2. Operational Amplifiers

2.1 Introduction

Operational amplifiers or *op-amps* are basically *high-gain voltage amplifiers* comprising a number of components such as transistors and resistors, and are packaged as an integrated circuit with connecting pins. Given that the number of transistors alone can be about 20 or so depending on design, a detailed analysis of this *multi-stage amplifier* is beyond the scope of this module. We will therefore treat the op-amp as a 'black box' and study how the overall device functions as part of a circuit. There are many different types of op-amp with varying specifications, but here we will focus on a classic version, namely the 741 op-amp. (For more information about the internal circuitry of the 741 or indeed other types of op-amp, there is an abundance of information available on the internet and in texts regarding these devices).

Figure 2.1.1(a) shows the circuit symbol for the op-amp where, as can be seen, there are five terminals. Firstly, there are dual-supply voltage terminals V_{CC}^{+} and V_{CC}^{-}. These represent a positive and negative voltage respectively. (The '$_C$' written twice in the subscript of 'V_{CC}' originates from the word 'collector' which tells us that the 741 consists of BJTs). This dual-supply typically has a value +15V and -15V with a mid-rail voltage of 0V (ground). Moreover, there are two inputs, one known as the inverting input V_- and the other known as the non-inverting input V_+. These two

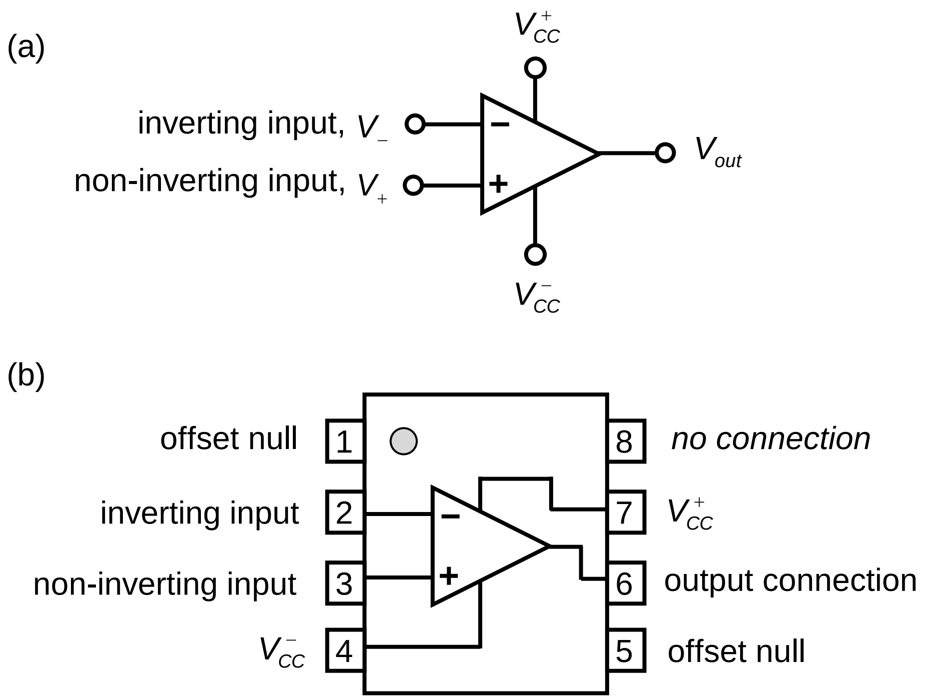


Figure 2.1.1: (a) The op-amp circuit symbol and (b) how the op-amp's terminals correspond to the pins on its packaged integrated circuit. A circular notch is located adjacent to pin 1 for identification.

voltage inputs are both measured relative to ground. Finally, there is an output V_{out}, again also measured relative to ground.

The circuit symbol is shown again in Figure 2.1.1(b) in order to demonstrate how its connections relate to the pins of the packaged integrated circuit. As can be seen, there are two pins concerning an 'offset null' which we will deal with in Section 2.5 later on, when we reflect upon the practicalities of op-amps.

The operation of an op-amp can be summarised as follows:

The output voltage is proportional to the difference between the two input voltages.

Mathematically, this can be written as

$$V_{out} = A_{OL}(V_+ - V_-) \qquad (2.1)$$

where A_{OL} is the 'open-loop' voltage gain which for the 741 can be of the order $2\text{x}10^5$. (We will see in Section 2.3 how we are able to connect a line from the output to the inverting input to 'feedback' a proportion of the output voltage or to 'close' the loop. Open-loop refers to a circuit that does not have such a connection). With such a high open-loop amplification factor, we may expect to see very large voltages appearing at the output of the op-amp. However in reality, V_{out} in Equation (2.1) is limited by two saturation voltages V_{max}^- and V_{max}^+ where

$$V_{max}^- \le V_{out} \le V_{max}^+ \qquad (2.2)$$

The two saturation voltages have values slightly below and above the positive and negative supply voltages respectively where

$$V_{max}^- \approx V_{CC}^- + 1\text{Volt} \qquad (2.3)$$

and

$$V_{max}^+ \approx V_{CC}^+ - 1\text{Volt} \qquad (2.4)$$

As can be seen from Equations (2.3) and (2.4), the output cannot have a voltage greater in magnitude than the op-amp's power supply itself. This means that unless the difference between the two inputs is very small, when operated in 'open-loop' mode, the amplifier will typically saturate.

Normally in an op-amp circuit we would hold one of the inputs at a fixed value whilst the other input is allowed to vary above or below this fixed 'reference' voltage. Figure 2.1.2 demonstrates this where the non-inverting input V_+ is given a fixed voltage (known as V_{REF}) and the inverting input V_- (which now becomes V_{in}) is made to vary above and below this value. As can be seen, when the op-amp is not saturating (i.e. the region between the vertical dashes), there is a linear relationship between input and output i.e. the amplifier's output is directly proportional to variations in the difference between the two inputs.

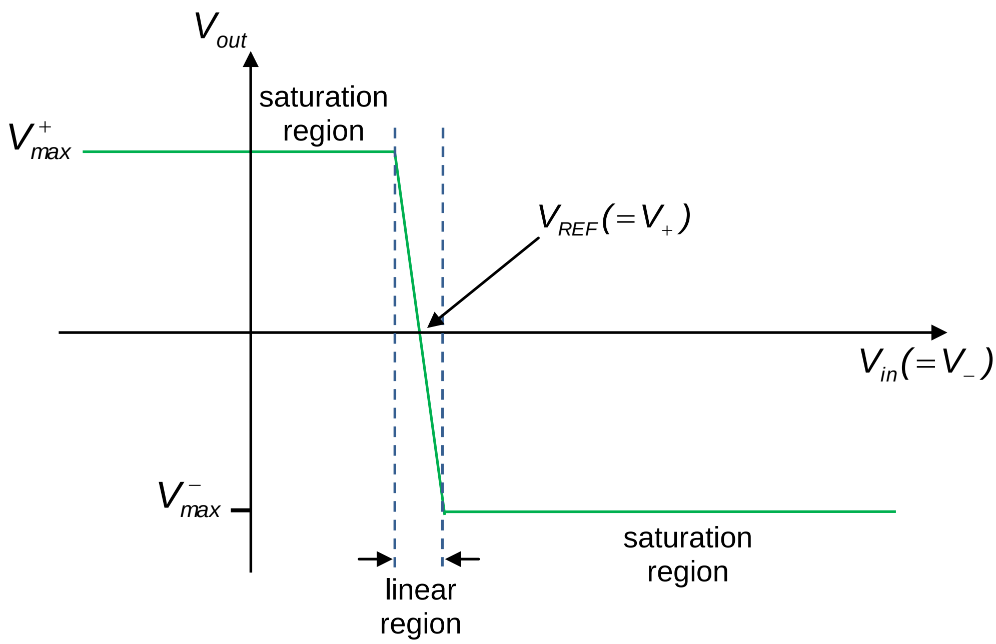


Figure 2.1.2: With the non-inverting input of the op-amp held at a fixed reference voltage, this graph plots output voltage as a function of variations in the inverting input voltage.

With reference to Figure 2.1.2, in order to quantify the range of voltages for which the input can vary without causing the op-amp to saturate, we can begin by looking at the maximum range of possible output voltages and taking into consideration the amplifier's gain. With a dual supply of ±15V and thus saturation values of about ±14V from Equations (2.3) and (2.4) we can say

$$\frac{\text{range of } V_{out} \text{ between saturation limits}}{A_{OL}} = \text{range of } V_{in} \text{ within linear region} \qquad (2.5)$$

$$\Rightarrow \frac{V^{+}_{max} - V^{-}_{max}}{A_{OL}} = \frac{14\text{V} - (\text{-}14\text{V})}{2\text{x}10^{5}} = \frac{28}{2\text{x}10^{5}} = 140\mu\text{V} \qquad (2.6)$$

However, given that the value of 140µV corresponds to values of $V_{in}(=V_{-})$ ranging equally above and below $V_{REF}(=V_{+})$ then the actual difference between the two inputs V_{+} and V_{-} is never any greater than half of this value i.e. 70µV. In other words, if the difference between the two inputs of the 741 op-amp is greater than about 70µV, then the output will saturate. Whether the output saturates to a positive or negative value depends on Equation (2.1). Clearly if the inverting input has a greater voltage than the non-inverting input, the output will be negative and vice versa.

Note: The 741 op-amp gain of $2x10^5$ is approximately correct for low frequencies. However, as input frequency increases, the op-amp gain will roll off (gradually decrease). We will discuss more about this in Section 2.5.

2.2 Non-linear applications (op-amp as a comparator)

It was mentioned in the previous section that the op-amp can be used in two basic modes: open-loop and closed-loop. So far we have not analysed the closed-loop circuit – we save this for Section 2.3. Here, we will continue to look at the properties of the open-loop circuit which as we have seen, will saturate given a small difference between its two inputs, and hence can be described as *non-linear*.

The property of open-loop 'saturation' can be useful for some applications. If we assume that the small difference in voltage between the inputs which causes the op-amp to saturate is negligible compared to the saturation output voltage itself, then we effectively have a device that can 'compare' the two input voltages. In fact such a device is called a *comparator*. The op-amp comparator will compare the two inputs and will give a (saturated) positive or negative output depending on which of the inputs is larger.

Arrays of many comparators can be used for example in analogue to digital converters (ADCs), although circuits of this kind go beyond the scope of this text. Some more simple applications of comparator circuits are shown in the following sections.

2.2.1 Sine-wave to square-wave converter

If we hold the inverting input (V_-) at a fixed (reference) voltage and connect a sine-wave generator to the non-inverting input (V_+), as long as the sine wave has a reasonable amplitude, say ~1V, then the output will be very nearly a square wave. This is because the time during which the input is in the range ±70μV is very small compared to the overall period of the waveform.

With the inverting input (V_-) at 0V, the output voltage of the op-amp will switch between positive and negative saturation levels as the sine-wave input passes through zero. This is demonstrated in Figure 2.2.1 where the particular circuit and waveforms are shown. Note that the frequency of the output waveform is the same as the frequency of the sine-wave input. Moreover, the output is in phase with the input (i.e. the output rises as the input rises and falls as input falls) because we have chosen the non-inverting input to be V_{in} (in contrast to the example shown in Figure 2.1.2 above where the *inverting* input was used as V_{in}).

The sine-wave to square-wave converter can also be thought of as a type of <u>zero crossing detector</u> given that the output is basically identifying when the input crosses the 0V mark by displaying positive or negative saturation.

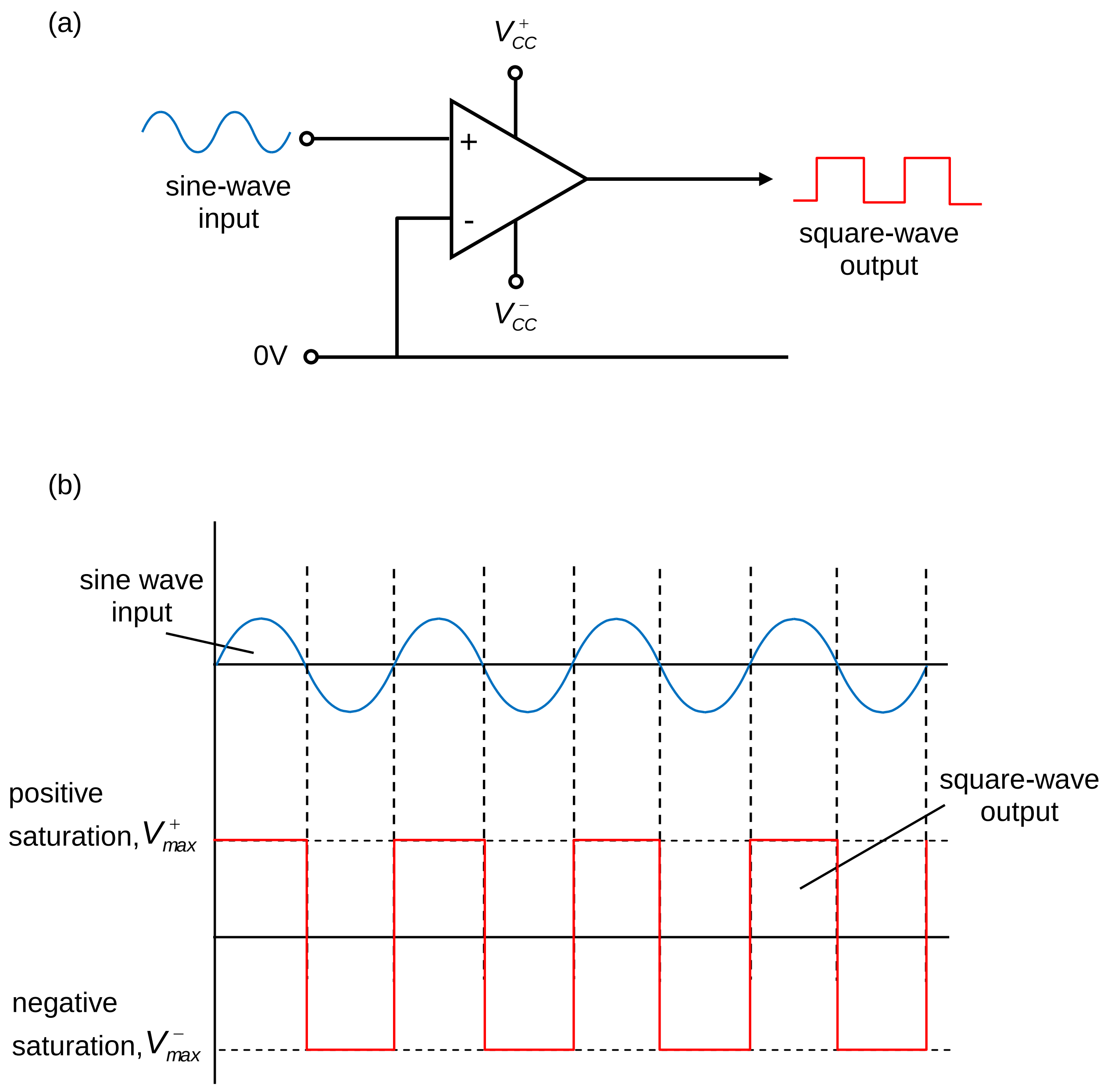


Figure 2.2.1: A sine-wave to square-wave converter which utilises an op-amp comparator. (a) The basic circuit and (b) the input and output waveforms.

2.2.2 Square-wave generator with variable pulse width

By this time applying a *triangular* waveform to the non-inverting input, and a *variable reference* (V_{REF}) to the inverting input, a variable pulse width (mark-space ratio) can be produced. The circuit and the input and output waveforms are shown in Figure 2.2.2, where the two graphs give examples of two different values of V_{REF}. As V_{REF}

increases, then V_+ is greater in value than V_{REF} for a shorter period of time over its cycle, and therefore the saturated output V^+_{max} has a shorter duration.

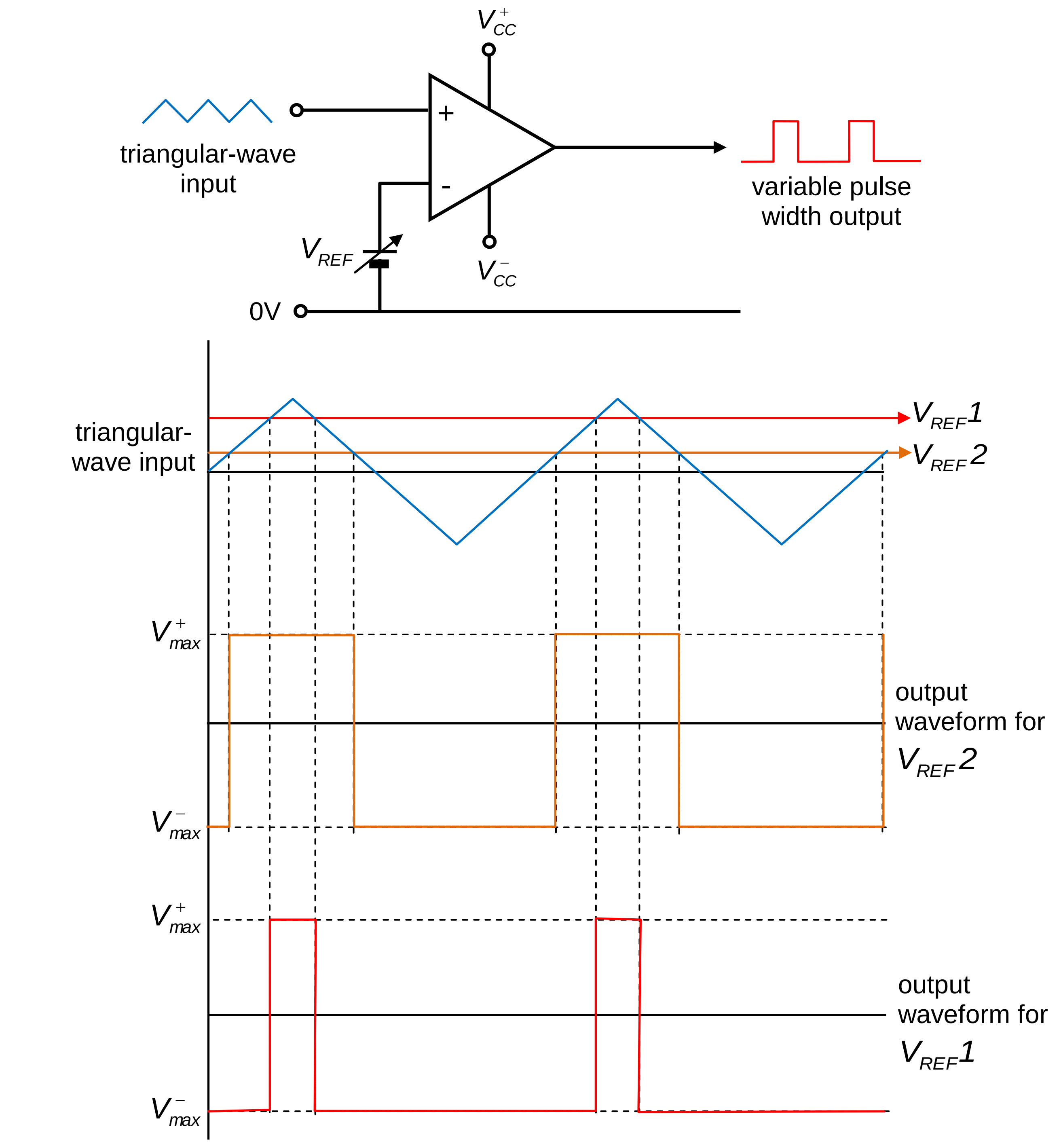


Figure 2.2.2: An op-amp comparator square-wave generator with variable pulse width capability. (a) The simple circuit and (b) examples of waveforms.

2.2.3 High-temperature warning circuit

This high-temperature warning circuit uses a simple bridge circuit to provide the input voltage for the op-amp. The temperature-sensing element of the circuit is a negative temperature coefficient (NTC) thermistor. A description of the NTC thermistor was given in Section 1.6.7, but as a reminder, the resistance of this type of thermistor decreases with increase in temperature.

A bridge circuit consists two pairs of series resistors, connected in parallel. Each parallel pair are further connected or 'bridged' by another circuit component from the centre of each parallel pair. Here the circuit is 'bridged' by the op-amp. Probably the best-known type of bridge circuit is the 'Wheatstone Bridge' which is used principally for measuring resistance.

A schematic of the circuit is shown in Figure 2.2.3, where it can be seen that the inverting input of the op-amp is held at a constant reference voltage (+3V) by the '*RR*' potential divider. Here, the particular op-amp is a 'single-supply' op-amp (as opposed to dual-supply).

At low temperatures the resistance of the thermistor is much higher than the values of fixed resistors *R* (and therefore has more than 3V across it). Consequently the voltage V_+ is lower than V_{REF} and the output voltage is 0V. The warning lamp will be switched off.

If the temperature rises, the resistance of the thermistor sensor will fall. Once the thermistor resistance value is fractionally less than *R* Ohms, V_+ will be greater than V_{REF} and the output voltage of the op-amp will switch to its positive saturation value (approximately +6V) and the warning lamp will illuminate.

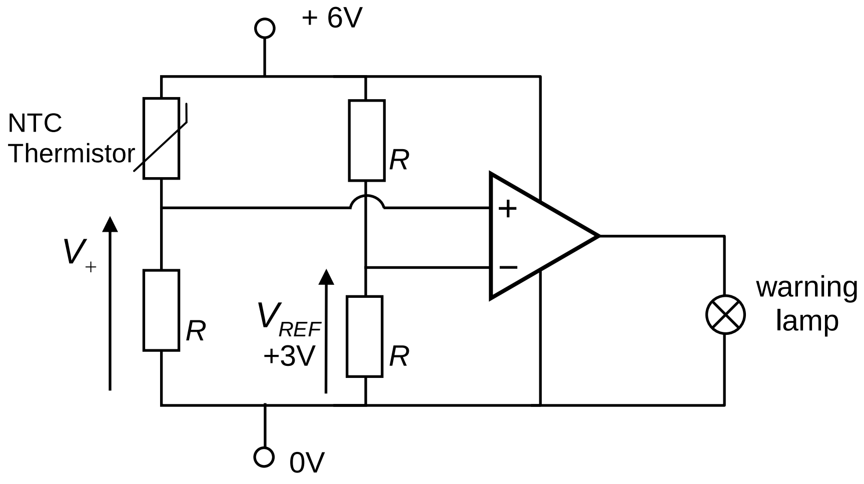


Figure 2.2.3: Use of an op-amp comparator to produce a high-temperature warning circuit.

2.3 Linear applications (op-amp with feedback)

The comparator circuits described above did not include a feedback element and were therefore open-loop. However, a more common use of the operational amplifier is with feedback, i.e. closed-loop. Circuits with feedback produce an output that varies *linearly* with changes to its input over the full operating range.

The feedback connection runs from the output to the inverting input which in turn causes the inverting input to be driven towards the non-inverting input value, by 'feeding back' a proportion of the output voltage. If the inverting input rises to become greater than the non-inverting input, then the output voltage will move towards a more negative value, which in turn will drive the inverting input back down. If on the other hand, the inverting input falls to become less than the non-inverting input, then the output will be positive and drive the inverting input back up. This is the basic principle of 'feedback', although there is more to the story as we will see below.

2.3.1 Golden rules for op-amp circuit analysis

In order to analyse some typical variations of the closed-loop op-amp, we must apply two approximate rules. The rules are known as the *golden rules of ideal linear op-amp operation*, and will help us in the first instance to analyse the circuits relatively straightforwardly.

> The golden rules are as follows:
>
> (i) The output will do whatever is necessary to make the voltage difference between the two inputs zero.
> (ii) No current flows into the two inputs.

2.3.2 Examples of (closed-loop) op-amp circuits

There are several typical variations of operational amplifier circuits with feedback and we shall examine these below. In each case, a *general transfer function* will be derived which tells us what the output V_{out} is as a function of input V_{in} for the particular circuit. As will be seen, many of the applications are based on mathematical functions - indeed op-amps were originally designed to perform mathematical functions in analogue computers (before digital processors took over). Op-amps continue to have many applications and to be used widely, for example in active filters, control systems and audio preamplifiers to mention just a few.

2.3.2.1 Inverting amplifier

We begin with the simple *inverting amplifier* which is shown in Figure 2.3.2.1. Note that the non-inverting input has a fixed reference of 0V and that V_{in} is connected to the inverting input via resistor R_1. A feedback resistor R_F is positioned between the output V_{out} and the inverting input.

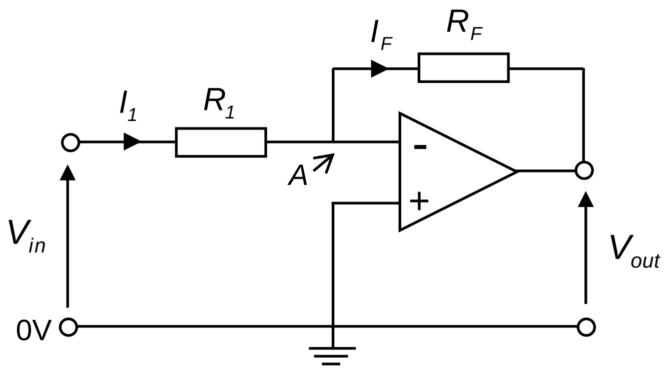


Figure 2.3.2.1: The inverting operational amplifier.

Given that the non-inverting input is connected to ground, we can say that point *A* is also at a potential of 0V from golden rule (i). (In fact point *A* is often referred to as a *virtual earth* for this reason). We will label the potential difference of point *A* relative to ground as V_A in order that we can include it in the calculations that follow.

We begin by determining the current I_1. Given that the potential difference across the resistor R_1 is V_{in} - V_A, then from Ohm's Law

$$I_1 = \frac{V_{in} - V_A}{R_1} = \frac{V_{in}}{R_1} \tag{2.7}$$

Next, if we use Kirchhoff's Voltage Law, (which was covered in an earlier part of this module), we can say that

$$V_A - I_F R_F - V_{out} = 0 \tag{2.8}$$

But given that $V_A = 0$ from golden rule (i), and $I_1 = I_F$ from golden rule (ii), then by combining Equations (2.7) and (2.8) we finally get

$$V_{out} = -I_1 R_F = -\frac{V_{in}}{R_1} R_F \tag{2.9}$$

Finally, we arrive at the *general transfer function for the inverting amplifier* which can be stated as follows:

$$\boxed{V_{out} = -\frac{R_F}{R_1} V_{in}} \tag{2.10}$$

As can be seen, the output is inverted as expected, and has a gain factor determined by R_F and R_1 only.

2.3.2.2 Non-inverting amplifier

As can be seen in Figure 2.3.2.2, in the case of the *non-inverting amplifier* V_{in} is directly applied to the non-inverting input whilst the feedback line continues to be connected to the inverting input, this time via resistor R_1. The feedback line is also connected to ground via resistor R_2. Once again we identify a point *A*, where V_A is the potential difference between point *A* and ground.

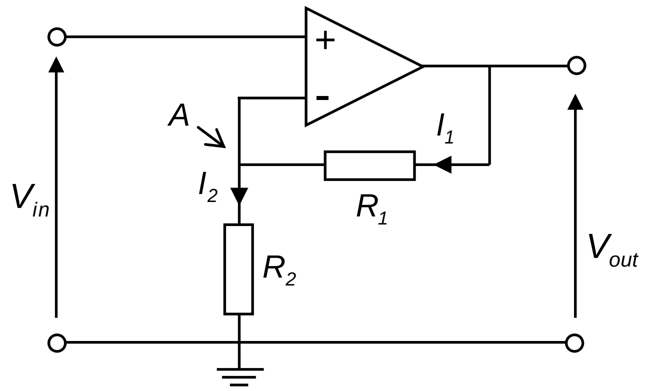


Figure 2.3.2.2: The non-inverting operational amplifier.

By golden rule (i), we can first of all state that

$$V_{in} = V_A = I_2 R_2 \tag{2.11}$$

Moreover, as a consequence of golden rule (ii), we can write

$$I_1 = I_2 \tag{2.12}$$

Also, by once again using Kirchhoff's Voltage Law, we can say that

$$V_A + I_1 R_1 - V_{out} = 0 \tag{2.13}$$

From Equations (2.11), (2.12) and (2.13) we get

$$V_{out} = V_A + I_1 R_1 = V_A + I_2 R_1 = V_{in} + \frac{V_{in}}{R_2} R_1 \tag{2.14}$$

Finally we rearrange slightly to reveal the *general transfer function for the non-inverting amplifier* which can be stated as follows:

$$\boxed{V_{out} = \left(1 + \frac{R_1}{R_2}\right) V_{in}} \tag{2.15}$$

In Equation (2.15), the output is non-inverted as expected. Interestingly, the amplifier once again has a gain which depends on circuit resistors only.

2.3.2.3 Voltage follower

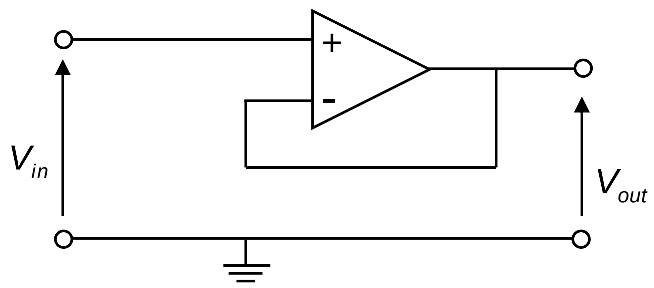


Figure 2.3.2.3: The voltage follower, or buffer circuit.

The *voltage follower* (also sometimes called a *buffer*) has an analysis that is very simple. With reference to Figure 2.3.2.3, given that V_{out} is connected directly to the inverting input, which by golden rule (i) is equal to the input voltage V_{in}, we can write the *general transfer function for the voltage follower* directly as follows:

$$\boxed{V_{out} = V_{in}} \qquad (2.16)$$

The voltage follower op-amp appears on the face of it to be rather useless because its output is apparently equivalent to its input! However, there is more to it than this! All op-amps have very high input impedances – in fact our golden rule (ii) requires that op-amps have infinite input impedance! (We will discuss this statement in practical terms in Section 2.5). *Moreover, all op-amps have low output impedances.* As a consequence of these parameters, the voltage follower is very useful when positioned between a high impedance voltage source and a low impedance load. Here, the op-amp prevents the voltage in the system from being 'divided up' such that most of the voltage sits across the output of the high impedance source, with little voltage across the low impedance load. The voltage follower's input and output impedances will match more closely the source and load impedances respectively. Use of a voltage follower in this way ensures that significant signal loss from source to load is prevented.

2.3.2.4 Summing amplifier

The *summing amplifier*, also known as an *adder circuit*, is shown in Figure 2.3.2.4. The op-amp circuit is basically an extension of the inverting amplifier described above, this time involving a number of inputs in parallel.

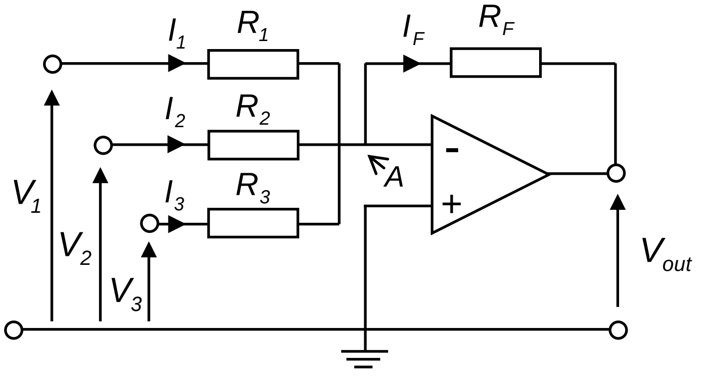


Figure 2.3.2.4: The summing operational amplifier.

The number of inputs of the summing amplifier can vary depending on the application, although three are shown in this example. The analysis is the same however many inputs there are, except that an extra term appears throughout the derivation and in the final transfer function for each additional input.

As determined previously, golden rule (i) tells us that

$$V_A = 0 \tag{2.17}$$

As a consequence, we can use Ohm's Law to say that

$$I_1 = \frac{V_1}{R_1},\ I_2 = \frac{V_2}{R_2} \text{ and } I_3 = \frac{V_3}{R_3} \tag{2.18}$$

Moreover, from Kirchhoff's Current Law and golden rule (ii) we know that

$$I_F = I_1 + I_2 + I_3 \tag{2.19}$$

Also, Kirchhoff's Voltage Law gives

$$V_A - I_F R_F - V_{out} = 0 \tag{2.20}$$

Finally, by combining Equations (2.17) – (2.20) we end up with the *general transfer function for the summing amplifier*

$$V_{out} = -\left(\frac{R_F}{R_1}V_1 + \frac{R_F}{R_2}V_2 + \frac{R_F}{R_3}V_3\right) \qquad (2.21)$$

where any extra inputs would simply result in extra terms within the brackets

$$... + \frac{R_F}{R_i}V_i + ... \text{ etc.}$$

As can be seen in Equation (2.21) the summing amplifier provides a weighted sum of the input voltages where the weighting is determined by the resistor values. This can be used for example as a simple <u>*digital to analogue converter (DAC)*</u>*, where each input represents a 'bit' of information. (We will see in the section of this course which focusses on digital electronics that the digital binary system of 'ones' and 'zeros' is characterised by two distinguishable voltages). With 4 inputs, a 4-digit binary number can be converted to an analogue value by weighting the inputs to match the binary scale e.g.*

$$1111_2 = 1x2^3 + 1x2^2 + 1x2^1 + 1x2^0 = 8 + 4 + 2 + 1 = 15_{10}$$

Thus by selecting the input resistors such that the R_F/R_i *values are weighted 8, 4, 2, 1 relative to each other, we will achieve a single analogue (voltage) value for the digital 4 bit input.*

If all the input resistors in the summing amplifier R_1 *to* R_i *are made to be variable resistors, then the circuit could be used as the basis of an* <u>*audio mixer*</u>*, used for example, to mix percussion and instrument sounds to any proportion in an electronic keyboard. In this case, overall volume can be set by a variable resistor in series with* R_F *.*

<u>Note:</u> If the summing amplifier is to be used for *adding non-weighted values*, i.e. a straightforward linear adder, this can be achieved by selecting resistors such that

$$R_1 = R_2 = R_3 = R_F \qquad (2.22)$$

which will give the *general transfer function:*

$$V_{out} = -(V_1 + V_2 + V_3) \qquad (2.23)$$

2.3.2.5 Differential amplifier

The *differential operational amplifier* seen in Figure 2.3.2.5 has an output which is proportional to the difference between its two inputs. When used for analogue computers the differential amplifier was used as the ‘subtract’ mathematical function. Nowadays, it is used as the basis of circuits where *small differences* in voltage are required to be measured. For example in *medical applications*, differential amplifiers can be used within circuits which monitor the electrical activity of the heart and the brain (electrocardiogram and electroencephalogram respectively).

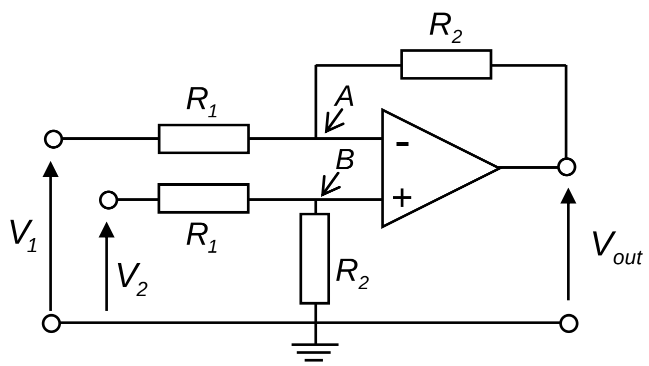


Figure 2.3.2.5: The differential operational amplifier.

With reference to Figure 2.3.2.5, golden rule (ii) tells us that no current flows into either op-amp input, therefore the voltage V_B at point *B* (relative to ground) is

$$V_B = \frac{R_2}{R_1 + R_2} V_2 \tag{2.24}$$

Moreover

$$V_A - V_{out} = \frac{(V_1 - V_{out})R_2}{R_1 + R_2} \tag{2.25}$$

and golden rule (i) tells us that

$$V_A = V_B \tag{2.26}$$

Solving Equation (2.25) for V_A and plugging into equation (2.26) along with Equation (2.24) gives

$$\frac{(V_1 - V_{out})R_2}{R_1 + R_2} + V_{out} = \frac{R_2}{R_1 + R_2} V_2 \tag{2.27}$$

Multiplying Equation (2.27) throughout by $\frac{R_1 + R_2}{R_2}$ gives

$$(V_1 - V_{out}) + V_{out}\frac{R_1 + R_2}{R_2} = V_2 \qquad (2.28)$$

Rearranging gives

$$V_{out}\left(\frac{R_1 + R_2}{R_2} - 1\right) = V_2 - V_1 \qquad (2.29)$$

and therefore

$$V_{out}\left(\frac{R_1}{R_2} + 1 - 1\right) = V_2 - V_1 \qquad (2.30)$$

Finally, we end up with the *general transfer function for the differential amplifier*

$$\boxed{V_{out} = \frac{R_2}{R_1}(V_2 - V_1)} \qquad (2.31)$$

where it is clear that the output voltage gives the difference between the two input voltages weighted by the factor $\frac{R_2}{R_1}$.

Note that in the differential op-amp circuit we have chosen to use two sets of equivalent resistors R_1 and R_2. Had we chosen to make all four resistors an equal value we would have ended up with the *general transfer function*

$$\boxed{V_{out} = V_2 - V_1} \qquad (2.32)$$

2.3.2.6 Integrator

The *op-amp integrator* performs the mathematical operation of integration. As a consequence, the magnitude of the voltage output is determined by the length of time a voltage is present at its input. More specifically, as we will see in the analysis below, the output is proportional to the integral of its input, with respect to time.

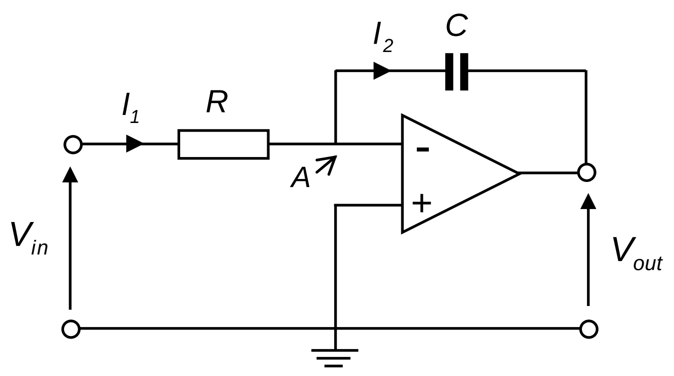


Figure 2.3.2.6: The operational amplifier integrator

With reference to the integrator circuit of Figure 2.3.2.6, from golden rule (i)

$$V_A = 0 \tag{2.33}$$

Moreover, Ohm's Law informs us that

$$I_1 = \frac{V_{in}}{R} \tag{2.34}$$

and Kirchhoff's Voltage Law gives

$$V_A - \frac{Q}{C} - V_{out} = 0 \tag{2.35}$$

(You will have studied how voltage varies across a capacitor,
i.e. $V_C = \dfrac{Q\,(charge\,stored)}{C\,(capacitance)}$ in a previous part of this module).

Additionally, from golden rule (ii)

$$I_1 = I_2 \tag{2.36}$$

and the charge stored by the capacitor is

$$Q = \int I_2 dt \tag{2.37}$$

From Equations (2.33) and (2.35) - (2.37) we get

$$V_{out} = -\frac{Q}{C} = -\frac{1}{C}\int I_1 dt \tag{2.38}$$

and finally, from Equations (2.34) and (2.38), the *general transfer function for the op-amp integrator*

$$\boxed{V_{out} = -\frac{1}{RC}\int V_{in}dt} \tag{2.39}$$

where the output voltage is equal to the time integral of the input voltage weighted by the factor $-\frac{1}{RC}$.

Integrator circuits are useful as <u>ramp generators</u>. If we apply a constant positive or negative voltage at the integrator's input, the output ramps down or up at a steady rate. Ramp generators can be used in timing circuits given that the output voltage is proportional to time elapsed since the input was first applied.

2.3.2.7 Differentiator

Finally we come to the last example of an op-amp circuit – *the op-amp differentiator* which is shown in Figure 2.3.2.7.

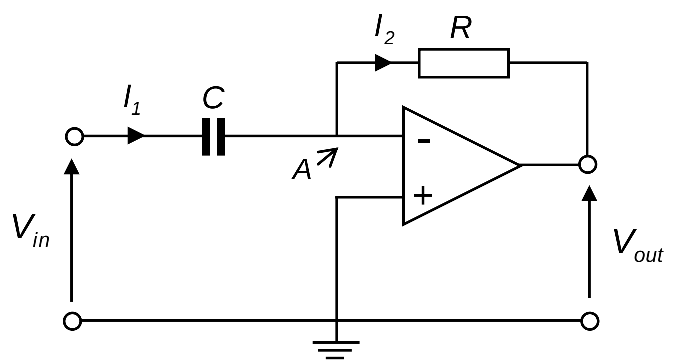


Figure 2.3.2.7: The operational amplifier differentiator

Golden rule (i) gives

$$V_A = 0 \tag{2.40}$$

and therefore

$$V_{in} = \frac{Q}{C} \tag{2.41}$$

Taking the time derivative of Equation (2.41) gives

$$\frac{dV_{in}}{dt} = \frac{1}{C}\frac{dQ}{dt} = \frac{1}{C}I_1 \qquad (2.42)$$

Moreover, Kirchhoff's Voltage Law along with Equation (2.40) gives

$$V_{out} = -I_2 R \qquad (2.43)$$

and by golden rule (ii) we get

$$I_1 = I_2 \qquad (2.44)$$

From Equations (2.42) – (2.44) the *general transfer function for the op-amp differentiator* can be written as

$$\boxed{V_{out} = -RC\frac{dV_{in}}{dt}} \qquad (2.45)$$

Equation (2.45) tells us that the output of the op-amp differentiator is the time derivative of the input, weighted by the factor $-RC$.

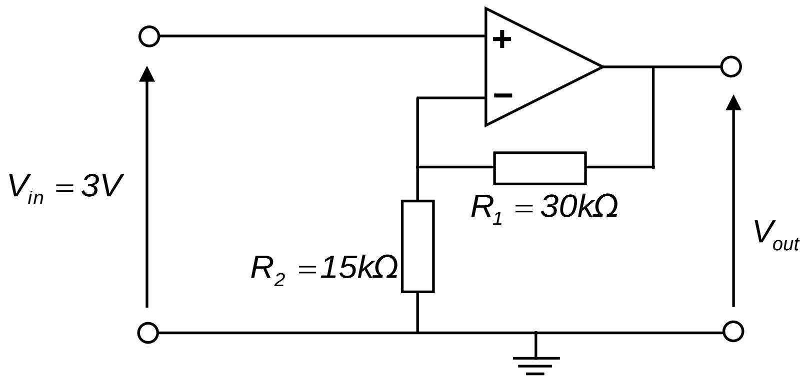
2.4 Op-amp worked examples

In this section there are some simple example questions with solutions on op-amps which should help to consolidate understanding of this topic and assist in developing an approach to op-amp problem-solving.

<u>NOTE</u>: In *Example 3* a distinction is made between a *general transfer function* and a *circuit transfer function* which you should be aware of.

Example 1

Find V_{out} for the following circuit:



Example 1 (solution)

The first step is to identify what type of op-amp it is. From the previous sections, we can see that it is a *non-inverting amplifier*.

The *general transfer function* for the non-inverting amplifier (identical to Equation (2.15)), is

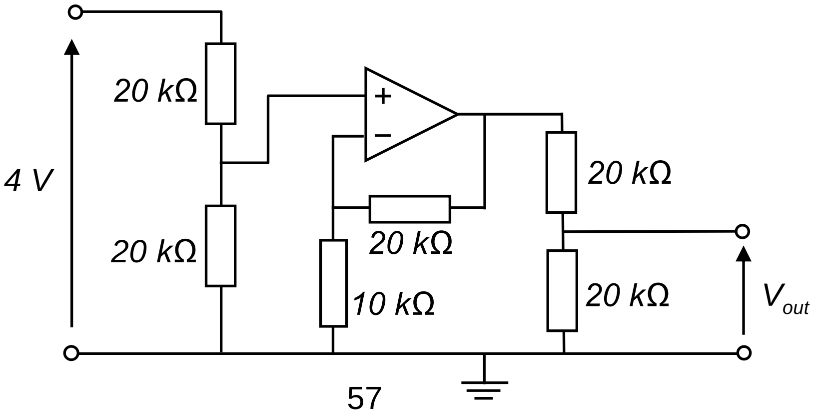
$$V_{out} = \left(1 + \frac{R_1}{R_2}\right)V_{in} \qquad (2.46)$$

therefore

$$V_{out} = \left(1 + \frac{30k\Omega}{15k\Omega}\right)3V = 9V \qquad (2.47)$$

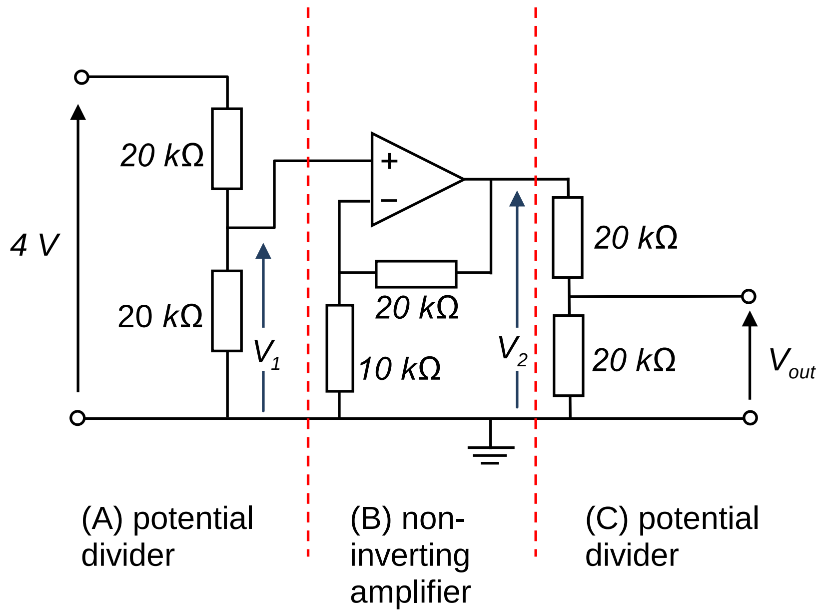
Example 2

Find V_{out} for the following circuit:



Example 2 (solution)

At first sight, this problem may seem complicated. However, it is just a case of breaking the circuit down into its component parts, and solving bit by bit. Below is the same circuit, with its component parts more visible.



As can be seen, the circuit is just a non-inverting amplifier (B), with a potential divider at its input (A) and a potential divider at its output (C). The input voltage to the *non-inverting op-amp part of the circuit* is labelled V_1 and the voltage at the output of the *non-inverting op-amp part of the circuit* is labelled V_2 .

By inspection, given that the potential divider (A) consists of 2 resistors of equal value, we can conclude that

$$V_1 = \frac{V_{in}}{2} = 2V \qquad (2.48)$$

Now that we know what V_1 is, we know what the input voltage is to the op-amp: 2V. Now we can use the *general transfer function* for the non-inverting amplifier, remembering that the output from the op-amp is V_2 i.e.

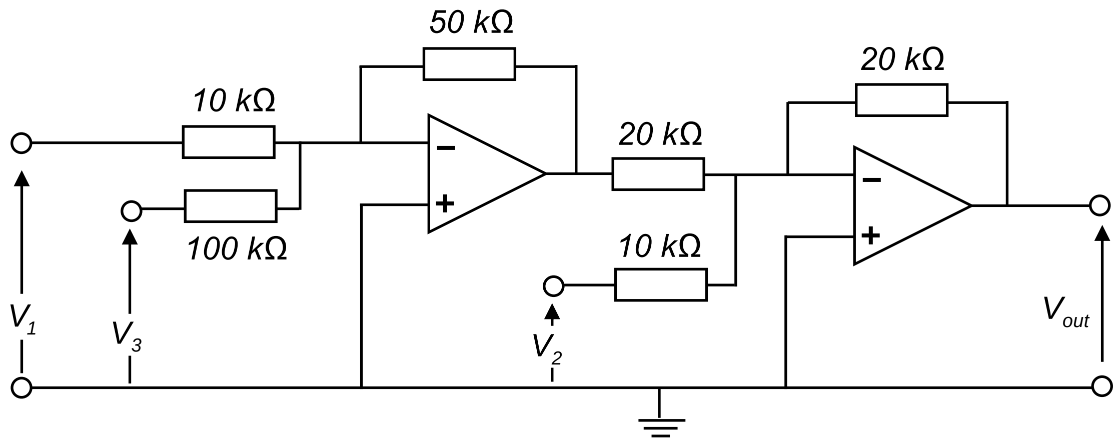
$$V_2 = \left(1 + \frac{20k\Omega}{10k\Omega}\right)2V = 6V \qquad (2.49)$$

Finally, V_2 is subject to another potential divider (C) at the output of the circuit. Again, by inspection we can see that this potential divider consists of two equal resistors therefore

$$V_{out} = \frac{V_2}{2} = 3V \qquad (2.50)$$

<u>*Example 3*</u>

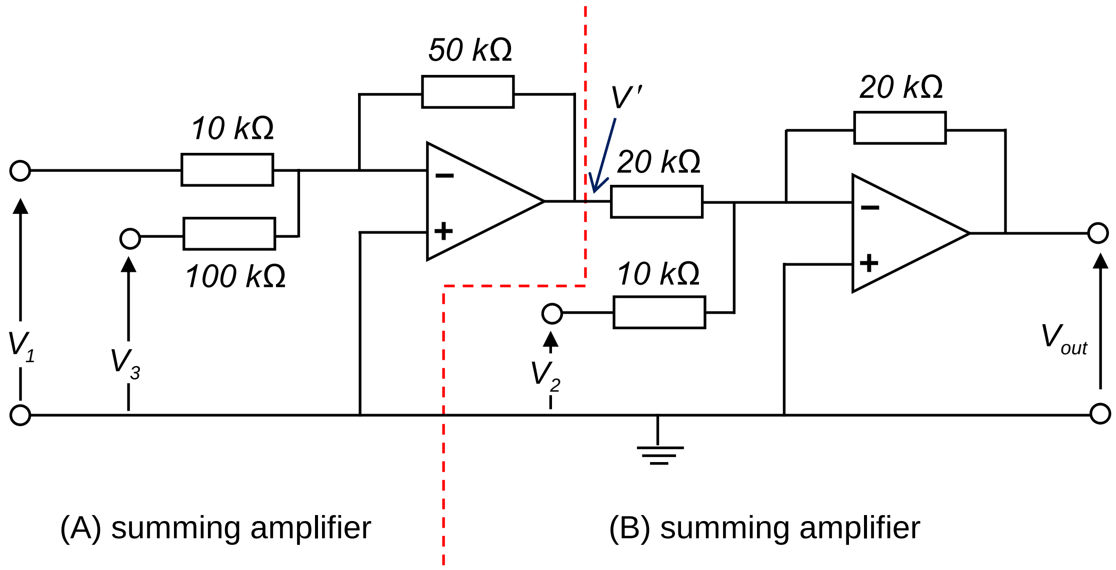
For the circuit shown below obtain the *circuit transfer function*.



<u>*Example 3 (solution)*</u>

Here, we have more than one op-amp in the circuit, and the output of one op-amp serves as part of the input of the other op-amp. Moreover, the question is asking for a *circuit transfer function* (sometimes called the *voltage transfer function*). This is the transfer function for this particular (complete) circuit as opposed to a *general transfer function* which is applied to the individual standard op-amp circuits described previously.

The first step in tackling the problem is to divide the circuit up into its constituent parts i.e.



As can be seen, the circuit consists of two summing amplifiers. The output from the first amplifier (A) is labelled V'.

The *general transfer function for the summing amplifier* (identical to Equation (2.21)) is

$$V_{out} = -\left(\frac{R_F}{R_1}V_1 + \frac{R_F}{R_2}V_2 + \frac{R_F}{R_3}V_3\right) \qquad (2.51)$$

Adapting Equation (2.51) to accommodate two inputs only gives

$$V_{out} = -\left(\frac{R_F}{R_1}V_1 + \frac{R_F}{R_2}V_2\right) \qquad (2.52)$$

Therefore in the case of section (A) of the circuit (with inputs V_1 and V_3) we get

$$V' = -\left(\frac{50k\Omega}{10k\Omega}V_1 + \frac{50k\Omega}{100k\Omega}V_3\right) = -5V_1 - 0.5V_3 \qquad (2.53)$$

Consequently the output from the second op-amp (B), and therefore the output from the circuit is

$$V_{out} = -\left(\frac{20k\Omega}{20k\Omega}V' + \frac{20k\Omega}{10k\Omega}V_2\right) = -\left(-5V_1 - 0.5V_3 + 2V_2\right) \qquad (2.54)$$

Finally, the *circuit transfer function* becomes

$$V_{out} = 5V_1 - 2V_2 + 0.5V_3 \qquad (2.55)$$

2.5 Practical considerations for op-amps

So far in our analysis of (closed-loop) op-amps, we have applied two approximate rules: *the golden rules of linear op-amp operation*. Application of these rules enabled us to derive general transfer functions of particular op-amp circuits relatively easily. On a practical level, the derived general transfer functions work very well and can be relied upon as such for circuit design. However, there are a handful of additional considerations that we must be mindful of in order to be successful in our use of op-amps. These are discussed below.

(i) Bias currents

Our derivations of the general transfer functions of typical op-amp circuits were partly based upon the assertion given in golden rule (ii), which stated that ‘no current flows into the two inputs’.

In fact, currents *do* flow into each input and are essential for the op-amp to function properly. Indeed a small current needs to flow into both op-amp inputs in order to bias the input transistors, especially in op-amps with BJTs. However, these DC currents, known as *bias currents*, are very small and this is why the golden rule works so well. Typically, for the 741 op-amp, the bias currents are specified as less than 500nA, and therefore small enough to be ignored. For FET-based op-amps, bias currents are of the order of a few picoamps.

(ii) Input voltage offset

When the two op-amp inputs are equal, the output voltage should be zero. In practical amplifiers, this may not be the case because of asymmetries between the internal circuits driven by the inverting and non-inverting inputs. A potentiometer can be connected between the op-amp *offset null* terminals (introduced in Figure 2.1.1) to adjust the output voltage to zero. By connecting the ends of the potentiometer (typically of value 10kΩ) to the offset null terminals and also to the V_{CC}^{-} as shown in Figure 2.5.1 the output can be adjusted to 0V.

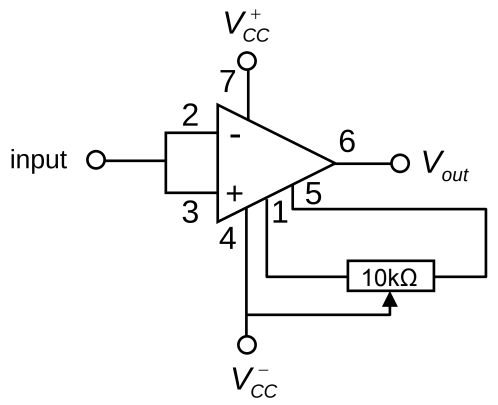


Figure 2.5.1: Necessary connections for making adjustments to the op-amp 'offset null'. The numbered op-amp pins first introduced in Figure 2.1.1 are also shown.

(iii) Slew rate

Slew rate is the maximum rate at which the output voltage of an operational amplifier can swing, and it is generally measured in volts per microsecond, a typical value being 10V/µs. A slew rate that is not sufficient could, for example, lead to a square wave being generated with unacceptable distortion as shown in Figure 2.5.2. Clearly an op-amp with an appropriate slew rate needs to be chosen for each application.

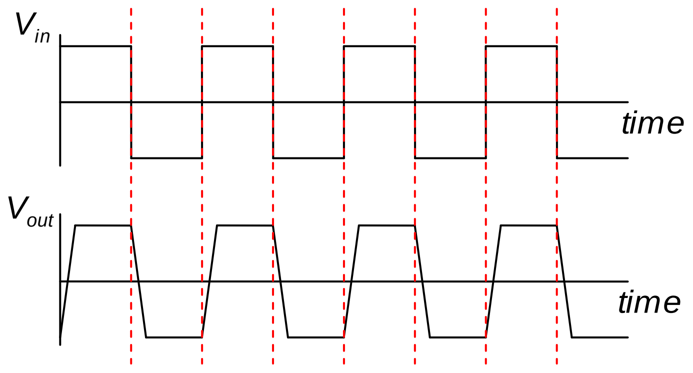


Figure 2.5.2: Distortion of a square wave due to slew rate limiting

(iv) Frequency response

The op-amp gain calculated with DC does not apply at higher frequencies. To a first approximation, as can be seen in Figure 2.5.3, the gain of a typical op-amp is inversely proportional to frequency. This means that an op-amp is characterized by its *gain-bandwidth product*. For example, an op-amp with a gain bandwidth product of 1 MHz would have a gain of 5 at 200 kHz, and a gain of 1 at 1 MHz. This low-pass characteristic is introduced deliberately, to avoid oscillation at high frequencies.

Typical low cost, general purpose op-amps exhibit a gain bandwidth product of a few megahertz. However, high speed op-amps can achieve gain bandwidth products of hundreds of megahertz.

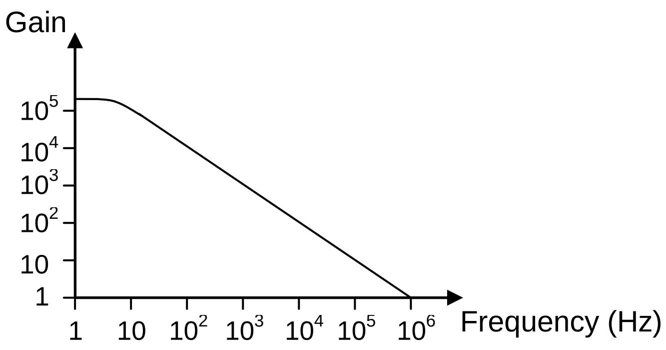


Figure 2.5.3: Frequency response of the 741 operational amplifier.

Note: with regards to the two *'golden rules'* introduced in Section 2.3.1, we have addressed one of these in the above section on bias currents: golden rule (ii). In doing so, we justified use of this approximate rule. Use of golden rule (i) however, has not been justified directly. As a final note to this section on op-amps we must therefore remind ourselves that golden rule (i) is also an approximation. However, use of rule (i) can be justified because the gain of an op-amp is very high as we have already discussed and therefore the voltage difference between the two inputs will always constitute a tiny fraction of the output. For example, the 741 will have a difference of inputs in the region of 0.001% of its output. This is small enough to ignore and explains why golden rule (i) works well.