Direct Sensing

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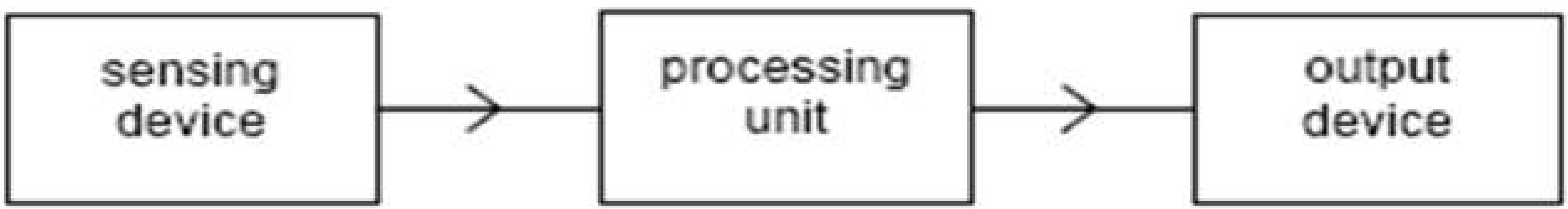
Direct sensing

- This topic deals with how circuits incorporating ***sensing device/s*** that detect changes in the physical properties produce ***output voltages*** that will operate an ***output*** .
- A ***functional system*** may be thought of as made up of 3 parts namely;
  - a ***sensing device,***
  - a ***processing unit,***
  - an ***output device***



LDR
Thermistor
Piezo-electric transducer
Strain gauge

Potential divider
Operational Amplifier

LED
Relay

Sensing devices

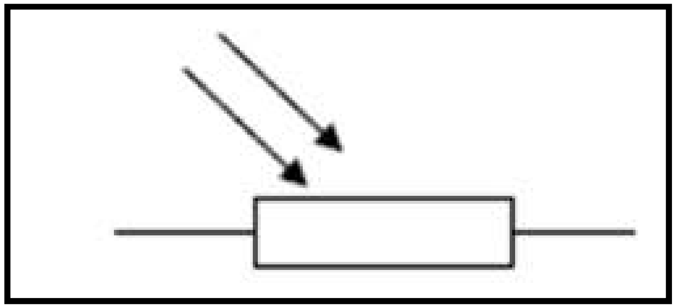
- There are simple sensors and complex sensors but whatever they are they need to ***provide a voltage at its output.***

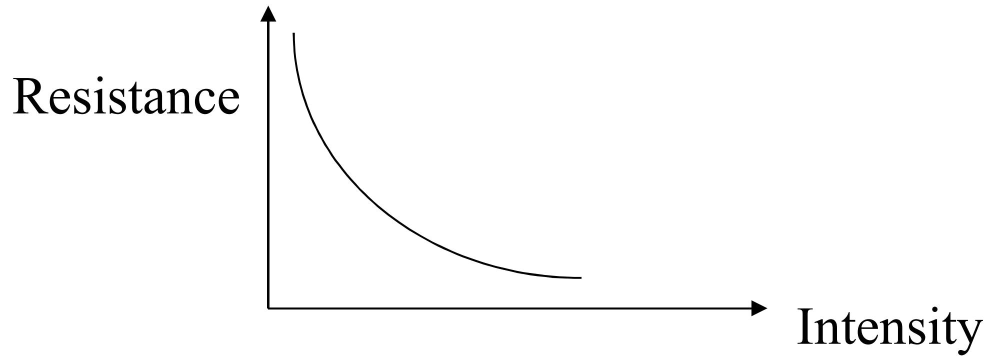
  Simple sensors e.g. those detecting temperature in a thermostat or a sensor detecting light levels in an automatic switch for a lamp.

  Complex sensors e.g. those detecting whether a car wheel is skidding in a braking system and the circuit controlling not only the brakes but also to stop the skidding and to stop further skidding.

- The sensing device is the 1st stage of any electronic sensor and is the means by which whatever is to be detected or monitored is converted into an electrical signal i.e. a voltage.
- Ideally, the generated voltage should be proportional to the external change causing it.
- Sensing devices detect many different types of changes – e.g. changes in length, mass, force, velocity, acceleration, current, voltage, light intensity, temperature, sound level, humidity, pressure, strain, magnetic field
- We shall consider 4 sensing devices – ***light dependent resistor(LDR), thermistor, piezo-electric transducer and the metal wire strain gauge.***

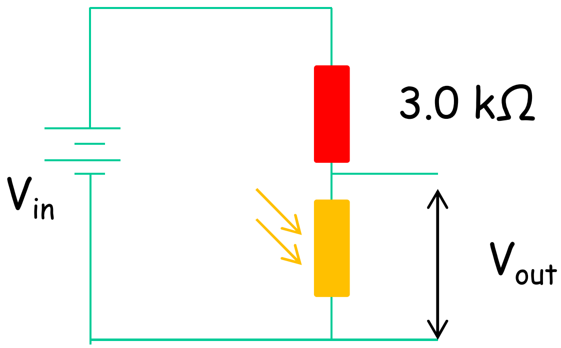
Sensing devices: LDR (1)





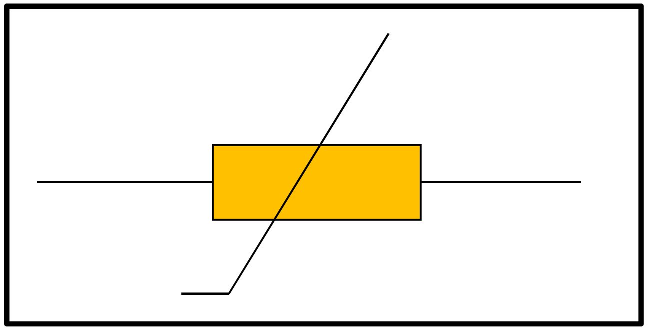
- Symbol is as above.
- It consists of 2 metal electrodes with a film of cadmiun sulphide.
- The higher the intensity of light on the LDR, t***he resistance of the LDR decreases*** , hence more current can flow.
- In complete darkness, its resistance is about 10 MΩ but in bright sunlight, its resistance falls to about 100 Ω.
- So how does LDR used as a sensing device? A voltage is needed to drive the output device yet LDR only produces a change in resistance.
- The sensor must use this change in resistance to produce a change in voltage.
- The solution is to place the LRD in series with a fixed resistor.

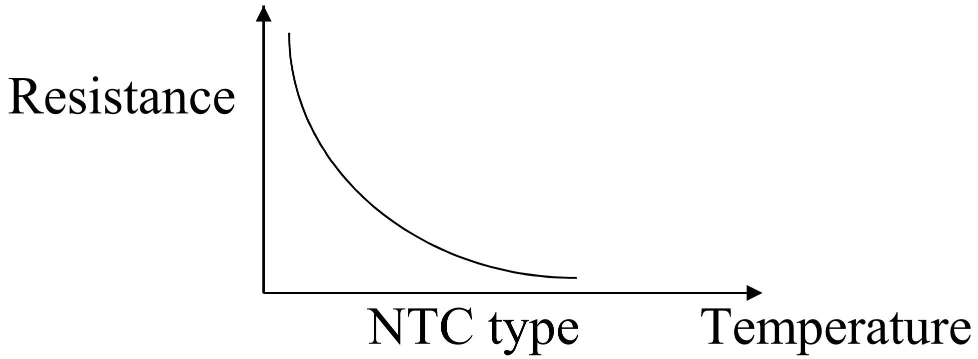
Sensing devices: LDR (1)



- The voltage of the supply is shared between the two resistors in proportion to their resistance, so as the light level changes, and the LDR's resistance changes, so does the voltage across each of the resistors.
- The two resistors form a potential divider.

Sensing devices: NTC Thermistor (2)





- Symbol is as above.
- Thermistor is a temperature dependent resistor which is manufactured in various shapes and sizes.
- There are 2 types:

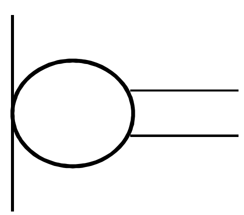
  (i) positive temp coefficient, PTC - R increases with temp rise.

  (ii) negative temp coefficient, NTC - R decreases with temp rise.

- NTC are made of semiconductor material and metal oxides.
- Thermistor can be used as a sensing device in the same way as the LDR, instead of sensing a change in intensity, it senses a change in temperature.

Sensing devices: Piezo electric transducer (3)

- A transducer is any device that converts energy from one form to another.
- A piezo-electric transducer is a sensor that detects differences in pressure (sound wave) .
- This variation in pressure will result in an a.c voltage being generated. The magnitude of the voltage generated depends on the magnitude of the pressure on the crystal.
- The polarity of the voltage depends on whether the crystal is compressed or expanded. The crystal and its amplifier may be used as a simple microphone for converting sound signals into electrical signals.



Symbol for
a microphone

Sensing devices: Piezo electric transducer (3)

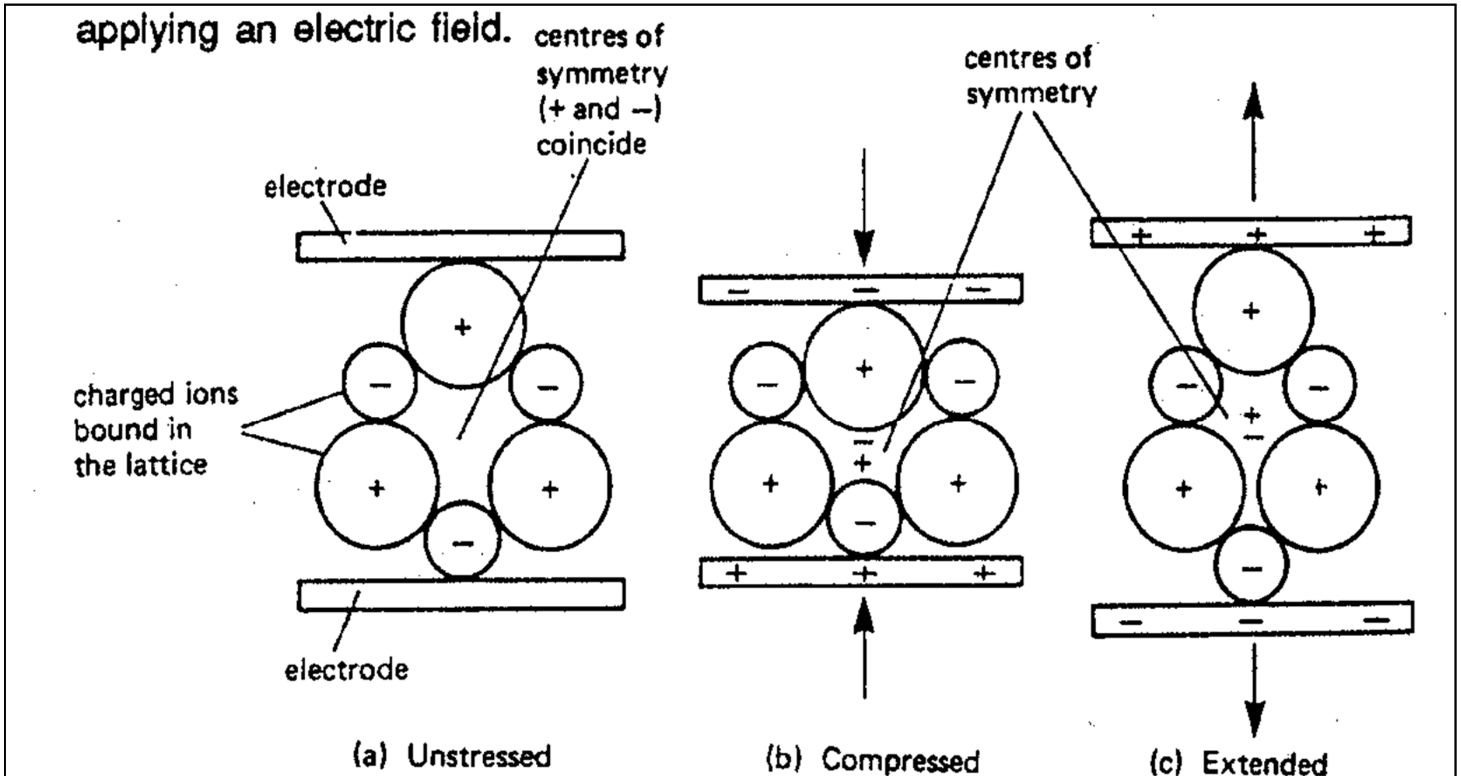
- A piezo-electric transducer is made up of material that can exhibit piezo-electric effect. A well known piezo-electric material is called quartz.

- A quartz is a crystal consists of positive and negative ions in a regular arrangement. When this crystal is stressed (being applied pressure), a small voltage is produced between the faces of the crystal. The phenomenon is known as piezo-electric effect.

- In the piezo-electric transducer, the quartz crystal is made into a thin sheet with metal connections on both sides. When sound wave hits one side of the sheet, the compressions and rarefactions cause the pressure to decrease and increase.

- The crystal changes shape in response to these pressure changes and a small voltage is generated across the metal connections.

Sensing devices: Piezo electric transducer (3)

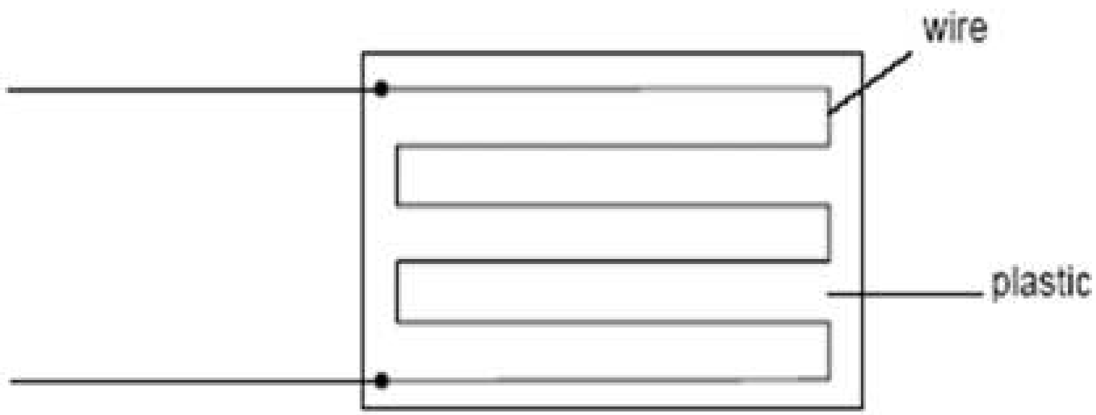


The piezo-electric effect

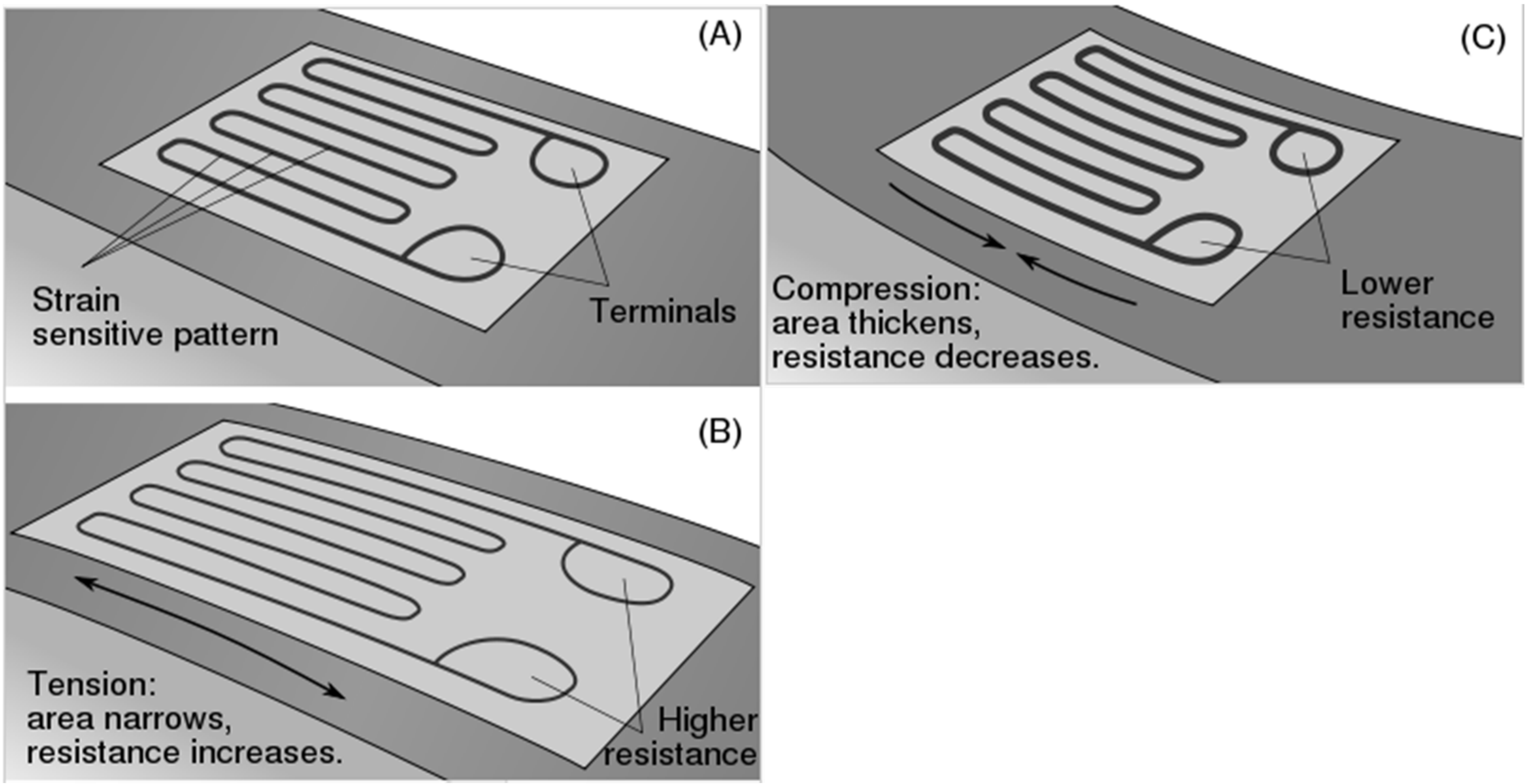
Sensing devices: Strain Gauge (4)

- In engineering, it is frequently required to test for the strains experienced in different parts of structures. (crack of a building, aircraft wing.)
- This is achieved by using a length of very fine wire embedded in a zigzag manner and sealed into a small rectangle of thin plastic known as a ***strain gauge.***
- The resistance changes when the gauge is stretched.

  The wire since it is strained increases in length together with the plastic.
- ***As the length increases the cross sectional area decreases causing an increase in the electrical resistance of the wire.***



Sensing devices: Strain Gauge (4)



Sensing devices: Strain Gauge (4)

- From knowledge of resistors:

$$\boxed{R = \rho L/A}$$

- If a wire increases in length by only a small amount **ΔL**, then the change in the cross-sectional area can be assumed to be negligible and the new resistance is given by:

$$\boxed{(R + \Delta R) = \rho(L + \Delta L)/A}$$

- By subtracting the above 2 expressions, the change in resistance **ΔR** is given by:

$$\boxed{\Delta R = \rho \Delta L/A}$$

- Hence **<u>ΔR is directly proportional to ΔL</u>** since it is assumed that **A** is a constant and **ρ** is also a constant.

- **Since strain is proportional to the extension, then the strain is also proportional to the change in resistance.**

Processing units

- The change in the physical property of a sensing device must be processed in some way before the change can be displayed, measured or is used to control.

- This is carried out by the **processing unit** which is some form of an electrical or electronic circuit that is connected to the sensing device.

- If the voltage is small, it is usually necessary to amplify it or it may require further processing before the voltage can be used to control an output device.

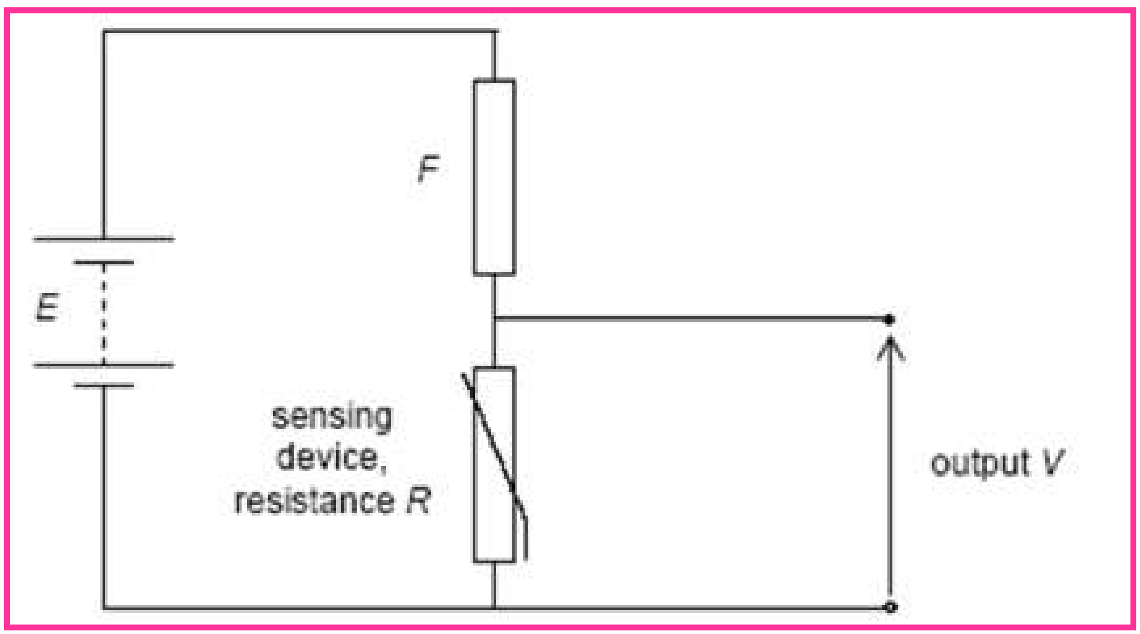
- 2 such circuits are the **potential divider circuit** and the **operational amplifier circuit (op-amp).**

Processing unit: Potential Divider (1)

- A change in resistance of a sensing device results in a change of voltage across the sensor if the sensor is connected to the circuit and forms one part of a potential divider.

- $V = R/(R+F) \times E$ **,** assuming internal resistance is negligible.

- **As the resistance of the sensing device increases, the output voltage increases.**

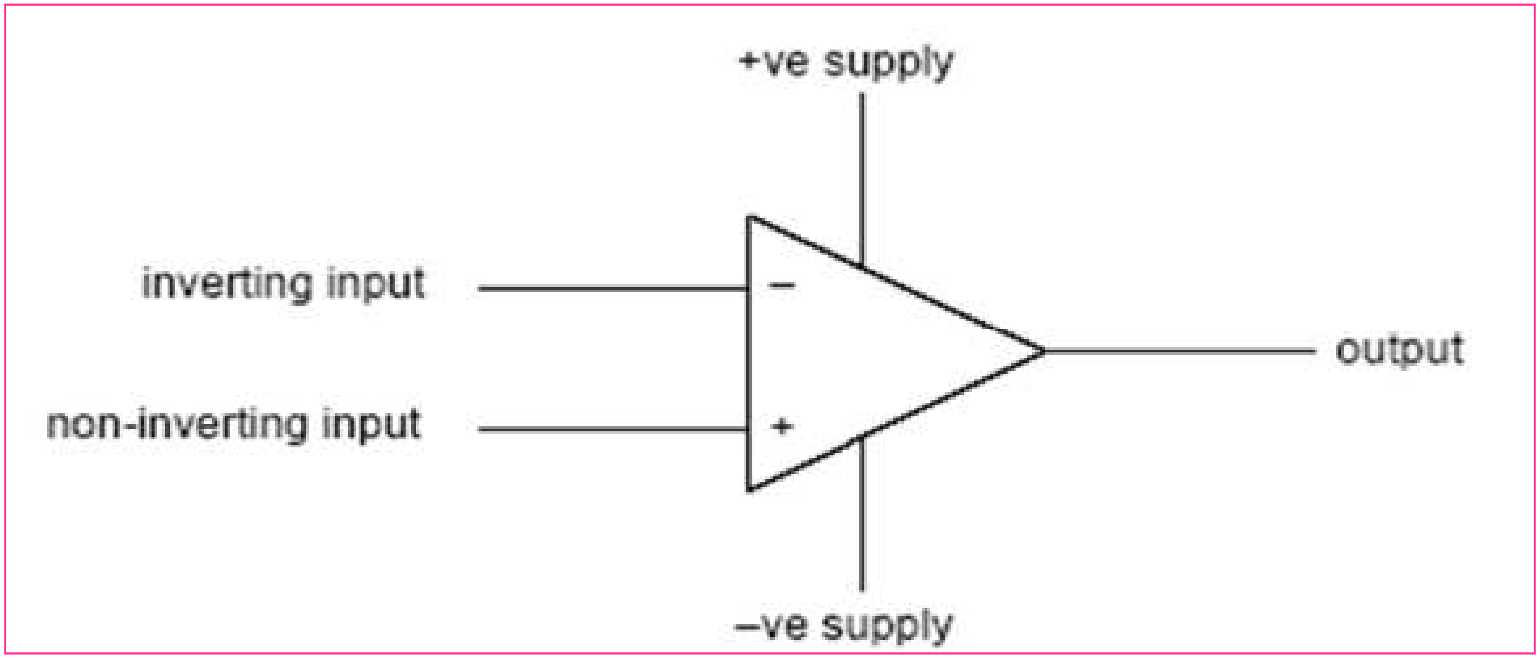


Processing unit: Op-Amp (2)

- What is an Op-Amp?
- It stands for operational amplifier.
- Is a low cost electronic circuit consisting of
  - transistors
  - resistors
  - capacitors
- In some applications, the change in output voltage from the potential divider is too small. Any small change can be amplified using an electrical circuit incorporating an operational amplifier.
- An op-amp is an integrated circuit (IC) of about 20 transistors together with resistors and capacitors, all formed on a small slice of silicon. The slice is sealed in a package from which emerge connections to the external circuit.

Processing unit: Op-Amp (2)

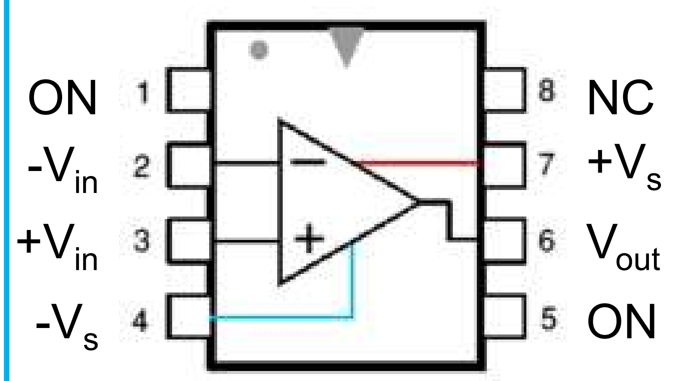
- A op-amp has **2 input terminals** and **1 output terminal** plus some other connections and its symbol is as shown below:



Processing unit: Op-Amp (2)

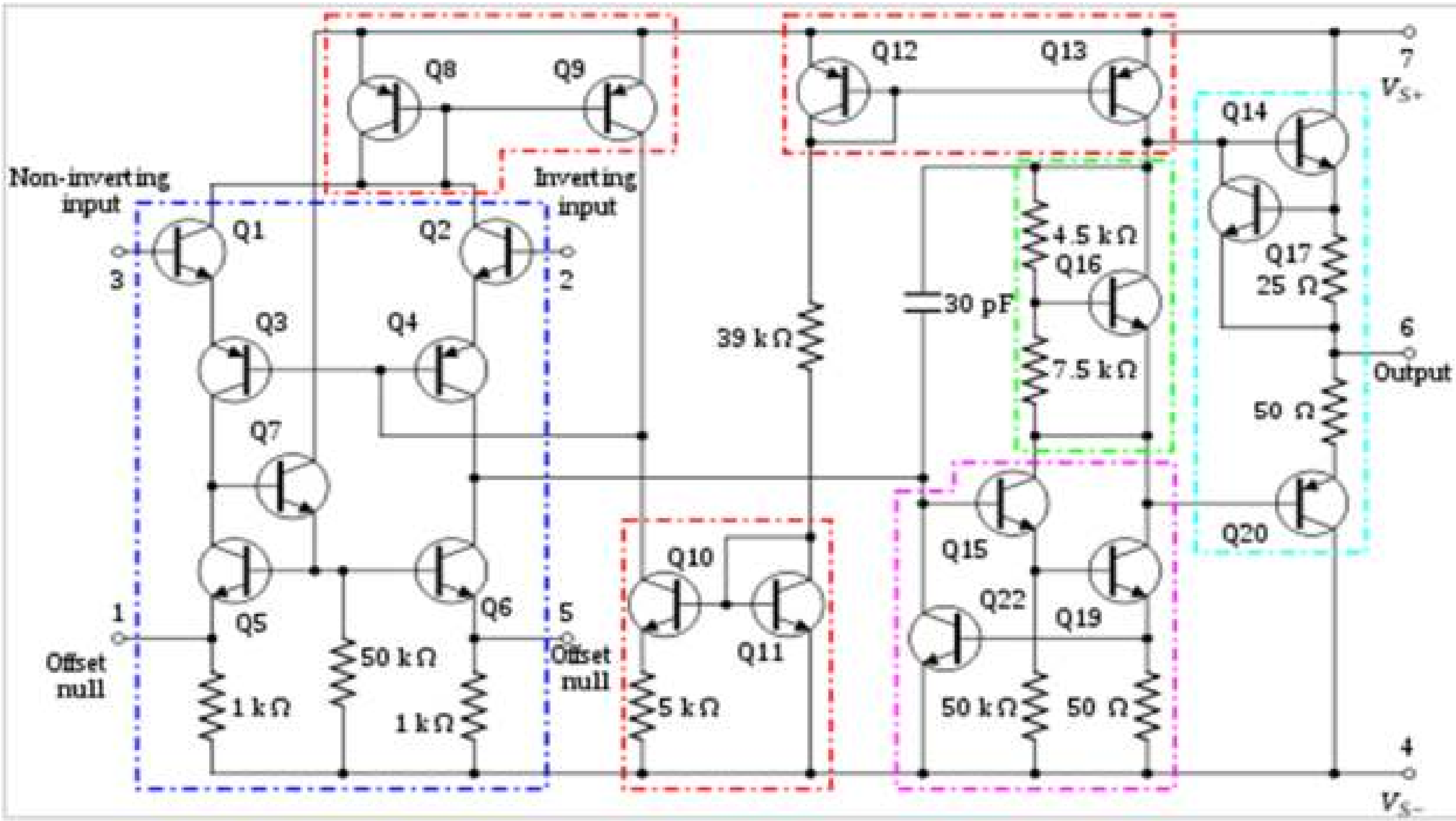
- $+V_{in}$: input (non-inverting)
- $-V_{in}$: input (inverting)
- $+V_s$: power supply (positive)
- $-V_s$: power supply (negative)
- V_{out} : output voltage
- ON : Offset Null (don't care)
- NC : Not Connected (don't care)

741 in 8-pin DIL (Dual In Line) pack



Processing unit: Op-Amp (2)

- Op-amp – how it looks on the inside



Op-Amp: Input terminals

- An op-amp has 2 input terminals:

  1.) non-inverting input (V_+)

  2.) inverting input (V_-)

- V_+ and V_- terminals do not mean that the voltage connected to these terminals must be positive and negative accordingly, but **whether they invert or do not invert the input voltage.**

- If both input are used:

  if $V_+ > V_-$ the output is positive (+)

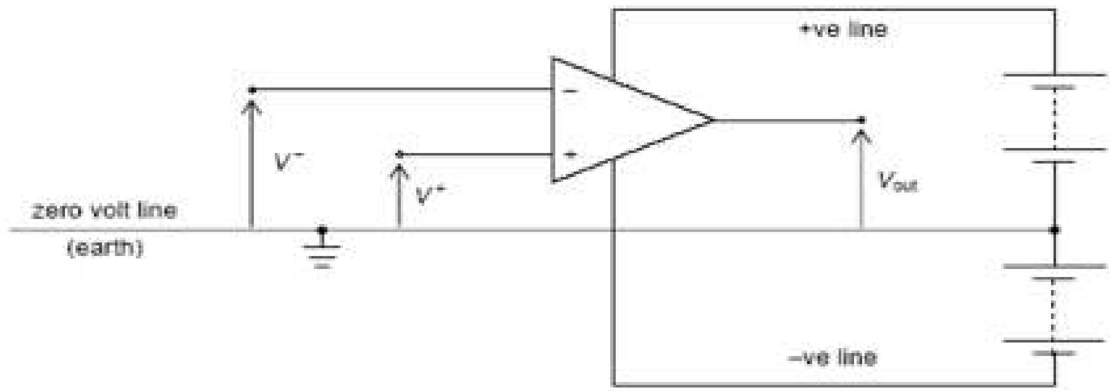
  if $V_+ < V_-$ the output is negative (-)

  if $V_+ = V_-$ the output is zero

- If only one input is in use and the other is at zero voltage,
  - a ***positive voltage*** on the ***inverting input*** causes a ***negative output voltage.***
  - a ***positive voltage*** on the ***non-inverting input*** causes a ***positive output voltage.***

Op-Amp: Power Supply terminals

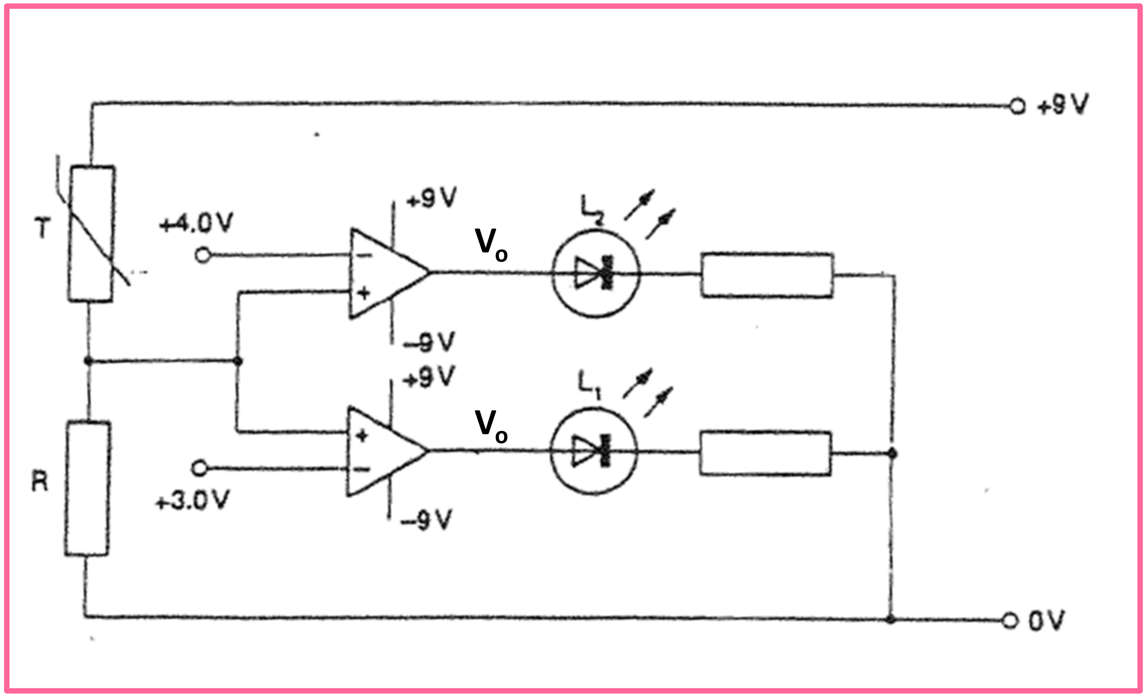
- The power supply for an op-amp is a 3-terminal DC supply made up of 0 V earth and typically +/- 9 V. This a called a **dual or split power supply.**
- The op-amp is powered by this dual power supply. Current that flows within the op-amp comes from the power supply.
- Power supply lines connect to the power supply. (eg. battery)



- The common link between the two sets of batteries or power supplies is termed the **zero-volt, or earth line.**
- This forms the reference line from which all input and output voltages are measured.

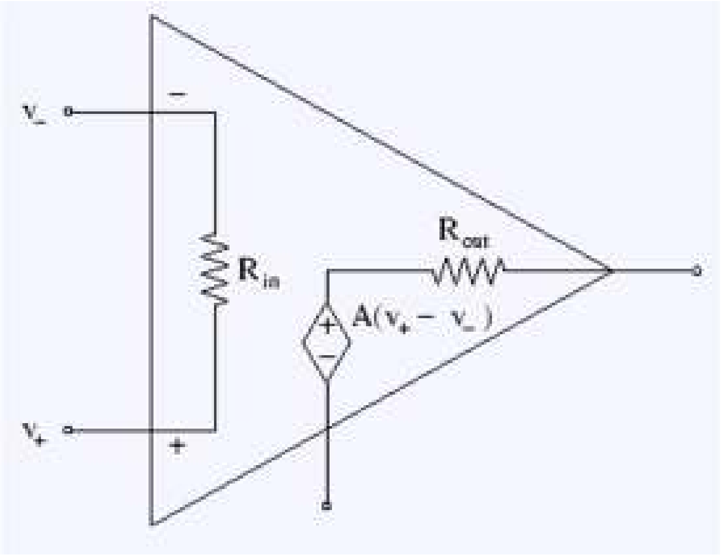
Op-Amp: Output terminal

- The output terminal connects to any output device. (e.g. LED, relay, bulb)



<u>Ideal</u> op-amp

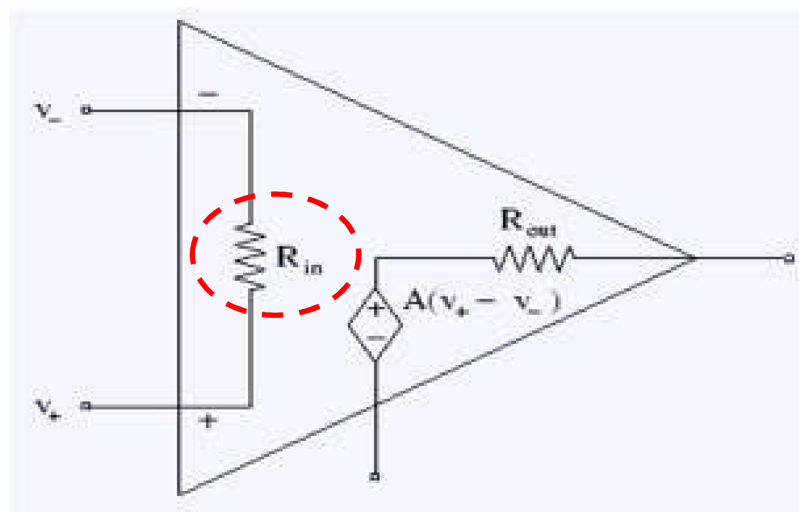
- There are 5 main properties of an ideal op-amp:
  1) ***Infinite input impedance***
  2) ***Zero output impedance***
  3) ***Infinite open-loop gain***
  4) ***Infinite bandwidth***
  5) ***Infinite slew rate***



- In reality op-amps are not ideal.

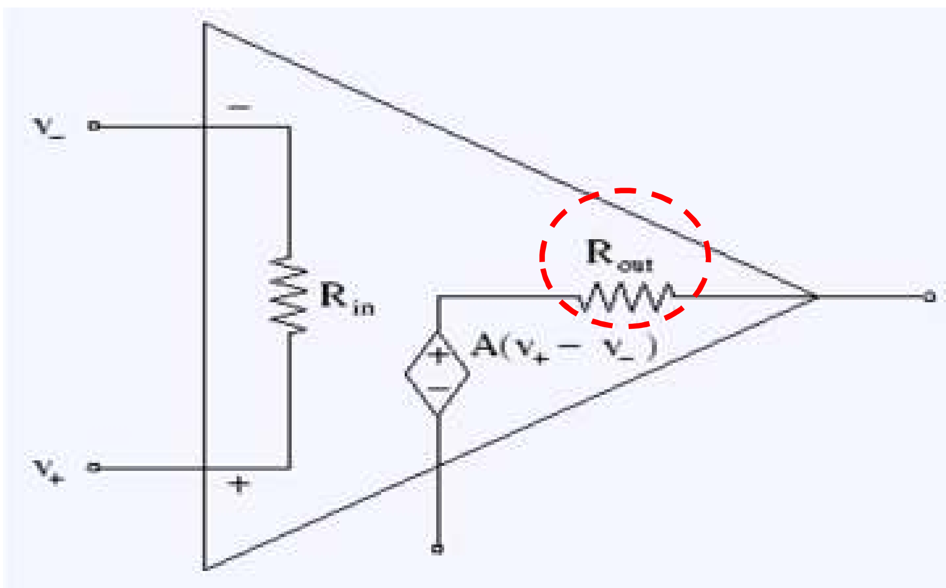
Ideal Op-Amp: Infinite Input impedance

- Impedance is similar to resistance but it is more than that.
- While a capacitor **does not have resistance** in a d.c. circuit, in an a.c. circuit it has **reactance** (similar to resistance, also in Ω). The combined resistance of a resistor and reactance of a capacitor is known as **impedance** (in Ω).
- **Input impedance** refers to the **internal impedance** **between** **the two input terminals.** **Infinite input impedance** means **no current enters or leaves either of the input terminals.**
- When a sensing circuit is joined to an op-amp, ideally no current should flow into the op-amp through the input terminals otherwise, the voltage in the sensing circuit will be altered.
- This is analogous to a voltmeter where a voltmeter should have infinite resistance so that when joined across a component, it should draw very little current and thus ***no change occurs to the voltage it tries to measure.***
- In reality, the input impedance is in the range $10^6 – 10^{12}$ ohm.



Ideal Op-Amp: Zero Output impedance

- Output impedance refers to the impedance inside the op-amp near the output terminal.
- An ideal op-amp should have **zero output impedance** so that **all the output voltage is seen across the load connected to the output.**
- This is analogous to a battery of zero internal resistance where all the voltage supplied by the battery should fall across the external circuit.
- In reality, the output impedance is about 10^2 ohm.



Ideal Op-Amp: Infinite open Loop Gain

- ***Gain is defined as:***

  [***the ratio of output voltage to input voltage***]() and the symbol is ***A***

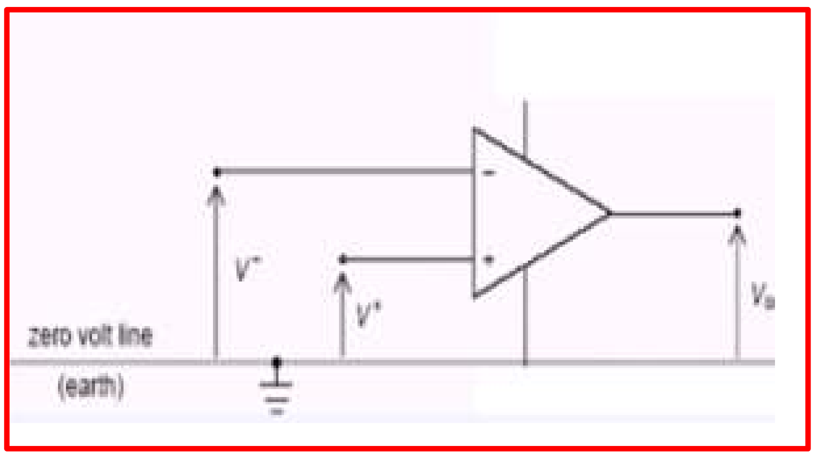
  i.e. how many times the output is greater than the input i.e. ***amplification***

  e.g. if the output is 9 V and the input is 0.1 V, gain A = 9/.1 = 90
- The way an op-amp is connected in a circuit will produce 2 different types of gain

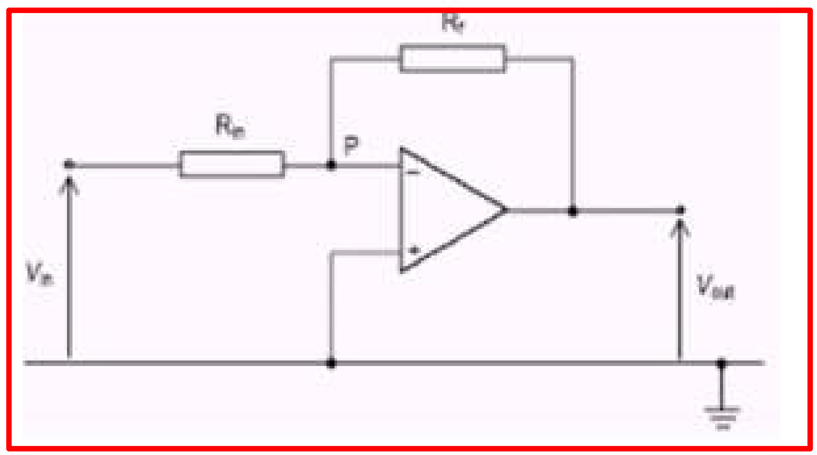
  (a) ***open loop gain***, symbol A_o and

  (b) ***closed loop gain, A***

Open-loop



Closed-loop



Ideal Op-Amp: Infinite Open-Loop Gain

- An op-amp actually amplifies the difference between the two input to the op-amp, ($V_+ - V_-$). That is why it is sometimes known as a differential amplifier.

  So $\boldsymbol{A_o = V_{out} / (V_+ - V_-)}$

  hence $\boldsymbol{V_{out} = A_o (V_+ - V_-)}$

- When there are no components connected between the output and the input terminal, the gain that is measured is said to be open-loop gain.

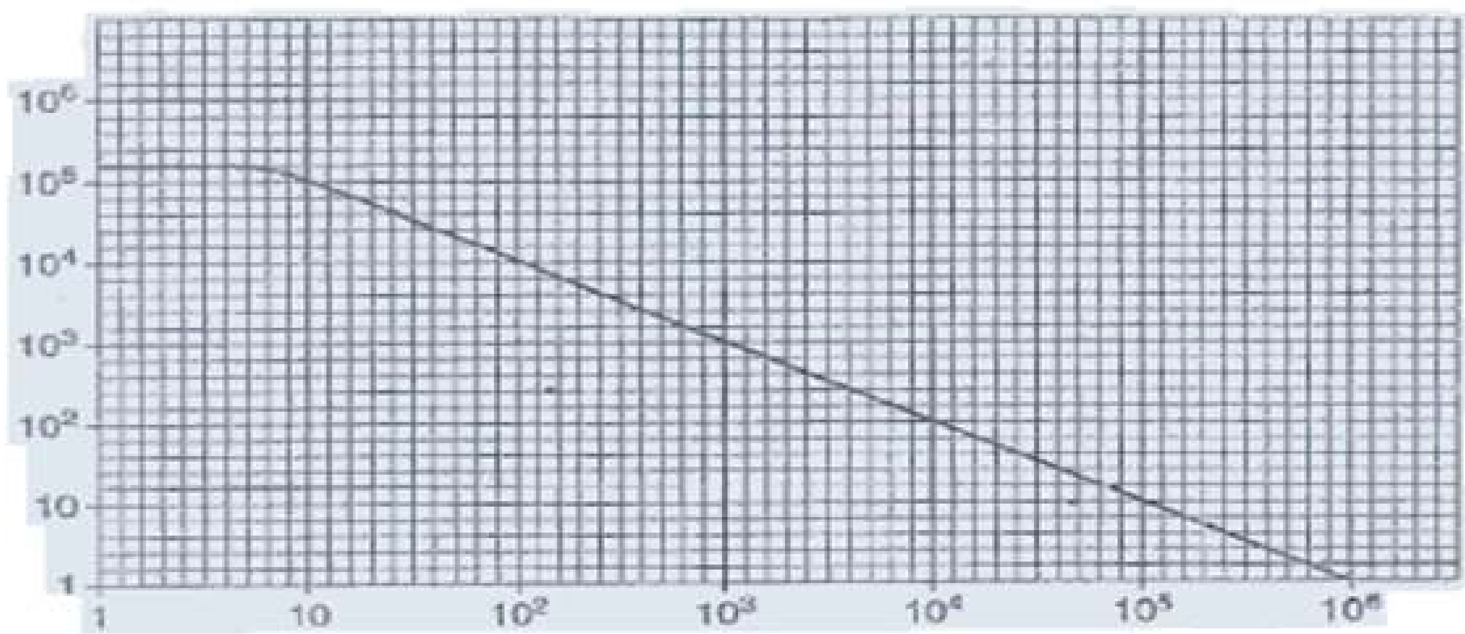
  (***Closed-loop*** gain will be examined later)

- An ideal op-amp should have **infinite open-loop gain** which means that when there is only **a very small input voltage, the output will have the same value as the supply voltage** since the output of the op-amp cannot be greater than the supply voltage.
- The amplifier in this state is said to be saturated.
- In reality, the open-loop gain is not constant and is in the order of 10^5.

Ideal Op-Amp: Infinite Bandwidth

- When an ac voltage is connected to the two inputs of an op-amp, the output voltage is different for different frequencies of the ac voltage.
- In other words, the gain varies with the frequency, f.
- Below is a graph of open-loop gain, A_o versus frequency, f called the **frequency response** of the amplifier. The range of frequencies over which the gain is constant is known as the **bandwidth** of the amplifier.

Gain, A_o



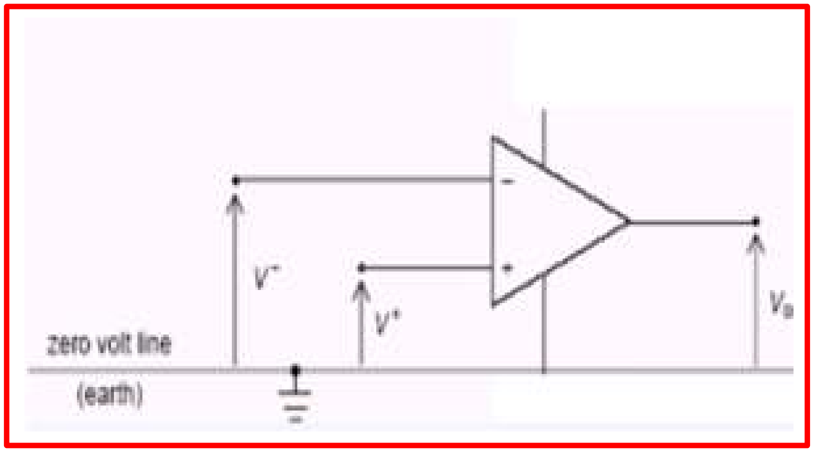
Frequency, f

- **Infinite bandwidth** means that **all frequencies of the input are amplified equally.**

Ideal Op-Amp: Infinite Slew rate

- When the input signal is changed, the output signal will also change.
- The output voltage may not be in synchronization with the input voltage meaning to say when the input voltage has changed with time, the output voltage may not have changed yet.
- An ideal op-amp should have **infinite slew rate** meaning that there should be **no delay between changes in the input and consequent changes in the output.**
- A high slew-rate implies a short time delay.
- In reality, the slew-rate is about 10 V μs^{-1}

Op-Amp as a Comparator



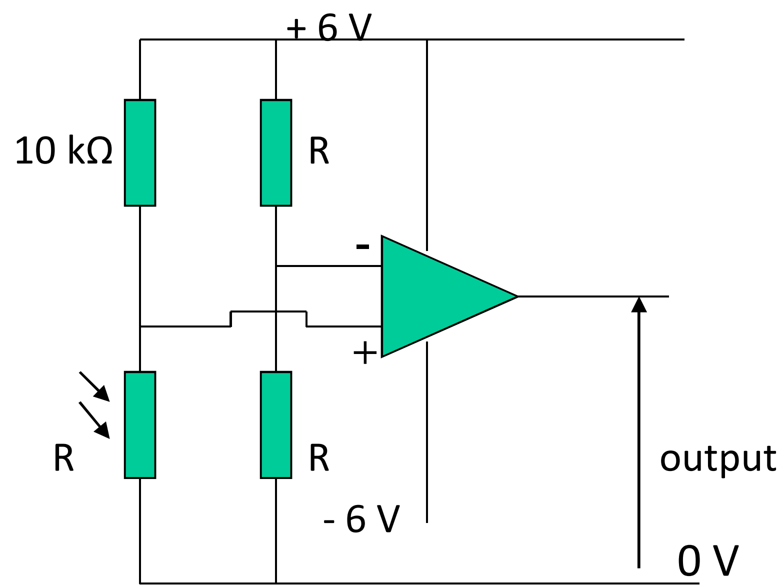
- Consider the case where the non-inverting input V_+ is 0.95 V, the inverting input V_- is 0.94 V, open-loop gain $A_0 = 10^5$, and the supply voltages at ± 6 V
- Using $V_{out} = A_o (V_+ - V_-)$ we get *1000 V* which from energy considerations is impossible as the output voltage can never exceed the power supply voltage.
- This means that the amplifier is saturated and the output voltage will be +6 V. So if $V_+ > V_-$ the output is $+ V_{supply}$

  and if $V_- > V_+$ the output is $– V_{supply}$

- Because this circuit compares the voltages applied to the non-inverting and the inverting inputs and then gives an output it is called a **comparator.**

Op-Amp as a Comparator

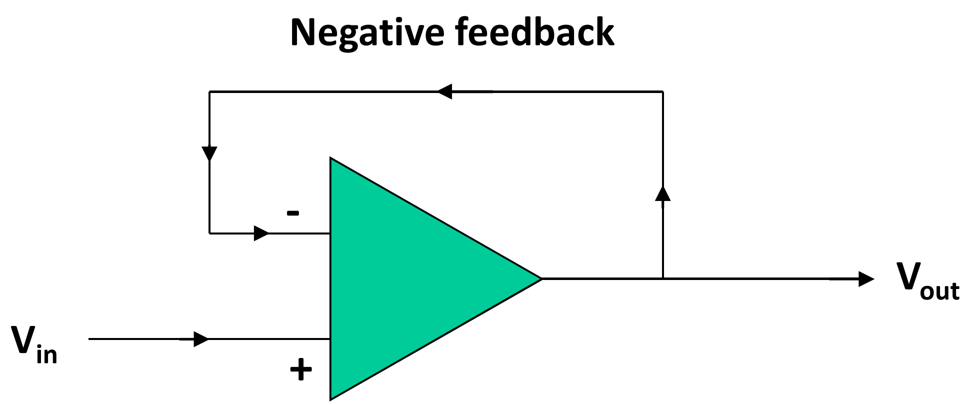
- When a circuit incorporating an op-amp is used as a comparator, it is usual to connect each of the input to a potential divider.



- The 2 resistors of equal resistance provide an input voltage of 3 V at the inverting input
- When the LDR is in darkness its resistance is greater than 10 kΩ, hence the voltage at the non-inverting input is greater than 3 V and the output will be at + 6 V.
- In daylight the resistance of the LDR will be less than 10 kΩ and the voltage at the non-inverting input will be less than 3 V and the output will switch to -6 V
- The output therefore depends on the level of light illumination and the values of the resistors in the potential divider. In practice one of the 2 resistors would be a variable resistor.

Negative Feedback

- **Negative Feedback** is a process whereby **the (fraction) output of any processing device is fed back to the inverting input so as to assist in the control of the output.**



- Effects of negative feedback:

  i.) Reduce distortion

  ii.) System can operate with greater stability

  iii.) Reduce amplifier gain

  iv.) Increase bandwidth

Negative Feedback

- When an op-amp is configured in any negative-feedback arrangement, it will reduce the gain of the amplifier. In order to calculate the value of the new gain (closed loop gain), recall the following two rules:

  1.) The inputs to the op-amp draw no current.

  2.) The op-amp will do whatever it can to make the voltage difference between the two inputs to be equal to zero.

- Now, we will look at how op-amp function as an inverting amplifier & non-inverting amplifier.

Op-Amp: The Inverting Amplifier

- When an op-amp is connected as an inverting amplifier:

  - The non-inverting input (+) is connected to the 0V live.

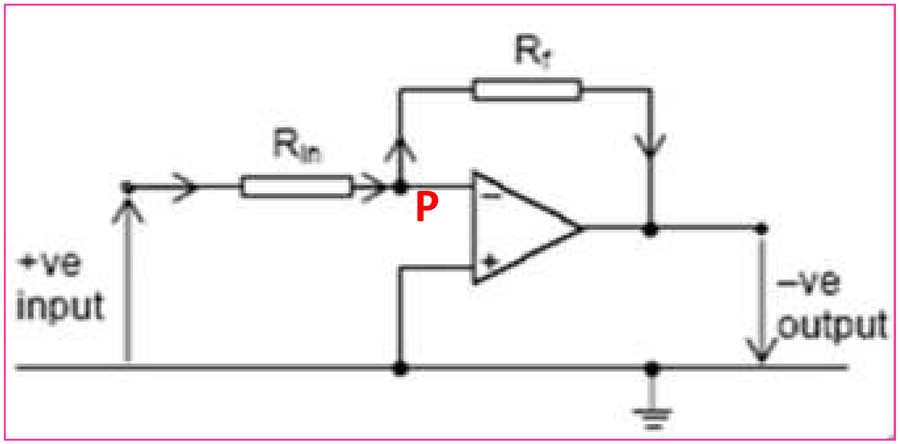
  - Part of the output voltage is connected to the inverting input (-) via negative feedback.

  - The input voltage is connected to the inverting input.

- To understand how the inverting amplifier works, you need to understand the concept of **virtual earth approximation**. It is an approximation that the **potential at the inverting input (-) is very close to 0V.** Why is this true?
- There are 2 steps in the argument.
- Firstly, the op-amp multiplies the difference in potential between inverting & non-inverting inputs to produce the output. Because open loop gain is very high, the difference between V_+ and V_- must be very small (almost zero) in order not to reach saturation.
- Then, since V_+ is connected to the zero volt line ($V_+ = 0V$), thus V_- must also be close to zero and the inverting input (-) should be almost at earth potential.
- Since the output is the inverse of the input, the amplifier is referred to as an ***inverting op-amp*** and the output voltage is ***180^o out of phase(π)*** with the input voltage

Op-Amp: The Inverting Amplifier

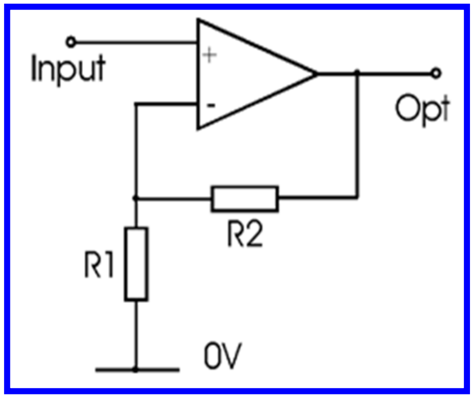
- **Point, P is known the virtual earth.**
- The virtual earth approximation can help us to find the expression for the gain of this inverting amplifier.
- At point P the potential is zero.
- current across R_{in} = current across R_f
- $$\frac{V_{in} - 0}{R_{in}} = \frac{0 - V_{out}}{R_f}$$
- $$\boxed{V_{out} = -\frac{R_f V_{in}}{R_{in}}}$$
- $$\boxed{\text{Gain, } A = -\frac{R_f}{R_{in}}}$$

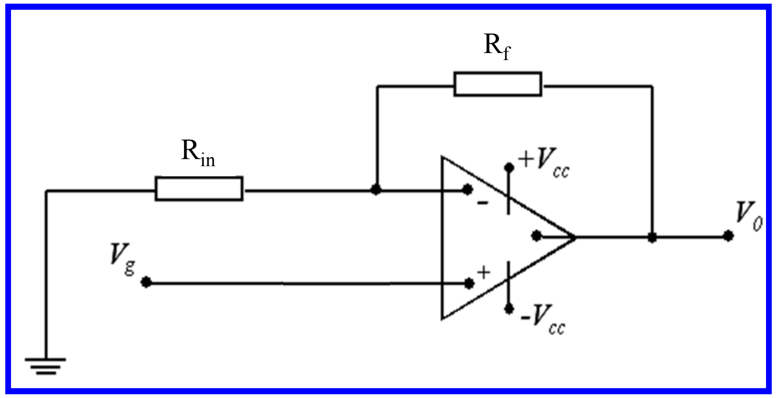


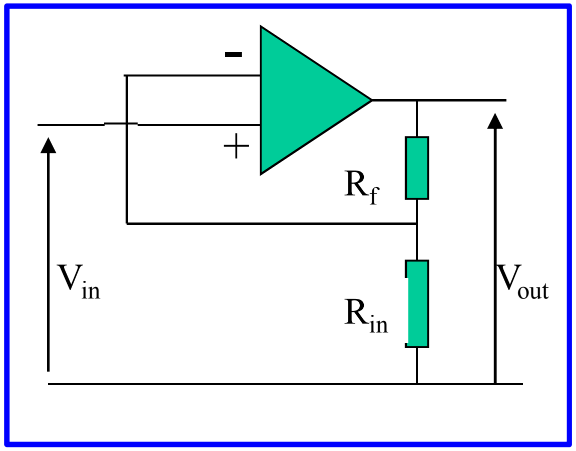
- The minus sign indicates that the output is inverted. Notice that the gain of the amplifier is independent of the open-loop gain of the op-amp.
- Since the new gain depends only on external components R_{in} and R_f , the gain is not affected by any changes that may take place inside the op-amp, such as change in gain due to temperature change inside the op-amp. Thus, negative feedback provides stability.

Op-Amp: The Non-Inverting Amplifier

- For this configuration, the input voltage is applied directly to the non-inverting input.
- Part of the output voltage is fed back to the inverting input.



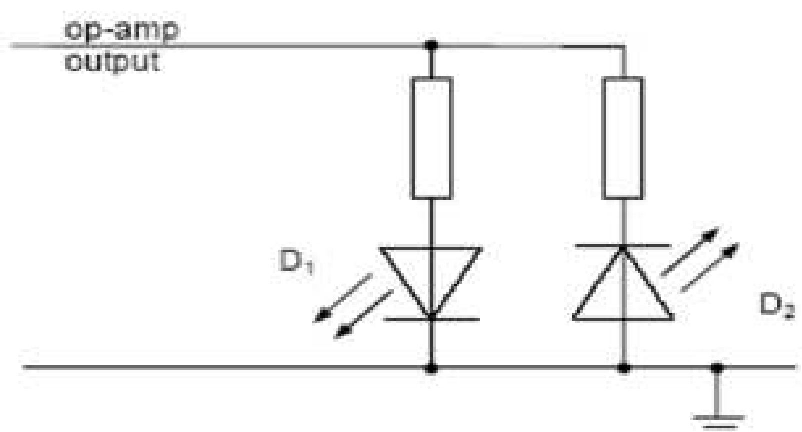




- $\dfrac{V_{out} - V_{in}}{R_1} = \dfrac{V_{in} - 0}{R_f}$
- $\boxed{V_{out} = (1 + \frac{R_f}{R_{in}})\, V_{in}}$
- $\boxed{\text{Gain, } A = (1 + \frac{R_f}{R_{in}})}$

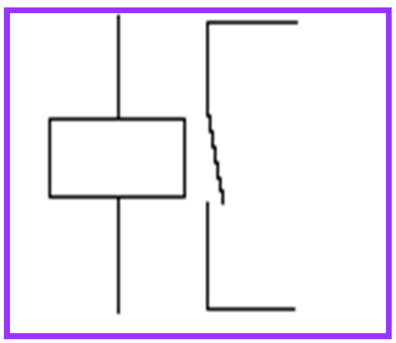
Output devices

- Circuits incorporating op-amps produce an output voltage.
- If this output voltage is connected across some form of resistor, there will be a current from the output of the op-amp to the resistor, which can then be used to operate ***output devices*** such as ***relays***, ***digital/analogue meters, motors,*** warning ***lamps e.g. LEDs*** etc.
- Output current of op-amps usually does not exceed about 25 mA otherwise the op-amp would be destroyed.
- Op-amps ICs are designed and built to contain an output resistor so that, should the output be ‘shorted’, the op-amp will not be damaged.

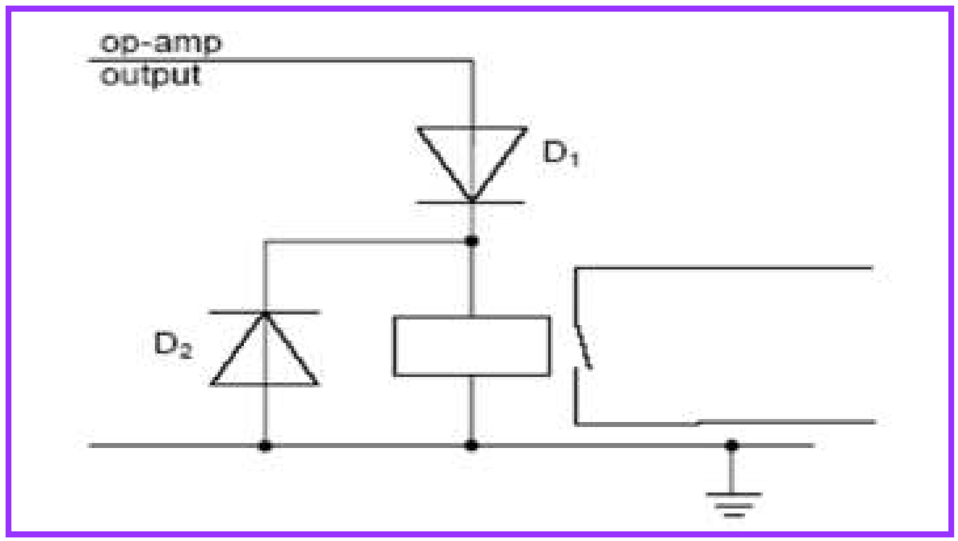


Output device: Relay (1)

- In order that electronic circuits e.g. an op-amp may be used to switch on and off appliances that require large currents to operate them, a relay may be used.
- A ***relay*** is an ***electromagnetic switch that uses a small current to switch on or off a larger current.*** The small current energises an electromagnet that operates contacts, switching on or off the larger current.
- The diode D_1 conducts only when the output is positive with respect to earth and thus the relay coil is energised only when the output is positive. When the current in the relay coil is switched off, a back e.m.f. is generated in the coil that could damage the op-amp. A diode D_2 is connected across the coil to protect the op-amp from this back e.m.f.

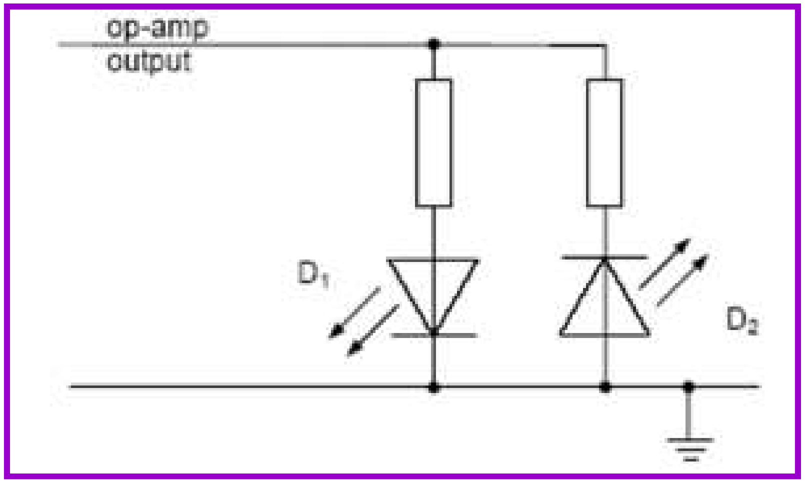


Symbol for relay



Output device: LED (2)

- There are many instances when all that is required of a sensor is a visible indicator i.e. a lamp when a high or low is detected.
- The ***light emitting diode(LED)*** which is available in many colours, is a semiconductor device that is very robust, reliable and low power consumption.
- A LED emits light only when it is forward biased and the typical maximum current is 20 mA.
- A LED may be damaged if the reverse-bias voltage exceeds approximately 5 V (called the ***breakdown voltage***).
- A LED is often connected in series with a resistor so that when the LED is forward biased (the diode is conducting), the current is not so large as to damage the LED.
- From the circuit on the right, when output is positive, diode 1 will conduct and emit light. Diode 2 will not conduct because it is in reverse biased.
- If polarity changes, then diode 2 will conduct and emit light, while diode 1 will not.



Calibration

- When the output of an op-amp does not saturate, the output voltage can be used to indicate the magnitude of whatever is being sensed e.g. level of light intensity.
- A digital or analogue voltmeter for example connected between the op-amp output and earth will indicate the output voltage.
- The output voltage will be proportional to the input to the processing unit which is dependent on the magnitude of whatever is being sensed.
- As the digital or analogue voltmeter reads a potential difference and not the quantity that is being monitored and measured, the voltmeter reading is unlikely to vary linearly with the change in this quantity and hence the voltmeter needs to be **calibrated.**
- In order that the property can be measured, a calibration curved is required. The reading on the voltmeter is recorded for known values of the property X. A graph is then plotted showing variation with the property X of the voltmeter reading. The value of the property X can then be read from the graph for any particular reading on the voltmeter.