AREA OF STUDY 2:
Electronics and photonics

Review of basic electricity

Electric current I (A) is defined as the amount of charge Q (C) passing through in a unit time (s).

$$I = \frac{Q}{t} \text{ and } \therefore Q = It .$$

$$1 \text{ A} \equiv 1 \text{ Cs}^{-1}$$

In an electric circuit current through a component is measured with an **ammeter** connected in series with it.

Electric potential V (v) at a point is the amount of electric potential energy E (J) possessed by each unit of charge at that point.

$$V = \frac{E}{Q} \text{ and } \therefore E = VQ .$$

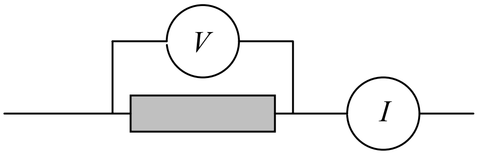
$$1 \text{ v} \equiv 1 \text{ JC}^{-1}$$

Electric potential difference, also denoted as V and measured in v is the difference in potential between two points. When current flows from high to low potential, electric potential energy of the charges changes to other forms of energy. The amount of energy change is also given by $E = VQ$ where V is the potential difference measured with a **voltmeter** connected to the two points.

$$\therefore E = VIt \text{ and } P = \frac{E}{t} = VI .$$

The *resistance* R of a conductor is a measure of the ability of the conductor in reducing electric current and it is defined as the ratio of potential difference V to current I.

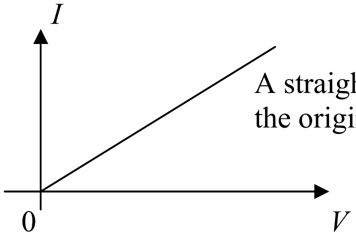
$$R = \frac{V}{I} .$$



Ohm's law

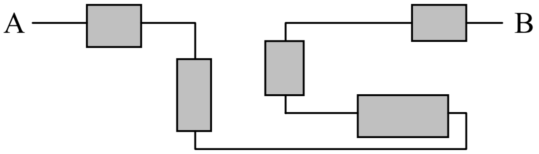
Ohm's law states that for some conductors the resistance stays <u>constant</u> when the potential difference and current vary.

Conductors that obey Ohm's law are called **ohmic conductors** (**resistors**) and have the following *I-V* characteristics.



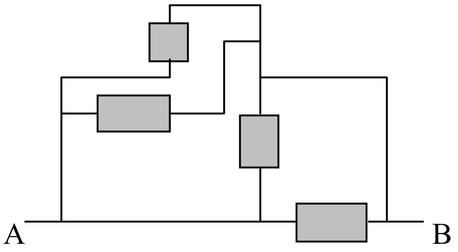
A straight line through the origin.

Components connected in series



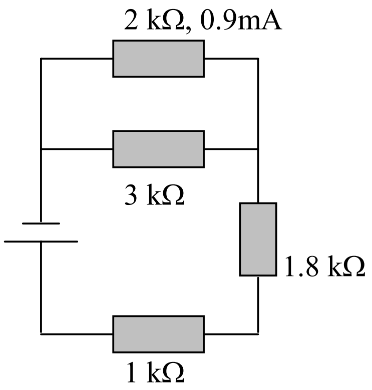
1) $I = I_1 = I_2 = I_3 = ...$
2) $V_{AB} = V_1 + V_2 + V_3 + ...$
3) $R_T = R_1 + R_2 + R_3 + ...$ remains constant if the components are ohmic resistors.
   Also $R_T = \frac{V_{AB}}{I}$.

Components connected in parallel



1) $V_{AB} = V_1 = V_2 = V_3 = ...$
2) $I = I_A = I_1 + I_2 + I_3 + ... = I_B$
3) $R_T = \dfrac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ...}$ remains constant for ohmic resistors.
   Also $R_T = \frac{V_{AB}}{I}$.

Example 1



a) Find the potential difference across each component.
b) Find the current through each component.
c) Calculate the voltage of the DC supply.
d) Calculate the total resistance of the circuit in two ways.

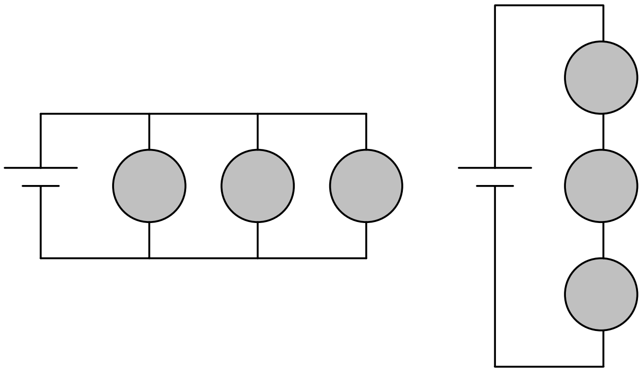
Power in series and parallel circuits

The total power consumption in a parallel or series connection of components is the sum of the individual power of the components in the connection.

The power of a component in a parallel connection is the same power as when it is alone, hence the total power of the parallel circuit is higher than that of a single component by itself.

The power of a component in a series connection is less than the power of the component when it is alone and the total power of the series circuit is less than that of a single component by itself.

Example 1 Three identical light globes (3W12v) are connected in parallel and then in series. In each case the power is supplied by a 12v battery. Assuming that the globes are ohmic conductors, calculate a) the resistance of each globe, b) the power of each globe and the total power dissipated in the parallel circuit, c) the power of each globe and the total power dissipated in the series circuit, and d) the current through the battery in each circuit.



Voltage dividers

A series connection of two or more resistors forms a voltage divider. The supply voltage to the series connection is divided into voltages in the same ratio as the resistances of the components.

Example 1 A 2-kΩ and a 1-kΩ resistors are connected in series and the potential difference between the two ends of the series is 9.0v. Determine the voltage across each resistor.

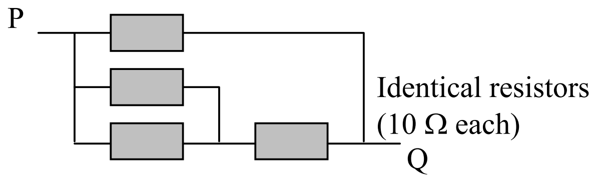
In general, $V_1 = \frac{R_1}{R_1 + R_2} \times V$ and $V_2 = \frac{R_2}{R_1 + R_2} \times V$, where V is the supply voltage.

Example 2 A 750-Ω and 1.25-kΩ resistors are in series, and the voltage across the latter is 7.5v. Find the voltage across the 750-Ω resistor and the supply voltage the series circuit.

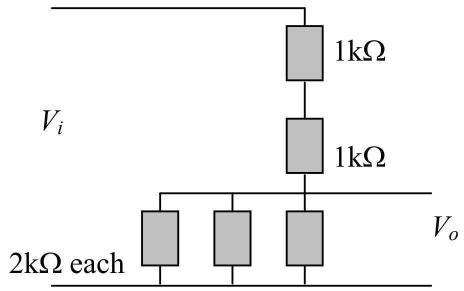
In general, $\frac{V_1}{V_2} = \frac{R_1}{R_2}$.

Simplifying circuits comprising parallel and series ohmic resistors and voltage dividers

Example 1 Replace the following circuit between P and Q with a single resistor.



Example 2 Simplify the following voltage divider to give the same output voltage with the same input.



Semiconductors

A substance able to conduct charge to some extent (between a metal and an insulator) can be classified as a semiconductor. The most common semiconductors are silicon and germanium. Each atom in the crystal lattice of a semiconductor shares its four outer-shell electrons with its four nearest neighbours to form covalent bonds. These outer-shell electrons are not really free to move around the lattice. At room temperature thermal energy causes a few of these electrons to break loose and wander through the crystal like the electrons in a metal.

The conductivity can be improved by replacing some of the lattice atoms with atoms of different elements that can provide more mobile charges. This process is called doping.

When a semiconductor is doped with atoms with 5 outer-shell electrons, the extra electron becomes a mobile charge and the semiconductor is called n-type semiconductor.

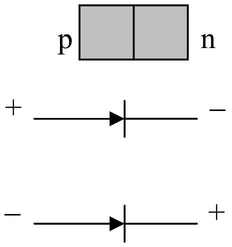
When a semiconductor is doped with atoms with 3 outer-shell electrons, there is one missing electron to form a covalent bond for each of these replacement atoms. 'Holes' are thus created in the lattice and neighbouring electrons may easily move into. An electron moving into a hole can be considered as a positive charge moving out of the hole. The semiconductor is called p-type.

pn semiconductor junction

A pn semiconductor junction is formed when a p-type and a n-type semiconductors are in contact. Many electronic devices are made of pn semiconductor junctions.

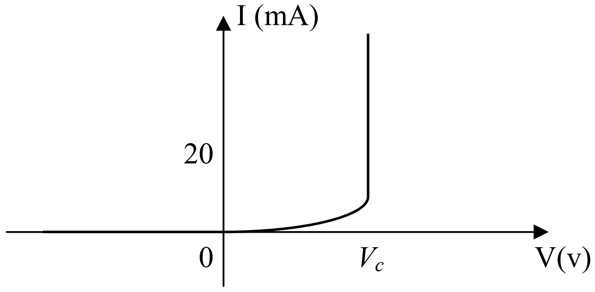
Non-ohmic conductors–diodes, thermistors and photonic transducers such as LDR, photodiodes and LED

A *diode* is an electronic device that can be used to control current and voltage. It is in fact a pn junction. It conducts when it is forward biased and the current drops to practically zero when it is reverse biased.



Forward bias, $R \to 0$.

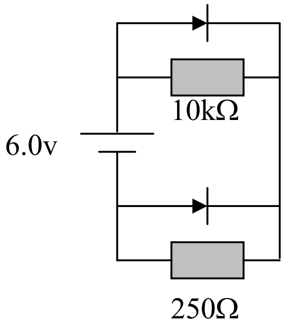
Reverse bias, $R \to \infty$.



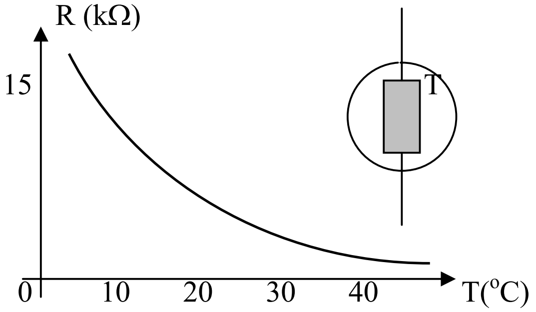
For a germanium diode, the voltage for conduction of current, $V_c \approx 0.2 - 0.3$ v; for a silicon diode $V_c \approx 0.6 - 0.7$ v. While a diode is conducting the voltage across it is fairly constant (V_c).

Example 1 A silicon diode and a 1.5-kΩ resistor is connected in series with a 6.0-v battery. Determine the current and the voltage across the resistor when the diode is forward biased. What is the voltage across the diode when it is reverse biased?

Example 2 Consider the following circuit with two silicon diodes. Determine the voltage across and the current through each component.



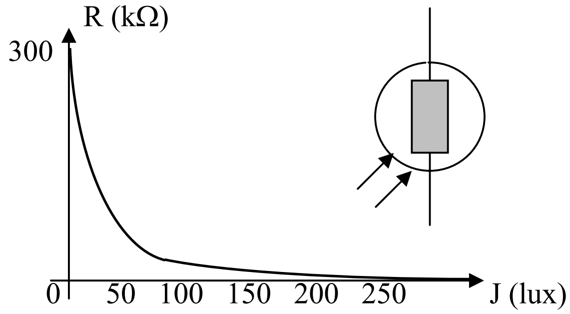
A *thermistor* is a semiconductor device whose electrical resistance varies with temperature. The following resistance versus temperature graph shows the characteristic for a thermistor.



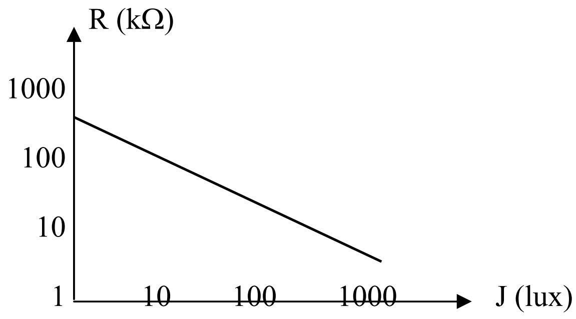
Example 3 A voltage divider consists of the above thermistor and a 1.2-kΩ ohmic resistor is powered by a 6.0-v battery. The voltage across the resistor is 1.5v. Determine the temperature of the thermistor.

Transducers are devices that change other forms of energy into electrical energy (input transducers) and vice versa (output transducers), e.g. thermistor is an input transducer; loudspeaker is an output transducer. *Photonic transducers* changes light (which carries encoded information) into electrical energy and vice versa. The following devices are photonic transducers.

A *light dependent resistor* (LDR) is a semiconductor device whose resistance changes with the intensity of light that it is exposed to. The following resistance versus light intensity (illumination) graph shows the characteristic for a typical LDR.



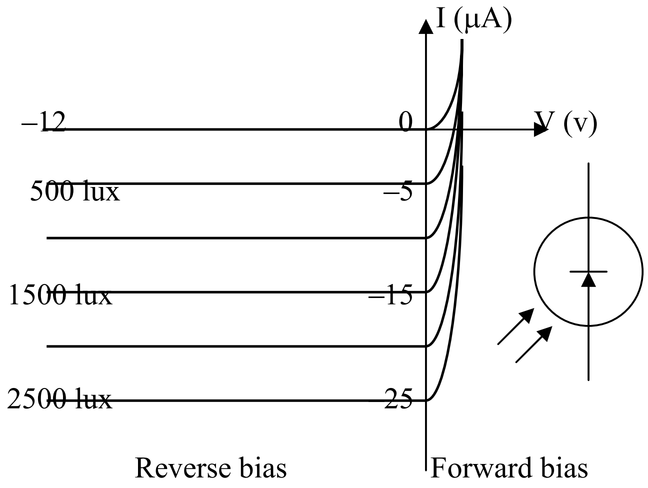
The above data are usually plotted on axes with logarithmic scales.



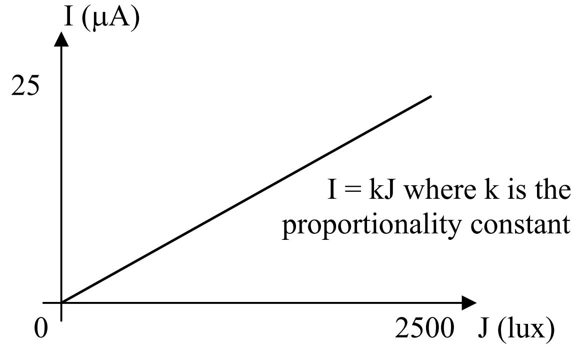
Condition	Light intensity (lux)	Resistance (kΩ)
Full moon	1	300
Dimly lit room	300	10
Winter outdoor	6000	2

Note: 1 lux ≈ 0.0016 Wm^{-2} of yellow light.

A *photodiode* is a diode whose conduction changes with illuminating light intensity when it is reverse biased. A reverse biased photodiode is said to be in *photoconductive mode*. Increasing the light intensity increases the reverse biased current through a photodiode. The following I-V graph shows the characteristics of a typical photodiode at different illuminating light intensities.

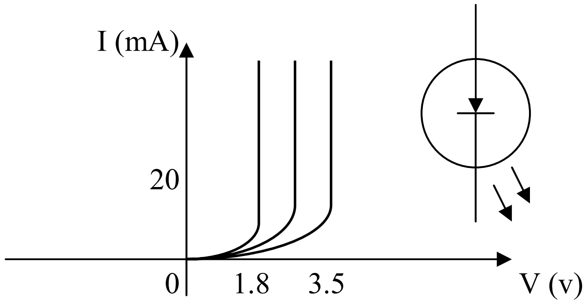


When a photodiode is reverse biased conducting current is directly proportional to light intensity.



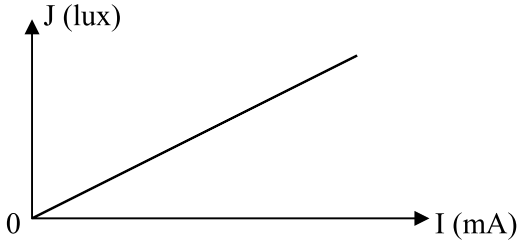
In comparison with a LDR (response time in the order of milliseconds), a reverse biased photodiode has a much faster response time and it is used to detect light signals with period less than a microsecond.

A *light emitting diode* (LED) emits light when it is forward biased. The common LEDs have V_c ranging approximately from 1.8 to 3.5v.



In fibre optic telecommunication LEDs emit light in the infrared region (λ ≈ 950 – 1550nm). Other common LEDs used in electronics emit red (660nm), yellow (590nm) and green light (550nm).

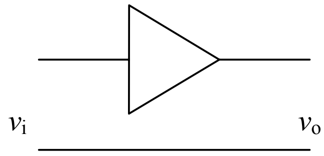
The intensity of emitted light is directly proportional to the current.

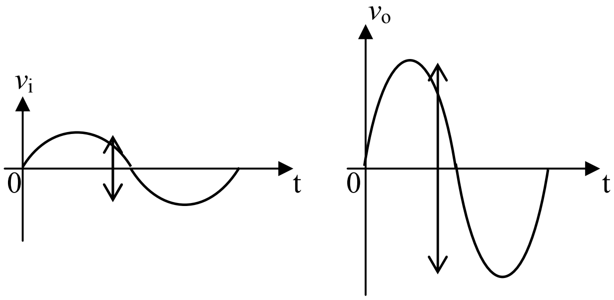


LEDs can respond to electrical signal with period < 1μs.

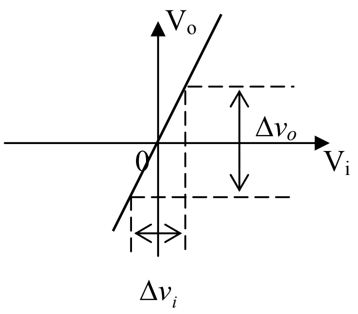
Ideal voltage amplifier

An ideal voltage amplifier gives at the output a true reproduction of the input signal voltages with larger amplitude.



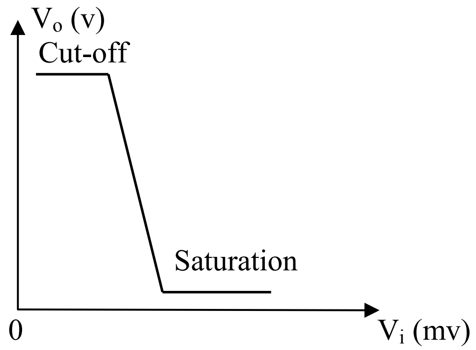


Both v_i and v_o are centred at zero volt.
When V_o is plotted against V_i , the graph is a straight line through the origin for an ideal voltage amplifier.



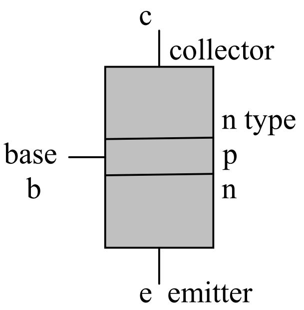
The amplification factor of the device is called the **voltage gain** and it is defined as the ratio $G_v = \frac{\Delta v_o}{\Delta v_i}$, i.e. the gradient of the linear graph.

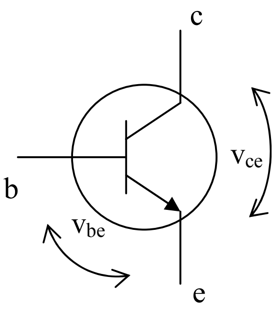
An example of a practical voltage amplifier is a npn transistor voltage amplifier (circuit diagram on next page). The graph of V_o versus V_i is shown below.



The amplifier is said to be *saturated* when it is in its maximum conducting condition. At *cut-off* the current is essentially zero. Linear amplification is achieved when the time-varying input signal voltages are between the cut-off and saturation. The linear section has a negative gradient (hence negative value for voltage gain) resulting in an inverted output signal.

npn transistors

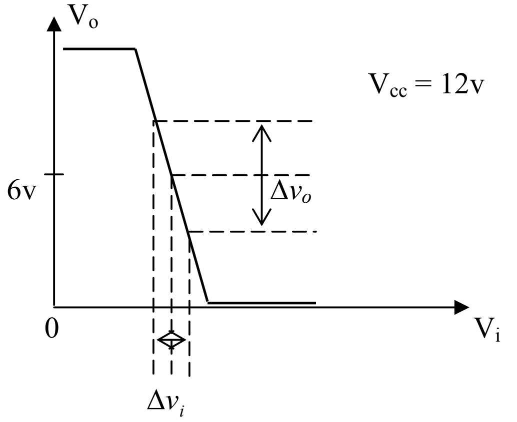




Using npn transistor as a voltage amplifier

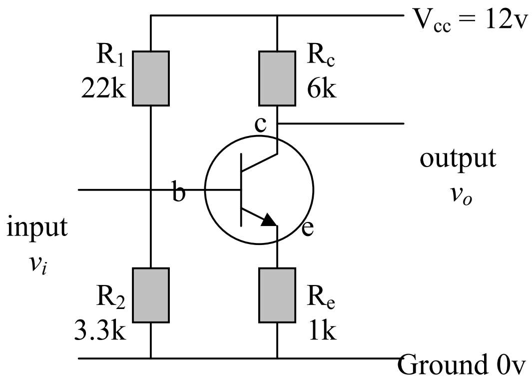
When a npn transistor is in linear operation mode the base-emitter voltage V_{be} is essentially constant (≈ 0.6 – 0.7v).

To make full use of the linear operation of a npn transistor the input signal must be 'centred' at the mid-point of the linear section. The output signal will then be centred at the mid-point of the full output range (0 – V_{cc} approx). V_{cc} is the supply voltage to the transistor.



Biasing npn transistors

A satisfactory npn transistor bias circuit working as a voltage amplifier is shown below where I_c = 1mA when there is no input signal, and the potential difference between the base and the emitter V_{be} remains constant at 0.6v.



The manufacturer usually specifies the ratio of the dc collector current to the dc base current, i.e. $G_I = \frac{I_c}{I_b}$ which is known as **current gain**. In this case $G_I \approx 50$.

$I_e = I_c + I_b$ and because $I_b << I_c$, $\therefore I_e \approx I_c$.

Example 1 Refer to the biased npn transitor amplifier discussed earlier. (a) Find the currents and voltages at different points when the there is no input signal ($\Delta v_i = 0$). (b) Find the currents and voltages at different points when the input signal causes V_b to change by +0.4v. (c) Determine the voltage gain of the amplifier.

(a) I_c = 1mA, $V_c = V_{cc} - I_cR_c = 12 - 1 \times 6 = 6$v.

$I_e \approx I_c$ = 1mA, $V_e = I_eR_e = 1 \times 1 = 1$v, $V_{ce} = 6 - 1 = 5$v.

V_{be} = 0.6v, $V_b = V_e + V_{be} = 1 + 0.6 = 1.6$v.

$V_{R1} = V_{cc} - V_b = 12 - 1.6 = 10.4$v,

$$I_{R1} = \frac{V_{R1}}{R_1} = \frac{10.4}{22k} = 0.47 \text{ mA.}$$

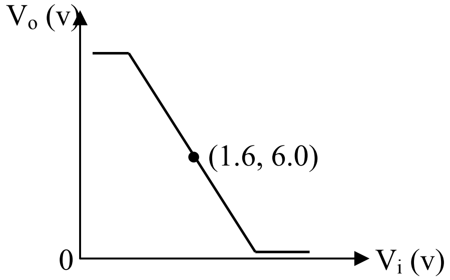
$$I_b = \frac{I_c}{50} = 0.02\text{mA, } I_b << I_c.$$

Note (1) Because I_b is comparative small, V_b can be calculated approximately by considering R_1 and R_2 as a voltage divider,

$$V_b = V_{R2} = \frac{R_2}{R_1 + R_2} \times V_{cc} = \frac{3.3}{22 + 3.3} \times 12 = 1.6 \text{ v, and}$$

$$I_{R1} = \frac{V_{cc}}{R_1 + R_2} = \frac{12}{22k + 3.3k} = 0.47 \text{ mA.}$$

Note (2) The centre of the linear region is approximately (1.6v, 6.0v).



(b) ΔV_b = +0.4v, $\therefore V_b = 1.6 + 0.4 = 2.0$v,

$V_e = V_b - V_{be} = 2.0 - 0.6 = 1.4$v,

$$\therefore I_e = \frac{V_e}{R_e} = \frac{1.4}{1k} = 1.4 \text{ mA, } I_c \approx I_e = 1.4\text{mA.}$$

$V_c = V_{cc} - I_cR_c = 12 - 1.4 \times 6 = 3.6$v,

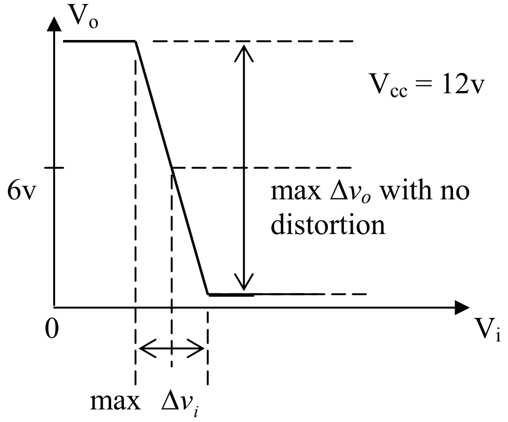
$\therefore \Delta V_c = 3.6 - 6 = -2.4$v.

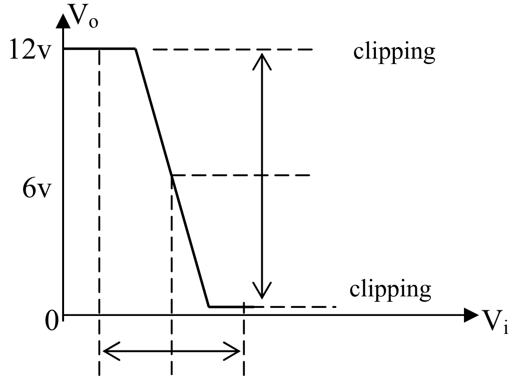
(c) Voltage gain $G_v = \frac{\Delta v_o}{\Delta v_i} = \frac{\Delta V_c}{\Delta V_b} = \frac{-2.4}{0.4} = -6$.

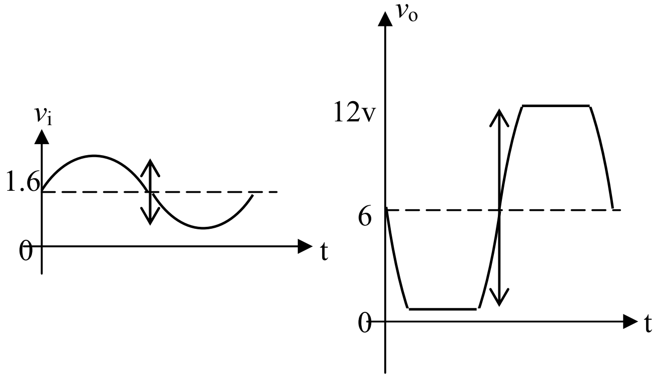
Note: For large R_c and R_e (i.e. $\geq$ 1kΩ), $G_v \approx -\frac{R_c}{R_e}$.

Maximum amplitude of input signal

Because the output signal is restricted by the cut-off and saturation voltages, the input signal must be correctly centred and have its peak-to-peak voltage within certain range otherwise '*clipping*' will occur and give rise to a distorted output signal.







Example 1 Determine the maximum amplitude of the input signal to avoid clipping from happening for the correctly biased npn transistor amplifier discussed previously.

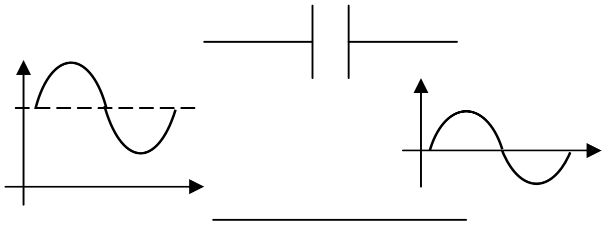
Example 2 A signal of the same amplitude (as in example 1) is not centred correctly due to incorrect biasing of the transistor. Draw diagrams showing the input and the corresponding output signals.

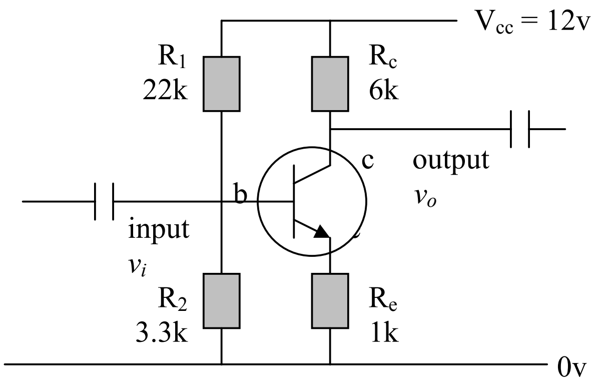
Coupling and decoupling capacitors

Signals coming from input transducers usually contain both dc and ac components. When these signals are fed into the biased npn transistor amplifier they upset the biasing of the transistor and cause it to operate away from the centre of the linear section.

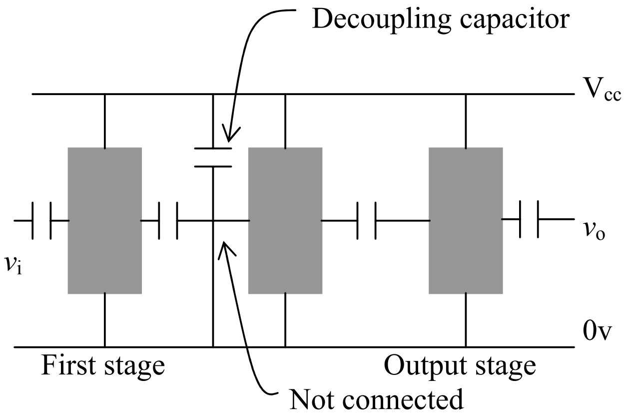
One of the functions of a capacitor is to filter out the dc component from a signal and allow only the ac component to pass through it. Such a capacitor is called a **coupling capacitor**.

The output signal of the amplifier also contains both dc and ac components. The dc component is removed with a second coupling capacitor before the signal is fed into an output transducer or a second biased transistor amplifier for further amplification.



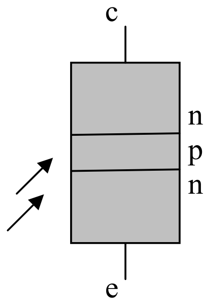


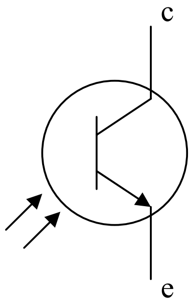
When three or more stages of amplification are cascaded it is usually necessary to decouple the power supply of the first stage from the remaining stages with a **decoupling capacitor**. This prevents **feedback** from the output stage that can alter the bias on the first stage.



Phototransistors

Phototransistors are photonic input transducers. A phototransistor has only two terminals, they are the collector and the emitter. The base terminal is not required because the base current is produced by light falling on the base-emitter (pn) junction. The collector current is directly proportional to the light intensity.

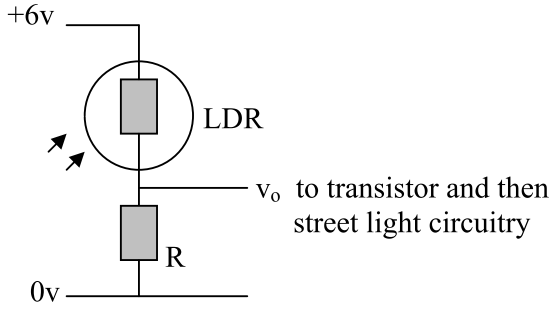




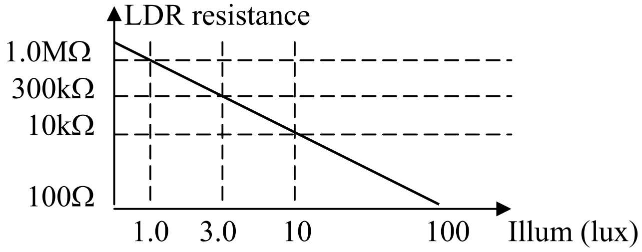
Phototransistors can detect light signals with period > 1μs.

Design and analyse electronic circuits comprising ohmic resistors and photonic transducers

Non-contact switch consisting of a LDR and an ohmic resistor, e.g. in street lighting:

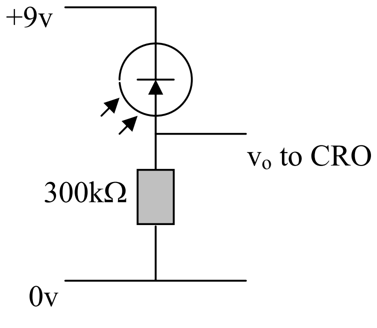


Example 1 Suppose the above LDR has the characteristics shown in the graph below, and street lighting turns on when $v_o \leq 1.5$v corresponding to light intensity (illumination) ≤ 10 lux. Calculate the resistance of R to meet these requirements. Explain.

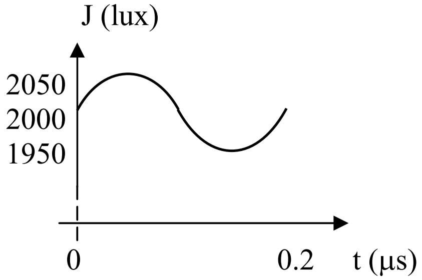


Example 2 Refer to example 1. If the resistance of R is set at 100kΩ, what is the outside light intensity that turns on the street lighting?

Light sensor comprising a photodiode and an ohmic resistor for detection of time-varying light signals of very short periods (i.e. very high frequency):

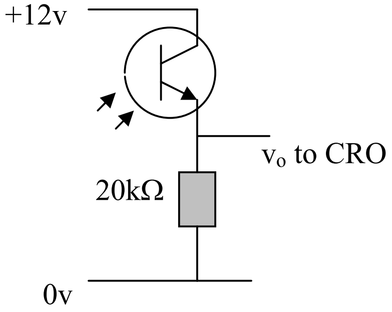


Example 3 Refer to the characteristics of the photodiode discussed on p5. The photodiode is exposed to a time-varying light signal as shown below:

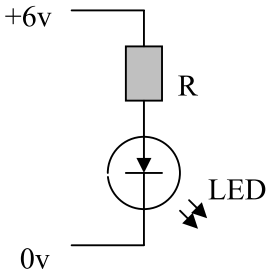


Sketch a graph showing v_o as a function of t.

Note: In the light sensor discussed previously, the photodiode can be replaced with a phototransistor and it is suitable for detecting light signals with periods greater than a microsecond (μs).



Light source circuit comprising a LED and an ohmic resistor:



The emitted light intensity is directly proportional to the forward bias current through the LED.

Example 4 In the above circuit the voltage across the LED is 2.0v when it is forward biased and R = 200Ω. Calculate the forward bias current. What R value will double the intensity of light emitted?

The skin effect*

The tendency of electrical signal (alternating current) to flow near the surface of a metal conductor, thereby restricting the current to a small part of the total cross-sectional area. This is known as the **skin effect**. Since resistance is inversely proportional to the cross-sectional area that the current flows through, thus the resistance to the flow of current increases.

The skin effect increases as the frequency of the signal increases. Hence low frequency electrical signals, in comparison with high frequency signals, travel through a metal conductor with relatively low reduction in intensity.

Information-carrying capacity (bandwidth) of metal wires and optical fibres*

Bandwidth refers to the information carrying capacity of a communication medium, device or network. It is determined by the highest frequency that can be practically transmitted.

For a 1-km long typical copper telecommunication cable, due to the skin effect, the bandwidth is only around 500kHz.

The skin effect does not exist for light signals travelling through optical fibres, and therefore much higher frequencies can be transmitted through them. Theoretically the bandwidth is unlimited.

The bandwidth required to send a signal or to transmit information depends on the type of signal.

Signal	Bandwidth
Telephone (normal voice)	4 kHz
AM radio (audio)	10 kHz
FM radio (high fidelity audio)	200 kHz
Television (video + audio)	6 MHz

Copper cable is a suitable medium for telephone communication and audio signal transmission.

* No longer required according to the revised study design.

Long distance transmission of information using cables

Analogue electrical signals in metal conductor can be changed to intensity modulated light signals (to be sent through an optical fibre) by means of an electrical-optical converter, e.g. a laser diode.

[A laser diode works very much like a LED.
There are some important differences:
The light emitted from a laser diode has a very narrow wavelength range of 1–5 nm. The wavelength range for LED is typically 30–80 nm.
Laser diodes have a much faster response than LEDs. They respond to electrical signals with periods less than a nanosecond.]

An opto-electronic converter such as a laser diode has a bandwidth in the order of GHz.

At the other end of the optical fibre, the intensity modulated light signals are changed back to electrical signals by an optical-electrical converter, e.g. a photodiode. Photodiodes can respond to light signals with periods $< 1\mu s$. Hence their bandwidth is in the order of MHz.

Example 1 What is the bandwidth of the opto-electronic communication system discussed above? If the photodiode is replaced with a LDR, what will be the bandwidth of the system? Will it work well for high fidelity music transmission?

Energy transformations in opto-electronic converters

Example 1 LED, a semiconductor pn junction, is an example of *light source* in photonics in which electrical energy is transformed to light energy.

When it is forward biased by an applied voltage, electrons move from the n region to fill the holes in the p region. When an electron fills a hole, a ‘packet’ of light energy called *photon* is emitted.

When the forward biased current increases, the number of holes filled by electrons increases and thus the number of photons emitted increases, and hence the light intensity increases. This explains why emitted light intensity is directly proportional to the forward biased current through the pn junction.

Example 2 Photodiode, also a semiconductor pn junction, is an example of *light detector* in photonics in which light energy is transformed to electrical energy.

When a photodiode is reverse biased and light intensity is very low, practically there is zero current in the junction.

When light intensity increases (i.e. the number of photons hitting the pn junction increases), the number of electrons freed from the valence bonds increases and thus the reverse biased current (called photocurrent) through the pn junction increases. This results in the direct variation relationship between photocurrent and light intensity.