# Electronics for Model Railways

## Chapter 1

**Basic Electronics**

By Davy Dick

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**By Davy Dick**



In memory of Margaret

# Introduction

For most railway modellers, power is supplied to the loco's motor through the track. With the help of electronics, our layouts can be further improved. How about control of points, signals, lights, turntables, crossing gates and barriers, uncouplers, sound effects – and much more.
We can even detect where trains are on our layouts or automate activities, with or without computers.

At first sight, this may seem complicated – but layout wiring and controls often consist of lots of little individual circuits, each carrying out its own function (e.g. switching a point or lighting an LED).

The chapters try to look at each issue and show how they fit together.

If you like, you can read through from start to finish. However, it is not meant to be read as a book. If you are new to electronics, this book covers a lot of ground.
You are not meant to understand it all after just a quick read through.
You will also find that you already know some parts – and are not currently interested in other parts.

I would suggest that everyone have a read of the first chapter – even if you think you already know all the basics.

> Also, as you are working with a hot soldering iron, knives and cutters, drills and so on , be aware of safety at all times.
> **Please read the section on safe working in the chapter on toolkits.**

Hopefully, there is something of interest in here for all railway modellers.

*Davy Dick*

Model Electronic Railway Group member 1853

# Contents

# Basic electronic terms

## Units of measurement

Before we start looking at volts, amps, etc., you should note that there are large variations in electrical and electronic units of measurement.
For example, the steel pylon that brings power to your home might be carrying up to 400,000 Volts, while an LED (light emitting diode) in your layout might be working at around 3 Volts.

Here is a chart that lists the most likely values that you will come across in model railway electronics.

| | | |
|---|---|---|
| pico | One millionth of a millionth ($10^{-12}$) | Tiny measurement, usually of capacitance |
| nano | One thousandth of a millionth ($10^{-9}$) | Tiny measurement, usually of capacitance |
| micro | One millionth ($10^{-6}$) | 1µF = one millionth of one Farad |
| milli | one thousandth ($10^{-3}$) | 1 amp = 1,000 milliamps |
| kilo | 1,000 times ($10^{3}$) | 1 kilohm = 1,000 ohms |
| mega | 1 million times ($10^{6}$) | 1 megohm = 1,000,000 ohms (or 1,000 kilohms) |

If you have not come across terms such as $10^3$ or $10^{-12}$ before, its not that difficult.
$6 \times 10^3$ means 6 multiplied by ten three times, in other words 6 x 10 x 10 x 10 = 6,000
Put another way $10^3$ means add three zeros to the end of the number.
Similarly, $6 \times 10^{-3}$ means 6 divided by ten three times, in other words 6 /10 /10 /10 = 0.006

### Examples

An N gauge loco motor might draw a current of 250 milliamps (written as 250mA); this is the same as a quarter of an Amp.
An electric fire might be rated at 1 kilowatt (written as 1kW); this is the same as 1,000 Watts.

**Note**

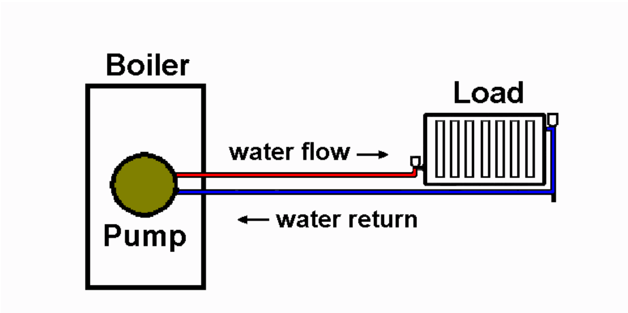
Computers use a different definition of some terms, as they operate in binary (i.e. off and on) states. So, everything is in multiples of 2.
Here, kilo is 1024 ($2^{10}$) and mega is 1,048,576 ($2^{20}$).
These multiples are used to described memory size and disc drive and memory stick capacity.

# Current

You cannot see electricity. However, you can see, and often feel, its effects.
Electrical current drives motors, lamps, relays, electric heaters, etc.
It produces light, heat, radiation and induction.

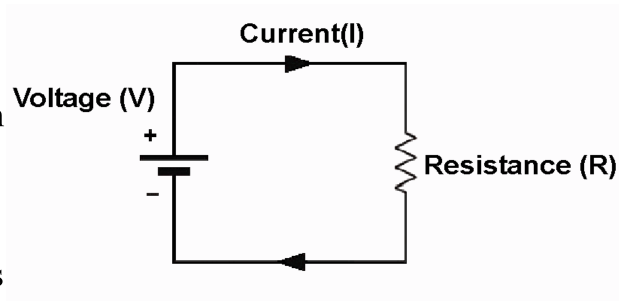
So, what exactly is current?
Current is simply the flow of electrons along a material that allows its passage. Electrical current always flow in a loop and a common analogy is to imagine marbles circulating inside a hula hoop.
You will already have noticed that a battery has two terminals and the mains supply has a live and a neutral. Both have an out and a return.
Of course, something has to push the electrons round the circuit.
An often used comparison is made between the flow of water and the flow of electrons.

This illustration shows a basic central heating system.
The water drops flow round the system, passing through the boiler's pump, the pipes and the radiator. The water is heated before being pumped into the outgoing pipe. The water dissipates much of its energy in the form of heat in the load (the radiator).
The cooler water returns to the boiler to be reheated and pumped back round again.




Compare that system with how a lamp on a bicycle works. As the wheel turns, it spins a dynamo (an electrical 'pump'); the electricity is taken by wires to the load (the lamp bulb) and returned again to the dynamo. The energy created by the dynamo is dissipated in the lamp as light.
In fact, the electricity in your home is also organised this way, except on a much larger scale, with huge power stations and the National Grid distribution network.

Now look at this basic electrical diagram. It shows a battery as the electron 'pump', the wire that carries the current to the load and the return wire that conducts the electrons back to the battery.
In this case, the load can be a lamp, a relay, a locomotive motor – or one of many other things that will convert the electrical energy for its own use.




While the water flow is measured in gallons that are pumped round, the flow of electrons is measured in Amps (short for Amperes), or in milliamps.

Just for the record (there is no need to remember this), one Amp is 6,250,000,000,000,000,000 electrons passing a particular point in one second!

**Note**

Early pioneers of electricity thought that current flowed from positive to negative potentials. In fact, electrons move from negatively charged to positively charged areas.
To 'save confusion', you will often find texts talking about *'conventional current'* (the long-standing but wrong description) and *'electron flow'* (which is what actually happens). So, all the arrow symbols that you see in diagrams (e.g. diodes, transistors) are showing conventional current flow, not actual electron flow. Just something we have to live with!

# Voltage

Let's continue with the central heating analogy for a moment.
The pump is pushing out water at one end, thus creating a shortage of water at the other end. This difference in water pressure results in the flow of water round the house.
As you would expect, increasing the pump pressure results in more water being pumped round.
With electrical circuits, the power source creates an excess of electrons at one end and a shortage at the other. This is known as the 'potential difference' and this results in the electrons flowing round the circuit. This is true of any two points in a circuit; if one point is at a more negative potential than another point, electron current will attempt to flow towards the less negatively charged point.

Water pressure is measured in 'psi' (pounds per square inch) or 'bars' (one bar is the force required to raise water to a height of 10 metres).
The difference in potential of an electrical power source is measured in Volts (or kV or mV).
The power source can be a battery (as used in your watch, mobile phone, laptop, car, etc.) or a mains supply (us used for your cooker, washing machine, house lights, etc.).
For model railways, the mains supply is too high a voltage and has to be brought down to a lower level. Many loco controllers either use an external power unit, or an internal unit, to reduce the voltage from the 240 volt mains supply to the 12 volts commonly used for model railways. (more later).

# Resistance

The amount of water flowing through your central heating pipes depends on the water pressure, as already mentioned. But, it also depends on how easily the water is able to flow. So, for example, if we replaced old wide pipes with new narrow pipes, it would lower the flow. Similarly, if we screwed down the radiator valve, the flow would be lowered.

The flow of electricity will similarly be affected by the material it has to pass through. Some materials, such as copper, offer only a very low resistance to the passage of electrons and such materials are known as *'conductors'*. Other materials, such as plastic and glass, offer a very high resistance and these are known as *'insulators'*. That is why wire is made from copper inside a PVC sheath. The copper conducts the electrons and the PVC prevents shorts to any other conductors.

Different materials have different resistances and properties, and this is used to good effect in model railway electronics. You can deliberately introduce extra resistance into a circuit to reduce the voltage on other components (e.g. to control loco speeds) or limit the current flowing through other components (e.g. when illuminating LEDs).
On other occasions, the resistance is inherent in the materials you use. Your layout wiring, your loco motors, your point actuators, etc. all add their own resistance.

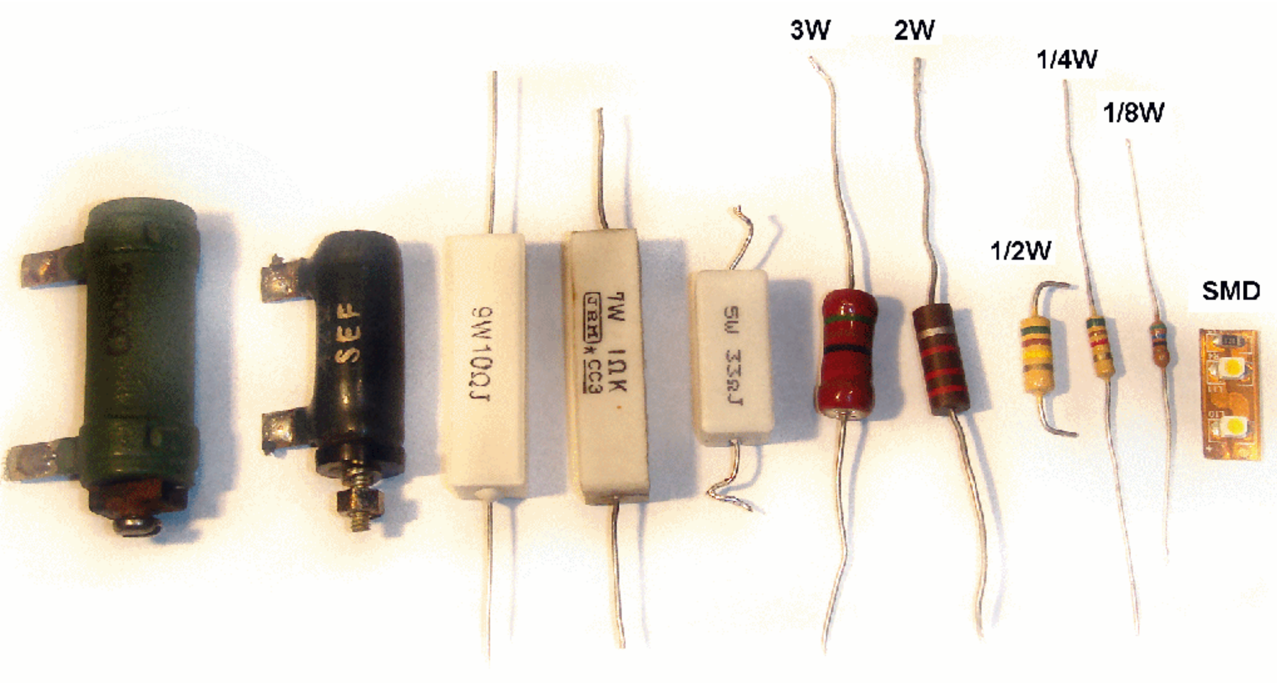
The measurement of resistance is in Ohms (named after Georg Ohm, a German physicist). The symbol for Ohms is Ω, (the Greek letter Omega) but this is seen less often in diagrams and textbooks nowadays.

Although resistances are measured in decimal amounts, the decimal point is not used in texts and diagrams as it is easy to miss.
The letters R, k and M are used, where R represents the decimal point, k represents one thousand an M represent one million.
Here are some example resistor values:

560R is 560 ohms
R47 is 0.47 ohms
47R is 47 ohms
3R9 is 3.9 ohms
2k7 is 2,700 ohms
1M2 is 1.2 megohms

# Resistors

These are available in various shapes, sizes and performance.




The main characteristics of resistors are:

## Value

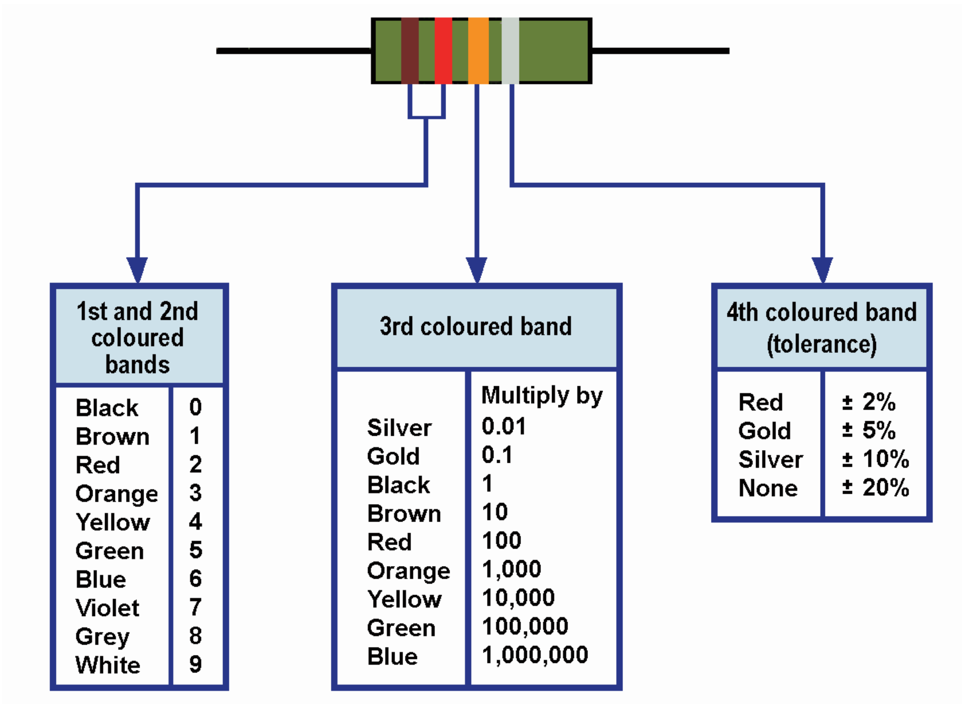
You can buy resistors with values as small as a fraction of an Ohm, up to resistors with millions of Ohms of resistance.

Clearly, it is not possible to manufacture and stock every possible value in between. Instead, resistors are manufactured in limited fixed ranges of values. These were the standards set up by the now defunct Electronic Industries Alliance, commonly known as *'preferred values'* and these are shown in the table below.

| Preferred series | Values available in that range |
|---|---|
| E6 | 1.0, 1.5, 2.2, 3.3, 4.7, 6.8 |
| E12 | 1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2 |
| E24 | 1.0, 1.1, 1.2, 1.3, 1.5, 1.6, 1.8, 2.0, 2.2, 2.4, 2.7, 3.0, 3.3, 3.6, 3.9, 4.3, 4.7, 5.1, 5.6, 6.2, 6.8, 7.5, 8.2, 9.1 |

## Colour coding

Larger-sized resistors have their values printed on them.  In most cases, the values are deduced from the coloured marking round the resistor body.
Most resistors use a numbering code that uses four coloured bands.



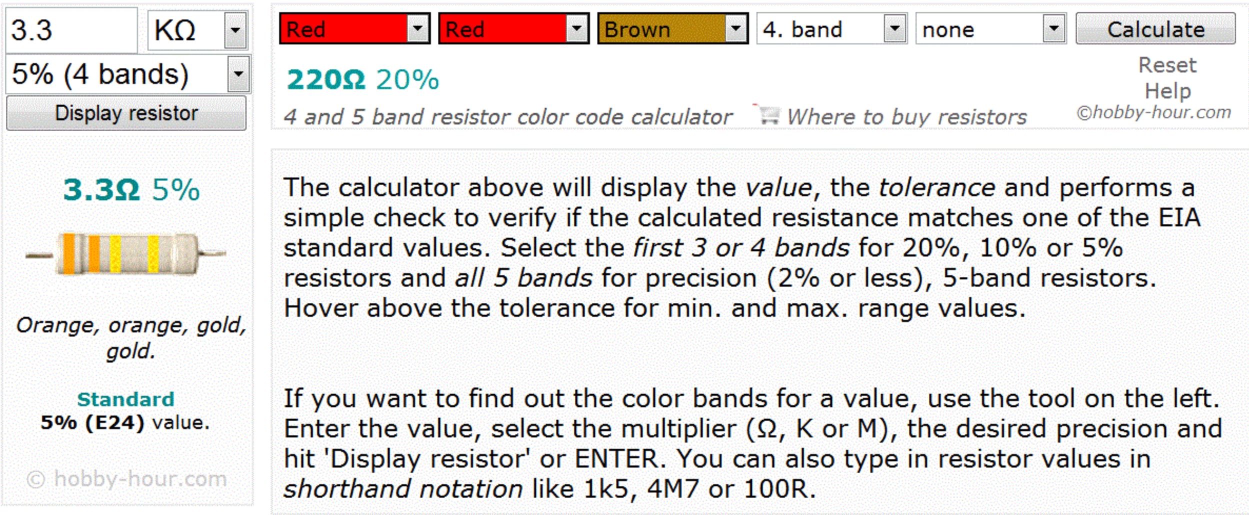

For example, the resistor shown in the illustration can have its value calculated thus:

1st band is brown = 1
2nd band is red = 2
3rd band is orange = multiply by 1,000 (simply add three zeros)

So the value is 12000 ohms, commonly known as a 12k resistor.
The fourth band is silver, which indicates that the resistor tolerance is + or – 10% (the actual resistor value can be greater or lower then 12k by as much as 10%).
If you prefer, you can use one of the many free software calculators that you will find on the internet.
This one can be found at

www.hobby-hour.com/electronics/resistorcalculator.php

# Resistor color code calculator




Another calculator can be downloaded from
www.merg.org.uk/merg_resources/resistors.php

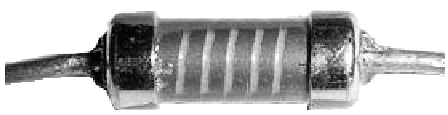
## Wattage

The more current that flows through a resistor, the more it heats up (that's how your electric fire or soldering iron works). Of course, we don't use resistors as heating elements – its just a by-product of using them to reduce voltage or current in a circuit. In fact, excessive heat will eventually destroy a resistor. The wattage rating of a resistor tells you how much power it can dissipate over a long period of time without being damaged.
Resistors fitted to electronic circuits where only tiny signals are being carried may use 1/8$^{th}$ of a Watt, while heavy current usage requires higher wattage handling (e.g. a car lamp bulb or soldering iron may be 25W).
Most electronic circuits probably use resistors with ¼W or ½W ratings.

## Tolerance

Resistors are manufactured in their millions. To keep their price down, they are not exactly precise, with their deviation between the actual resistance value and the stated value being known as its *'tolerance'*. Of course, you can buy resistors with very low tolerances – at a higher price. It depends on what you want to use it for. Most resistors are produced with tolerances of either ± 2%, ± 5%, ± 10%, or ± 20%. Close tolerance resistors are used where precision is important, such as transmission equipment (to work at the correct frequency) or measuring equipment, such as your multimeter. In most situations, the cheaper wider tolerance resistors are commonly used.
E6 series resistors have a 20% tolerance, while E12 series resistors have a 10% tolerance or occasionally 5%. E24 series resistors are mostly 5% but some are available in 2%.

## Material

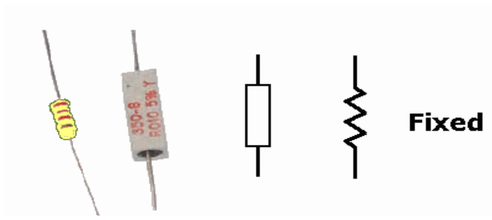


Most model railway applications use carbon film resistors. They are made up of a ceramic rod with a spiral of carbon deposited on it, and with wire connections at each end.
They are the most common and are cheap and readily available.

Other types are produced for specialist purposes. For example, resistors made from a metal film ( nickel chromium) spiral are used in audio amplifiers as they produce less noise than carbon resistors, and are less affected by heat and voltage changes
Where very high currents are being passed through a resistor, wire wound types are used. They are constructed in a similar way to the element that winds round a bar of an electric fire. They are often used for high precision measuring or where high power ratings are required (some handle up to 300W). Early locomotive controllers used large wirewound resistors to control loco speeds.
Surface mount resistors are now the standard for manufactured boards and are becoming more used for hobby kits. They are tiny, with no leads, and require practice to solder to boards.

# Types

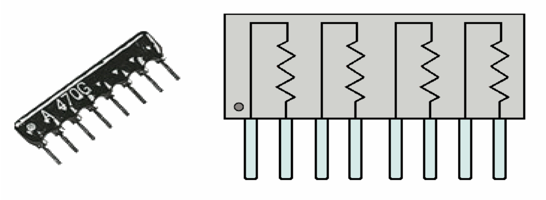
## Fixed



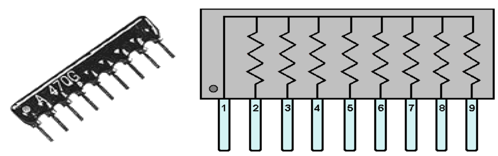

Most resistors are of the *'fixed'* type. That means that they are manufactured to a specific value and that value cannot be varied by the user. It is just a component with two leads.
The illustration shows a couple of fixed resistors (one is carbon and the other wirewound).
The symbol for a fixed resistor that you see in electronic diagrams is either a zig-zag sawtooth-like shape or mostly commonly a simple rectangle.
Single resistors are not polarised. That means that they work whichever way they are connected. The only exception is for commoned resistor arrays mentioned below.

## Arrays

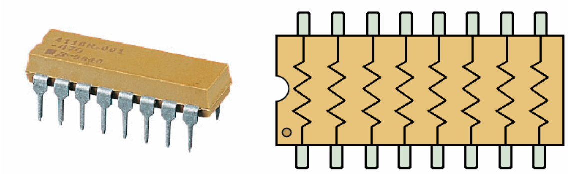
Most circuits use a collection of individual resistors in their construction. Sometimes, however, there are occasions when a collection of the same value are used in close proximity, usually for a common purpose (e.g. connecting to a set of LEDs or to a group of switches). In these situations, it is neater and saves space to use resistor arrays (sometimes shortened to *'resnets'*)
These illustrations show a type known as SIL resistor networks . SIL means single in line, a single row of pins.
As you will notice, some resnets are *'isolated'*.; each resistor has its one set of pins and has no connection to any other resistor.



The other, known as *'commoned'*, has one end of all resistors taken to a single output pin.
The dot on the resnet case indicates pin 1, which is the common pin for commoned resnets.



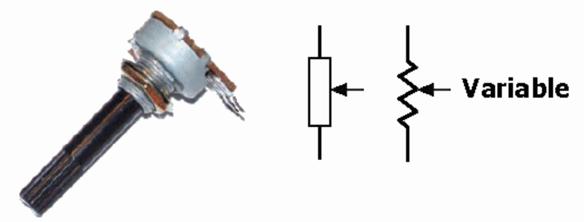
Another array is the DIL (dual inline) with two rows of pins. All eight resistors in the network will have the same value of resistance and there is no internal connection between any resistor.



### Variable

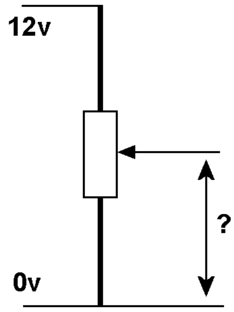
You will already be familiar with variable resistors as they can be found as volume controls in many audio systems and as a speed control for a model railway controller.

They are three-terminal devices and are often referred to as *'potentiometers'* (sometime shortened to *'pots'*)




Some are altered by turning a knob while others use a slider to change value. In both cases, a wiper slides over the resistive material and the result is taken out to a third terminal.

The symbol for a variable resistor is similar to a fixed resistor, with an arrowhead on the side to show that its value can be varied.



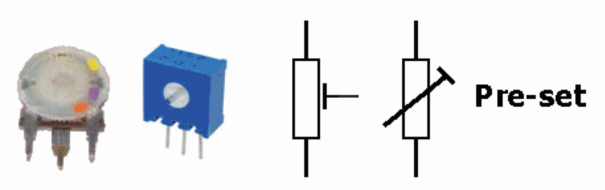

Take this example of a *'linear potentiometer'* with a value of 100k. That means that there will always be 100k across its outer terminals. Its the value seen at the wiper terminal that is changed when the knob or slider is varied.

In our example, the outer terminals have 12V across them.

As the inner material has a consistent coating, the voltage is spread evenly across the entire inner surface. So, the coating at the top terminal will be at 12V, while the coating at the bottom terminal will be at 0V. It follows that the middle of the coating should be at 6V. If we turn the knob (or move the slider) to mid position, the wiper should be at 6V. So, by moving the wiper, we can control the voltage that we use.

Note

There is another type of potentiometer known as the *'logarithmic'* type. They are specially made for audio purposes, as our hearing levels are logarithmic. Make sure you always use a linear type for model railway projects.




This illustration shows a couple of examples of *'preset potentiometers'*. These are much smaller than standard pots and have no external rod or slider to alter values. Instead, they have a small slot that allows the wiper's output to be set by a screwdriver.

These are common on printed circuit boards where there is no need for constant adjustment. The wanted value is set and then left alone.

The symbols used are slightly different from variable resistors.

# Ohms Law

Lets have one last analogy with central heating.

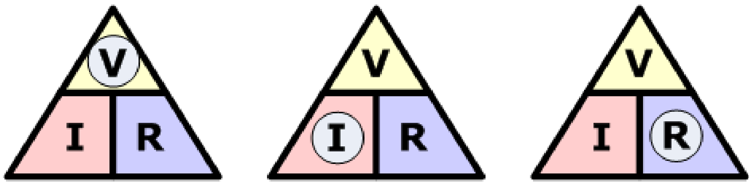
The amount of water flowing round your system depends on the amount of pressure being provided by the pump, and the stifling of the flow from valves, narrow pipes and clogged pipes. The three are interrelated. If you increase the pump pressure, more water flows round. If you turn down radiator valves less water flows in that radiator, and so on.

And so it is with electrical current.

The current flowing in a circuit is directly proportional to the voltage (greater voltage means more current) and inversely proportional to the circuit's resistance (greater resistance means less current).

So, if you know any of two properties, you can calculate the third. The calculations use V to represent voltage, I to represent current and R to represent resistance.

The illustration shows a simple way to remember the three formulae.




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

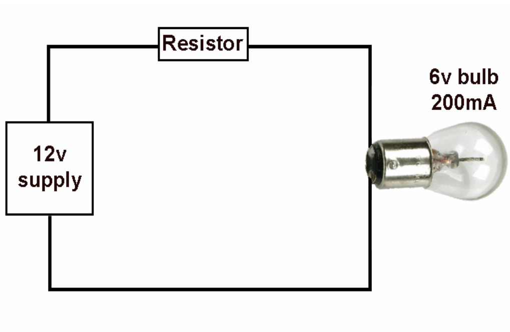
From the middle pyramid, we can deduce that I = V/R (i.e. that current flow *increases* with increased voltage but *reduces* with increased resistance).

These calculations are known as *'Ohms Law'* (remember Georg?).

## Some examples

- If you place a12V battery across a 6V bulb, you get double the current. The excessive heat burns out the bulb filament.
- If you have a short in a circuit, you get as much current as the supply can produce – until the fuse blows - or worse.
- If you have a bad connection or use wire that is too thin, you have introduced excessive resistance. The diminished current flow will probably result in the device working badly, or not at all.

## Some calculations




You have a 6V bulb but your supply is 12V. The bulb says it works on 200mA (0.2A).
We know that if we add extra resistance, the current flow will be reduced. We also know that the current flowing through the resistor we added will now drop some of the voltage across it.
So how do we calculate the value for the resistor?
Well, the resistance of the bulb filament when hot must be R=V/I = 6/0.2 = 30 ohms.
We want 6V to be dropped across the resistor, to leave just 6V across the bulb.
So the value of the resistor can be calculated thus: R=V/I = 6/0.2 = 30 ohms.
You could probably have guessed it would be the same value since we wanted to halve the voltage.

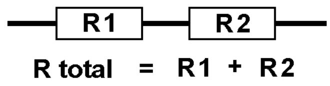
How about when we have a 4.8V 300mA bulb?
The calculations are only slightly more complicated.
We want to drop 7.2V across the resistor (12V-4.8V).
So, the resistance value must be R=V/I = 7.2/0.3 = 24 ohms.

**Note**

In these examples, we deliberately introduced added resistance to achieve our needs. In model railways, the introduction of unintended resistance is a source of problems. When your loco runs slower in one section of track compared to another; when your solenoid doesn't quite move the point as snappily as it used to; when the lights dim unexpectedly – these are all symptoms of unwanted resistance. This is covered in detail in the chapter on layout wiring.

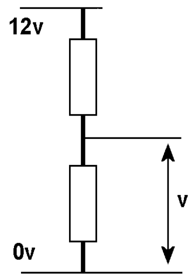
## Series circuits

When you have more than one resistance, they can be in series with each other, or be connected in parallel.
The illustration shows a simple series circuit.
You simply add the resistance values together to get the total resistance between the two ends.




As the resistances are in series with each other; the same amount of current will pass through all the resistances – no matter what value of resistance they have.
But, according to Ohm's Law, the same current flowing through different resistances results in different voltages across each resistance.
This is used to good effect in many electronic circuits.

The illustration shows two resistors in series across a 12 volt supply.
The 12 volts is distributed across the resistors depending on their values, hence its name as a *'voltage divider'*. The resulting voltage at their junction depends on the ratio between the two resistors.
If both resistances were equal, there would be 6Vpotential between the junction of these two resistors and 0V potential.
All voltages are relative to the 0V line.

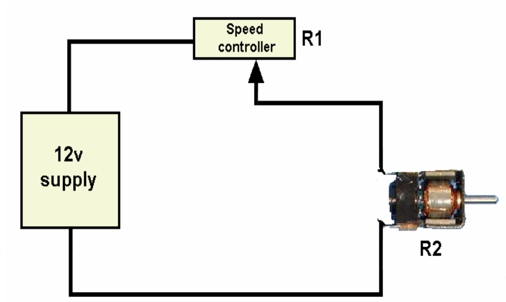



Other examples include:

10k on top, 1k on bottom results in 1.091V at the junction.
47k on top, 12k on bottom results in 2.441V.
47k on top, 33k on bottom results in 4.95V.

As always, there is an online calculator to make life easier.
Try: www.raltron.com/cust/tools/voltage_divider.asp

The voltage divider effect was widely used in early loco speed controllers such as the H&M models. Like many others, it had a large wirewound variable resistor. As the rheostats's knob was turned, the wiper rubbed across the windings and varied the amount of resistance placed in series with the locomotive's electric motor.
Turning the knob clockwise decreased the added resistance, increasing the voltage across the motor, thus increasing the current flow and the motor speed.



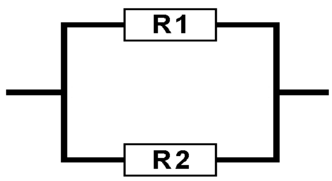

Nowadays, we use more sophisticated ways of controlling loco speeds (see later).

**Tip :**
If you need a value that you don't have in your spares box, make one up from other resistors in series. For example, wiring a 820 ohm and a 180 resistor produces a 1k resistor.

## Parallel circuits

Not all circuits are wired in series.
Your house lights, domestic appliances, PC, etc. are all wired in parallel with each other. They all receive the same 240V supply but each consume different amounts of current from the common supply.

In model railways, we use parallel circuits when we operate locos, points, lights, etc.
The illustration shows how to calculate the resulting resistance from two resistors wired in parallel.




$$\frac{1}{\text{R total}} = \frac{1}{\text{R1}} + \frac{1}{\text{R2}}$$

If there are only two resistors, the equation can be simplified to

$$\text{R total} = \frac{\text{R1} \times \text{R2}}{\text{R1} + \text{R2}}$$

To avoid awkward calculations, specially if you have many resistors, you can use on-line calculators such as:

www.sengpielaudio.com/calculator-paralresist.htm

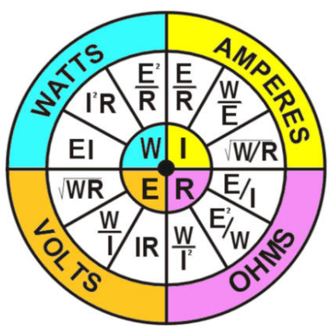
Tip : If you want a value that you don't have in your spares box, you can make one up from other resistors in parallel. For example, wiring two 1000 ohm resistors in parallel will give you a 500 ohm resistor.

Other examples include:

560ohms and 470ohms give 255 ohms.
100ohms and 150ohms give 60 ohms (or you could use 33ohms and 27ohms in series).

# Wattage

We mentioned wattage earlier but how do we calculate the power being used by any given device?
You can calculate the amount of power if you know two of the three electrical values – voltage, current and resistance.
See the formulae in the wheel (E, like V, is used to indicate voltage).

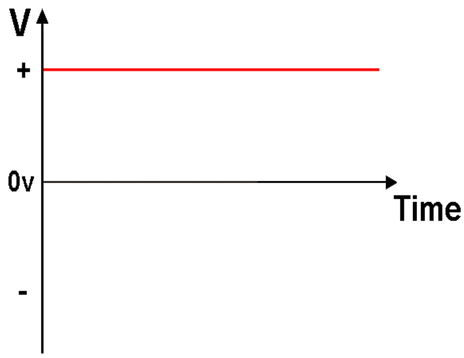



So, using W = E x I, we can make some calculations like those below:

If your loco uses 1Amp at 12 volts, then is consumes 12 watts.
A 240V light bulb uses 0.417 amps (470millamps) to be a 100watt bulb.
A 2 kilowatt kettle uses 8.333 amps (240 x 8.333 = 2000)

# What is DC

DC stand for *'direct current'*.
A battery is a typical store of DC energy. It has two terminals, with a potential difference between them. One terminal (the -ve) has a surplus of electrons, compared to the other (+ve). Place it in a device, switch the device on and the electrons start to flow.
All battery powered devices, such as your watch, mobile phone, iPod, etc. depend on a constant flow of direct current during their operation.
The graph shows the voltage unchanging over time.



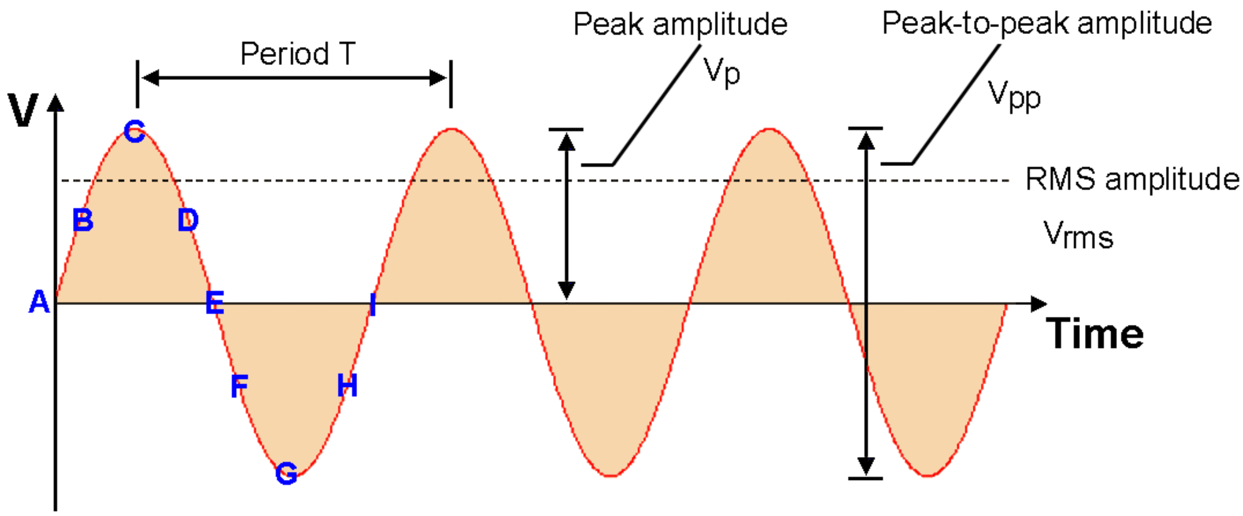

Electrons will always flow from the negative terminal to the positive terminal.
Its true that you can reverse the wires from a battery pack to a loco and train will go in the opposite direction. However, although the current is flowing through the motor in the opposite direction, the current itself is still flowing in the same direction between the battery terminals. The voltage from a DC supply may vary and the current flow may vary (either intentionally or through a battery weakening) but its polarity never reverses.

DC is used inside nearly all electronic apparatus, including industrial, domestic and hobby devices.
DC is used extensively in model railways for loco motors, LED lights, most point motors, DCC decoders and more.
Even devices that are connected to the mains use DC for their internal components (transistors, microchips, logic circuits, etc.). The incoming mains is converted from AC to DC as will be shown later.

# What is AC

With DC, the current flow is unidirectional; it always flows in one direction.
Alternating current (AC) is completely different.
If you could look at the two pins of an AC supply, you would see that the voltage is constantly changing, getting larger, then smaller then changing direction.
The image shows a *'figure of 8'* mains plug and below is a typical AC waveform, like the sine wave type you receive on your mains supply.


The illustration shows three complete cycles of the waveform as time passes and the stages of supplying current to a circuit during a single time cycle are:




- At the beginning **A**, there is no voltage difference between the pins, therefore no current will flow.
- As time passes, see **B**, pin 1 has a higher voltage than pin 2, so current will flow out of pin 1, round the circuit and back to pin 2.
- Later, at point **C,** pin 1 is at its greatest compared to 2, with maximum current flowing round the circuit.
- At point **D,** the voltage difference has started to decrease, with reduced current flow.
- At point **E**, there is again no voltage difference between the pins and no current flows.
- At point **F,** the voltage difference is ***reversed***. Pin 2 is now at a higher voltage than pin 1, Current will again flow in the circuit – but in the ***opposite*** direction.
- At point **G,** pin 2 is at its greatest compared to 1, with maximum current flowing in the circuit from pin 2 to pin 1
- The AC mains supply then reduces again, see **H**.
- At point **I**, there is again no voltage difference between the pins and no current flow.
- The same cycle starts all over again... and again... and again...

You may wonder why such a complicated system is used instead of normal DC.
AC is more efficient to generate and distribute and cheaper and more reliable. AC in the UK is supplied at 240 volts AC as the standard domestic mains supply. It is used directly, without any modification, to power your cooker, electric fire, incandescent light bulbs, etc.

## Frequency

The time taken to complete this cycle is measured in time as its *'period'*.
In the domestic supply for the UK, Australia, New Zealand, most of Europe, this cycle happens 50 times every second (60 times per second for the USA, Canada and parts of South America).
The number of times the polarity reverses is known as the *'frequency'* and is measured in *'cycles per second'* (CPS) or *'Hertz'* (Hz). So the UK mains frequency operates at 50Hz. That means that the mains goes through a complete cycle every 1/50$^{th}$ of a second – i.e. 20milliseconds. Consequently, the frequency = 1/ period.

# Voltage

The total movement from zero volts to full voltage in any direction is known as the *'peak amplitude'*, with the *'peak-to-peak amplitude'* measuring the total swing.

You will have noticed that AC power does not supply a constant voltage and current; it is constantly varying. We need some way to measure the effectiveness of the power. This is done by measuring the heating effect of AC compared to DC.

Obviously, 200 volts of AC would not produce the same heating effect as 200 volts DC. In fact, the equivalent heating effect of a sinusoidal waveform compared to DC is 0.707 of its peak value. This value is known as the *'root mean square'* or effective value and just written as RMS.

When you read that the UK household electricity supply is 240V, it is really saying that it is 240V RMS. It is providing the same heating value as if it was 240V DC.

**Note**

If we measure the mains voltage with a multimeter set on the AC range, we will read 240V, as the meter reads RMS values.
If we measure the same mains supply with an oscilloscope (which displays the actual waveform), we will see that the UK mains has a peak amplitude of 340V and a peak-to-peak amplitude of 680V.

The RMS voltage is 120V in the USA and Canada and 230V for most of Europe, Australia and New Zealand.
The UK voltage is also meant to 'harmonise' with EU standards but still supplies at 240 (being within the 230V ±10% rule).

As a quick method, multiply the RMS value by 1.414 to get the peak value, or multiply the peak value by 0.707 to get the RMS value.
So, for example, a 15V AC socket on the rear of your loco controller has a peak voltage of 21.21V.

The difference between RMS and the peak value becomes even nore important when we consider the mains voltage.
A mains supply of 240V RMS has a peak value of 339V!

# Analogue and digital

Electronic circuits operate with either analogue or digital signals and both can be found in use in model railways.

## Analogue

Also known as 'analog' in the US
A useful definition of an analogue signal is:

*"A nominally continuous electrical signal that varies in amplitude or frequency"*

Consider, for example, a simple loco controller with a potentiometer to control the output voltage. Turning the knob will result in an output between 0V and 12V – and every possible value in between. Depending on the pot's physical construction, and the steadiness of your hand, you could have an infinite number of outputs values.
The *'nominally continuous'* part means that after you set the loco speed, the output voltage will stay at that same level forever – or at least until you change the speed again.
Analogue technology is also widely used in audio devices such as a microphone, a tape recorder, a DJ's turntable, loudspeakers and headphones.

## Digital

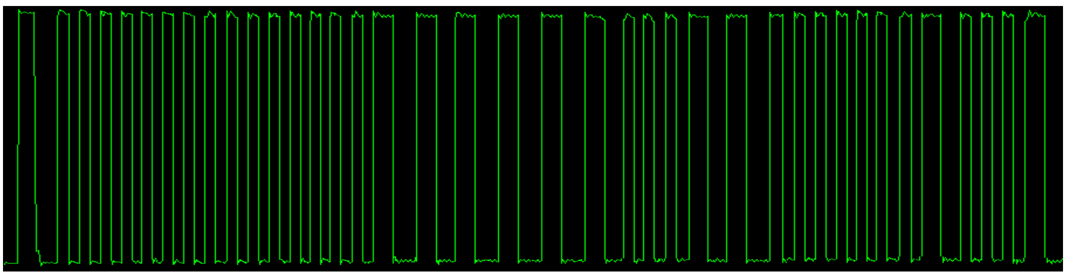
Digital technology takes a signal and converts it into a series of high and low voltages.
It has been around for a long time (Samuel Morse invented the Morse Code back in 1837) but has really taken off in recent decades. The supreme example must be computers, where every word, every picture, every sound or video clip is reduced to a long set of zeros and ones (i.e. OFFs and ONs).
Other domestic examples include digital radio, digital TV, CD players, etc.

Sometimes, we even have both at the same time. If you have broadband internet in your home, you probably are using ADSL technology (digital) on the same incoming telephone as your normal telephone calls (analogue as far as the exchange).

In model railways, digital signals are increasingly being used to enhance layouts.
Some examples are:

- Operating points using servos.
- Pulse width modulation (PWM) controllers to run locos.
- DCC controllers and locos fitted with digital decoders.
- The CBUS system to control accessories and traction.

The image below is the actual digital waveform from a DCC controller.



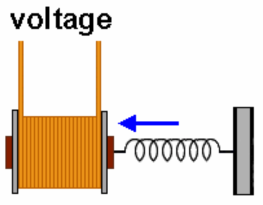
As you can see, the commands sent to the loco use a series of pulses and it is the pattern and length of the pulses that contain the information.

# Electro-magnetism

If you pass current through a wire, magnetic field lines are formed around it.
If the wire is formed into a coil, this effect is magnified and concentrated; you have created an electro-magnet with similar properties to a permanent magnet.
This is put to use in a huge number of appliances including shavers, doorbells, buzzers, etc.
In model railways, it was the basis of the majority of *'solenoid'* type electrically-operated points and for magnetic uncouplers.

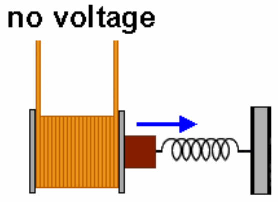
Let's look at some examples of electro-magnetism in action.

## How a solenoid works



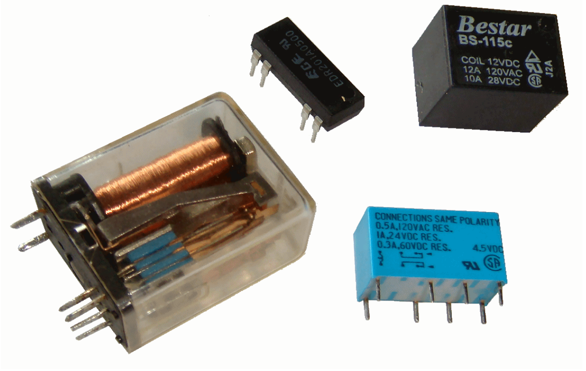

When the voltage is applied to the ends of the coil, the current flowing through the coil creates a magnetic field that pulls the metal rod into the coil. When the voltage is removed, the magnetic field dissipates and the spring pulls the rod back out of the coil.

Although a very simple mechanism, it can be found in many everyday appliances such as washing machines, dishwashers, car starters, door locks, electric typewriters, circuit breakers, chime type doorbells, vending machines, automatic tellers, etc.

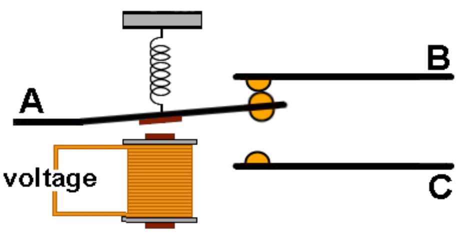



A variation is to have two coils – one that pulls the rod in one direction and another coil that pulls the rod in the opposite direction.
For model railways, it is the basic technique used in Seep and Hornby point motors (see later).

## How a relay works

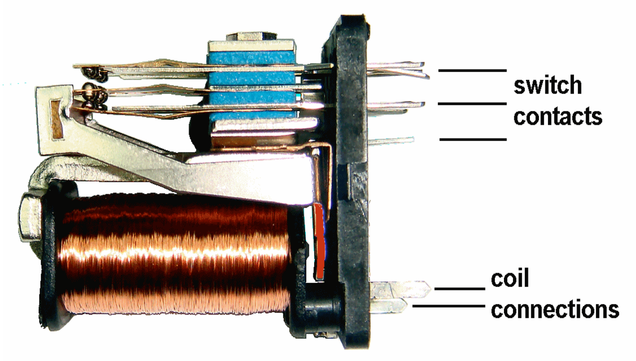



If the wire is wound round a metal core, the magnetic field is strengthened and this is the most effective way to create electromagnets.
A relay is just a switch that is operated by an electromagnet instead of your finger.
As the image shows, they are available in a range of different shapes and sizes, with different specifications for voltage and current handling and the number of switch contacts.




The illustration shows the principle of operation.
A voltage is applied to the ends of the coil and the current through the coil creates a magnetic field that attracts the small block of metal (called the 'armature') towards the coil. The armature is attached to the moving part of the switch and results in an electrical connection between switch contacts A and C.
Removing the voltage collapses the magnetic field and the moving contact is pulled back to its original position by the spring. If the relay is of a changeover type, there will be another contact (B in the illustration). In that case, contacts A and B are made when the relay is not energised.

This image shows a close-up of one of the relays. The moving part is L-shaped, with the longer section being used to move the switch contacts. The short section is close to the coil (shaded red just for the sake of clarity).
When the coil is powered, the shorter (red) section is attracted towards the coil and this forces the longer section to pivot upwards. This movement breaks the connection between the middle and lower contacts and the middle contacts now touch the upper contacts.
While some relays use a spring to return the armature when power is removed, this relay has its spring built in to the contact blades.




A main feature of relays is that there is complete electrical separation of input and output. This provides a number of advantages:

- A small current to energise the coil can result in large currents (say 5A) being switched.
- A small voltage across the coil (e.g. 5V) can result in higher voltages of 12V or even 240V being switched
- A relay can switch AC or DC.
- A relay can switch audio or data.
- A relay can have multiple contacts that switch at the same time.

The main disadvantages of relays are:

- Being mechanical, they can be quite large compared to other electronic components.
- Like all moving parts, they could be affected by dirt, rust, moisture, etc.
- They are slower to operate than electronic components.
- Some need more current than can be supplied directly be a module. This often means that they need extra components to interface relays to electronic circuits.

Relays are relatively cheap and are easily understood.
Although they don't need any special handling precautions (they are not prone to damage from static for example), they should always be used within their specifications.
The relay with the blue case shown in the earlier image is designed to be operated at 4.5V. While it will still operate happily at 5V, it should not be operated at a greatly higher voltage; the coil will overheat and burn out. On the other hand, the relay in the black cube is designed to operate at 12V. While it may still operate at a slightly lower voltage, too low a voltage will lead to unreliable operation.

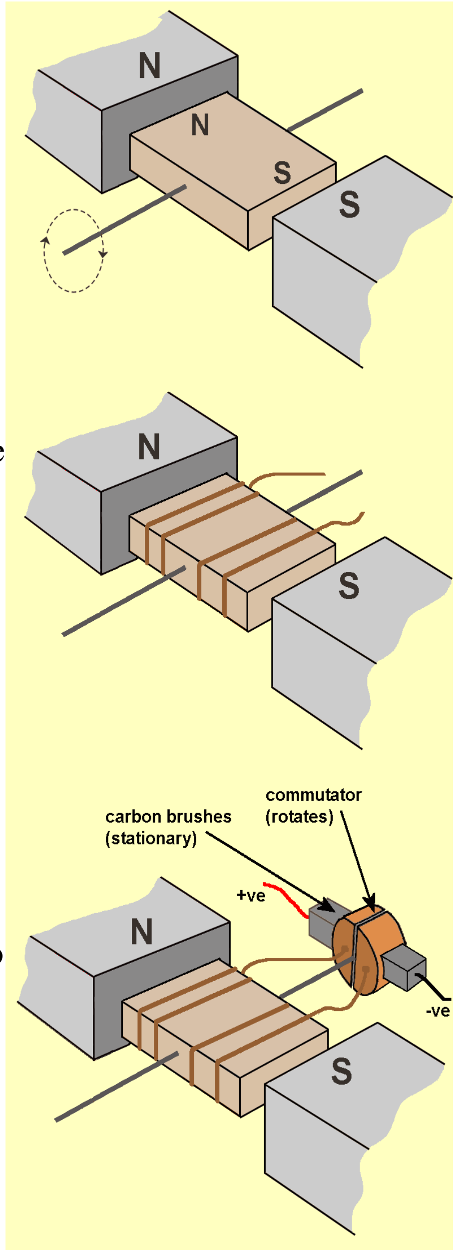
It is also best to avoid switching higher voltages or currents than the relay is rated for. This can easily lead to pitting of the contacts or even welding the contacts together.

Operating relays within their ratings usually provides many years of trouble-free operation.

In model railways, relays are used to great effect for section switching and frog switching (more later).

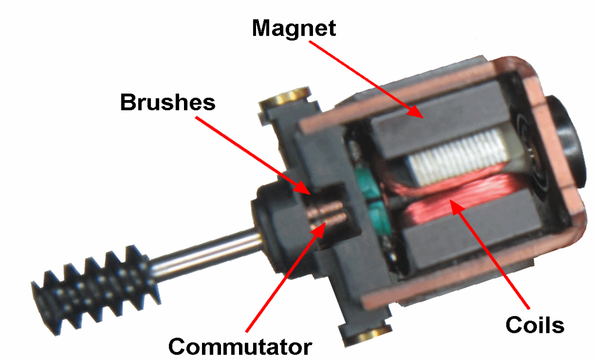
## How a motor works

The most common type of motor used in model railways is the *'Brushed DC motor'*. Although AC motors exist, they are mostly run at mains voltage for use in domestic and industrial appliances. A huge amount of research has gone into motor design but we can see how a simple DC motor works without delving too deeply into the physics of it all. These illustrations take us through the stages of creating a DC electric motor.




Everyone knows that if you try to place two magnets together with their North poles facing each other, the magnets will repel each. Similarly, if two South pole faces are placed close to each other. Opposites attract and likes repel.
In the first illustration, a magnet is fitted on a rotatable shaft and positioned between a pair of magnets.
Since the two magnet's faces have opposing poles, the middle magnet will be repelled and make a half rotation to align opposite poles.
The second illustration shows the middle magnet being replaced with an electromagnet (a coil wound round a piece of metal), usually called the *'rotor'*
When power is applied to the coil, it creates an electromagnet whose magnetic poles are identical to the magnet in the first illustration (i.e. N pole on the left, S pole on the right). This magnetic field results in the same 180° rotation (the N pole now has moved to the right-hand magnet). If the polarity on the coil is now reversed, the electromagnetic magnetic field would produce a magnetic field identical to the first field, the N pole is once again on the left-side – and the rotor will again spin 180°.

Since the rotor is continually turning, the power to the coil is fed as shown in the third illustration. The coil is wired to separate sections of a *'commutator'* which rotates along with the rotor. It has conductive sides, usually copper, and a bar of carbon is held in touch with each of the copper areas. These brushes are connected to the DC supply.



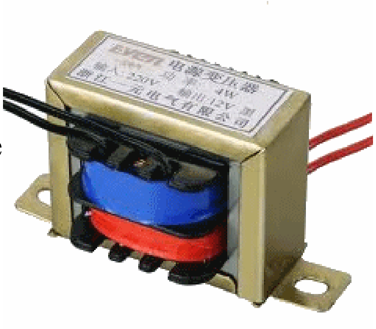

So, as the rotor spins, the voltage being fed out of the commutator into the coil is reversing regularly. This ensures continual rotation while the power is switched on.

The image shows an actual DC motor.
A motor may have multiple windings (3-pole, 5-pole or 7-pole) and multiple segments on the commutator, to ensure the smoothest rotation with maximum torque.

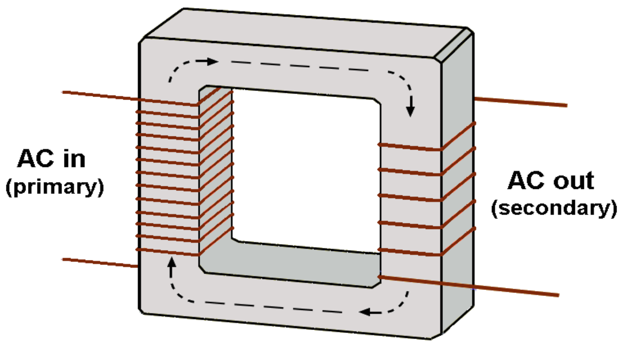
## How a dynamo works

The dynamo is basically a motor being operated in reverse.
With the motor, movement was created by passing current through a coil.
With a dynamo in a circuit, current is created by passing a coil through a magnetic field.
So, if you take a DC motor and manually rotate its shaft, a DC output can be taken from its brushes.
Current is only generated by the movement of the coil through the magnetic field; stop rotating the shaft and the current will stop; turn the shaft faster and a greater current will be generated.

## How a transformer works



A transformer takes an AC voltage input and produces an AC voltage output.
Sometimes the transformer is wired to produce an output voltage that is the same as the input voltage. This is called an *'isolation transformer'* as the device connected to the output has no direct connection to the mains supply. This helps minimise electric shocks and unwanted electrical interference.




Many domestic devices, including model railways, run on much smaller voltages than the 240V mains supply.
In these cases, the input is still at 240 volts but the output has to be wired to produce a much lower voltage (typically 6V, 12V, or 15V).

The illustration shows the basics of a transformer. There are two coils of wire wrapped round an iron core.
The input voltage is fed to the *'primary'* winding and the constantly varying voltage (in both amplitude and direction) results in a constantly varying magnetic flux around the core.
The varying magnetic field then produces an AC voltage on the output coil, the *'secondary'*.
Its like an electromagnet (on the primary) and an alternator (on the secondary) sharing the same iron core.

The actual output voltage depends upon the *'turns ratio'* of the coil on the secondary compared to the primary. If the two coils had the same number of turns, the output voltage would equal the input voltage (ignoring any losses).

Transformers can be *'step-up'* or *'step-down'* types. Step-up transformers have more turns on the secondary and are used to produce the high voltages used in the old cathode-ray-tube TV sets, and in car ignition systems.

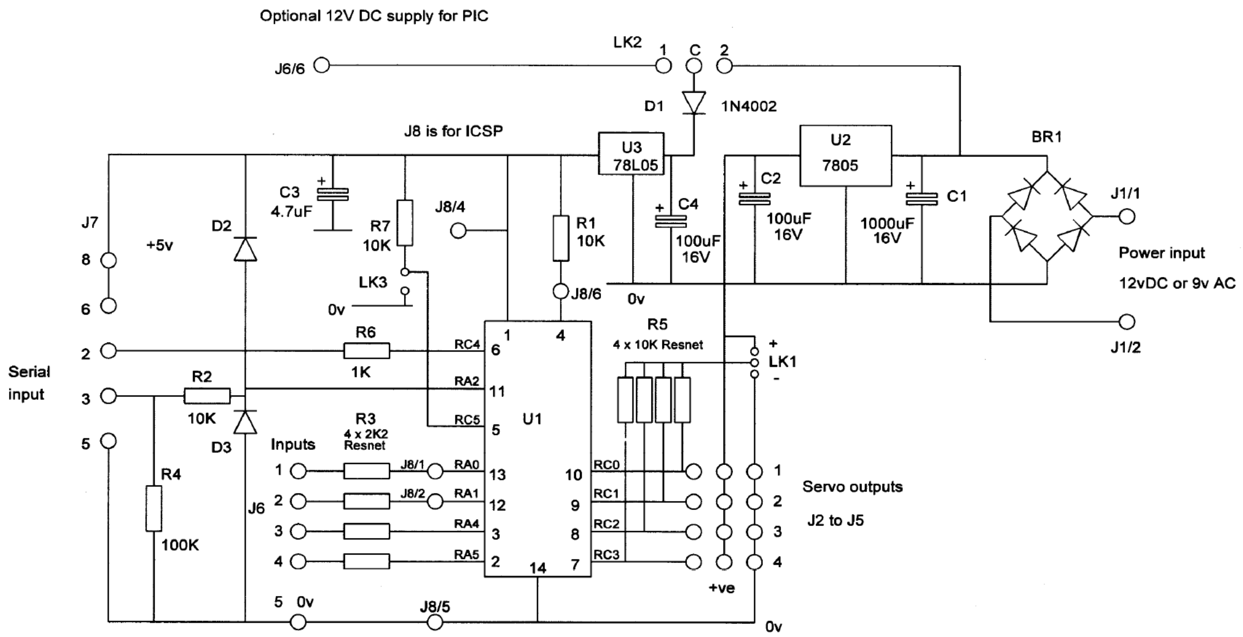
For model railways, we use step-down transformers. So for example, if we wanted a 12 AC output, the transformer secondary would only have a single turn for every 20 on the primary. The 1:20 ratio would result in a 240V input producing a 12V output.

Since a transformer has an AC output, it has to be converted to DC for use by most devices.

# Reading circuit diagrams

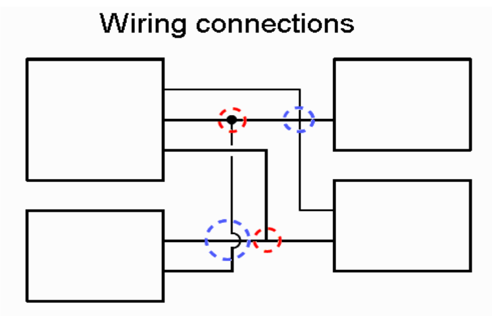
When a project is being designed, it is all about what components to use and how they should be connected together. This might be done by scribbling on a piece of paper or might be achieved through sophisticated software.
Either way, the result is a *'circuit' diagram'* or *'schematic'*. This does not try to show how the project would look when built – just a guide to what connects to what. This allows someone to see how the stages of a circuit work and trace inputs and outputs.
The working project is then developed, showing the printed circuit board tracks and where components sit on the board. This layout is used when constructing a kit.

Circuit diagrams can often be overwhelming at first sight, with lines darting all over the page. Here is an example of a module that is used to control four servo motors.



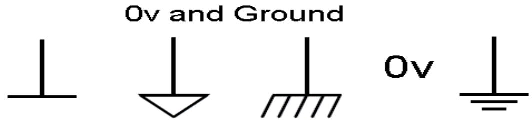

Before looking at individual components and their symbols, it is useful to know that there are different ways of indicating the same thing. Although we will look at various options, it soon becomes clear which symbols are being used on a particular diagram, as they are not mixed on any one diagram.

## Wiring symbols




The illustration show four devices that are wired together. Some wires are connected to each other, while others cross each other without connecting. The red circles show two ways of connecting wires together (you will see both being used in magazines). In the top example, a blob is used to show that they connect to each other, while the other example shows wires connecting at a 'T' junction to indicate that they connect.
The blue circles show two ways of wires crossing each other. In the lower example, one wire 'humps' over the other, while the other two simply cross over. Just below the upper red circle, the wire seems to 'break' and this is just another way of showing that the wires cross each other without connecting.

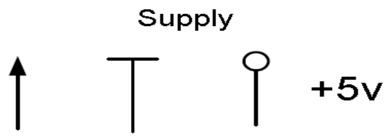
## Ground symbols



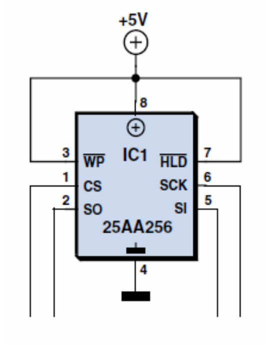

This illustration shows different ways of showing the common 0V point in a circuit, as many components often have one leg wired to 0V.
This is used as a common reference point for taking voltage readings (e.g. a pin on a chip may be 3V positive with respect to ground).
Most diagrams show the 0V line along the bottom of the diagram, with the +ve line along the top.
The diagram on the previous page just used the inscription “0V” to indicate the 0V line. The other symbols may also be found in diagrams, depending on how old the diagram is or whether it a UK or US circuit. Some circuits simply use the inscription “Gnd” to indicate the 0V line.
The symbol on the far right is the *'Earth'* symbol which is sometimes used, although it dates back to a time when the connection was physically taken to real earth by burying a metal rod in the ground. If you look at component C3 on the top left-hand side of the diagram on the previous page, you will see that one end goes to the positive supply (see the +5V) and the other goes to the first symbol in the illustration (the *'Circuit Ground'*). This just means that one end of the resistor is connected to the 0V line. It saves having to draw the line all the way down to the horizontal 0V line and thus makes the diagram look less cluttered.

The second symbol from the left is that of the *'Signal Ground'*. This is the common return line for any signals travelling along the circuit. Often, this is used in the same way as the first symbol.
The third symbol from the left is that of the *'Chassis Ground'*. This is a common point for components using the metal chassis of a device. It is often at 0V but not necessarily so.

## Power symbols

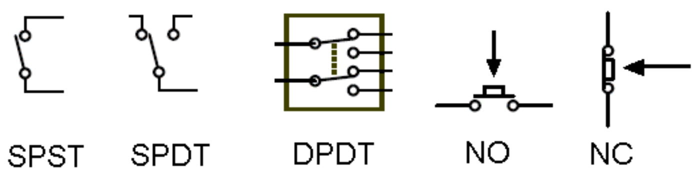



In the same way as you can simplify the drawing of a diagram by using symbols for ground, there are various symbols that indicate the supply voltage, whatever level that may be.




The diagram on the previous page used +5V to indicate the positive 5V supply line.
The three symbols shown are also used to indicate that the connection should be taken to the positive supply line.
This snippet from a circuit shows both the supply and ground symbols being used.

## Switches




The symbols shown are for three varieties of lever switch and two push buttons.
SPST stands for *'single pole single throw'*. It has two terminals that are connected together when the switch is operated. The 'pole' indicates how many moving wipers are in the switch, while 'throw' indicates how many contacts the wipe can connect to. In this case, it is a single wiper that can either be connected to the other terminal or not – a simple ON-OFF switch.

The SPDT switch stands for *'single pole double throw'*, so the one wiper can touch two possible terminals depending on which direction the switch lever is operated – a changeover switch.
A variation on the SPDT switch is the SPCO variety. It stands for *'single pole centre off'* and this switch can be moved to one of three positions. In the middle position, the wiper touches neither of the terminals.
The DPDT switch stands for *'double pole double throw'* and is really two SPDT switches in the one switch body. It has two input terminals and four output terminals. The dotted line indicates that both wipers move at the same time.

The NO pushbutton stands for *'normally off'*. The two terminals are only connected to each other when the button is pressed.

The opposite type is the NC pushbutton. It stands for *'normally connected'* so the connection is broken when the button is pressed,

## Electronic components

Most of these components are covered later.
In the meantime, here are their symbols.