Core Concepts

Core concepts introduction

The emphasis throughout the course is on practical investigation – an essential element of electronics. The best way to demonstrate ability and understanding in electronics is to design, build and test an electronic system to satisfy a given brief.

This section, however, is not intended to generate experimental work. Much of it will be familiar to you from earlier studies.

This is a reference area for whenever you need a reminder about the basic circuit concepts during the course.

1. Electronic Systems

Learning Objectives:

At the end of this topic you should be able to:

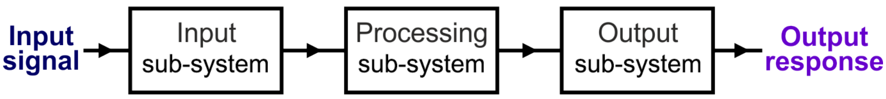
- recognise that electronic systems are assembled from sensing, processing and output sub-systems;
- state the need for and use driver sub-systems;
- design, analyse or modify a block diagram of a system.

An electronic system responds in a *predictable* way when it receives input signals.
It processes the input signals and provides a signal to drive an output device.

Non-electrical input signals are converted into electrical form by **input sensing units.**
For example, a switch unit converts pressure applied to the contacts into an electrical signal.

The output response is often non-electrical in nature. **Output devices** convert the processed electrical signal into another form. For example, a buzzer unit converts an electrical signal into sound.

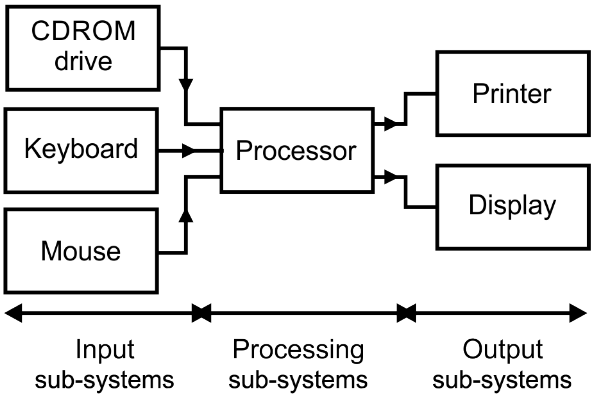
In its simplest form, an electronic system can be represented by the following block diagram.



Sub-systems form the 'building blocks' that make up the complete system, each performing a specific function.

Example:

The Personal Computer (PC) is a system which has been designed to process digital data. Data can be fed into the system through various input sub-systems. The PC processes this data and can provide us with the result through its output sub-systems.



Electronic Sub-systems

There are three sections to an electronic system:

- input sub-systems;
- signal processing sub-systems;
- output sub-systems.

Input Sub-systems

Processing sub-systems can only process electrical signals. The input sub-systems convert non-electrical signals, e.g. light, into electrical form.

They can be subdivided into two types:

- digital sub-systems;
- analogue sub-systems.

The following table describes the action of a range of input sub-systems.

Name	Type	Action
Switch unit	Digital	Detects pressure applied to it and outputs a ‘high’ or ‘low’ signal.
Light-sensing unit	Analogue	The output signal changes as the light level changes.
Moisture-sensing unit	Analogue	The output signal changes as the moisture level changes.
Temperature-sensing unit	Analogue	The output signal changes as temperature changes.
Reed switch unit	Digital	Detects a magnetic field and outputs a ‘high’ or ‘low’ signal.

The next sub-system is also usually classed as an input sub-system.

Name	Type	Action
Pulse generator unit	Digital	Converts a steady DC signal into a stream of pulses.

Signal Processing

These include driver sub-systems. These are needed wherever the processing sub-system is incapable of providing enough current to drive the output devices.

They are often based on two components, the bipolar transistor, such as a NPN transistor, and the MOSFET. Motors and solenoids require a large current and need heavy-duty driver circuits.

The driver is always connected directly before the output sub-system.

You will use a wide range of processing sub-systems during the course, including logic, delay and counting units.

Output Sub-systems

These convert the electrical signal from the processing section into some other physical form, such as heat, light or movement.

The following table describes the action of a range of output sub-systems.

Name	**Action**
Lamp unit	Converts an electrical signal into light.
Buzzer unit	Converts an electrical signal into sound
Motor unit	Converts an electrical signal into rotational motion
Solenoid unit	Converts an electrical signal into linear motion
Servo unit	Converts an electrical signal into an angular position

Designing electronic sub-systems

Follow this procedure:

- select appropriate input sub-systems;
- select appropriate output sub-systems;
- select appropriate processing sub-systems;
- draw a block diagram of the system;
- set up and test the system;
- make changes, if required, re-test and modify the block diagram of your design.

2. Fundamental Circuit Concepts

Learning Objectives:

At the end of this topic you should be able to:

- distinguish between electrical charge, current and voltage;
- distinguish between energy supplied and power rating;
- recall and use the formula: **P** = **I** × **V**;
- distinguish between conductors, insulators and semiconductors in terms of their electrical conduction properties;
- distinguish between series and parallel connections;
- recall that ammeters are connected in series with the component under investigation, that voltmeters are connected in parallel with the component under investigation and that multimeters combine the functions of ammeter and voltmeter.

Electrical quantities:

Nearly all electrical effects - heating, magnetic and chemical - come from the behaviour of tiny particles called electrons, constituents of all atoms. These carry a small quantity of negative electrical **charge** and so repel other bodies carrying negative charge and attract positively charged bodies.

Usually, an electric **current** is a flow of electrons. It could be measured in units of 'electrons per second'. However, they are far too small to see or count. Instead, we use a unit called the ampere, or amp (**A**) for short.

The electrical **charge** they carry is minute. We measure charge in units called coulombs (**C**). An electric current transfers charge from one region to another. A current of 1 A transfers a charge of 1 C every second.

The **voltage** of a power supply is the driving force that pushes current around a circuit. The larger the voltage, the bigger the push. Put another way, it is a measure of the energy transferred by the electrons as they flow. **Energy** occurs in a wide variety of forms - heat, light, movement etc. It can be changed from one form to another. It is measured in joules (**J**). The energy transferred by a single electron is too small to measure. Instead, voltage measures the energy transferred by a coulomb of charge.

Power measures the rate at which energy is transferred from one form to another. The unit, the watt, indicates that one joule of energy is being transferred every second.

Electrical formulae

The relationship between electrical charge transferred **Q** in time **t** and current **I** is: $\mathbf{Q} = \mathbf{I} \times \mathbf{t}$

The energy **E** delivered in time **t** by a power source **P** is: $\mathbf{E} = \mathbf{P} \times \mathbf{t}$

The energy **E** transferred when a charge **Q** moves between two points with a voltage **V** across them is:
$\mathbf{E} = \mathbf{V} \times \mathbf{Q} = \mathbf{V} \times \mathbf{I} \times \mathbf{t}$

The relationship between electrical power **P**, voltage **V** and current **I** is: $\mathbf{P} = \mathbf{V} \times \mathbf{I}$

Example 1:

A 1.5 W lamp is switched on for 12 s. What energy does it deliver?

Using $E = P \times t$

$E = 1.5 \times 12$

$= 18$ J

Example 2:

A lamp is connected to a 12 V supply. As a result, a current of 0.1 A flows through it.
What energy does it deliver in 30 s?

Using $E = V \times I \times t$

$E = 12 \times 0.1 \times 30$

$= 36$ J

Conductors and insulators:

Some materials allow electric currents to flow through them with little opposition. In these, some electrons are only loosely attached to the atoms and need very little energy to free them and allow them to wander through the material. These are called **conductors**. Most metals, copper and gold for example, are good conductors.

In others, the electrons are tightly bound to the atoms and cannot take part in an electric current. These are called **insulators**. Examples include polythene, glass and rubber.

A third class of materials allows some current to flow and their electrical properties can be altered radically by adding specific impurities to them. These are called **semiconductors**. Silicon and germanium are examples of semiconductors. They play a very important role in modern electronics.

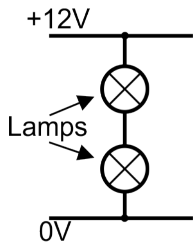
Types of circuit:

Components can be connected in two ways - **series** connections and **parallel** connections.

In series components:

- are connected in a line, one after the other;
- are connected to each other only at one point;
- offer only one path for the electric current.

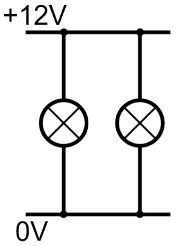
The circuit shows two lamps connected in series.



In parallel components:

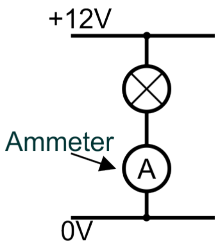
- are connected independently to the power source ;
- are connected to each other at both ends;
- offer a choice of path for the electric current.

The circuit shows two lamps connected in parallel.

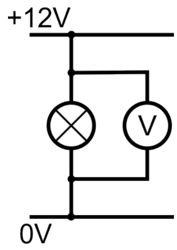


Measuring electricity:

Electric current is measured using an **ammeter**. It is connected **in series** with the component under investigation, a lamp is shown in the diagram.

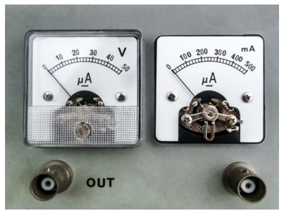


Voltage is measured using a **voltmeter**. It is connected **in parallel** with the component under investigation, again a lamp is shown in the diagram.



These meters come in both analogue and digital format.

Analogue meters usually have a pointer that moves across a scale as the quantity changes.



The digital version gives a direct readout of the quantity.

The multimeter is a very cost effective way to buy electrical instrumentation.
It can measure both current and voltage, both
AC and DC, over a range of a wide range of readings.
Many multimeters offer other functionality, such as the ability to measure resistance, capacitance and frequency.

Be aware

The ammeter ranges are protected by a fuse located inside the body of the multimeter. This fuse may have ‘blown’, in which case the ammeter ranges will not work.

3. Three important laws

Learning Objectives:

At the end of this topic you should be able to:

- apply the formulae:

$$V = I \times R,\ I = \frac{V}{R},\ R = \frac{V}{I};$$

- explain why resistors are made only in distinct values in, for example, the E24 series;
- perform calculations involving power rating, voltage and current in a resistor;
- apply Kirchhoff's laws to series and parallel connections;
- obtain and use the Thevenin equivalent circuit for a given circuit to predict the effect of loading the output.

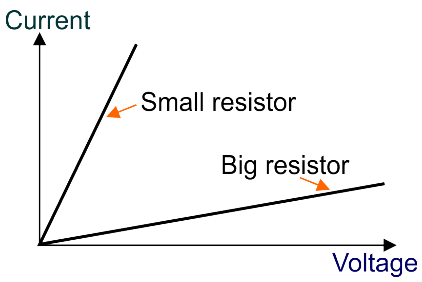
Ohm's law:

For many conductors of electricity, the electric current flowing through them is directly proportional to the voltage applied to them, provided the temperature stays the same.

Put another way:

- when the applied voltage doubles, the current doubles;
- when the applied voltage quarters, the current quarters;
  and so on… provided the resistor doesn't warm up,

This relationship is shown in the diagram opposite.



Ohm's law leads to the idea of the 'resistor' - a component that restricts the flow of current by converting the electrons' energy to heat.

A big resistor is one which needs a large voltage to make it pass a small current. A small resistor passes a large current when even a small voltage is applied.

Using Ohm's law, the resistance **R** of a conductor is given by:

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

Manipulating this formula gives the alternative forms:

voltage $V = I \times R$

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

Resistance is measured in units called ohms (Ω), though, in electronics, we usually encounter resistors measured in kilohms (kΩ = 1000 Ω or 10^3Ω) or in megohms (MΩ = 1000000 Ω or 10^6Ω).

Care is needed with units when using these formulae. They must belong to the same group.
For example:

- Group 1: volts / amps / ohms
- Group 2: volts / milliamps / kilohms
- Group 3: volts / microamps / megohms

Example 1:
A current of 0.1 A flows through a 20 Ω resistor. What is the voltage across the resistor?

$$\begin{aligned} \mathbf{V} &= \mathbf{I} \times \mathbf{R} \\ &= 0.1 \times 20 \\ &= 2\ \text{V} \end{aligned}$$

Example 2:
A 10 Ω resistor is connected across a 5 V power supply. What is the resulting current?

$$\begin{aligned} \mathbf{I} &= \frac{\mathbf{V}}{\mathbf{R}} \\ &= \frac{5}{10} \\ &= 0.5\ \text{A} \end{aligned}$$

Example 3:
A current of 100 mA flows through a resistor when the voltage drop across it is 12 V.
What is its resistance?

$$\begin{aligned} \mathbf{R} &= \frac{\mathbf{V}}{\mathbf{I}} \\ &= \frac{12}{100} \\ &= 0.12\ \text{k}\Omega \\ &= 120\ \Omega \end{aligned}$$

The E24 series:

Resistors range in value from 1 Ω to 10 MΩ. It is impractical to make every single value. Instead, manufacturers cover the same range with a much smaller number of resistors, each of which is made to a stated tolerance (accuracy).

The E24 series has a tolerance of 5% and provides the following 24 values:

10, 11, 12, 13, 15, 16, 18, 20, 22, 24, 27, 30, 33, 36, 39, 43, 47, 51, 56, 62, 68, 75, 82, 91

and multiples of these, e.g. 130 Ω, 3900 Ω, 180 kΩ, 1.2 kΩ, 8.2 MΩ etc.

Other series exist with different tolerances. This course uses the E24 series.

Power rating of resistors:

When a current flows through a resistor, electrical energy is converted into heat - the greater the current, the hotter the resistor.

Resistors are rated by the electrical power that they can dissipate safely. This is determined by its physical size - the greater its surface area, the more power it can dissipate. Resistors are commonly made with power ratings ranging from 1/8 W to 2 W.

The power formula can be combined with formulae from Ohm's law to give:

$$\mathbf{P} = \mathbf{V} \times \mathbf{I} = (\mathbf{I} \times \mathbf{R}) \times \mathbf{I}\text{, giving } \mathbf{P} = \mathbf{I}^2 \times \mathbf{R}$$

$$\mathbf{P} = \mathbf{V} \times \mathbf{I} = \mathbf{V} \times \left(\frac{\mathbf{V}}{\mathbf{R}}\right)\text{, giving } \mathbf{P} = \frac{\mathbf{V}^2}{\mathbf{R}}$$

Example 1:
What power is dissipated when a current of 0.05 A flows through a 100 Ω resistor?

$$\begin{aligned} \mathbf{P} &= \mathbf{I}^2 \times \mathbf{R} \\ &= 0.05^2 \times 100 \\ &= 0.25\ \text{W} \end{aligned}$$

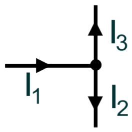
Example 2:
What is the biggest voltage that can safely be applied to a 10 Ω 0.5 W resistor?

$$\begin{aligned} \mathbf{P} &= \frac{\mathbf{V}^2}{\mathbf{R}} \\ 0.5 &= \frac{\mathbf{V}^2}{10} \\ \mathbf{V}^2 &= 5 \\ \mathbf{V}^2 &= 2.2\ \text{V} \end{aligned}$$

Kirchhoff's laws:

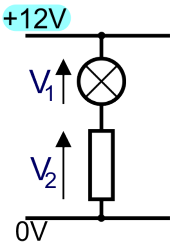
First Law:

The sum of currents entering a junction is equal to the sum of currents leaving it.
In the diagram opposite: $I_1 = I_2 + I_3$
This law is a restatement of the conservation of electrical charge.



Second Law:

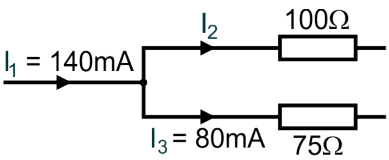
Around any loop in the circuit, the (vector) sum of voltages is zero.
For a series circuit, this means:
the sum of the voltages across the components is equal to the supply.
In the diagram opposite: $V_1 + V_2 = 12$ V
This is an important rule when analysing voltage divider circuits.



This course will use Kirchhoff's laws to calculate currents and voltages only in circuits consisting of a single DC power supply and a serial/parallel combination of components.

Example:

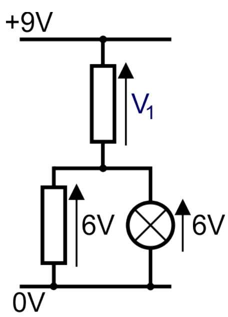
1. The diagram shows part of a circuit.
What current flows through the 100 Ω resistor?



Using Kirchhoff' first law :

$$I_1 = I_2 + I_3$$
$$140 = I_2 + 80$$
$$I_2 = 60 \text{ mA}$$

2. Part of a circuit is shown opposite.
Calculate the voltage V_1.

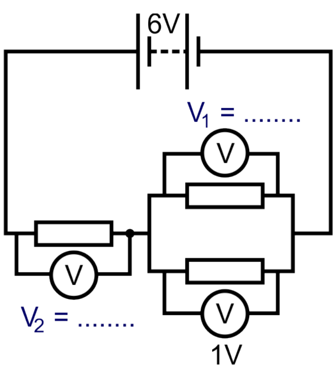


Using Kirchhoff' second law:

$$V_1 + 6 = 9 \text{ V}$$
$$V_1 = 3 \text{ V}$$

3. The circuit opposite contains three voltmeters and is powered by a 6 V battery.

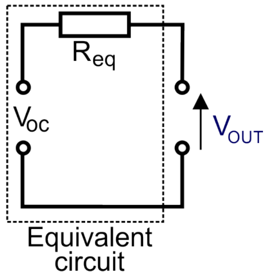
One voltmeter is giving a reading of 1 V.
What are the readings V_1 and V_2 on the other voltmeters?



Using Kirchhoff' second law:

$$V_1 = 1 \text{ V}$$
$$V_2 = 6 - 1$$
$$V_2 = 5 \text{ V}$$

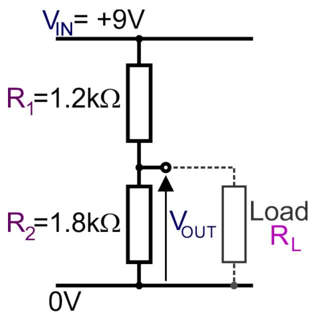
Thevenin's theorem:



Any combination of power supplies and linear components, (e.g. resistors) can be replaced by a single ideal voltage source and a single ideal resistor connected in series.
Thevenin's theorem is used to simplify analysis of more complicated circuits.
The Thevenin equivalent circuit is shown opposite.
To derive this circuit, calculate:

- the open circuit voltage, V_{OC}, (when no current is taken from the output);
- the short circuit current, I_{SC}, (when the output terminals are short-circuited);
- the equivalent resistor, R_{eq}, (as $R_{eq} = \frac{V_{OC}}{I_{SC}}$).

Example:



What is the minimum load resistor R_L that can be connected to the voltage divider in the diagram while ensuring that the output voltage V_{OUT}, does not fall below 5 V?

Step 1: Derive the Thévenin equivalent circuit for the voltage divider: Use the voltage divider formula to obtain V_{OC}, the open circuit voltage (when the output current is zero).

$$V_{OUT} = \frac{R_2}{R_1 + R_2} V_{IN}$$
$$= \frac{1.8}{1.2 + 1.8} \times 9$$
$$= 5.4 \text{ V}$$

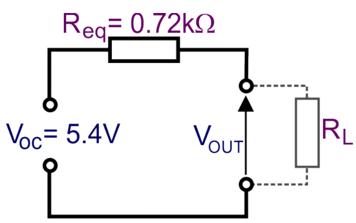
Step 2: Calculate the short circuit current, I_{SC}:

$$I_{SC} = \frac{V_{IN}}{R_1} = \frac{9}{1.2}$$
$$= 7.5 \text{ mA}$$

Step 3: Calculate the equivalent resistor, R_{eq}:

$$R_{eq} = \frac{V_{OC}}{I_{SC}} = \frac{5.4}{7.5}$$
$$= 0.72 \text{ k}\Omega$$

The equivalent circuit is:



The load resistance is the minimum permissible when V_{OUT} falls to 5 V.
Then, the voltage drop across R_{eq} is V_{eq} = 0.4 V.
The current then flowing through the load is the same as that flowing through R_{eq}.

This can be calculated using $\frac{V_{eq}}{R_{eq}} = \frac{0.4}{0.72} = 0.56$ mA.

Hence, when the load resistance is the minimum permissible, it has a voltage drop of 5 V across it and passes a current of 0.56 mA.

Using $R = \frac{V}{I}$, this minimum resistance is: $\frac{5}{0.56} = 9$ kΩ

4. Combinations of Resistors and Applications

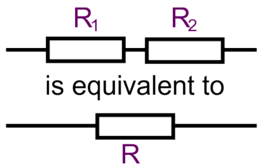
Learning Objectives:
At the end of this topic you should be able to:

- calculate the total resistance of a number of resistors connected:
  - in series;
  - in parallel;
- calculate the total resistance of a mixed series / parallel combination of resistors;
- perform calculations on voltage divider circuits, given suitable data;
- recall that the voltage divider equation assumes that no current is drawn from the output;
- appreciate that the current through a voltage divider should be at least ten times that drawn from the output;
- describe the structure of a potentiometer;
- use a potentiometer as:
  - a voltage divider;
  - a variable resistor;
- design and construct voltage divider sensing circuits using photosensitive devices, (including the LDR and the phototransistor), ntc thermistors and switches;
- explain how a Schmitt inverter can be used to provide signal conditioning

Resistors in series

The diagram shows two resistors, R_1 and R_2, connected in series, and the single resistor, **R**, which has the same effect - passes the same current for the same voltage.
It can be shown that:

$$R = R_1 + R_2$$

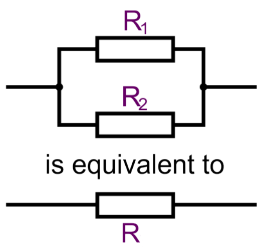


This relationship is valid for any number of resistors connected in series. Putting this relationship in words, the total resistance of resistors in series is equal to the sum of the individual resistances.

Resistors in parallel

For resistors connected in parallel, it can be shown that the total resistance, R_T, obeys the equation:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$



This equation can be extended for any number of resistors connected in parallel.

Notice that:

- for two identical resistors, **R**, in parallel, the total resistance is **R** / 2;
- for **n** identical resistors, **R**, in parallel, the total resistance is **R** / **n**;
- for two resistors, R_1 and R_2, connected in parallel, there is an easier formula:

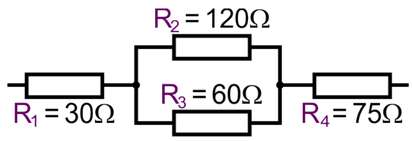
$$R = \frac{R_1 \times R_2}{R_1 + R_2}$$

(This formula works **only** for two resistors.)

- the total resistance of resistors in parallel is always less than the value of the smallest individual resistance.

Example:

What single resistor could replace the combination of four resistors, shown in the diagram, and have the same effect?

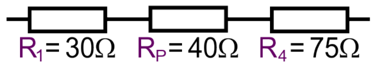


The combination is a mixture of series and parallel connections.

R_2 and R_3 are connected in parallel.
They can be replaced with a resistor R_P with a resistance of:

$$R_P = \frac{R_2 \times R_3}{R_2 + R_3} = \frac{120 \times 60}{120 + 60} = 40\Omega$$

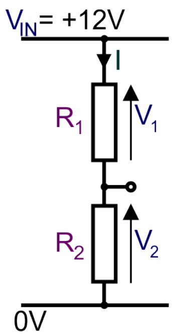
In other words, the combination reduces to three resistors in series:



The total resistance = 30 + 40 + 75 = 145Ω.

A 145Ω resistor would have the same effect as the combination of four resistors.

Voltage dividers



Two resistors connected in series with each other and with a power supply divide the supply voltage between them (obeying Kirchhoff's second law).

Using the symbols in the diagram:

$$V_1 + V_2 = V_{IN}$$

As the resistors are in series:

- the total resistance, R_T, is found from the equation:
  $$R = R_1 + R_2$$
- the same current, **I**, flows through them, assuming that no current flows from the output.

This current can be calculated using: $$I = \frac{V_{IN}}{R_1 + R_2}$$

Using the formula from Ohm's law: $$V_1 = \frac{V_{IN}}{R_1 + R_2} \times R_1$$

and $$V_2 = \frac{V_{IN}}{R_1 + R_2} \times R_2$$

Dividing these two equations gives: $$\frac{V_1}{V_2} = \frac{R_1}{R_2}$$

The ratio of the voltages across the resistors is the same as the ratio of their resistances.

- When R_1 equals R_2, each resistor has V_{IN} divided by 2 (6 V) across it.
- When R_1 equals 2 × R_2, V_1 = 2 × V_2, and so on…

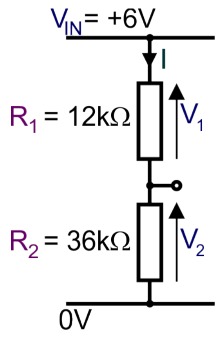
The equations obtained above for V_1 and V_2 are usually written in a slightly different form:

$$V_1 = \frac{R_1}{R_1 + R_2} V_{IN}$$

$$V_2 = \frac{R_2}{R_1 + R_2} V_{IN}$$

This is known as the voltage divider formula.

Example:



For the circuit shown calculate the voltages $\mathbf{V_1}$ and $\mathbf{V_2}$.

Using the voltage divider formula:

$$V_1 = \frac{R_1}{R_1 + R_2} V_{IN}$$

$$= \frac{12}{36 + 12} \times 6$$

$$= 1.5\text{ V}$$

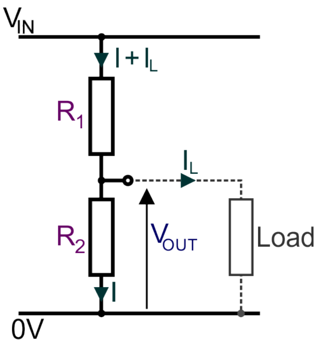
Using Kirchhoff's second law:

$$V_1 + V_2 = V_{IN}$$

$$1.5 + V_2 = 6$$

$$V_2 = 4.5\text{ V}$$

Effect of loading:



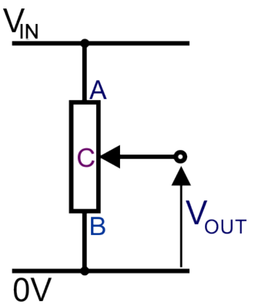
The voltage divider formula assumed that no current flowed from the output of the voltage divider. In other words, it assumed infinite load resistance.
With a finite load resistance, a current $\mathbf{I_L}$ flows through the load. As the diagram illustrates, this flows from the positive supply rail, through the load to 0 V. In doing so, it also flows through the upper resistor, $\mathbf{R_1}$. This results in a bigger voltage drop across $\mathbf{R_1}$ than that predicted in the voltage divider calculation. Actually:

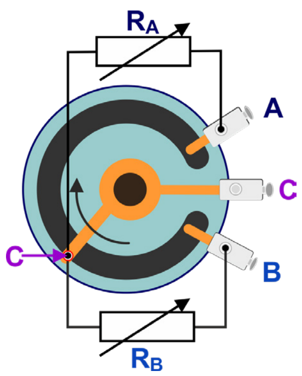
$$V_1 = (I + I_L) \times R_1$$

This is bigger than the voltage expected, ($\mathbf{I} \times \mathbf{R_1}$) by an amount ($\mathbf{I_L} \times \mathbf{R_1}$).
Rule of thumb - the current **I** should be at least ten times greater than $\mathbf{I_L}$.

The Potentiometer:

As a voltage divider:





The potentiometer (usually abbreviated to 'pot') has three terminals, labelled **A**, **B** and **C** in the diagrams.
There is a fixed resistor between **A** and **B**, sometimes in the form of a carbon track, sometimes in the form of a wire coil.
Terminal **C** is connected to a wiper that slides over the resistive track when the shaft of the 'pot' is rotated.
The effect of this is to change the resistance between **A** and **C** and between **B** and **C**. The overall resistance from **A** to **B** is unchanged.

The full supply voltage, $\mathbf{V_{IN}}$, is dropped across the resistance from **A** to **B**. The output voltage from **B** to **C**, however, changes as the shaft is rotated. As the resistance between **B** and **C** increases (and that between **A** and **C** decreases) $\mathbf{V_{OUT}}$ increases. When the shaft is rotated the other way round, $\mathbf{V_{OUT}}$ decreases.

Connected like this, with all three terminals in use, the 'pot' is a continuously-variable voltage divider.

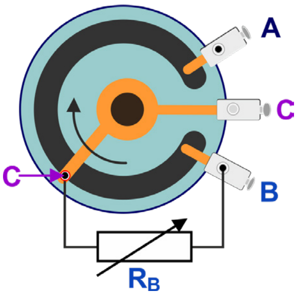
As a variable resistor:

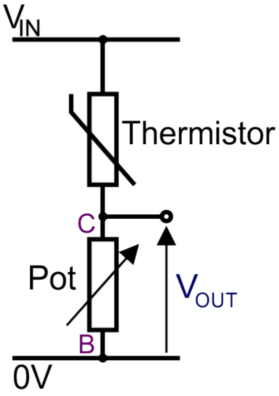
Resistors have two terminals and so do variable resistors. To use a ‘pot’ as a variable resistor, terminal **C** must be used together with **either** terminal **A or** terminal **B**.

The diagram shows a pot, used as a variable resistor and a thermistor, in a temperature-sensing unit.

Terminals **B** and **C** of the pot create the variable resistor. As the shaft is rotated clockwise, more of the resistive track is included between **B** and **C** and so the resistance between **B** and **C** increases.

The thermistor and pot form a voltage divider. As the resistance of the variable resistor increases, the output voltage, $\mathbf{V_{OUT}}$, increases.





Sensing circuits

As shown earlier, the output voltage from a voltage divider changes when the resistance of either resistor changes. In a sensing sub-system based on a voltage divider, one of the resistors is sensitive to changes in its environment - temperature, light-level etc. - making the output voltage also dependent on that factor.

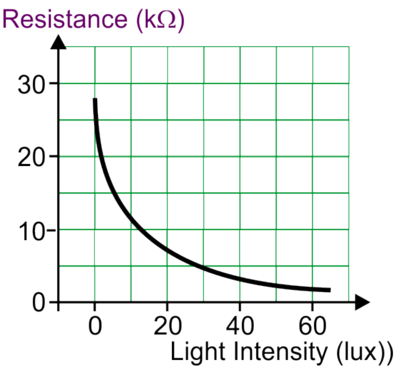
A potentiometer can be considered as a rotational sensor - the output voltage depends on the angle through which the shaft is rotated.

A light-sensing sub-system uses a component such as a phototransistor or a light-dependent resistor to sense changes in light intensity.

- The phototransistor, another semiconducting device, relies on the same basic mechanism but the electrons liberated create an input current into a transistor. The resulting transistor action amplifies this current, making the device very sensitive to light changes. In effect, the resistance between the collector and emitter of the device falls as the light intensity increases.

- The light-dependent resistor (LDR) is a component made from a semiconducting material. As light is absorbed, electrons are liberated, allowing them to take part in electrical conduction. Hence, its resistance changes when the intensity of light falling on it changes.

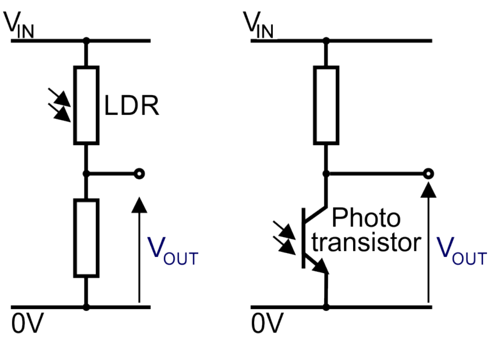
  The characteristics for a typical LDR are shown in the graph. The greater the light intensity, the lower the resistance of the LDR.



The behaviour of the light-sensing unit depends on which component in the voltage divider is light-dependent:

- In the circuit using the LDR, the output voltage $\mathbf{V_{OUT}}$ increases as light intensity increases.

- In the phototransistor circuit, the output voltage $\mathbf{V_{OUT}}$ decreases as light intensity increases.

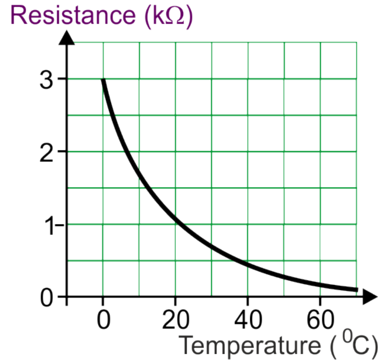


A temperature-sensing sub-system typically uses a thermistor (temperature-dependent resistor) to sense changes in temperature. These come in two types:

- ntc - negative temperature coefficient - its resistance falls as temperature rises;
- ptc - positive temperature coefficient - its resistance increases as the temperature rises.

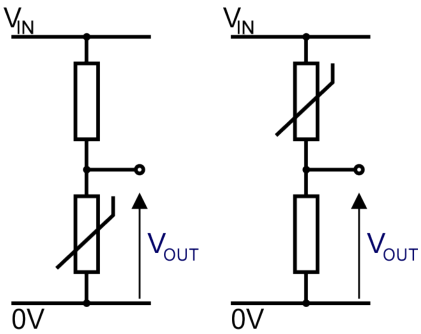
In this course, ptc thermistors are not used.

The graph shows the characteristics of a typical ntc thermistor.



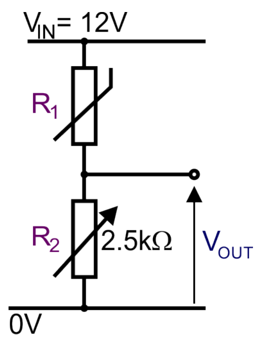
As with the light-sensing unit, the behaviour of the output voltage depends on which of the resistors in the voltage divider is the thermistor:

- In the left-hand circuit, the output voltage $\mathbf{V_{OUT}}$ falls as the temperature increases.
- In the right-hand circuit, the output voltage $\mathbf{V_{OUT}}$ rises as the temperature increases.



Example:

The circuit diagram shows a temperature-sensing unit.



The thermistor has a resistance of 1.5 kΩ at 10⁰C and 0.5 kΩ at 40⁰C.
The variable resistor is set to a resistance of 2.5 kΩ.

By how much will the output voltage, $\mathbf{V_{OUT}}$, change when the temperature rises from 10⁰C to 40⁰C?

Using the voltage divider formula:

At 10⁰C:

$$V_{OUT} = \frac{R_2}{R_1 + R_2} V_{IN}$$

$$= \frac{2.5}{1.5 + 2.5} \times 12$$

$$= 7.5\text{V}$$

At 40⁰C:

$$V_{OUT} = \frac{R_2}{R_1 + R_2} V_{IN}$$

$$= \frac{2.5}{0.5 + 2.5} \times 12$$

$$= 10\text{V}$$

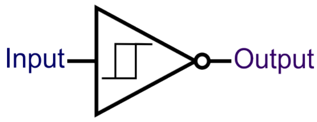
When the temperature rises from 10⁰C to 40⁰C, the output voltage rises by 2.5 V.

Signal conditioning:

Signal conditioning means processing the analogue signal created by one sub-system so that it matches the requirements of the following sub-system.

In this instance, it refers specifically to turning the analogue signal into a digital signal. It does so using two threshold voltages.

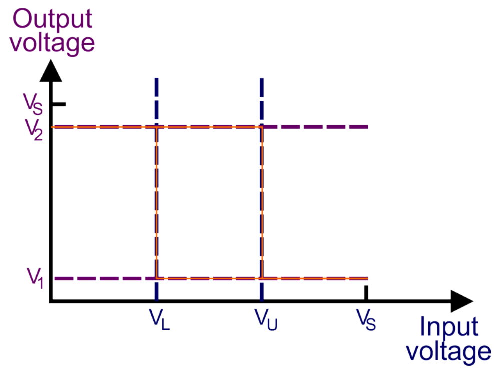
The Schmitt inverter is commonly used in signal conditioning.



Its characteristics are shown in the graph and described below.

(The graph looks like the inner part of the symbol but inverted.)

When the input voltage increases from 0 V, the output voltage:

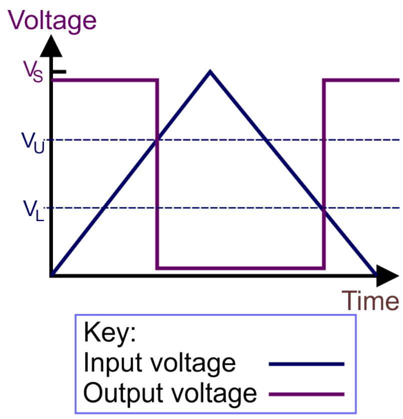


- sits at a steady high value, $\mathbf{V_2}$, near the supply voltage $\mathbf{V_s}$ to begin with;
- drops to a steady low value, $\mathbf{V_1}$, when the input voltage reaches voltage $\mathbf{V_U}$, called the upper threshold;
- stays at $\mathbf{V_1}$ while the input voltage continues to rise.

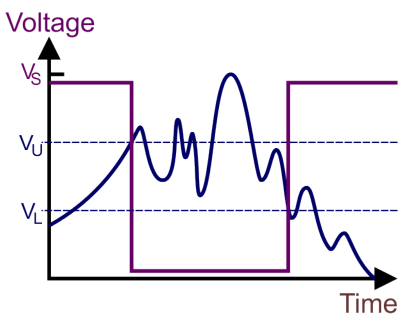
When the input voltage decreases from somewhere near $\mathbf{V_S}$, the output voltage:

- remains at the low value, $\mathbf{V_1}$, to begin with;
- jumps up to value, $\mathbf{V_2}$, when the input voltage falls to voltage $\mathbf{V_L}$, called the lower threshold;
- stays there while the input voltage continues to fall.

The next graph shows how the output of a Schmitt inverter changes when the input voltage rises and then falls.



When the input signal comes from a sensing unit, it may have some undesirable characteristics:



- a slow rise time;
  (The signal voltage changes only slowly over time. This can cause the following sub-system to overheat and can make its output unpredictable.)

- fluctuations near the threshold;
  (With devices that have only one switching threshold, this causes ‘chatter’ or ‘hunting’ - rapid changes in the output. As well as these output fluctuations being undesirable, another side-effect of the repeated rapid switching can be overheating in the following sub-system.)

The Schmitt inverter cures both of these, as the graph shows - the rise time is rapid and there are no fluctuations in the output signal.

5. Capacitors

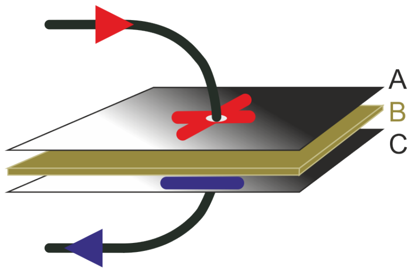
Learning Objectives:

At the end of this topic you should be able to:

- recall that capacitance is measured in farads;
- perform calculations using capacitance data in microfarads, nanofarads or picofarads;
- perform calculations using the formula: **Q** = **C** × **V**;
- calculate the total capacitance of a number of capacitors connected:
  - in series;
  - in parallel.

The principle: (This section is for information only)

A capacitor consists of two metal plates, **A** and **C**, separated by a slab of insulator, **B**, usually called the dielectric, for historic reasons.



When connected in a DC circuit, very little happens - the dielectric prevents the flow of steady current.

However, when the circuit is first connected, a brief pulse of electrons flows from the negative terminal of the power supply on to one plate, which becomes negatively charged as a result.

At the same time, some electrons from the other plate are attracted to the positive power supply terminal. As they leave, the plate becomes positively charged. Very soon, that initial current stops - the capacitor is fully charged.

A capacitor can be pictured as a 'bucket' for storing electric charge. Like some buckets, however, capacitors leak The dielectric is a very good insulator, but not perfect. It has a very high resistance, but not infinite. As a result, a tiny current flows from the positively charged plate, through the dielectric to the negatively charged plate. The capacitor slowly discharges.

In practice, the plates and dielectric are rolled up, in 'Swiss roll' fashion, to form a cylinder, in such a way that the plates do not touch. Plate **A** is then connected to one lead and plate **C** to the other.

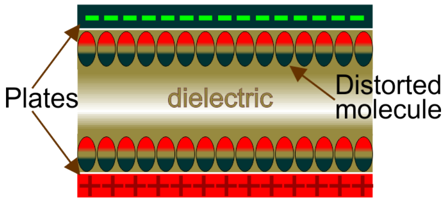
Capacitors are able to store more charge, for a given voltage, if the dielectric is made very thin. The image shows an electrolytic capacitor. In these, electrolysis within the capacitor creates an extremely thin dielectric layer on one of the plates. The disadvantage of this arrangement is that the resulting capacitor is 'polarised' - it must be connected so that the '+' plate is always at a more positive voltage than the '-' plate.

Factors affecting capacitance: (This section is for information only)

- Area of plates - the bigger the area, the more room there is to store electrons, so the greater the capacitance;

- Plate separation - when the plates are close together, the presence of negative charge on one plate tends to mask the positive charge on the other plate. This allows more charge to be stored, increasing the capacitance.

- The dielectric - is an insulator. However, the effect of electric charge on the plates is to distort the molecules of the dielectric. Their electrons spend more time near the positively-charged plate, giving that end of the molecules a negative charge and leaving the opposite end with a positive charge. These charges tend to mask the charges on the plates, allowing more charge to be stored. This increases the capacitance. Some insulating substances do this job better than others.



Capacitor parameters:

Capacitance - is the ability to store electric charge. It is measured in units called 'farads' (F). Practical capacitors have capacitances measured in microfarads (μF) - millionths of a farad, nanofarads (nF) - thousandths of a microfarad - or picofarads (pF) - thousandths of a nanofarad.

As discussed previously, there is a link between the amount of charge, **Q**, that can be stored on a capacitor, the voltage,**V**, across it and the value of its capacitance, **C**. The relationship between them is expressed in the equation:

$$Q = C \times V$$

Be careful with units when using this equation.

The charge:

- is in coulombs when the capacitance is in farads;
- is in microcoulombs when the capacitance is in microfarads;
- is in picocoulombs when the capacitance is in picofarads etc.

This is assuming in all cases, that the voltage is measured in volts.

Working voltage - To increase the capacitance of the capacitor, the dielectric is made deliberately thin, to bring the plates close together. As a result, too high a voltage can cause the dielectric to 'break down' and conduct electricity. This can damage the capacitor. Each comes with a 'working voltage' stamped on the casing, indicating the **maximum** voltage to which it should be exposed. Common DC working voltages range from 10 V to 400 V and are printed on the body of the capacitor.

Tolerance - Like resistors, capacitors are not manufactured with every value possible. Manufacturing constraints place limits on the accuracy to which they are manufactured. For a typical capacitor, the tolerance may be 20% of its stated value.

Leakage current - As pointed out earlier, capacitors 'leak' owing to the finite resistance of the dielectric. For electrolytic capacitors, which offer a high capacitance in a small volume, leakage currents are often measured in microamps. For small non-electrolytic capacitors, leakage currents are typically a thousand times smaller.

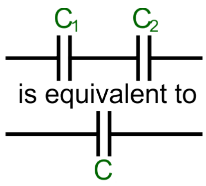
Combinations of capacitors:

It can be shown that the formulae for capacitors in series and in parallel are the mirror image of those for resistors in series and in parallel.

Capacitors in series

The total capacitance, **C**, of capacitors connected in series is given by the equation:

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$



Where there are only two capacitors, this formula reduces to:

$$C = \frac{C_1 \times C_2}{C_1 + C_2}$$

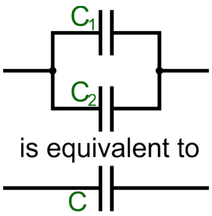
The total capacitance is smaller than any of the individual capacitors.

Effectively, the dielectrics of all the capacitors are added, end to end, making a much thicker dielectric, increasing the plate separation and reducing the capacitance.

Capacitors in parallel

The total capacitance **C** of two capacitors connected in parallel is given by the equation:

$$C = C_1 + C_2$$



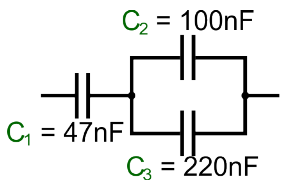
This relationship is valid for any number of capacitors connected in series.
In words, the total capacitance of capacitors in parallel is equal to the sum of the individual capacitances.

In this case, the left-hand plates of all the capacitors are connected together to make a big plate. The right-hand plates of all the capacitors are connected into one big plate.

This results in a single capacitor with much bigger plates and so a much bigger capacitance.

Example:

What single capacitor could replace the combination of three capacitors, shown in the diagram, and have the same effect?

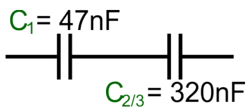


The combination is a mixture of series and parallel connections.

$\mathbf{C_2}$ and $\mathbf{C_3}$ are connected in parallel.

They can be replaced with a capacitor $\mathbf{C_{2/3}}$ with a capacitance of:

$$C_{2/3} = C_2 + C_3 = 100 + 220 = 320 \text{ nF}$$



The combination reduces to two capacitors in series:

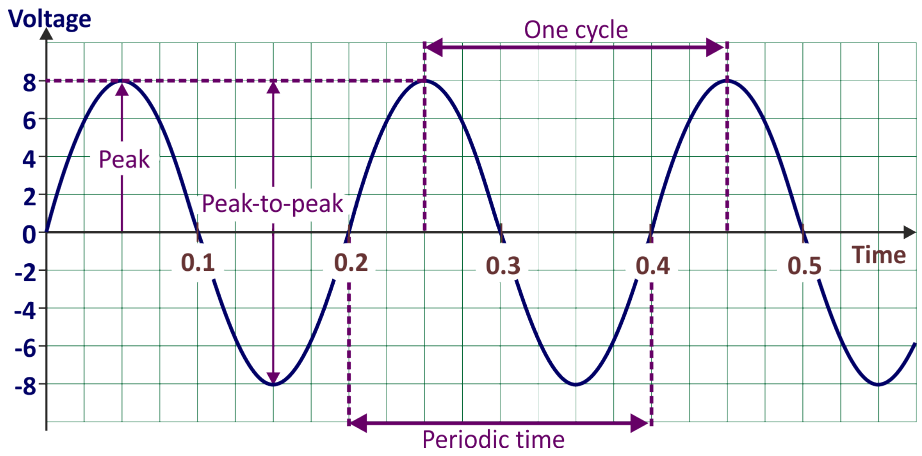
The total capacitance is obtained from the equation:

$$C = \frac{C_1 \times C_2}{C_1 + C_2}$$

$$C = \frac{47 \times 320}{47 + 320} = 41 \text{ nF}$$

A 41 nF capacitor would have the same effect as the combination of three capacitors.

Alternating current (AC):



The diagram shows the voltage / time graph for an AC signal, labelled with some important quantities:

Peak voltage - maximum voltage reached by the signal, (8 V in this case).

Peak-to-peak voltage - voltage difference between positive peak and negative peak voltage, equals two x peak voltage, (16 V in this case).

Periodic time - time taken by the signal to get back to its 'starting point'; - time taken for one complete cycle, (0.2 s in this case).

The scientific notation for the peak voltage is V_0 and for peak current is I_0.
Related to these is the **frequency f** of the signal - the number of cycles completed in one second.
Frequency is measured in units called hertz (Hz). A frequency of 10 Hz means that ten cycles of the wave are completed each second.
The relationship is logical: $f = \frac{1}{T}$ where **T** is the periodic time.

For the AC signal shown above, the frequency is: $f = \frac{1}{0.2} = 5$ Hz

Delivering power:

At times, an AC supply delivers zero volts. At other times, it delivers higher or lower values.
An interesting fact - the average voltage for an AC supply (any AC supply) is zero!
*This certainly does **NOT** mean that AC supplies do nothing - far from it.*
The average power delivered is **NOT** zero.
(For a resistor, **R**, power delivered = $\frac{V^2}{R}$, i.e. depends on voltage squared. Hence, the voltage may be negative but the power delivered is still positive. A negative voltage simply means that the current flows the other way around the circuit.)
For an AC supply, a measure more significant than average voltage is **rms voltage**. Although it stands for 'root-mean-square' voltage, it is better to think of it as the DC voltage which would deliver the same power to a load.

For a sine-wave signal, peak and rms voltage are linked by:

$$V_0 = V_{rms} \times \sqrt{2}$$

To a good approximation, this can be written:

$$V_0 = 1.4 \times V_{rms} \text{ or } V_{rms} = 0.7 \times V_0$$

Similarly, the rms current is given by:

$$I_0 = 1.4 \times I_{rms} \text{ or } I_{rms} = 0.7 \times I_0$$

Example 1:

An AC sinusoidal signal has a peak voltage of 20 V and a periodic time of 10 ms.

Calculate the rms voltage and frequency for this signal.

Using $V_{rms} = 0.7 \times V_0$

$V_{rms} = 0.7 \times 20$

$= 14\ V$

The rms voltage of the AC signal is 14 V.

Using $f = \frac{1}{T}$

$f = \frac{1}{0.01}$ (since 10 ms = 0.01 s)

$= 100\ Hz$

The frequency of the AC signal is 100 Hz.

Example 2:

A 120 Ω resistor has an AC sinusoidal signal applied to it.
This signal has a rms voltage of 2 V.

Calculate:

- the peak voltage across the resistor;
- the rms current through the resistor;
- the average power dissipated in it.

Using $V_0 = 1.4 \times V_{rms}$

$V_0 = 1.4 \times 2$

$= 2.8\ V$

The peak voltage across the resistor is 2.8 V

Using $I_{rms} = \frac{V_{rms}}{R}$

$I_{rms} = \frac{2^2}{120}$

$= 0.017\ A$ (=17 mA)

The rms current through the resistor is 17 mA.

Using $P = \frac{V_{rms}{}^2}{R}$

$P = \frac{2^2}{120}$

$= 0.03\ W$ (= 30 mW)

The power dissipated in the resistor is 30 mW.

Exercise

1. A 24 V, 50 mA lamp is working at its rated voltage and current.

(a) How much power is being dissipated in the lamp?

....

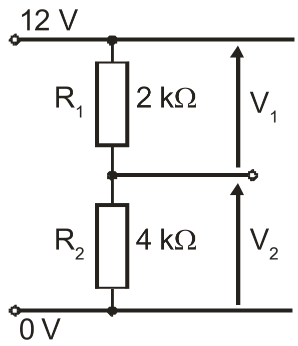
....

(b) The lamp is left on for 5 minutes. How much energy has been used during this time?

....

....

2. The circuit diagram below shows a voltage divider.



(a) What is the total resistance of R_1 and R_2?.................................

(b) Calculate voltage V_2.

....

....

(c) A second 4 kΩ resistor is connected in parallel with R_2.
What is the combined resistance of the two 4 kΩ resistors?

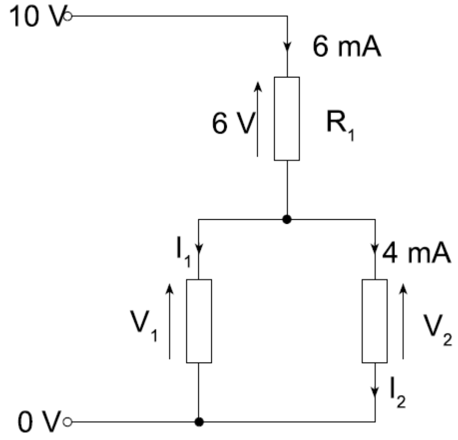
....

(d) Calculate the current in each of the 4 kΩ resistors.

....

....

3. Look at the diagram on the right:



(a) Write down the values of the following:

(i) I_1 ………………………

(ii) I_2 ………………………

(iii) V_1 …………………….

(iv) V_2 ……………………..

(b) Calculate the value of R_1.

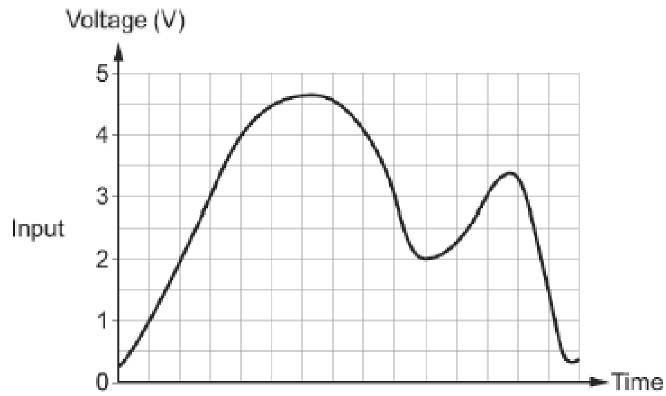
………………………………………………………………………………………………………

………………………………………………………………………………………………………

4. Here is a data sheet for a Schmitt inverter:

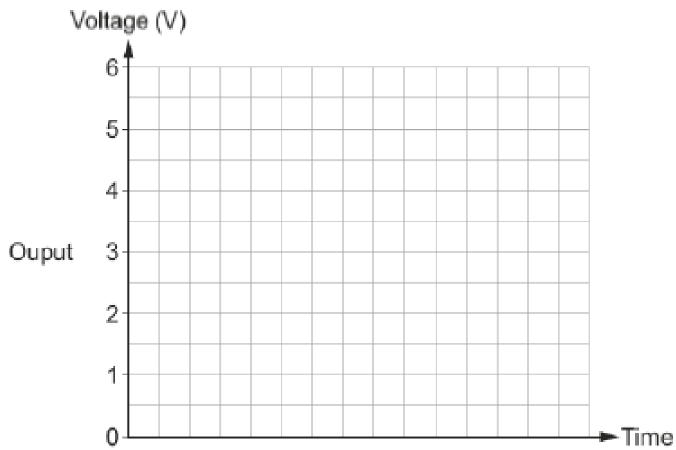
When connected to 5 V supply:

- Logic 0 = 0 V
- Logic 1 = 5 V
- The output changes from logic 1 to logic 0 when a **rising** input voltage reaches 3 V
- The output changes from logic 0 to logic 1 when a **falling** input voltage reaches 1.5 V



The signal produced by an analogue sensing sub-system is shown on the first set of axes.

Use the second set axes to draw the resulting output signal produced when the Schmitt inverter is used to convert the analogue input into a digital signal.



5. Draw a diagram to show how several 10 μF capacitors can be connected together to produce a capacitance of 35 μF.

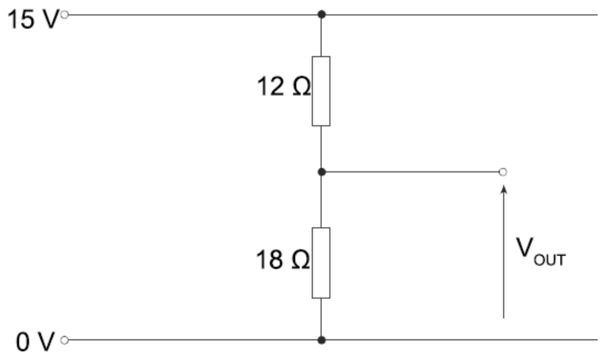
6. (a) Calculate the power dissipated in a 100 Ω resistor when connected to a 12 V DC voltage.

....

(b) Calculate the power dissipated in a 100 Ω resistor when connected to a sinusoidal AC voltage with a peak value of 12 V.

....

7. Thevenin's theorem is used to produce an equivalent circuit for the voltage divider circuit shown.



(a) Calculate the values of V_{OC} and R_{eq}.

....

....

....

....

....

(b) (i) Draw the equivalent circuit with a load resistance connected across the output terminals.

(ii) Use the equivalent circuit to calculate the maximum permissible load current to ensure the output voltage V_{OUT} does not fall below 8·0 V.

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