Physics notes – Electronics and photonics

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Review of basic electricity

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

$$I = \frac{Q}{t} \text{ or } Q = It$$

An ampere (A) is the passage of a coulomb of charges in a second, $1 \text{ A} \equiv 1 \text{ Cs}^{-1}$.

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

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

$$V = \frac{E}{Q} \text{ or } E = VQ$$

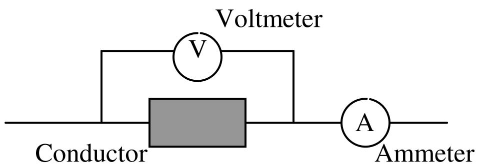
$$1 \text{ V} \equiv 1 \text{ JC}^{-1}$$

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, 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.

$\therefore E = VIt$, and power dissipated $P = \frac{E}{t} = VI$.

Resistance R (Ω) of a conductor is a measure of the ability of the conductor in restricting the flow of electric current, and it is defined as the ratio of potential difference V (V) to current I (A).

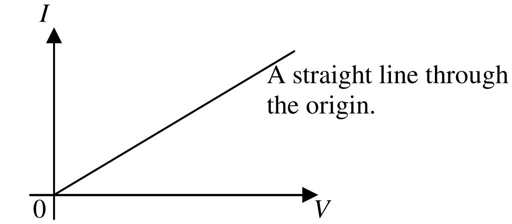
$$R = \frac{V}{I}$$



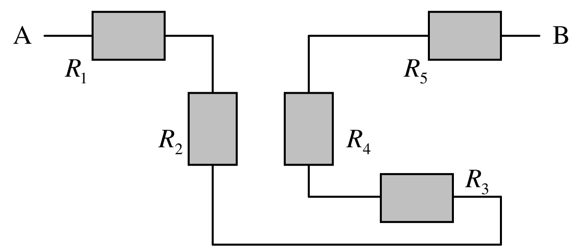
Ohm's law

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

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

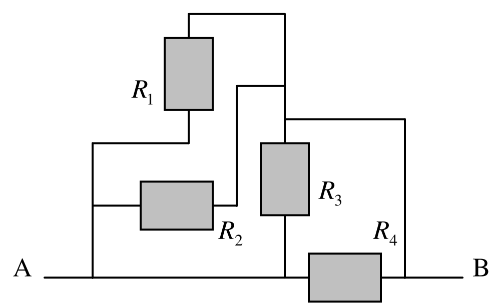


Components connected in series



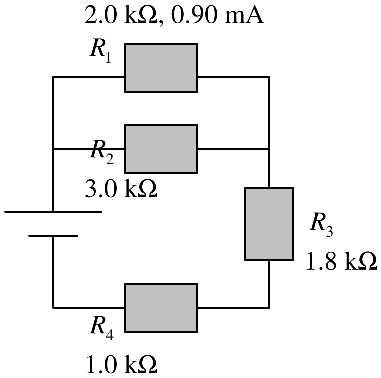
1) $I = I_1 = I_2 = I_3 = ...$
2) $V_{AB} = V_1 + V_2 + V_3 + ...$
3) $R_T = R_1 + R_2 + R_3 + ...$ remains constant if the components are ohmic resistors. Also $R_T = \frac{V_{AB}}{I}$.
4) $\frac{V_1}{V_2} = \frac{R_1}{R_2}$, $\frac{V_2}{V_3} = \frac{R_2}{R_3}$, ……, $\frac{V_a}{V_b} = \frac{R_a}{R_b}$.

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) $R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ...}$ remains constant for ohmic resistors. Also $R_T = \frac{V_{AB}}{I}$.
4) $\frac{I_1}{I_2} = \frac{R_2}{R_1}$, $\frac{I_2}{I_3} = \frac{R_3}{R_2}$, ……, $\frac{I_a}{I_b} = \frac{R_b}{R_a}$.

Example 1



(a) Find the potential difference and current across each component.
(b) Calculate the total resistance of the circuit in two ways.

(a) $V_1 = I_1 R_1 = (2.0\times10^3)(0.90\times10^{-3}) = 1.8$ V.

$V_2 = V_1 = 1.8$ V.

$I_2 = \frac{V_2}{R_2} = \frac{1.8}{3.0\times10^3} = 0.60\times10^{-3}$ A $= 0.60$ mA.

$I_3 = I_1 + I_2 = 0.90 + 0.60 = 1.5$ mA.

$V_3 = I_3 R_3 = (1.5\times10^{-3})(1.8\times10^3) = 2.7$ V.

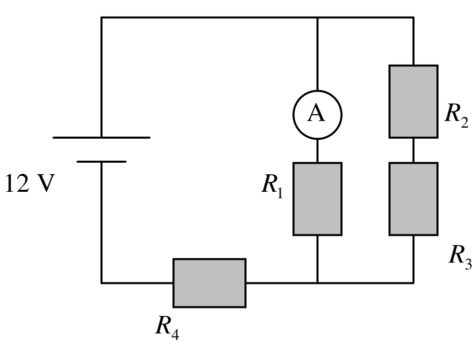
$I_4 = I_3 = 1.5$ mA. $V_4 = I_4 R_4 = (1.5\times10^{-3})(1.0\times10^3) = 1.5$ V.

$I_{battery} = I_4 = 1.5$ mA. $V_{battery} = 1.8 + 2.7 + 1.5 = 6.0$ V.

(b) $R_T = \frac{V_{battery}}{I_{battery}} = \frac{6.0}{1.5\times10^{-3}} = 4.0$ kΩ.

Alternatively, $R_T = \frac{1}{\frac{1}{2.0}+\frac{1}{3.0}} + 1.8 + 1.0 = 4.0$ kΩ.

Example 2 The resistors in the following circuit are identical and each has a resistance of R Ω, i.e. $R_1 = R_2 = R_3 = R_4 = R$. The ammeter reading is 5.0 mA. Find R.



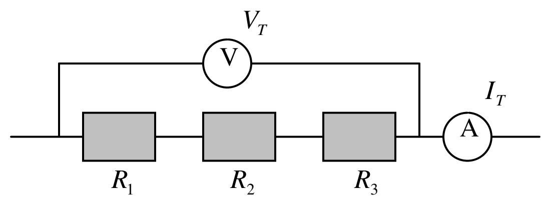
$\frac{I_2}{I_1} = \frac{R}{R+R} = \frac{1}{2}$. $\therefore I_2 = \frac{1}{2} I_1 = \frac{1}{2}\times5.0 = 2.5$ mA.

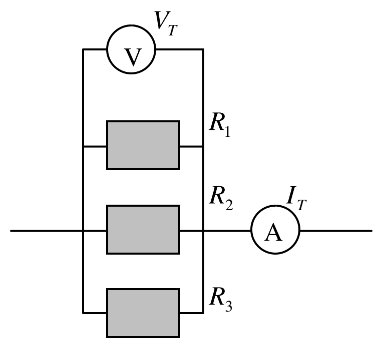
$\therefore I_4 = I_{battery} = 5.0 + 2.5 = 7.5$ mA.

$R_T = \frac{V_{battery}}{I_{battery}} = \frac{12}{7.5\times10^{-3}} = 1.6$ kΩ.

$\therefore \frac{1}{\frac{1}{R}+\frac{1}{2R}} + R = 1.6$, $\frac{5R}{3} = 1.6$, $R = 0.96$ kΩ $= 960$ Ω.

Power in series and parallel connections





For both types of circuits, $P_T = P_1 + P_2 + P_3 + \ldots$, where

$P_T = V_T I_T = \frac{V_T^2}{R_T} = I_T^2 R_T$,

$P_1 = V_1 I_1 = \frac{V_1^2}{R_1} = I_1^2 R_1$, $P_2 = V_2 I_2 = \frac{V_2^2}{R_2} = I_2^2 R_2$,

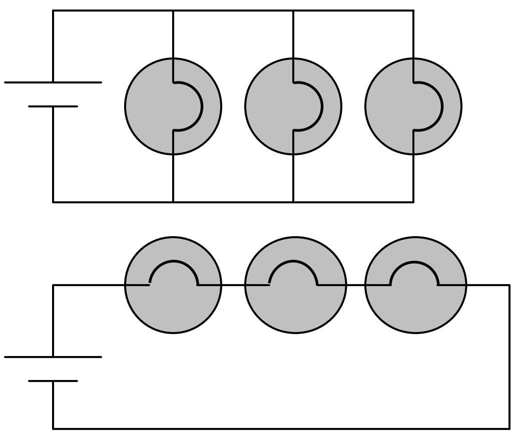
$P_3 = V_3 I_3 = \frac{V_3^2}{R_3} = I_3^2 R_3$, ……

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 alone.

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 alone.

Example 3 Three identical light globes (3W12V) are connected in parallel and then in series. In each case the power is supplied by a 12V battery. The globes are assumed to be ohmic conductors.
(a) Calculate the resistance of each globe.
(b) Find the power of each globe and the total power dissipated in the parallel circuit.
(c) Calculate the power of each globe and the total power dissipated in the series circuit.
(d) Calculate the current through the battery in each circuit.



(a) $R = \frac{V^2}{P} = \frac{12^2}{3} = 48\ \Omega$.

(b) $P = 3\,\text{W}$. $P_T = 3 + 3 + 3 = 9\,\text{W}$.

(c) $P = \frac{V^2}{R} = \frac{4^2}{48} = \frac{1}{3} = 0.33\,\text{W}$. $P_T = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1\,\text{W}$.

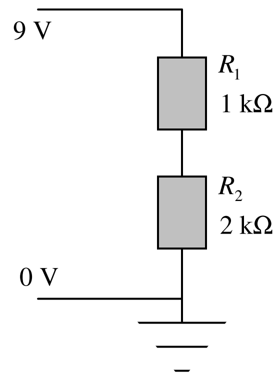
(d) $I_{battery} = \frac{P_T}{V_{battery}} = \frac{9}{12} = 0.75$ A for the parallel circuit.

$I_{battery} = \frac{1}{12} = 0.083$ A for the series circuit.

Voltage dividers

A series connection of two or more resistors forms a voltage divider. The voltage supplied to the series connection is divided into voltages in the same ratio as the resistances of the components in the unloaded voltage divider. If the voltage divider is loaded, the resistance of the load must be taken into account in calculating the voltages if it is comparable with the resistance of the voltage divider. The load resistance can be ignored if it is very much higher than the resistance of the voltage divider.

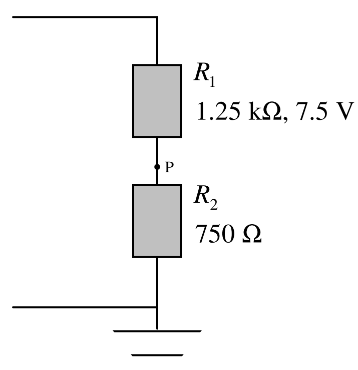
Example 1 A 1-kΩ and a 2-kΩ resistor are connected in series, and the potential difference between the two ends of the series is 9.0 V. Determine the voltage across each resistor.



The voltages V_1 and V_2 are in the same ratio as R_1 and R_2.
$\therefore V_1 = 3.0$ V and $V_2 = 6.0$ V, so that $V_1 : V_2 = R_1 : R_2$ and $V_1 + V_2 = 9.0$ V.

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 $V = V_1 + V_2$ is the supply voltage.
Also, $\frac{V_1}{V_2} = \frac{R_1}{R_2}$.

Example 2 A 750-Ω and 1.25-kΩ resistors are in series, and the voltage across the latter is 7.5 V.
(a) Find the voltage across the 750-Ω resistor.
(b) Find the potential at point P.
(c) Find the supply voltage the series circuit.

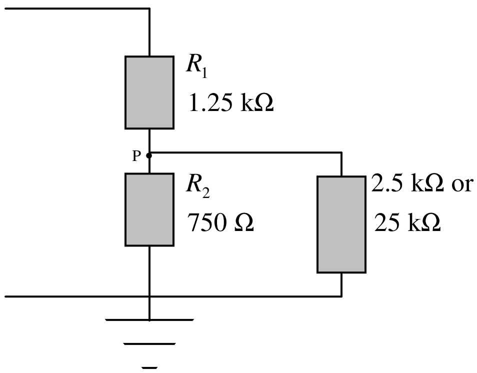


(a) $\frac{V_2}{V_1} = \frac{R_2}{R_1}$, $\therefore V_2 = \frac{R_2}{R_1} \times V_1 = \frac{750}{1250} \times 7.5 = 4.5$ V

(b) At point P, $V = 4.5$ V.

(c) Supply voltage $= 7.5 + 4.5 = 12$ V.

Example 3 The circuit in example 2 is now loaded. The supply voltage remains the same.
(a) Find the potential at point P when the resistance of the load is 2.5 kΩ.
(b) Find the potential at point P when the resistance of the load is 25 kΩ.



(a) Total resistance of R_2 and the load $R = \dfrac{1}{\frac{1}{750}+\frac{1}{2500}} = 577\ \Omega$.

Voltage across R_2 (or the load) $= \dfrac{577}{1250+577} \times 12 = 3.8$ V.

Potential at point P $= 3.8$ V.

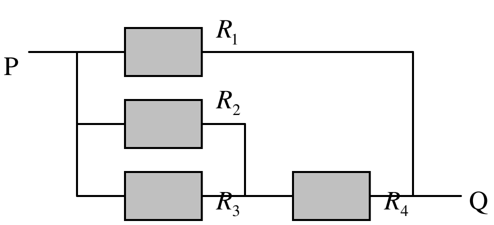
(b) Total resistance of R_2 and the load $R = \dfrac{1}{\frac{1}{750}+\frac{1}{25000}} = 728\,\Omega$.

Voltage across R_2 (or the load) $= \dfrac{728}{1250+728} \times 12 = 4.4$ V.

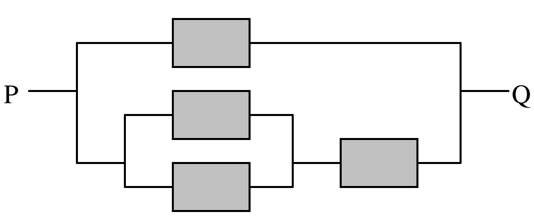
Potential at point P $= 4.4$ V. Very small change.

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. The resistors are identical 10Ω each.



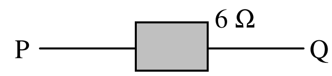
Redraw the diagram:



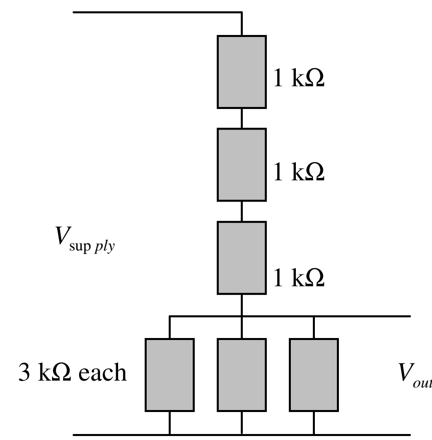
Effective resistance (i.e. total resistance) between P and Q:

$$R_T = \frac{1}{\frac{1}{10}+\frac{1}{10+\frac{1}{\frac{1}{10}+\frac{1}{10}}}} = 6\ \Omega.$$

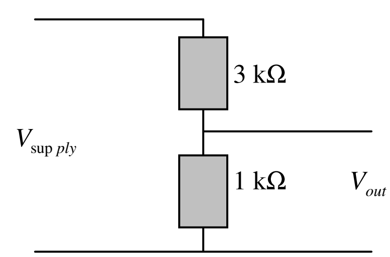
Use a 6-Ω resistor to replace the four resistors.



Example 2
(a) Simplify the following voltage divider to give the same output voltage V_{out}.
(b) Hence find V_{out} when $V_{sup\,ply} = 12$ V.



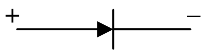
(a) Replace the three 3-kΩ resistors with a single resistor of $\dfrac{1}{\frac{1}{3}+\frac{1}{3}+\frac{1}{3}} = 1$ kΩ resistance, and replace the three 1-kΩ resistors with a 3-kΩ resistor.



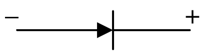
(b) $V_{out} = \dfrac{1}{3+1} \times 12 = 3$ V.

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

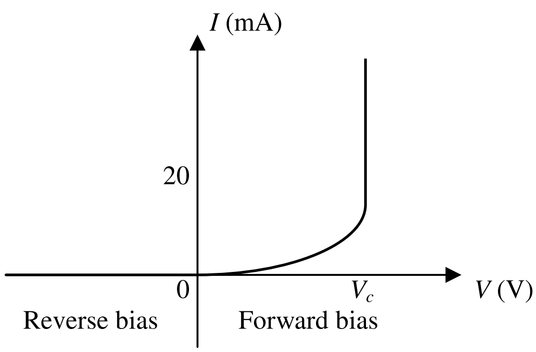
A *diode* is an electronic device that can be used to control voltage. It conducts when it is forward biased, and current drops to practically zero when it is reverse biased.



Forward bias, $R \to 0$.



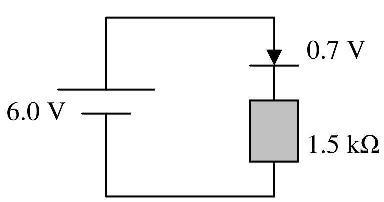
Reverse bias, $R \to \infty$.



For a germanium diode, the voltage for conduction of current $V_c \approx 0.3$ V, and for a silicon diode $V_c \approx 0.7$ V.
When a diode is in forward conductive mode, the voltage across it is fairly constant at V_c.

Example 1 A silicon diode and a 1.5-kΩ resistor is connected in series with a 6.0-V battery.
(a) Determine the voltage drop across the resistor and the current through it when the diode is in forward conductive mode.
(b) What is the voltage drop across the diode when it is reverse biased?

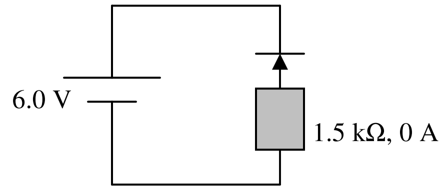
(a) In forward conductive mode:



$V_{resistor} = 6.0 - 0.7 = 5.3$ V.

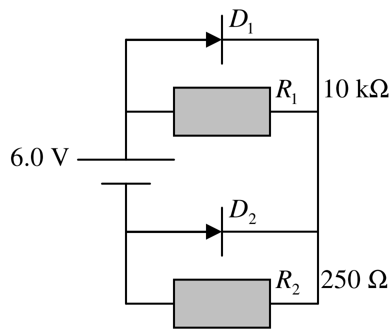
$I_{resistor} = \frac{V_{resistor}}{R} = \frac{5.3}{1.5 \times 10^3} \approx 3.5 \times 10^{-3}$ A, i.e. 3.5 mA.

(b) Reversed biased:



$I_{resistor} = 0$ A. $\therefore V_{resistor} = I_{resistor} \times R = 0$ V.
$\therefore V_{diode} = 6.0 - 0 = 6.0$ V.

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



D_1 is in forward conductive mode, $V_{D1} = 0.7$ V.
D_1 and R_1 are parallel, $\therefore V_{R1} = 0.7$ V.

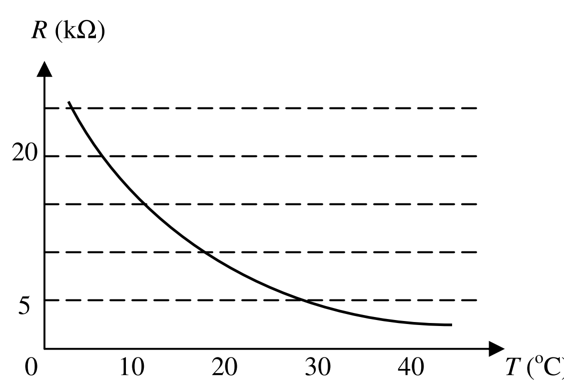
$I_{R1} = \frac{V_{R1}}{R_1} = \frac{0.7}{10 \times 10^3} = 7 \times 10^{-5}$ A ≈ 0 A.

D_2 is reversed biased and $\therefore I_{D2} = 0$ A.
The parallel connection of D_1 and R_1 is in series with the parallel connection of D_2 and R_2.

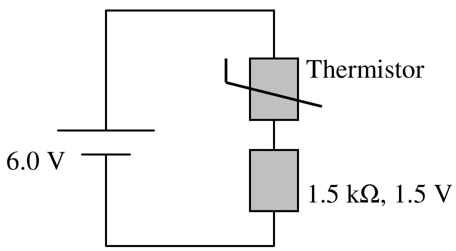
$\therefore V_{D2} = V_{R2} = 6.0 - 0.7 = 5.3$ V. $I_{R2} = \frac{V_{R2}}{R_2} = \frac{5.3}{250} = 0.0212$ A.

$I_{D1} + I_{R1} = I_{D2} + I_{R2}$, $\therefore I_{D1} \approx I_{R2} \approx 21$ mA.

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



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

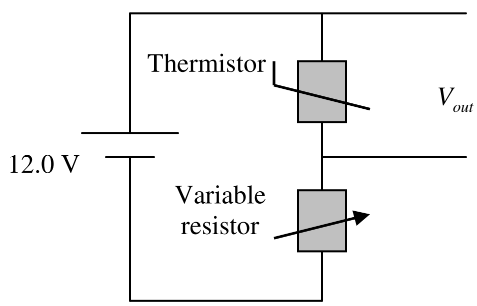


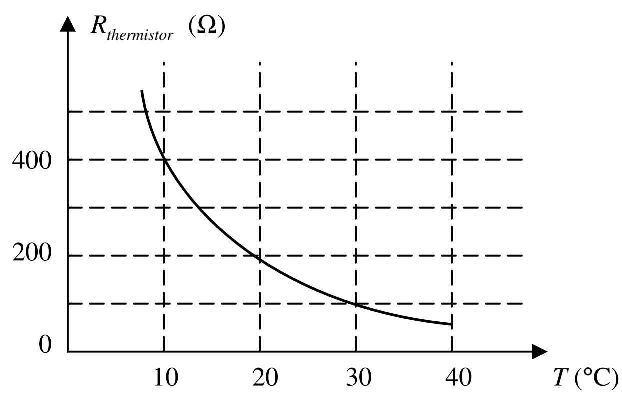
$V_{thermistor} = 6.0 - 1.5 = 4.5\text{ V}$.

$\frac{R_{thermistor}}{R_{resistor}} = \frac{V_{thermistor}}{V_{resistor}}$, $\therefore R_{thermistor} = \frac{4.5}{1.5} \times 1.5 = 4.5\text{ k}\Omega$.

Read from graph: $T \approx 30°\text{ C}$.

Example 4 A refrigerator is required to maintain its temperature below 10°C. The cooling unit is controlled by a thermistor. To turn the cooling unit on, a voltage $V_{out} = 4.0\text{ V}$ is required. What is the resistance of the variable resistor when the cooling unit is turned on?



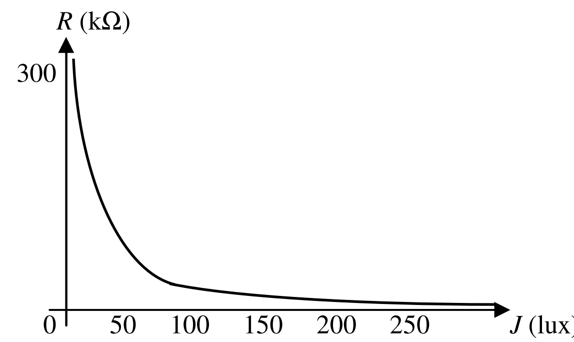


When $T = 10°\text{ C}$, $R_{thermistor} = 400\ \Omega$, $V_{thermistor} = V_{out} = 4.0\text{ V}$ and $V_{vr} = 12 - 4.0 = 8.0\text{ V}$.

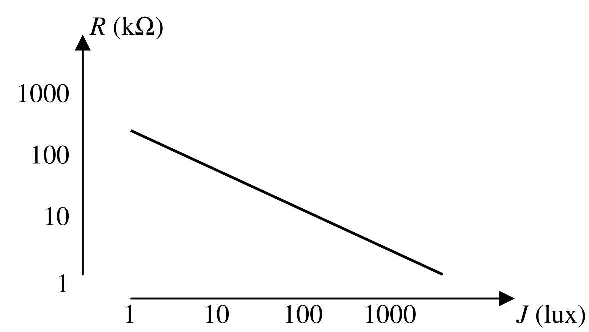
$R_{vr} = \frac{V_{vr}}{V_{thermistor}} \times R_{thermistor} = \frac{8.0}{4.0} \times 400 = 800\ \Omega$.

Transducers are electronic devices that change electrical energy into other forms of energy and vice versa, e.g. thermistors (heat to electrical) and loudspeakers (electrical to sound) are transducers. *Photonic transducers* change electrical energy into light (which carries encoded information) and vice versa. The following devices are photonic transducers.

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



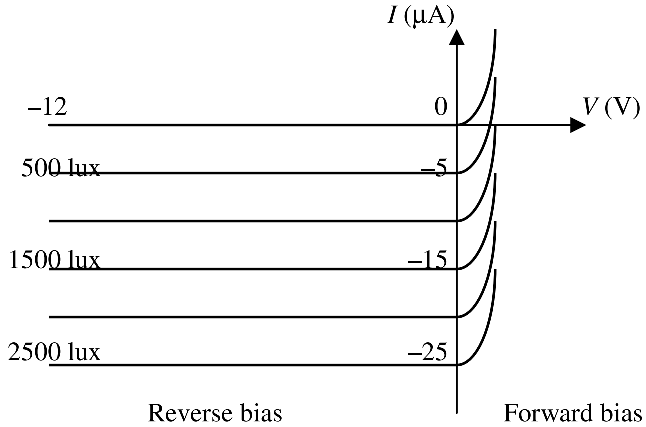
The above data are usually plotted on axes with logarithmic scales.



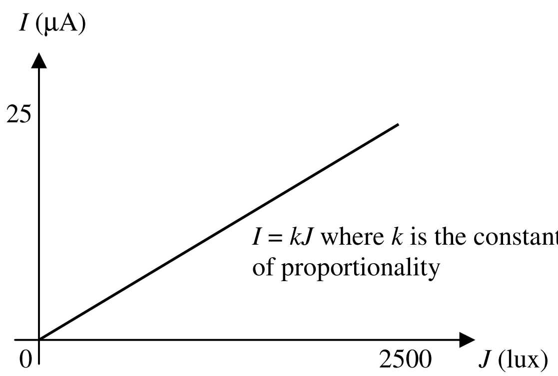
Condition	Light intensity (lux)	Resistance (kΩ)
Full moon	1	300
Dimly lit room	300	10
Winter outdoor	6000	2

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 (negative value) through a photodiode. The following *I-V* graph shows the characteristics of a typical photodiode at different illuminating light intensities.

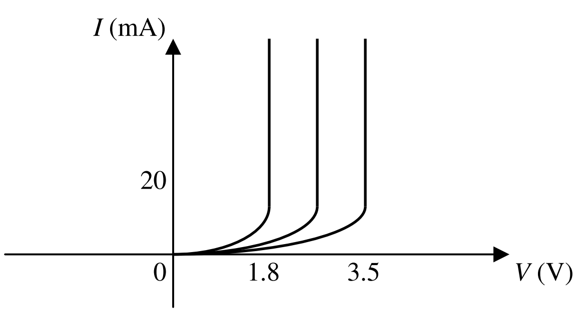


When a photodiode is reverse biased conducting current is directly proportional to light intensity.



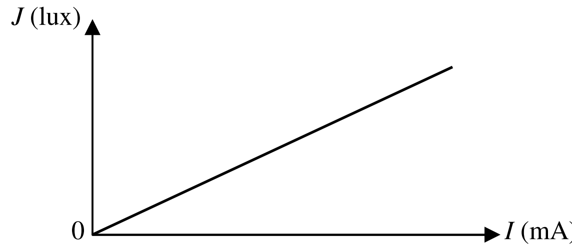
In comparison with a LDR (response time in the order of milliseconds), a reverse biased photodiode has a much faster response time and it is used to detect light signals with period less than a microsecond.

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



In fibre optic telecommunication LEDs emit light in the infrared region ($\lambda \approx 950 - 1550$nm). Other common LEDs used in electronics emit red (660nm), yellow (590nm) and green light (550nm).

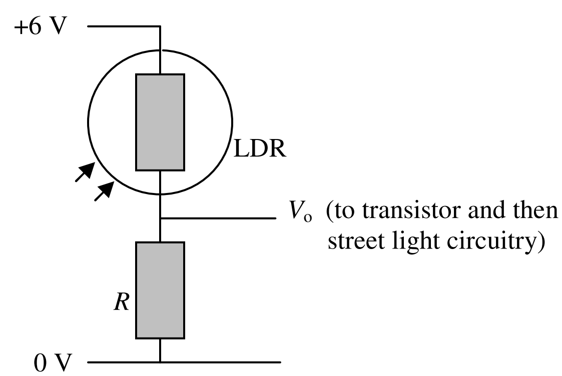
The intensity of emitted light is directly proportional to the current.



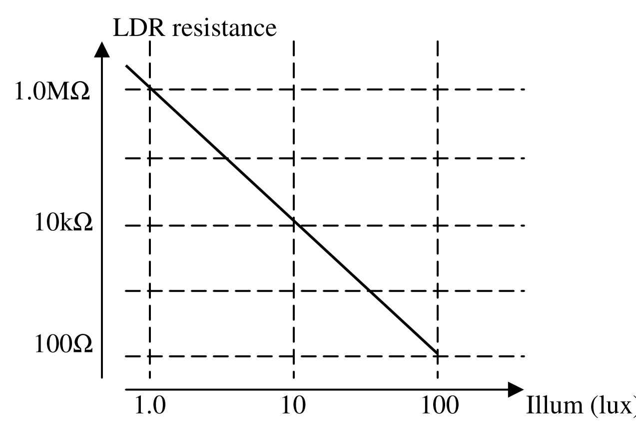
LEDs can respond to electrical signal with period < 1µs.

Design and analyse electronic circuits comprising ohmic resistors, electronic 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 characteristic shown in the graph below, and street light 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.



(Log scales, both axes)

Street light turns on when outdoor light intensity (illumination) drops to 10 lux, $V_o = 1.5$ V, $\therefore V_R = 1.5$ V.

From graph, $R_{LDR} = 10$ kΩ.

$V_{LDR} = 6.0 - 1.5 = 4.5$ V.

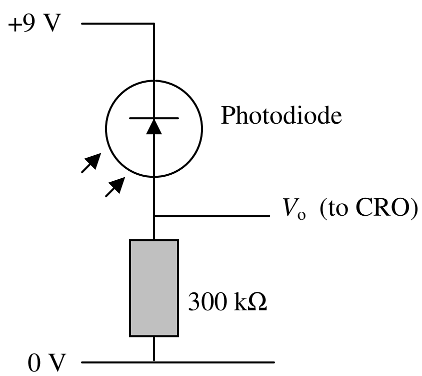
$$\frac{R}{R_{LDR}} = \frac{V_R}{V_{LDR}},\ R = \frac{V_R}{V_{LDR}} \times R_{LDR} = \frac{1.5}{4.5} \times 10 \text{ k}\Omega \approx 3.3 \text{ k}\Omega.$$

Example 2 Refer to example 1. Should the resistance of R be higher or lower if the street light is set to turn on when outdoor light intensity drops to 8 lux?

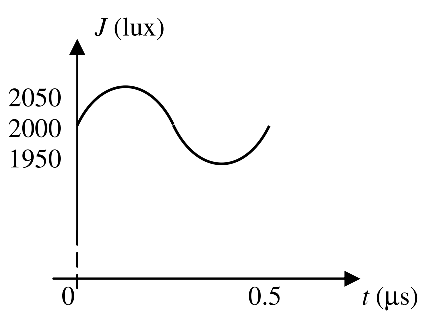
Street light is on when $V_o \le 1.5$ V, i.e. $V_R \le 1.5$ V and when the outdoor light intensity is 8 lux or lower. From the given graph $R_{LDR} > 10$ kΩ.

Since $R = \frac{V_R}{V_{LDR}} \times R_{LDR} = \frac{1.5}{4.5} \times R_{LDR}$, when $R_{LDR} > 10$ kΩ, $R > 3.3$ kΩ, i.e. higher.

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):



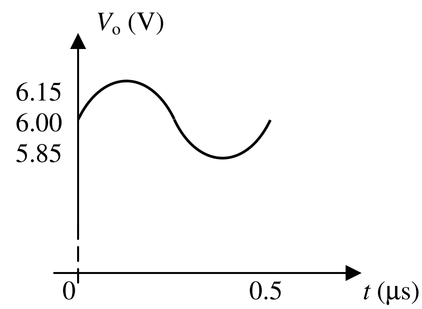
Example 3 Refer to the characteristics of the photodiode discussed on page 7. The photodiode is exposed to a time-varying light signal as shown below:



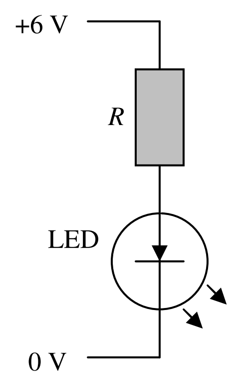
Sketch a graph showing V_o as a function of t.

From the characteristics of the photodiode on page 7, the photodiode current is centred at 20 μA, and varies between 19.5 and 20.5 μA.

$\therefore V_o$ is centred at $(20\times10^{-6})(300\times10^{3}) = 6$ V, and varies between 5.85 and 6.15 V.



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 2.0 V when it is forward biased and R = 200 Ω.
(a) Calculate the forward bias current.
(b) What value of R will double the intensity of light emitted?

(a) $V_R = 6.0 - 2.0 = 4.0$ V.

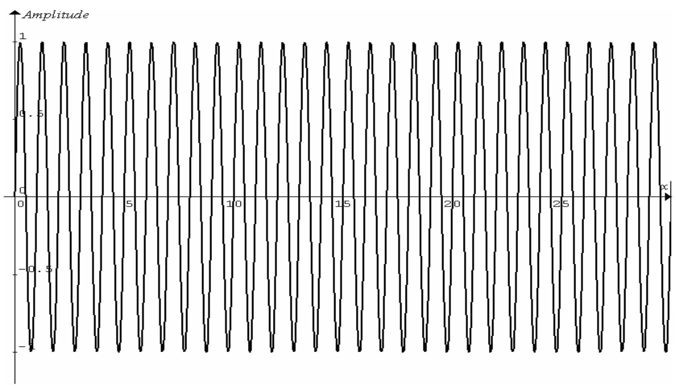
$$\therefore I_{LED} = I_R = \frac{V_R}{R} = \frac{4.0}{200} = 0.020 \text{ A} = 20 \text{ mA}.$$

(b) Since emitted light intensity is directly proportional to forward bias current through the LED, $\therefore I_{LED}$ needs to be doubled and hence R needs to be halved, i.e. 100 Ω.

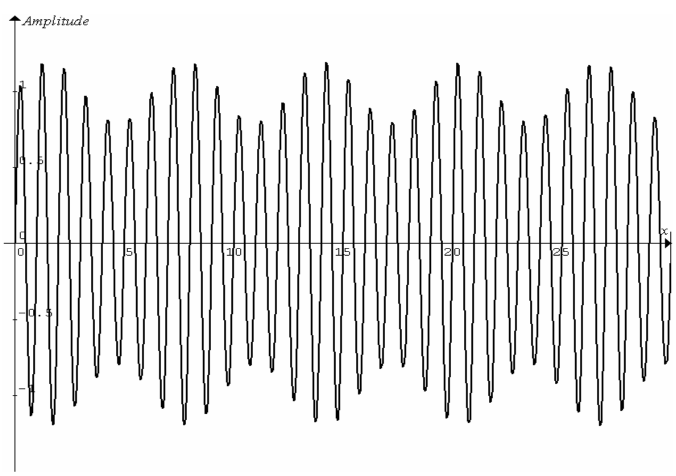
Transfer of information in analogue (non-digital) form via a fibre optic cable

In fibre optic telecommunication infrared light wave ($\lambda \approx 950 - 1550$nm) is usually used as the carrier of information.

The amplitude of the wave indicates the intensity of the carrier infrared light.

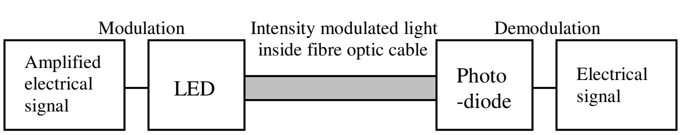


The amplitude (hence light intensity) of the carrier can be made to vary to replicate the amplitude variation of the information signal. This is known as **light intensity modulation**.

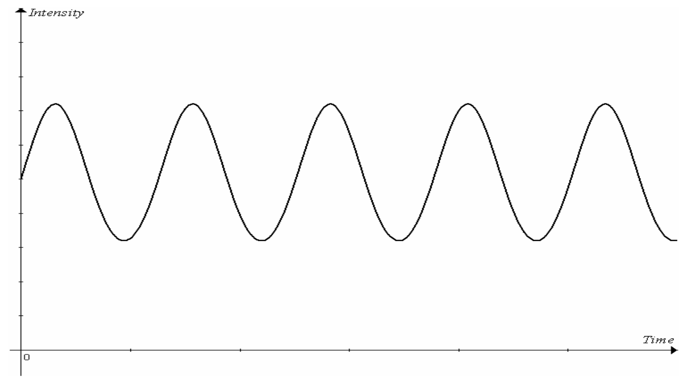


At the other end of the fibre optic cable, information signal can be separated from the carrier wave. This is known as **demodulation**.

The following schematic diagram shows an intensity-modulated fibre-optic link that is used to transmit information signal.

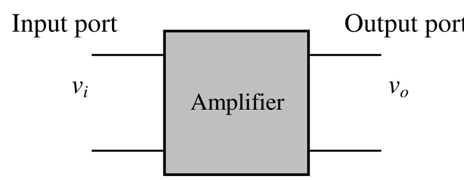


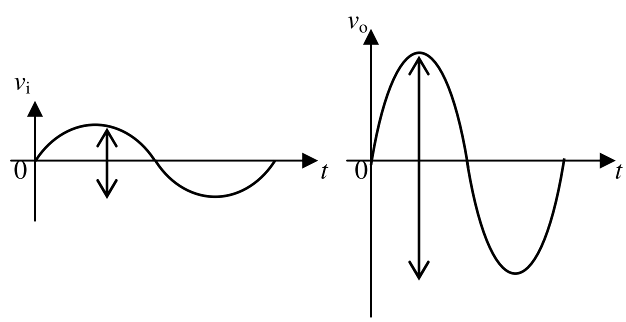
The following graph shows the intensity variation of light emitted by LED as a function of time.



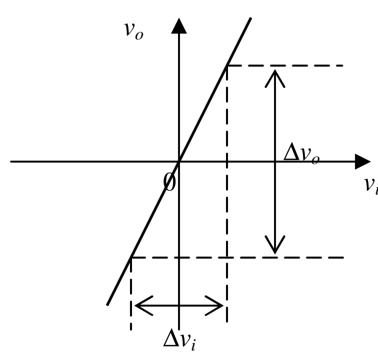
Voltage amplifier

Signal amplification is an operation that is common to almost all electronic systems. It is accomplished by specially designed electronic circuits known as **signal amplifiers**. The function of a signal amplifier is to produce an output signal that is a larger replica of the signal applied to its input port. The most common signal amplifier is the **voltage amplifier**.



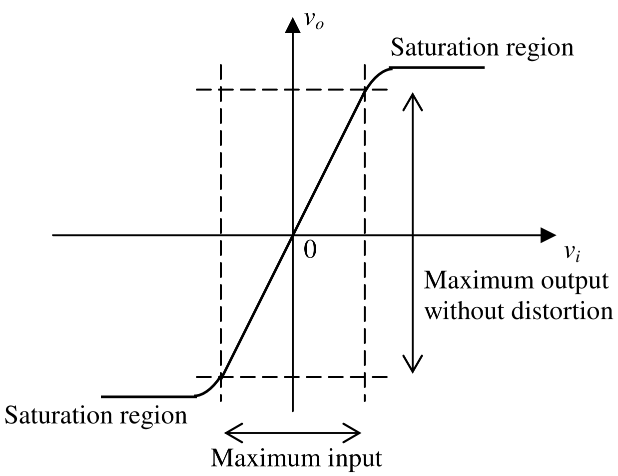


When v_o is plotted against v_i , the graph (called the **voltage-transfer characteristic** of the voltage amplifier) is a straight line through the origin for an *ideal* voltage amplifier.



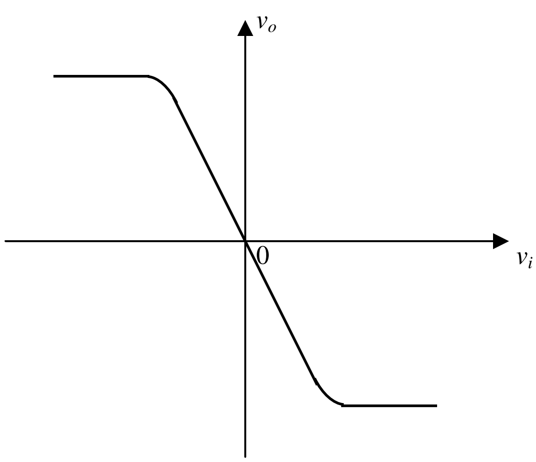
The amplification factor of the device is called the **voltage gain** and it is defined as the ratio $A_v = \dfrac{\Delta v_o}{\Delta v_i}$, i.e. the gradient of the linear graph.

The following graph shows the voltage-transfer characteristic of a *real* (practical) amplifier. The ability of a real voltage amplifier to perform its operation without distortion is restricted to the linear region (the middle section of the graph). The gradient of this linear section gives the voltage gain A_v .

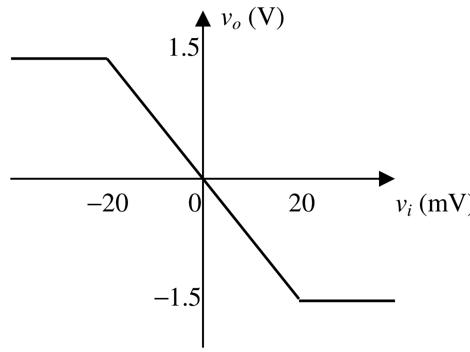


When the input signal becomes too large, it forces the output voltage into the **saturation regions**, resulting in **clipping** of the signal at the output.

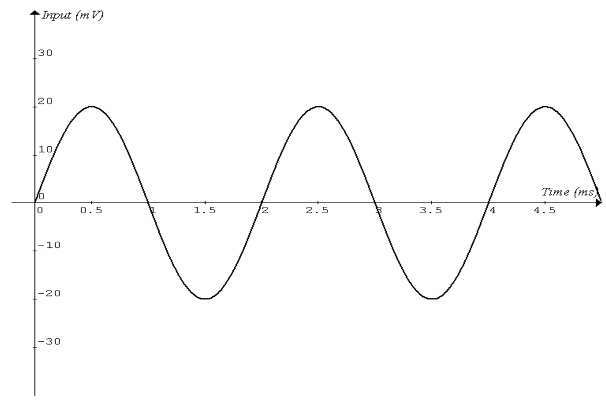
Some voltage amplifiers have inverted signals at the output. Hence they are called **inverted voltage amplifiers**. For an inverted voltage amplifier, the gradient of the linear section of the voltage-transfer characteristic and hence the voltage gain A_v is a negative value, indicating the output signal is inverted.



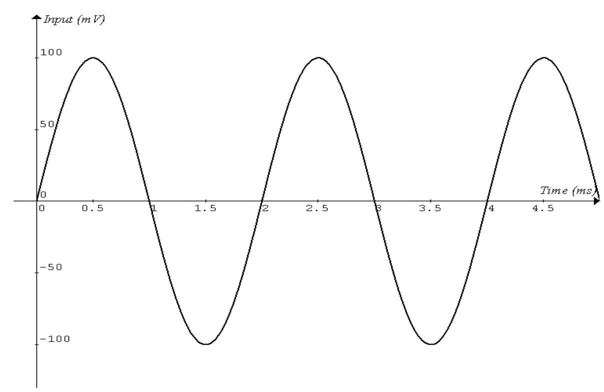
Example 5 A simplified voltage-transfer characteristic of a real voltage amplifier is shown in the following graph.



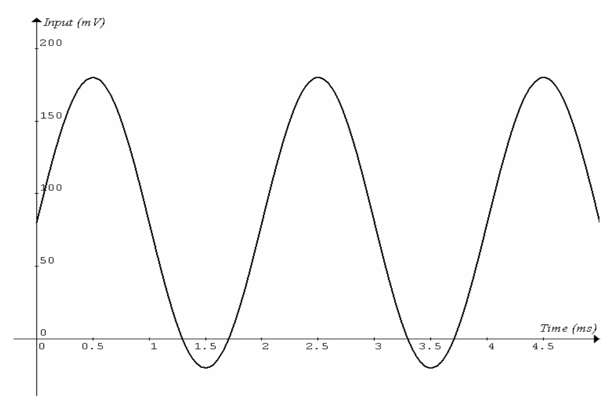
(a) Determine the voltage gain.
(b) Sketch the output signal for each of the following inputs.
i.



ii.



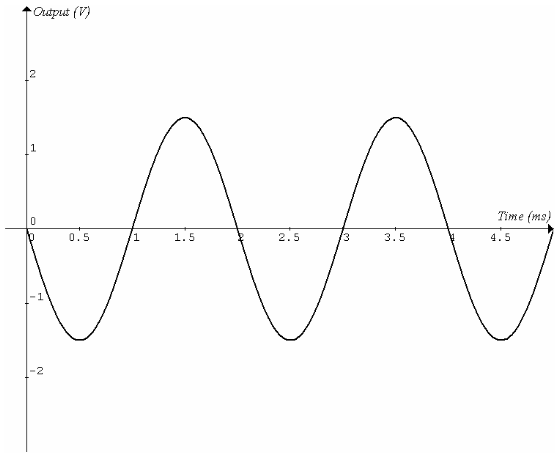
iii.



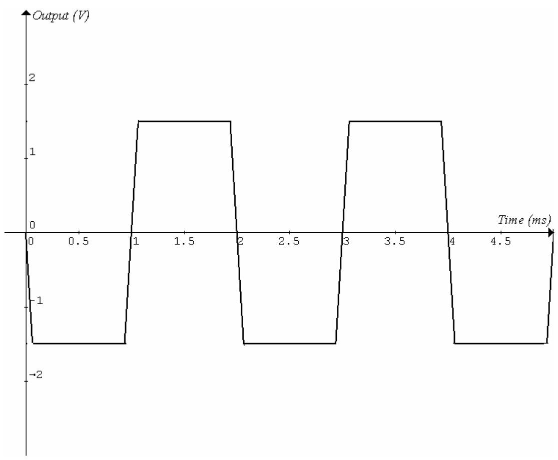
(a) Voltage gain $= \frac{1.5}{-20\times10^{-3}} = -75$.

(b)

i.



ii.



iii.