  $V_{0_{error}} = (1 + \frac{R_1}{R_2})V_{off}$ . Hence, if the input voltage becomes too large then with a given offset voltage the error voltage will become very large and the op-amp will not work well.

*Connect the output of the function generator between ground and the non-inverting input. Set the function generator to produce a 4  $V_{pp}$  sine wave signal and measure the output of the amplifier. Is the signal being properly reproduced? If not, why not?*

## 2.3 Measuring Gain

Now that we have a good feel for the operation of an op-amp, we are in a position to explore some of the particulars. To start:

*Set the function generator output so that it is producing a 1  $V_{pp}$  10 kHz sine wave output. Measure the output of the amplifier. Is it exactly 10 times the input? If not, can you explain why? Use the calibration knobs on the voltage range setting of the oscilloscope to make the input and output signals exactly the same height on the oscilloscope’s screen. Are the two signals the same? How do they differ? Draw a diagram.*

## 2.4 Slew Rate

We are now going to explore a new concept in op-amps called slew rate, which is particularly clear in square waves. Therefore, to start *set the function generator so it produces a 500 Hz square wave at 1  $V_{pp}$  and make the same observations as you did for the sine wave.*

To get a feel for the concept of slew rate, yet to be defined, first slowly increase the frequency of the function generator; ensure that the input and output waveforms are scaled with each other and overlapping on the oscilloscope display so that you can clearly see the effect. You should notice that when you get into the kHz range the slope of the output square wave begins to take on a finite value. This observation is a hint at the limiting behaviour of the op-amp. We can define slew rate as follows <sup>2</sup>:

<sup>2</sup>[http://www.engineering.uiowa.edu/~bme080/lecture\\_notes/SlewRateNotes.pdf](http://www.engineering.uiowa.edu/~bme080/lecture_notes/SlewRateNotes.pdf)

“The slew rate (SR) is defined as the maximum rate of change of the output of an op-amp circuit. The SR in general describes the degradation effect on the high frequency response of the active amplifier (one with an op-amp) near or at the rated maximum output voltage swing. This effect is generally due to the compensating capacitor and not to the transistor circuits internal to the op-amp. In short, the SR effect is due to the maximum supplied current available for charging up the compensating capacitor.”

This slew rate is the effect you observed a moment ago. *Increase the frequency to 5 kHz. Is the square wave still being faithfully reproduced? If not, what is the slope of the leading and lagging edges of the square wave in volts per microsecond?*

### 2.4.1 Maths

Recalling that we are looking at the slope of the output voltage, with:

$$V_0 = V_{max} \sin(\omega t),$$

then:

$$\begin{aligned} \frac{dV_0}{dt} &= \omega V_{max} \cos(\omega t), \\ \therefore \frac{dV_0}{dt} \Big|_{t=0} &= \omega V_{max}. \end{aligned}$$

From the definition of slew rate,  $SR = \max \frac{dV_0}{dt}$ , we get:

$$SR = 2\pi f_{max} V_{max} \tag{3}$$

NB: The above derivation is for a sine wave, without loss of generality, we can use this analysis for a square wave because a square wave is a Fourier series of sine waves. To find SR with Eq. 3, *increase the frequency to 10, 15, and 20 kHz and draw diagrams at each step noting the period and amplitude. You should notice the gain becoming less as the frequency increases. If not, simply increase the frequency some more until you observe this behaviour. Make a plot of gain versus frequency. This curve is called the frequency response curve, it tells you what the gain will be for a given input. Determine the maximum square wave signal frequency by noting the frequency at which the slope of your output begins to become finite. Calculate the maximum slew rate for your op-amp.*

## 3 Inverting Amplifier

Finally, let us get a feel for the inverting amplifier. It should be fairly clear how to wire up the inverting amplifier at this point.

The analysis of this circuit is almost as simple as that of the non-inverting amp. Note that there is a ground on the inverting input. By golden rule b, there is a virtual ground on the non-inverting input. Rule a states that the inputs draw no current, so the currents in  $R_1$  and  $R_2$  are the same. (The output will set itself such that  $V_0$ , in combination with the voltage divider network, will produce a ground at the non-inverting input). Therefore, if  $i$  is the common current, the junction rule gives:

$$\begin{aligned} i &= \frac{0 - V_0}{R_1} = \frac{V_{in} - 0}{R_2} \\ \Rightarrow V_0 &= -V_{in} \frac{R_1}{R_2} \end{aligned} \tag{4}$$

Using Eq. 4 and following the procedure of section 2.3 construct and analyse the inverting amplifier with a gain of 10.

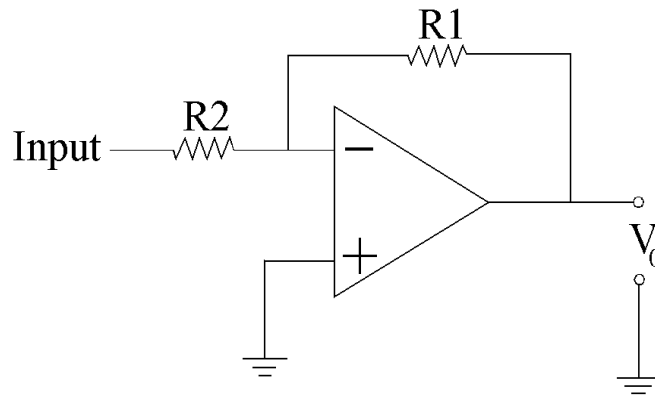


Figure 3: Inverting Amplifier

## 4 Conclusion

A full lab write up is not required for this experiment. Present your results, plots and calculations with any notes made regarding errors encountered during the lab.

*HAVE A NICE DAY!*