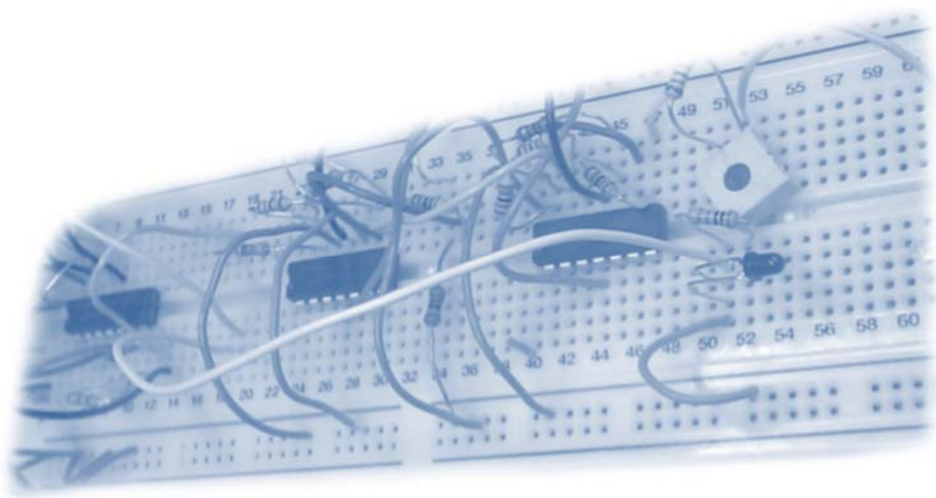
BIOENGINEERING - YEAR 1

BE1.HEEL – Electrical Engineering 1st year Laboratory

Laboratory Handbook

Circuits Practical 2

Op-Amp Applications



Operational Amplifier Applications

Equipment Required:
1 Experimental breadboard
1 Power Supply ±15V
1 Function Generator
1 Digital Multimeter
1 Oscilloscope
Resistors, Capacitors, Diodes
Connecting Leads

Contents

1. Introduction

1.1 Experimental Aims

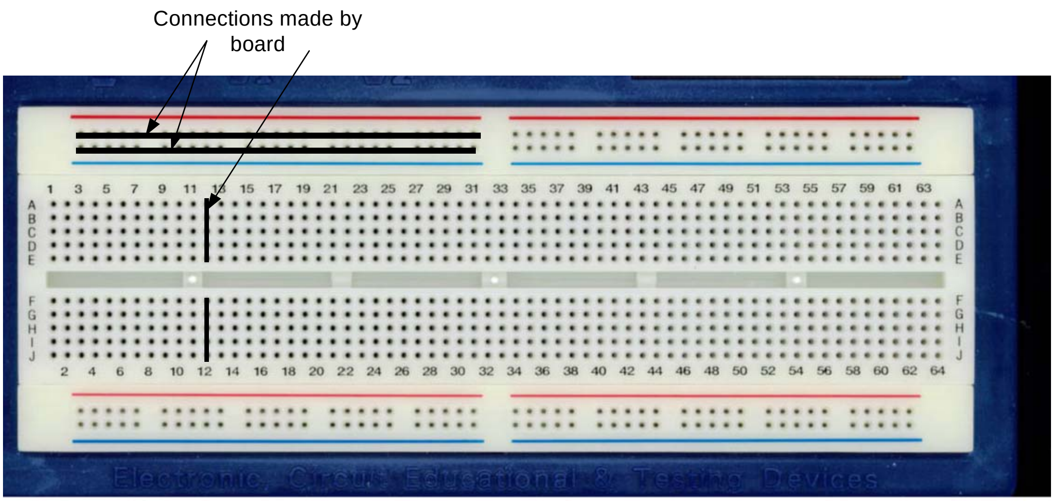
This experiment introduces you to the operational amplifier or op-amp, which is a building block from which most analogue circuits are constructed. The two aims of this experiment are:

(i) to demonstrate how powerful and versatile a building block it is,
(ii) to show some of its limitations and imperfections.
(iii) to implement some of the circuits you designed in SPICE

During the course or the experiment, you are asked to design some circuits; you will save time in the laboratory if you design them at home.

1.2 Experimental Equipment and Instruction

a) Use the breadboard . This has holes that leads can be pushed into. The holes are connected according to horizontal and vertical lines on the figure below.

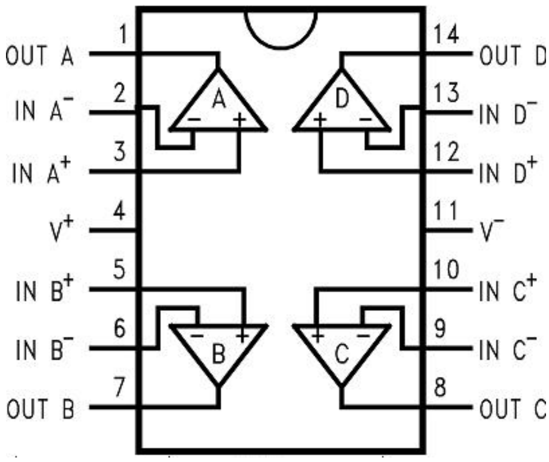


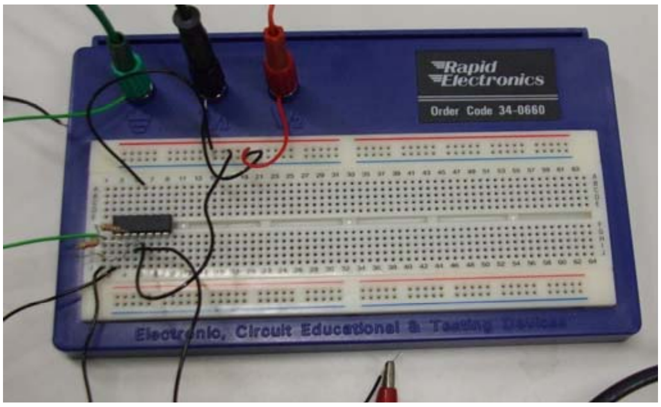
b) If not already done you will need to mount the 4mm sockets. green to earth, black to V1, red to V2, see figure below.

c) Use the Mercury or Volto power supply provided. Connect to the three 4mm sockets using the plug-plug cables, and make sure that the polarities and voltages are correct!. The blue plastic panel provided with the breadboard is not required. Connect wires from the 4 mm sockets to the breadboard.

d) You will need to mount the op-amp, make sure it straddles the central gap. The op-amp integrated circuit you are given is a LM 324 and actually has 4 op-amps on one chip. If you are making a circuit with more than two op-amps it may be better to add a second IC, and only use two of the op-amps on each IC, otherwise the circuit gets a bit crowded. The pin outs are in the figure below. The small round mark on the top of the IC denotes pin 1.

e) Connect the +15v to V_+ (pin 4), and the -15v to V_-(pin 11)





1.3 Hints and Tips

If the circuit does not work check

i) The power supply is switched on
ii) The correct voltages are getting to the IC. Use the scope probe to measure the dc voltages on the actual IC pins 4 &11, with the scope set to dc and 5v/div.
iii) Check +ve and –ve power are right way round,
iv) Check the wiring. It is easy to get the resistors in the wrong hole.
v) Despite what is said in Appendix 2, reading resistor colour bands is tricky. Often it is simpler to measure it. There is a component tester above the resistor drawers, or you can measure using your multimeter.
vi) On your multimeter, if the display is flashing you are over range, increase the range.
vii) When measuring voltages in a high impedance circuit with an oscilloscope you should always use an Oscilloscope Probe.
viii) Beware of the apparent precision of a DVM. The accuracy of the Hameg DVMs is about 0.1% for DC voltages and 0.2% for resistance; for AC signals the accuracy is about 1% between 40 Hz and 20 kHz, but declines rapidly outside this range - it is a waste of time using it at 1 MHz. To maintain the accuracies, always set the DVM to the most sensitive range that avoids overflow.

2. Experimental Exercises

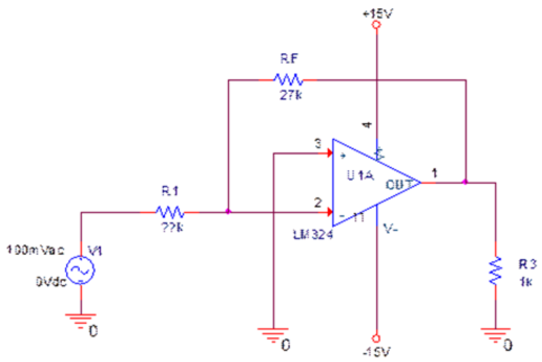
You should write down the results of these experiments in your lab books. These will be collected at the end of term and marked.

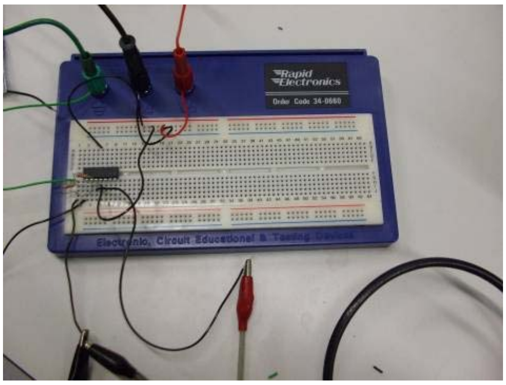
2.1 Inverting Amplifiers

Connect up the power supply and check the ±15V voltage levels. The +15V goes to pin 4, the -15v into Pin 11.

Exercise 1 :Build a single input version of the inverting summing amplifier circuit with the figure below to make an amplifier with a gain of -10 using a value of 27kΩ for $R_{F.}$ and you will need to calculate the value for R1. Use fixed value resistors available from the component drawers, see Appendix 2 for information on resistor values, and tip v). Connect the input and output signals to the two channels of your oscilloscope and check that it really does amplify a 1 kHz sine wave and that it has the correct gain. More details on amplifier circuits are given in Appendix 1.

Figure 2 : Circuit of exercise 1.

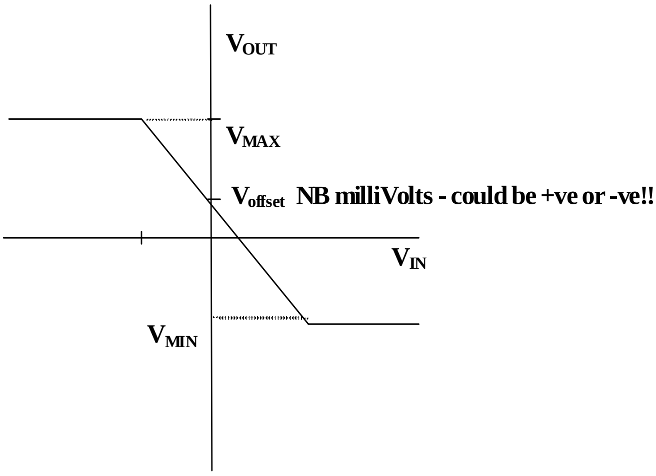




In this section of the experiment, we shall look at some of the properties of this simple amplifier and how to measure them: *voltage gain* , *output voltage range* and *output offset voltage.* You can use the table on the next page. The equations given in Appendix 1 for the gain of each circuit suggest that the absolute resistance values used do not matter as long as their ratios are correct: as we shall see later, the resistance values used do affect some of the other properties and their choice involves making a design compromise.

(i) Voltage Gain.
Measure the amplitude (peak to peak) of the input and output sine waves.
Use the meter to measure the exact resistor values as well and see how closely the gain conforms to theory.

(ii) Output Voltage Range and offset Voltage.
The output voltage of your amplifier will not be perfectly proportional to the input voltage but will have a graph something like:



Measure the maximum, minimum and offset voltages; note that the offset voltage will be much less than the other two, in the millivolt range. By setting your oscilloscope to X-Y mode, you should be able to display a graph like this on the screen; you will have to use a small input signal and low frequency to avoid phase shifts between input and output. Make sure that the 'scope input is switched to *DC* - why? What offset output voltage do you see, if both inputs are held at a common zero (You may find this easiest to measure with the dc meter)?

Fig 3 Input Output

Parameter		**Value**	**Units**
Voltage Gain (actual)			
Voltage Gain (predicted)			
Maximum Output	+ve		
	-ve		
Off Set			

2.2 Design problem 1

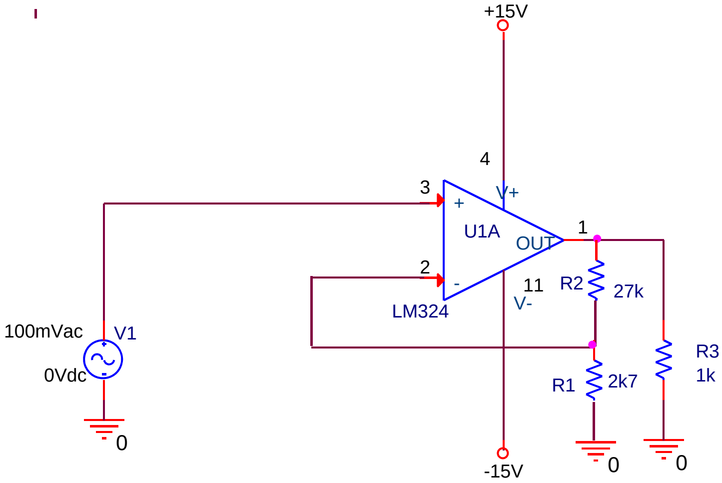
Using as few op-amps as possible, design a circuit (you can do this at home rather than in the lab session)

- Whose gain can be adjusted with a single potentiometer over the range 0 to -10.
- The gain should vary linearly with potentiometer rotation. (potentiometers are explained in Appendix 3, you are provided with a potentiometer.

Exercise 2 : Implement your circuit and check that it works as you expected.

2.3 Non-inverting Amplifiers

Exercise 3 :. Convert your circuit into a non-inverting amplifier as in the figure below by grounding the left end of R_1 and applying the signal to the op-amp's +ve input. Consult Appendix 1 if required. Measure the gain of your amplifier and input impedance.



2.4 Design problem 2

Design a second circuit with the same specifications as before but whose gain now varies linearly with potentiometer rotation over the range 0 to +10. (You may have to think a bit on how to get the gain less than 1. Hint, can you use a potentiometer (refer to Appendix 3) as a variable potential divider?)

Exercise 4 : Implement your circuit, check it works as you expected. Set its gain to +1 and see how its gain varies with frequency

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3. Non-linear Circuit

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3.1 Schmitt Trigger and Oscillator (You can skip this section if you are behind)

Any circuit that uses an op-amp as a linear amplifier must have *negative* feedback. If we construct a circuit with *positive* feedback at DC, the op-amp's output will always go to either its maximum or its minimum voltage (as measured in section 2.1b).

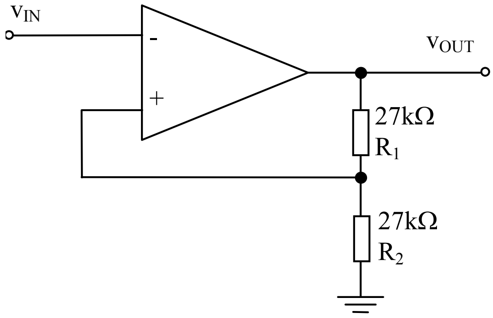
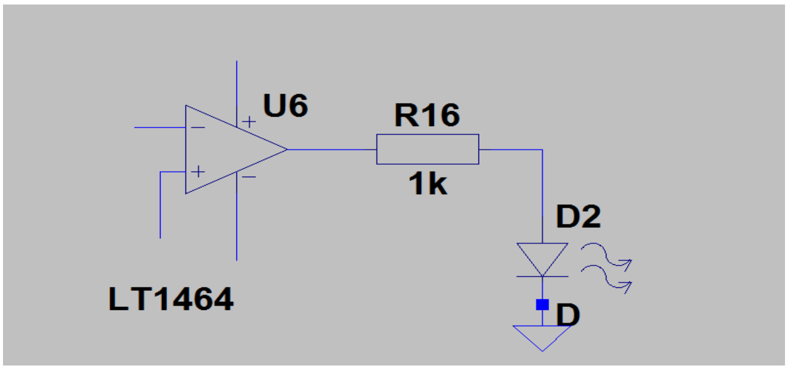


Fig 8

Exercise 5 Construct the *Schmitt trigger* circuit shown above and look at the output when an input sine wave of 20 V peak to peak is applied. Use the X-Y mode of the oscilloscope to sketch a graph of v_{OUT} versus v_{IN}. This graph has the characteristic shape of a circuit with *Hysteresis* - the output depends on the past history of the input as well as its present value.

Exercise **6** Connect the output of your Schmidt trigger to a 1kΩ resistor in series with a LED (light emitting diode) as in the circuit below. Make sure the diode is connected with the correct polarity. Turn the frequency down to about 1Hz. Can you see the diode flash?. You could use this on the output of your stethoscope circuit.



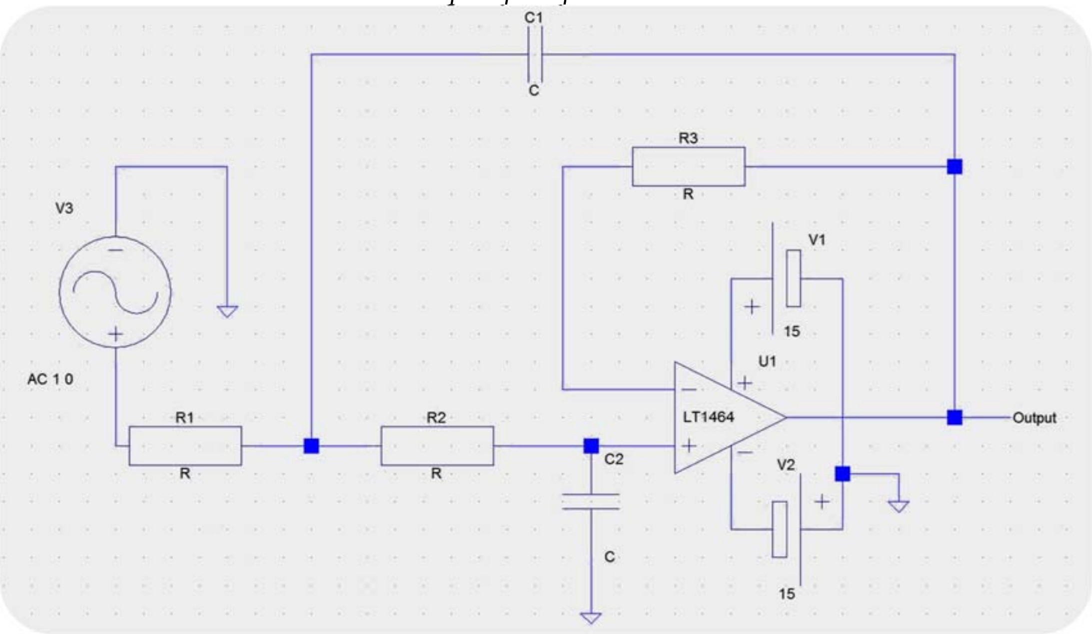
4. Filter

Exercise 7 : Construct a low pass filter as you designed in the SPICE exercise, details reproduced below. You may wish to build one that you designed for your stethoscope amplifier. Plot the frequency response by varying the signal generator frequency and check it is what you expect.

$$R_1 = R_2 = \frac{1}{2\,\pi \cdot f_c \cdot C_1}$$

Choose a value of C_1 in the range 100 pF – 0.1 μF.
Make $C_2 = C_1$ and set $R_3 = 2R_1$

- Low pass filter for exercise 6

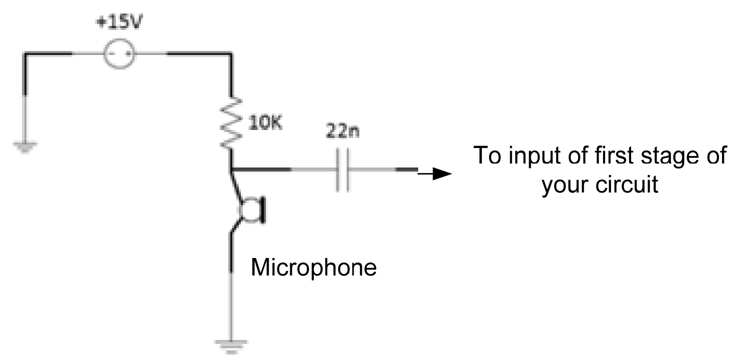


5 Heart Sound Amplifier

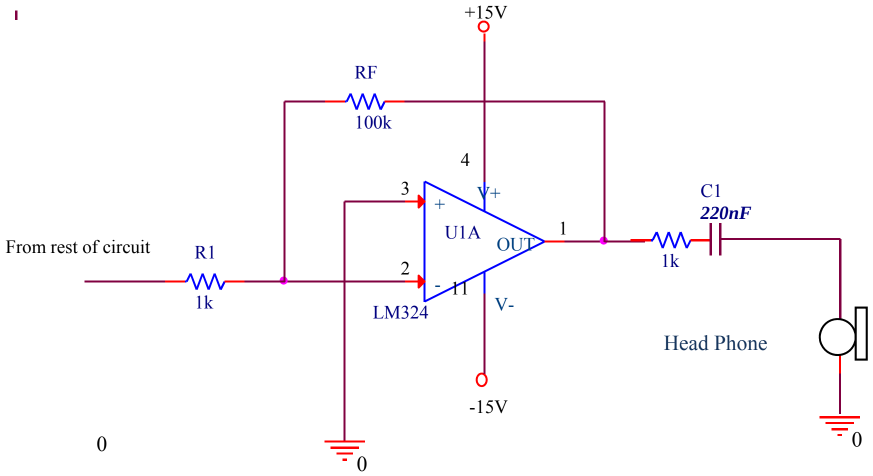
Exercise 8: You are asked to build an amplifier based on the stethoscope amplifier you designed in the SPICE sessions. Leave room for some additional components and an amplifier at the input. You may need to adapt it due to availability of components.

Characterise the amplifier you have built by measuring its gain, frequency response and any other parameters you choose. Due to the high overall gain you may need to measure the gain of one stage (amplifier) at a time. Alternatively you can create a small input signal using a potential divider.

Insert the following circuit at the input of your amplifier. The microphone has been assembled into a stethoscope bell and needs a defined low supply voltage, supplied by a 10k Resistor. So the first stage will look like this.



To connect to the headphones you will need to drive from the output of an op-amp via a 220nF capacitor as shown below. This should be before the Schmidt trigger if you have one.



With the microphone connected can you hear anything in the headphones. You can try tapping and then speaking into the microphone to see if you can hear. There is a dummy heart sound generator you can try to detect, called 'SAM'. If you can hear the heart sounds you have done well. Connect up to a Schmidtt trigger as well if you have time left.

6 Lab Report

The lab report instructions are as follows. This report should be a joint submission with your lab partner.

The deadline is **the end of term.** Look out for the exact time and date on your course-work calendar.

1. The lab report should only be on the work you do on the stethoscope/heart-rate amplifier. This includes the whole circuit, ie any filters you put into the circuits, as well as the gain stages. Most (60%) of the marks will be on the design and modelling. I am aware some of you will not have much time to build or test the whole circuit, you will get marks for what you do build, including gain stages and filters, you will get a few extra marks if the whole circuit works but do not worry if it does not.

2. You do NOT need to write up anything on the other parts of the SPICE or op-amp lab (but see point iii below).

3. If you are behind on the Op-Amp lab , then skip Exercises 5 & 6

4. You are expected to produce a report of no more than 5 pages (including your schematics, and references; your main circuit should probably go on 1 page) containing the following sections. The majority of the marks will be on Sections i) and ii).

i). The design of the ECG amplifier you produced in the SPICE modelling section

ii). Why you used this design, how the circuit works

iii) The circuit you built and an explanation of any differences to the original design. If you do not have time to build a full circuit just give some amplifier results, ie those you had in Section 2.2/2.3.

iv) Your measurements on its performance.

v) Any suggestions for future improvements.

vi) Before you ask 5 pages does mean 5 pages. It does not mean 6 pages or more.

5. This report should be a <u>joint</u> submission with your lab partner. One of you only needs to submit but remember to put both your names on it.

6. Your Lab books will also be marked. The lab books account for 20% of the course marks

7. The coursework is weighted as follows :
Lab report 50%; op-amp questions 30%; Lab book 20%

1A Theory of Op-Amps

1 Op-amps - Theory

Op-amps are high gain differential amplifiers; they have two inputs labelled + and - , and a single output. For an ideal op-amp, the inputs draw no current at all and the output voltage is entirely determined by the difference between the two input voltages:

$v_{OUT} = A(v_+ - v_-)$

where A, the open loop voltage gain, is very large, typically 10^5 or so at low frequencies. We shall see later that real op-amps, although very good, are not quite perfect: their inputs *do* draw current and the output voltage is affected by the output current drawn. In most applications however, these deficiencies have a minor effect on the performance of the circuits in which op-amps are used.

We shall use op-amps to make two sorts of circuit: *linear* and *non-linear*.

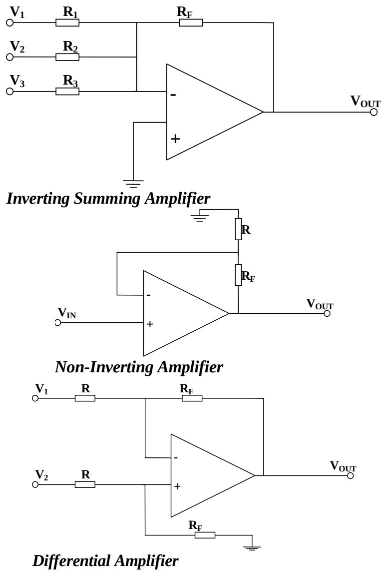
A *linear* circuit is one that obeys *superposition*, that is, it is a circuit for which adding input waveforms together causes the corresponding output waveforms to add together. Linear circuits are used as amplifiers and filters. In a linear circuit, a sine wave input will give a sine wave output of the same frequency but usually with a different amplitude and phase; if you know the gain and phase shift for all frequencies of sine wave input - the circuit's *frequency response* - you know everything worth knowing about the circuit's behaviour.

A *non-linear* circuit is one that does not obey superposition and will usually contain one or more non-linear component such as diodes which only allows current to pass in one direction. Any circuit whose behaviour alters depending on the amplitude or DC level of its input is non-linear; examples are threshold detectors, peak detectors and any switching or rectifying circuit. If you make the input amplitude to any op-amp circuit large enough it will become non-linear because its output can never be driven beyond, or even as far as, the power supply voltages which, for us, are ±15 V.

In all linear op-amp circuits, and many non-linear ones, the output is connected back to the -ve input, usually through some intermediate components. This *negative feedback* has two beneficial effects: it reduces the output impedance of the circuit, making it more like the perfection we are assuming, and it reduces the gain to a lower value that depends almost exclusively on the values of the external resistors and capacitors and hardly at all on the value of *A*. For this reason, the precise value of *A* is rarely important as long as it is much bigger than the actual gain you want from your circuit. A circuit in which the output is connected back to the +ve input has *positive feedback* and will almost inevitably be non-linear and/or oscillatory.

2 Basic Amplifier Circuits

The following three circuits form the basis of most linear op-amp applications:



$$v_{OUT} = -\left(\frac{R_F}{R_1}\right)v_1 - \left(\frac{R_F}{R_2}\right)v_2 - \left(\frac{R_F}{R_3}\right)v_3$$

$$v_{OUT} = +\left(1 + \frac{R_F}{R}\right)v_{IN}$$

$$v_{OUT} = \frac{R_F}{R}\left(v_2 - v_1\right)$$

Fig. 1 basic op-amp circuits

Notice that the feedback is negative in all cases: R_F goes from the output to the -ve input terminal. It is usual when drawing op-amp circuits to omit explicit mention of the power supply connections (±15 V) to the op-amp; a consequence of this is that you cannot use Kirchoff's current law to deduce that the output current from an op-amp is equal to the sum of the input currents because Kirchoff's law only works if you include *all* the connections to a point or sub-circuit. Nor is it true that that current going into one input terminal comes out of the other one: in fact both input currents normally flow in the same direction. However, as we shall see below, Kirchoff's law is useful in analysing op-amp circuits when it is applied to all the components connected to one or other of the op-amp input terminals.

The op-amp works in the same way in each of these circuits but its action is easiest to understand in the non-inverting amplifier. Since we assume that the op-amp input draws no current, R_F and R form a voltage divider and

$$v_- = v_{OUT}(R/(R_F+R)).$$

If the +ve terminal is at a higher voltage than the -ve terminal, then the op-amp will amplify this voltage difference by its open loop gain, A, and its output voltage will increase accordingly. The negative feedback then causes v_- to increase, thus counteracting the input voltage difference that originally caused the output to change. The process will come to a halt when

$$(v_+ - v_-) = v_{OUT}/A$$

If A is suitably enormous and v_{OUT} is in the range ±15 V, this will be when

$$v_+ \approx v_-$$

that is when $v_{IN} = v_{OUT}(R/(R_F+R)).$

A first-level analysis of any negative feedback op-amp circuit can therefore be performed by making the following two assumptions:

i) The inputs draw no current.
ii) The op-amp will set the output voltage to whatever level is required to make $v_+ = v_-$

As an exercise, use these assumptions to derive the gain of the inverting summing amplifier shown above. Use assumption (ii) to work out v_- , then apply Kirchhoff's current laws to the components connected to the input of the op-amp. By using assumption (i) and expressing each of the other currents as a voltage divided by a resistance, you should obtain the equation given above. If you are feeling brave you can derive the gain of the differential amplifier as well. It is easiest to use superposition: first calculate the output caused by v_1, when $v_2 = 0$ (this is just an inverting amplifier), then calculate the output caused by v_2 when $v_1 = 0$ (this is a potential divider followed by a non-inverting amplifier), and then add the two together.

If the +ve terminal of the op-amp is held at zero volts, the op-amp will by assumption (ii) force the -ve terminal to zero volts as well. The -ve terminal is then called a *virtual earth.* A circuit with several inputs joined at a virtual earth as in the inverting summing circuit above has a useful isolating property: the current drawn from each input depends only on the voltage at that particular input and is independent of the other input voltages. This means that the different inputs cannot interfere with one another.

2A Resistors

[(http://www.kpsec.freeuk.com/components/resist.htm)](http://www.kpsec.freeuk.com/components/resist.htm)

Function

Resistors restrict the flow of electric current, for example a resistor is placed in series with a light-emitting diode (LED) to limit the current passing through the LED.

Connecting and soldering

Resistors may be connected either way round. They are generally not damaged by heat when soldering.

Resistor values - the resistor colour code

Resistance is measured in ohms, the symbol for ohm is Ω.
1 Ωis quite small so resistor values are often given in kΩ and MΩ.
1 kΩ = 1000 Ω 1 MΩ = 1000000 Ω.

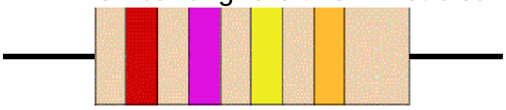
Resistor values are normally shown using coloured bands.
Each colour represents a number as shown in the table.

Most resistors have 4 bands:

- The **first band** gives the **first digit**.
- The **second band** gives the **second digit**.
- The **third band** indicates the **number of zeros**.
- *The fourth band is used to shows the tolerance (precision) of the resistor, this may be ignored for almost all circuits (further details are below).* The fourth band is nearly always silver or gold. there is a gap between the third and fourth bands. If there is a 5th band ignore this. If not clear you can always measure the value, see tip 1

The Resistor Colour Code

Colour	Number
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Grey	8
White	9



This resistor has red (2), violet (7), yellow (4 zeros) and gold bands.
So its value is 270000 Ω= 270 kΩ.
On circuit diagrams the Ω is usually omitted and the value is written eg 270K.

Resistor shorthand

Resistor values are often written on circuit diagrams using a code system which avoids using a decimal point because it is easy to miss the small dot. Instead the letters R, K and M are used in place of the decimal point. To read the code: replace the letter with a decimal point, then multiply the value by 1000 if the letter was K, or 1000000 if the letter was M. The letter R means multiply by 1.

For example:

`560R` means 560 Ω
`2K7` means 2.7 kΩ = 2700 Ω
`39K` means 39 kΩ
`1M5` means 1.5 MΩ = 1500 kΩ

Tolerance of resistors (fourth band of colour code)

The tolerance of a resistor is shown by the **fourth band** of the colour code. Tolerance is the **precision** of the resistor and it is given as a percentage. For example a 390Ω resistor with a tolerance of ±10% will have a value within 10% of 390Ω, between 390 - 39 = 351Ω and 390 + 39 = 429Ω (39 is 10% of 390).

A special colour code is used for the **fourth band** tolerance:
silver ±10%, **gold** ±5%, **red** ±2%, **brown** ±1%.
If no fourth band is shown the tolerance is ±20%.

Tolerance may be ignored for almost all circuits because precise resistor values are rarely required.

Real resistor values (the E6 and E12 series)

You may have noticed that resistors are not available with every possible value, for example 22kΩ and 47kΩ are readily available, but 25kΩ and 50kΩ are not!

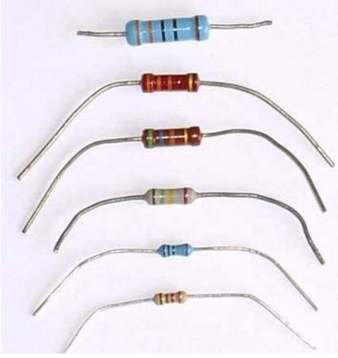
Why is this? Imagine that you decided to make resistors every 10Ω giving 10, 20, 30, 40, 50 and so on. That seems fine, but what happens when you reach 1000? It would be pointless to make 1000, 1010, 1020, 1030 and so on because for these values 10 is a very small difference, too small to be noticeable in most circuits. In fact it would be difficult to make resistors sufficiently accurate.

To produce a sensible range of resistor values you need to increase the size of the 'step' as the value increases. The standard resistor values are based on this idea and they form a series which follows the same pattern for every multiple of ten.

The E6 series (6 values for each multiple of ten, for resistors with 20% tolerance)
10, 15, 22, 33, 47, 68, ... then it continues 100, 150, 220, 330, 470, 680, 1000 etc.
Notice how the step size increases as the value increases. For this series the step (to the next value) is roughly half the value.

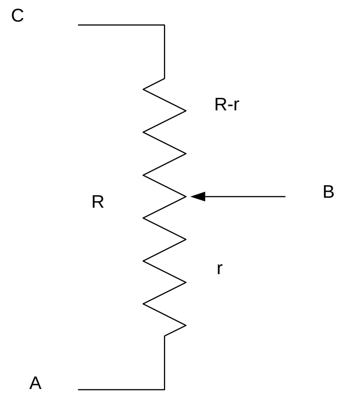
The E12 series (12 values for each multiple of ten, for resistors with 10% tolerance)
10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82, ... then it continues 100, 120, 150 etc.
Notice how this is the E6 series with an extra value in the gaps.

The E12 series is the one most frequently used for resistors. It allows you to choose a value within 10% of the precise value you need. This is sufficiently accurate for almost all projects and it is sensible because most resistors are only accurate to ±10% (called their 'tolerance'). For example a resistor marked 390Ω could vary by ±10% × 390Ω = ±39Ω, so it could be any value between 351Ω and 429Ω.



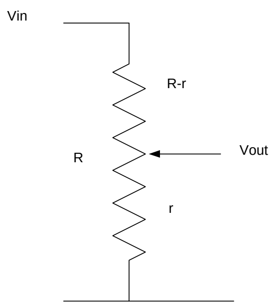
3A Potentiometers

A potentiometer is a variable resistor where a moveable contact can give a resistance value between the 0 and the full value of the resistor. The contact can be moved by turning a shaft or knob, or a screw head.



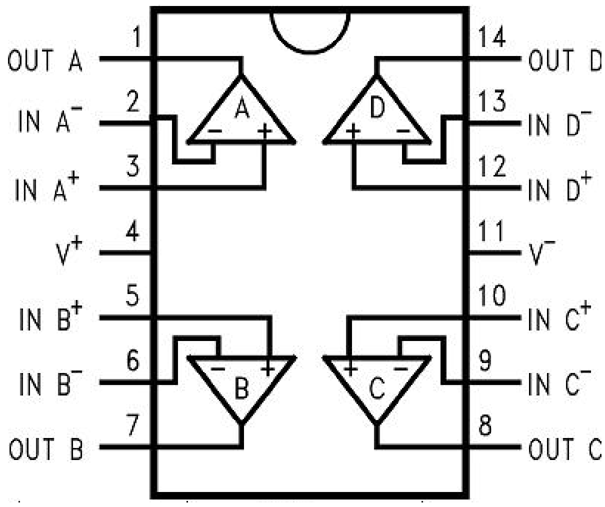
The resistance R between A and C is constant and depends on the Part. The resistance r between B and A can be varied from 0 to R, The resistance between B and C is R-r

This component can be used as a variable resistor by connecting between A and B.
Another use is as a variable potential divider as in the circuit below.



Here if r is set to be f.R then Vout = f.Vin (where f is fraction between 0 and 1). This arrangement is often used for volume controls on audio equipment, radios etc.
For applications that require adjustment during assembly but not afterwards we use a trimmer potentiometer as shown on the picture bottom right, this must be adjusted with a screwdriver.

Examples of potentiometer


OUT A
IN A⁻
IN A⁺
V⁺
IN B⁺
IN B⁻
OUT B
OUT D
IN D⁻
IN D⁺
V⁻
IN C⁺
IN C⁻
OUT C
1
2
3
4
5
6
7
14
13
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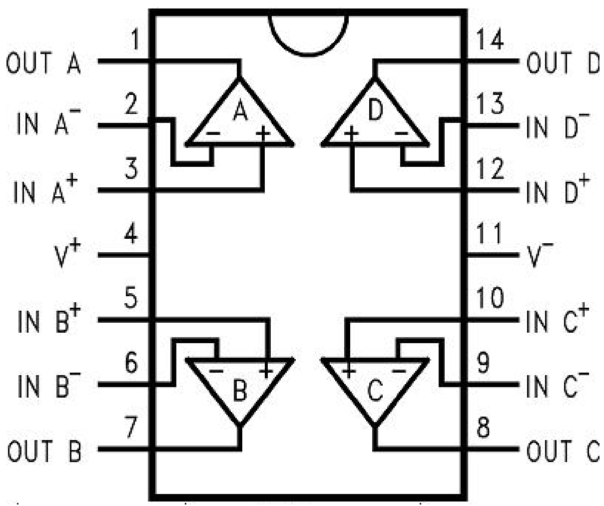
9
8
A
B
C
D


OUT A
IN A⁻
IN A⁺
V⁺
IN B⁺
IN B⁻
OUT B
OUT D
IN D⁻
IN D⁺
V⁻
IN C⁺
IN C⁻
OUT C
1
2
3
4
5
6
7
14
13
12
11
10
9
8
A
B
C
D