RESISTANCE, RESISTIVITY AND RESISTORS

A Companion to Books 3-8

RESISTIVITY

RESISTIVITY

The resistivity of a substance reflects how difficult it is to make current flow through the substance. It is *scale-invariant* the resistivity does not depend on the size of the sample.

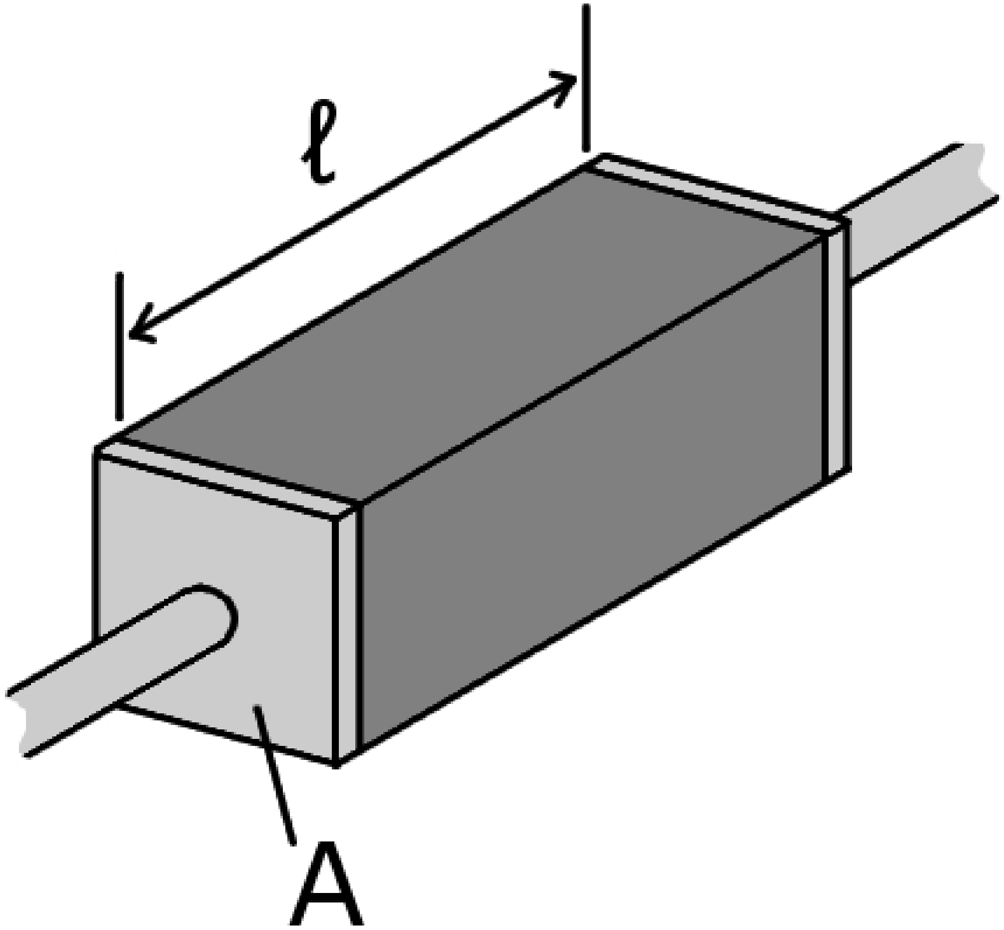
Resistivity has the symbol ρ, and units of **Ωm** (ohm-metres). It is described by:

$$\rho = \frac{E}{J}$$

Where E is the electric field strength (V m^{-1}) and J is the current density (A m^{-2}). The resistivity is used in the resistance formula:

$$R = \frac{\rho l}{A}$$

Where R is the resistance (Ωm), l is the length of the conductor (m), and A is the conductor area (m^2).



RESISTIVITY - EXAMPLES

Silver: 1.59×10^{-8} Ωm (best conductor)

Copper: 1.68×10^{-8} Ωm

Gold: 2.44×10^{-8} Ωm

Aluminium: 2.65×10^{-8} Ωm

Tungsten: 5.6×10^{-8} Ωm

Iron: 9.70×10^{-8} Ωm

Nichrome: 1.10×10^{-6} Ωm

Carbon: 5×10^{-4} Ωm

Germanium: 0.46 Ωm

Silicon: 640 Ωm

Glass: 10^{11} to 10^{15} Ωm

PVC: 10^{12} to 10^{15} Ωm

Hard rubber: 10^{13} Ωm

Air: 10^{9} to 10^{15} Ωm

Sulphur: 10^{15} Ωm (best solid element)

Fused quartz: 7.5×10^{17} Ωm

PET: 10^{21} Ωm

Teflon: 10^{23} to 10^{25} Ωm

TEMPERATURE COEFFICIENT OF RESISTIVITY (TCR)

The temperature can affect the resistivity of a substance.

Pure metals usually have a *positive* TCR. These are referred to as PTC (positive temperature coefficient).

Poor conductors (e.g. carbon) tend to have little dependence on temperature or a slight NTC characteristic.

Some materials are specially designed to have a certain temperature coefficient.

NTC materials can be used as temperature detectors.

PTC materials can be used as “self regulating heaters”.

Materials with a stable resistance with temperature are useful for heating elements. Nichrome is an example.

TCR - EXAMPLES

Silver: 0.00380 K^{-1}

Copper: 0.00404 K^{-1}

Gold: 0.00340 K^{-1}

Aluminium: 0.00390 K^{-1}

Tungsten: 0.00540 K^{-1}

Iron: 0.005 K^{-1}

Nichrome: 0.0004 K^{-1}

Carbon: −0.0005 K^{-1}

Germanium: −0.048 K^{-1}

Silicon: −0.075 K^{-1}

Temperature coefficients of resistivity only really apply in this way for conductors and some semiconductors (e.g. silicon, pictured below).

TCR CALCULATIONS

Metals have a TCR that is given as a *linear approximation.*

The TCR is given by α (alpha).

For example, copper has a TCR of 0.00427 K^{-1} (or $°C^{-1}$) at 0°C.

A 1 Ω resistor made of copper will have a resistance of 1.00427 Ω at 1°C, through 1.427 Ω at 100°C.

Beware: α depends on the base temperature.

The general formula is:

$$R_2 = R_1 \frac{1 + \alpha_0 \, (T_2 - T_0)}{1 + \alpha_0 \, (T_1 - T_0)}$$

Where R_1 is the temperature at T_1, and α_0 is the TCR at temperature T_0.

If $T_1 = T_0$, then the equation reduces to…

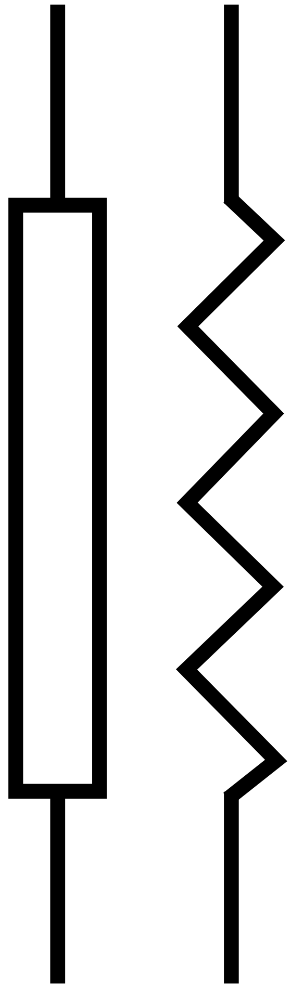
$$R_2 = R_0(1 + \alpha_0 \, (T_2 - T_0))$$

RESISTORS

RESISTOR SYMBOLS

There are two common resistor symbols: the IEC symbol (box), and the American version (squiggle).

The version may vary in different information sources.



RESISTORS

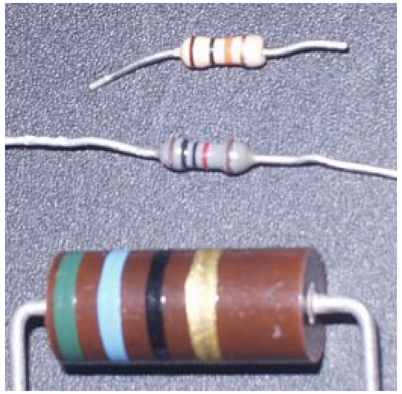
Resistors come in different types, dependent on a few factors, but the most important factors are

Voltage rating

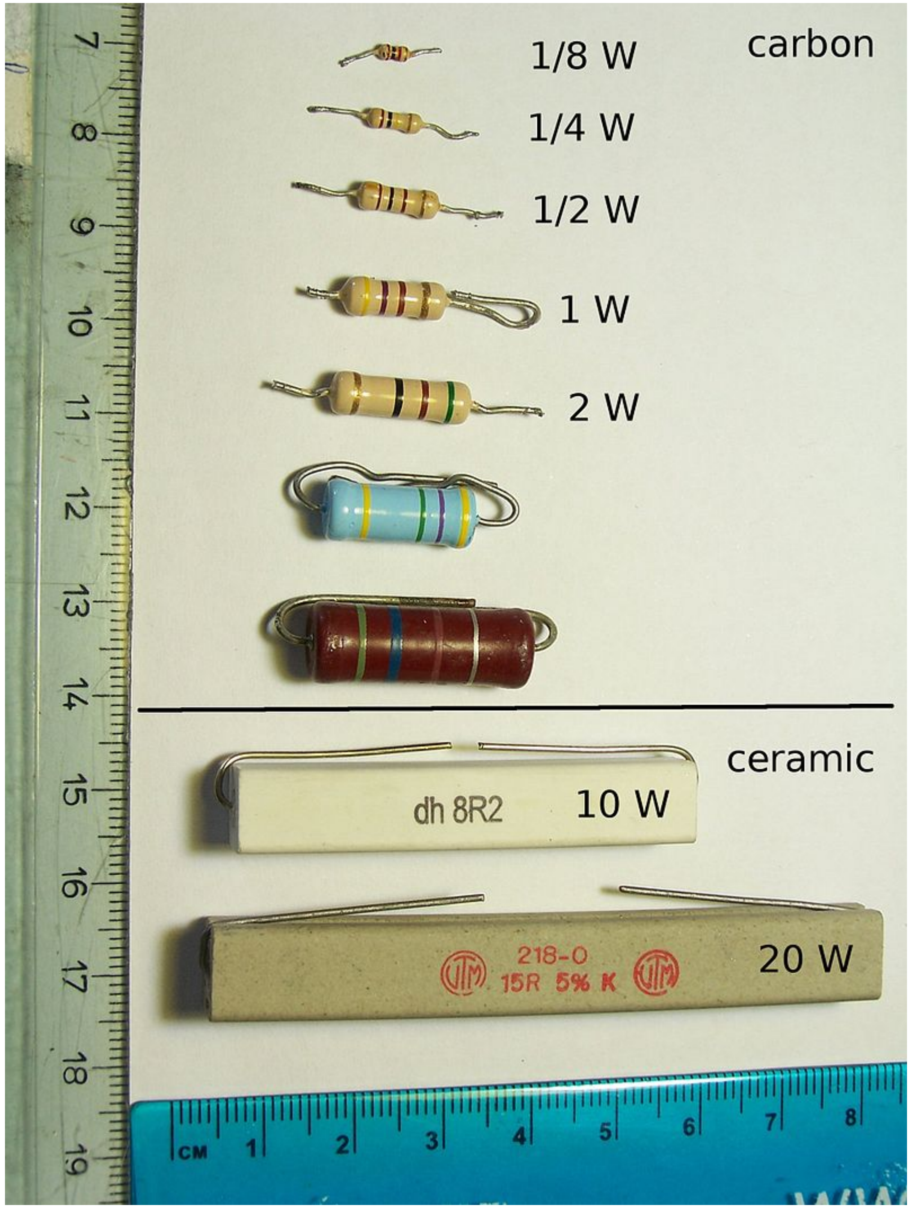
Power rating

Tolerance

Packaging



Resistors are manufactured with resistances of ~0.001 Ω to ~100 MΩ.



RESISTOR VALUES

Resistor values may be written directly e.g. 1.5 MΩ.

They may also use the prefix as the decimal point, or R if there is no prefix required.

Small resistors use a colour code or a number.

Examples

3.3 MΩ ⟺ 3M3

1.5 kΩ ⟺ 1k5

10 kΩ ⟺ 10k

4.7 Ω ⟺ 4R7

0.27 Ω ⟺ 0R27 or R27

103 ⟺ 10 kΩ

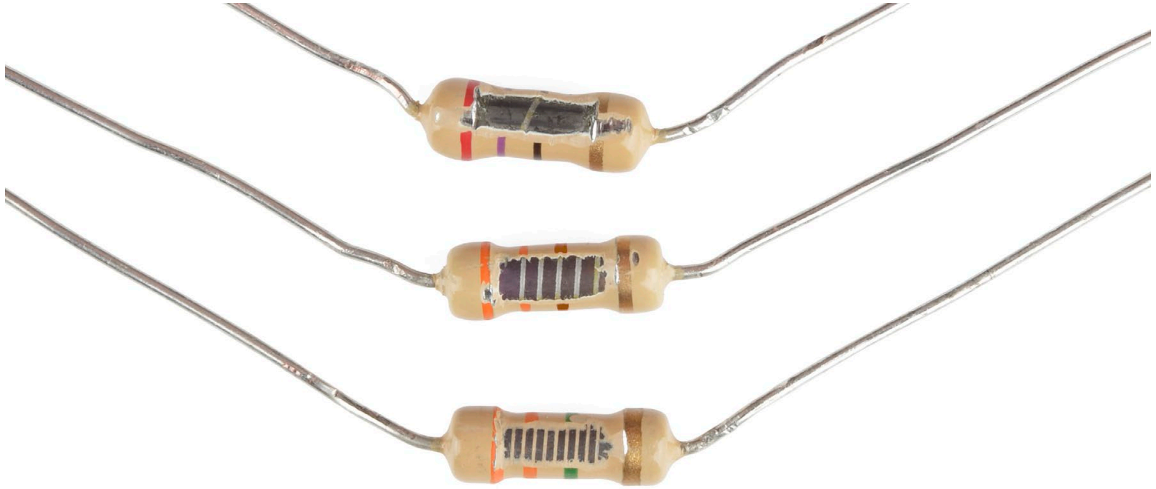
220 ⟺ 22 Ω

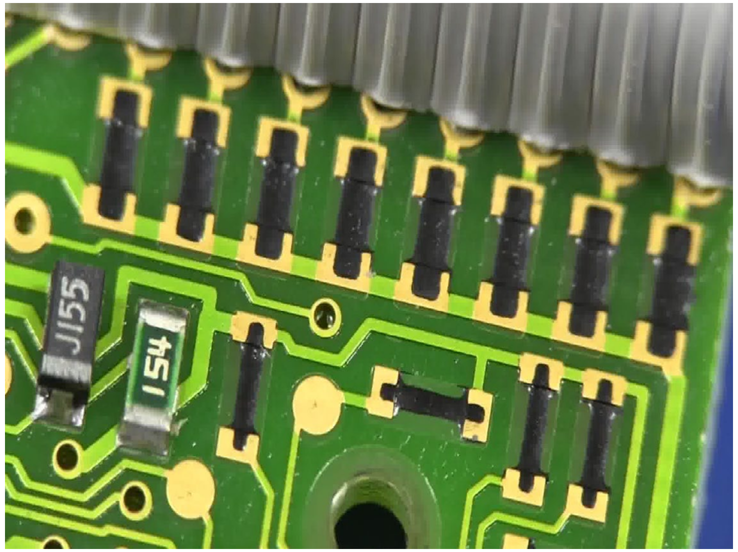
RESISTOR EXAMPLES

FILM RESISTORS

Film resistors consist of a layer of resistive material deposited on a surface. The film may have a spiral cut into it to achieve the desired resistance.

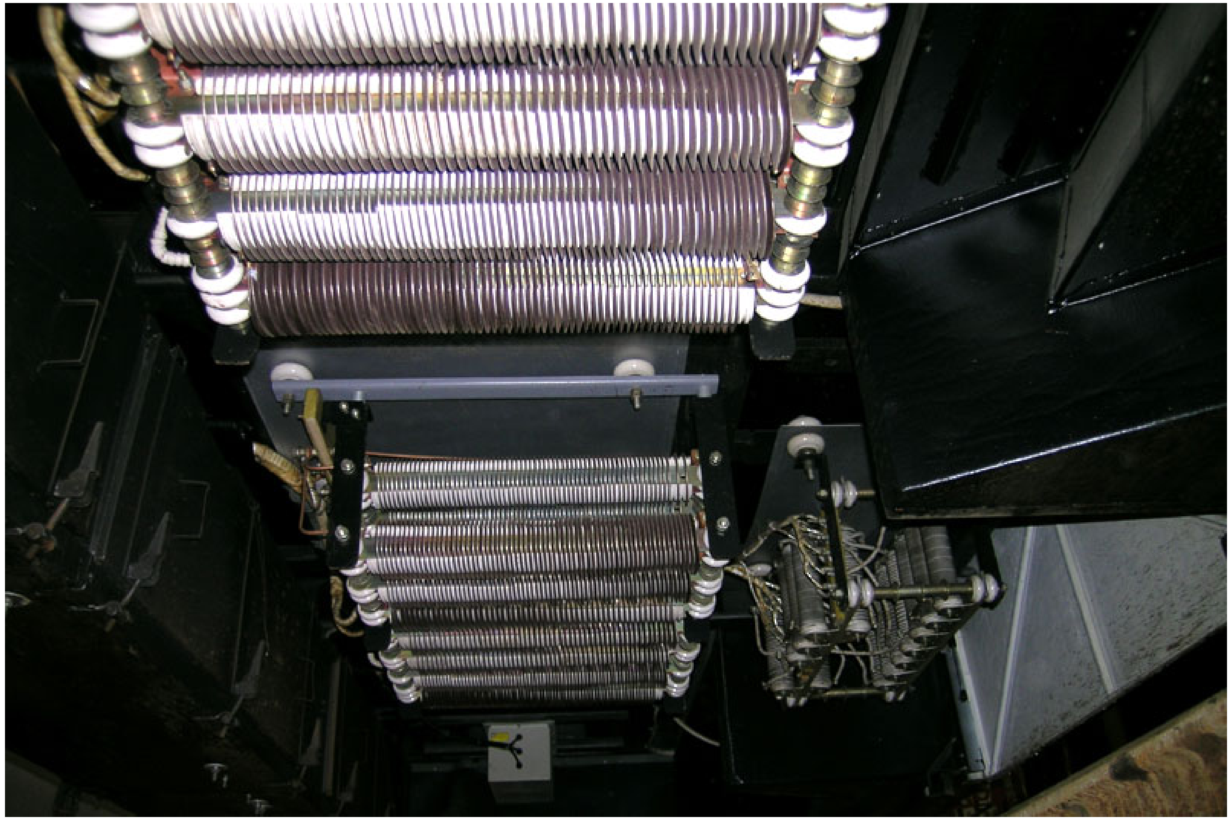
The most common types are carbon film and metal oxide film.





WIRE-WOUND RESISTORS

Wire-wound resistors consist of a length of nichrome resistance wire. They have higher power dissipation than film resistors.

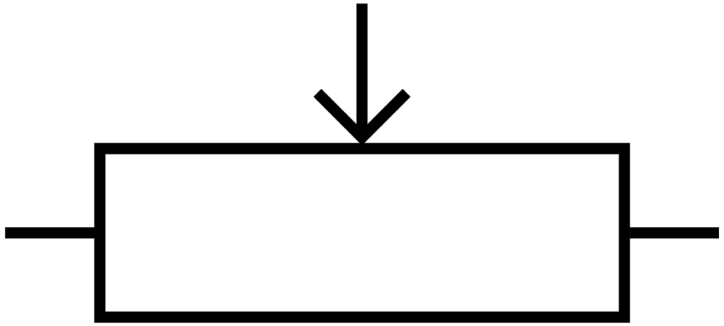


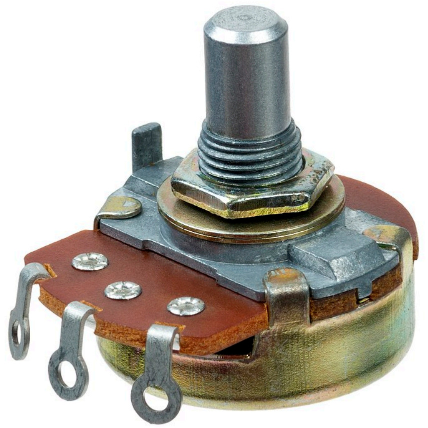
VARIABLE RESISTOR

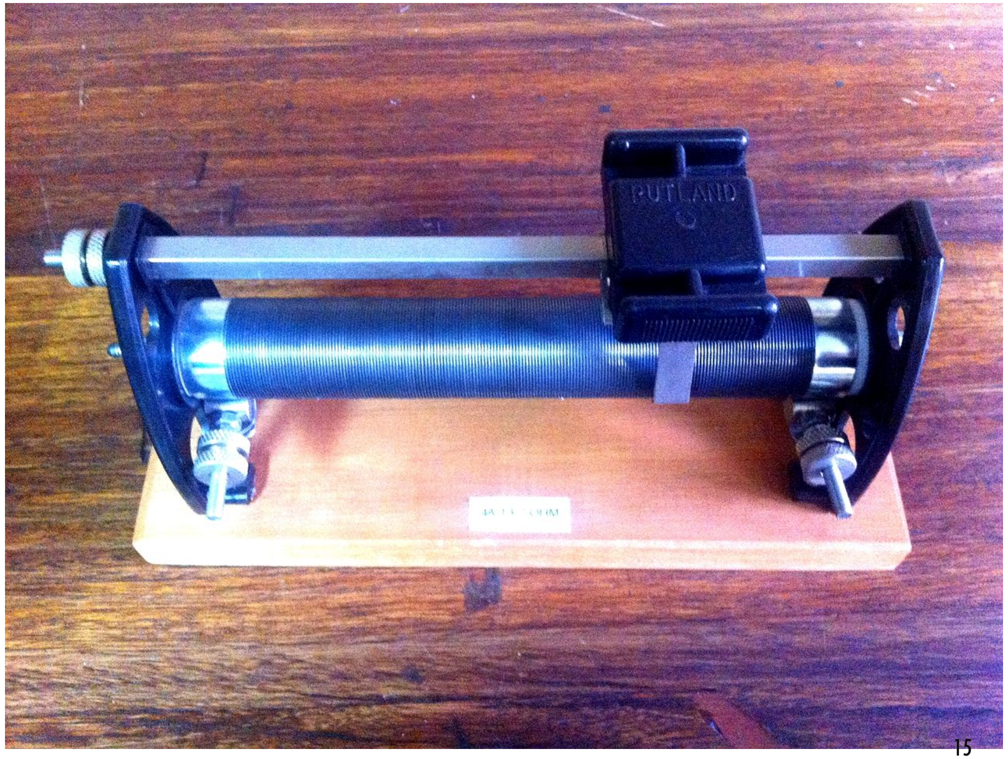
Sometimes referred to as a potentiometer, or pot.

Used to adjust the behaviour of circuits.

Widely used in light dimmers, volume controls etc. Symbol shown below.







SPECIAL-PURPOSE RESISTORS

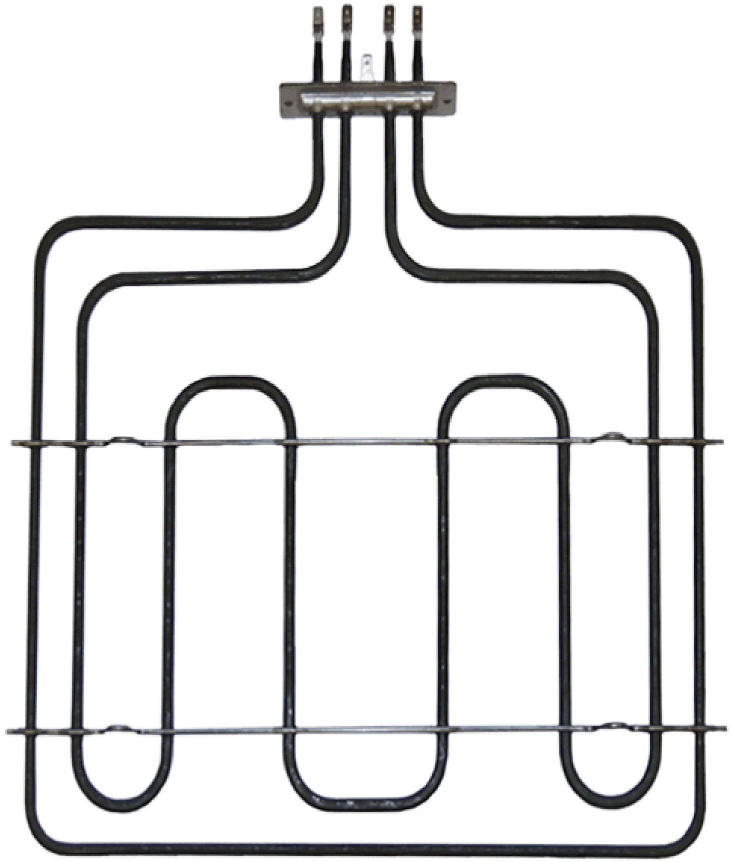
Resistors generate heat – sometimes this is not wanted. Other times, it's what we want resistors for.

OVEN ELEMENT

Used to heat the inside of an oven.

Rated 1500-2500 W.

The resistance wire is inside the outer metal cladding.



BURNER "RING"

For use on a stove top.

Rated 1000-2000 W.

The resistance wire is inside the outer metal cladding.

JUG ELEMENT

Main application: boiling water.

Rated 1500-2400 W.

The resistance wire is inside the outer metal cladding.

HOT WATER CYLINDER ELEMENT

Used for heating water in a hot water cylinder.

Rated about 3 kW, though no real upper limit on size.

The resistance wire is inside the outer metal cladding.

TOASTER ELEMENT

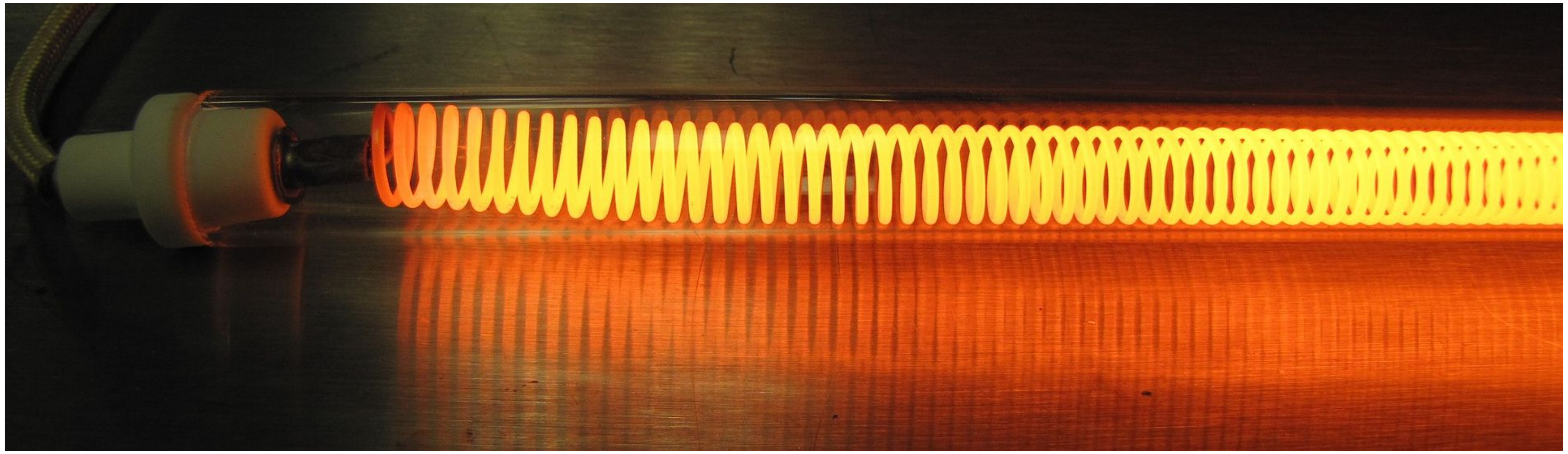
Consists of metal strap resistance wire on a mica former.

Toasts bread by infra-red radiation.

Rated about 2000 W.

RADIANT HEATER

Uses a filament to provide radiant heat directly. The element may be bare or enclosed in an aluminium oxide or fused quartz tube.



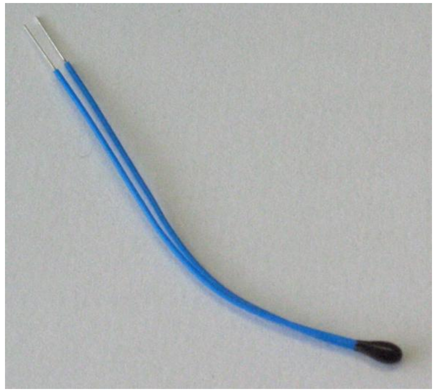
NON-LINEAR RESISTORS

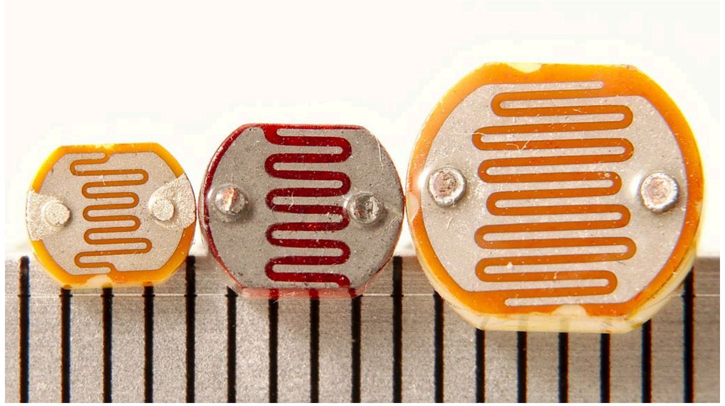
INTRODUCTION

Non-linear resistors have properties that depend on factors like applied voltage – or external factors like light or temperature.

These devices have specifically tailored properties.

Pictured (clockwise from top): thermistor, light dependent resistor, varistor.





LIGHT DEPENDENT RESISTOR

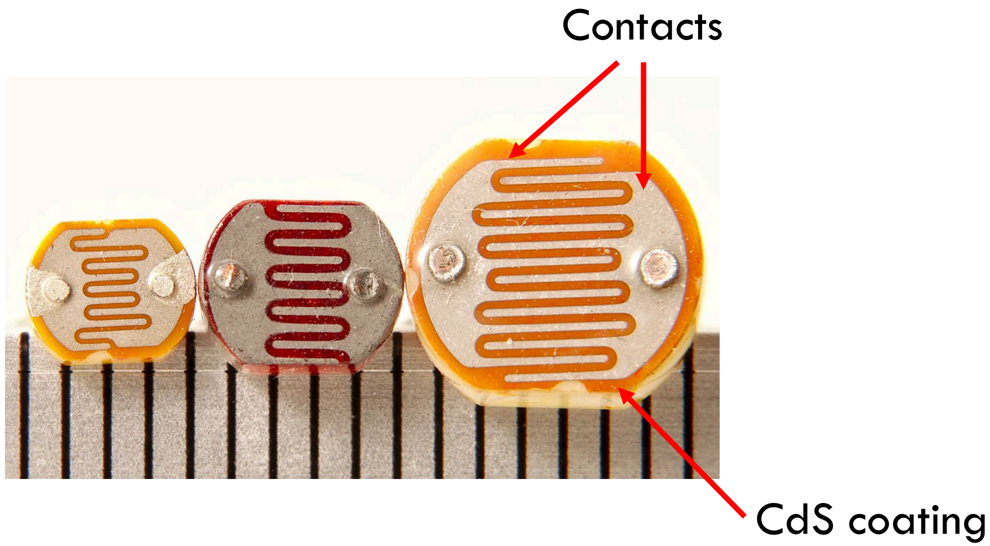
INTRODUCTION

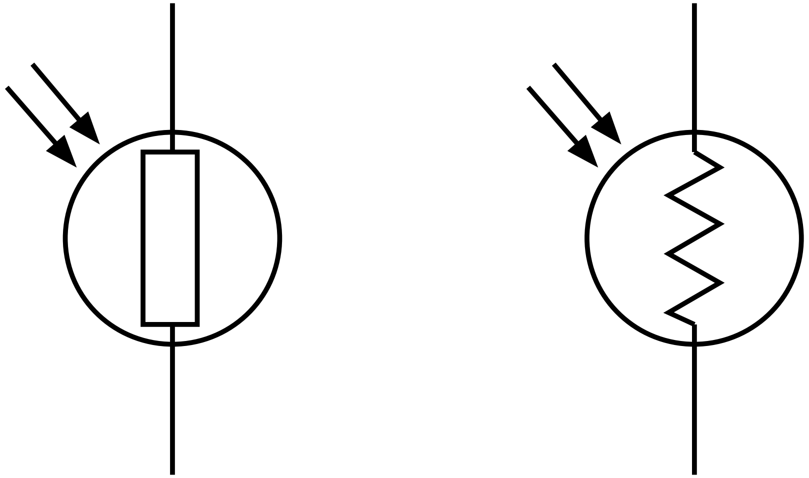
Light dependent resistors change their resistance in response to applied light.

The resistance when dark (<0.1 lux) is usually in the 100s of kΩ to MΩ range. The resistance when light (>100 lux) is usually a few kΩ or less.

The LDR consists of metal contact "fingers" each side of a region of cadmium sulphide (CdS). The resistance of the CdS area depends on the applied light.

The symbol is shown on the right.



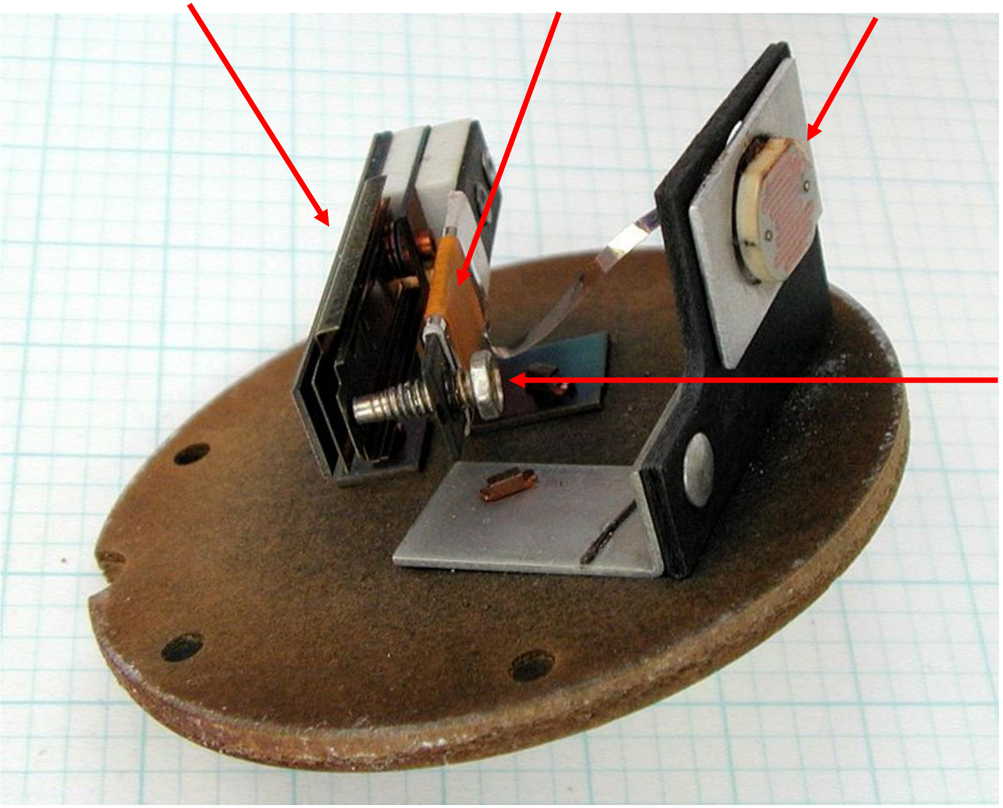


APPLICATION – STREETLIGHT CONTROLLER

The device on the right is a streetlight controller. When light, the LDR allows current to flow through the heating coil, allowing the heater to heat the bimetallic strip and turn off the streetlight.

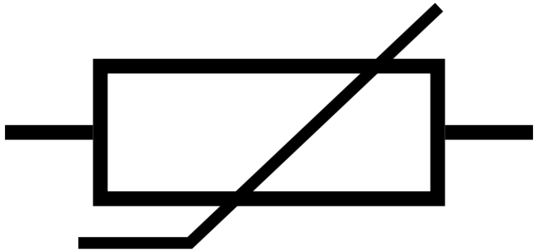
When dark, the LDR prevents current flow, the bimetallic strip cools and "relaxes", and the contacts to the streetlight close, turning the streetlight on.

LDRs are also used with electronics to achieve similar light sensing outputs e.g. security lights that are designed to not operate during the day.



THERMISTORS

THERMISTORS



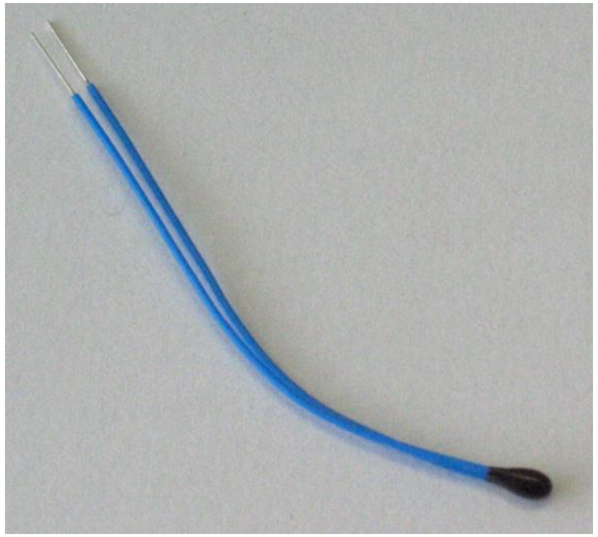
Thermistors come in two types: NTC and PTC.

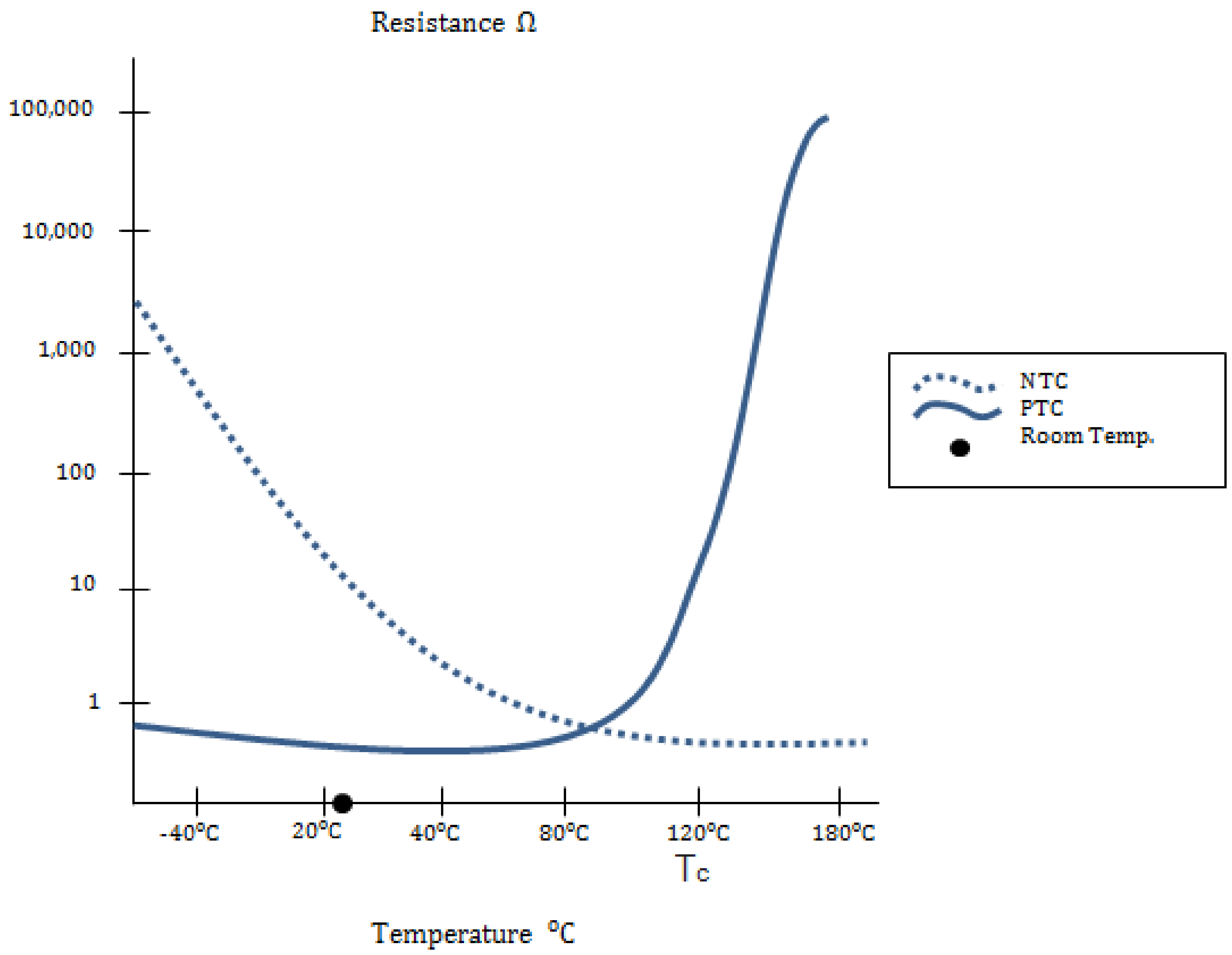
NTC thermistors have a resistance that goes down with temperature.

PTC thermistors have a resistance that goes up with temperature.

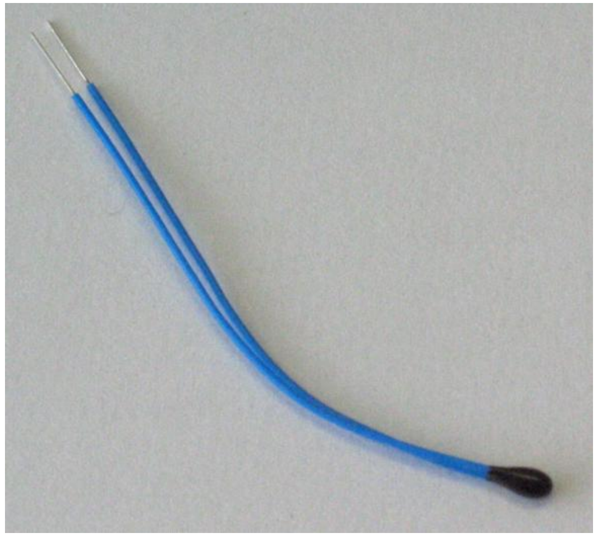
Thermistors can be used as sensing or power devices.

A common sensing thermistor has a resistance of 10 kΩ at 25°C.




Resistance Ω
100,000
10,000
1,000
100
10
1
-40°C
20°C
40°C
80°C
120°C
180°C
Tc
Temperature °C
NTC
PTC
Room Temp.

NTC APPLICATION – TEMPERATURE SENSOR

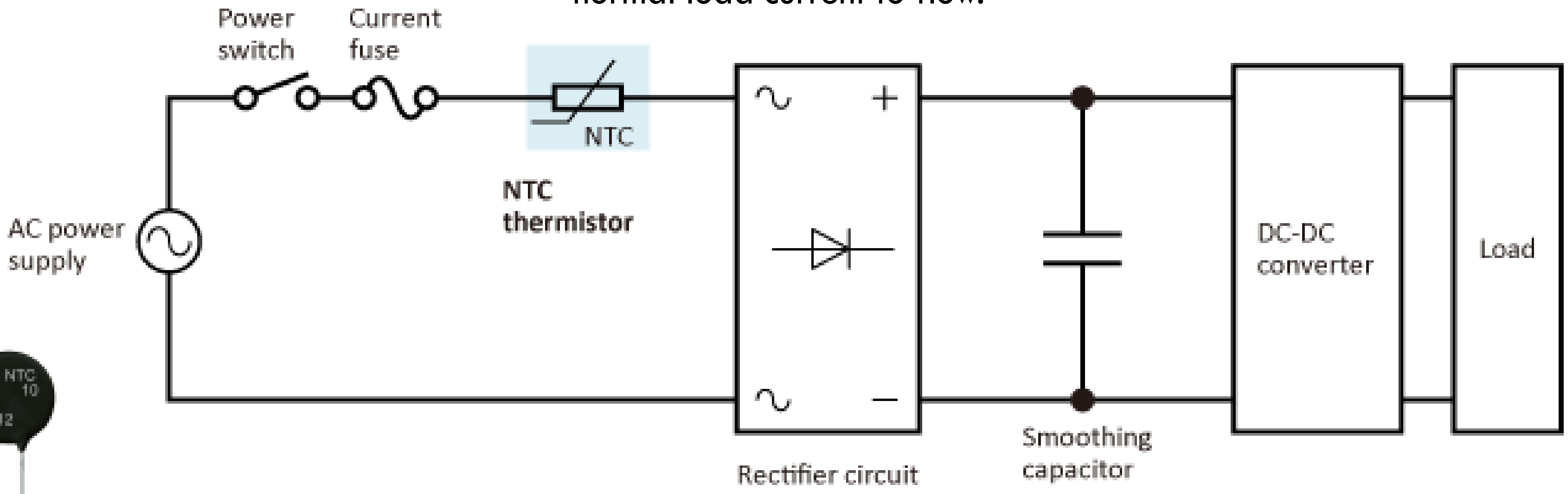


A common type of temperature sensing thermistor has a resistance of 10 kΩ at 25°C. They cannot switch loads themselves, but they are used with sensors.

They are often sold with pre-terminated leads.

NTC APPLICATION – IN-RUSH LIMITER

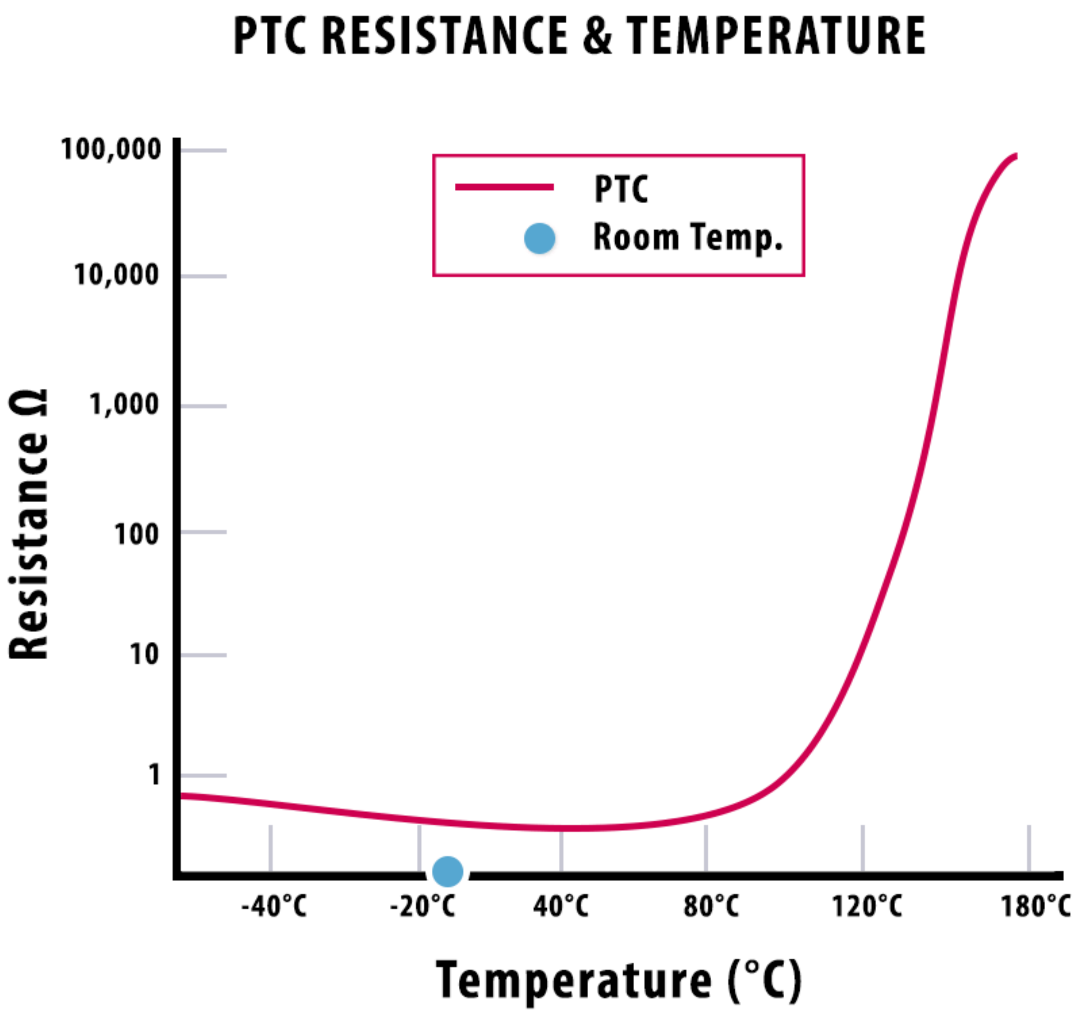
The NTC thermistor has high resistance when cold, then as load current flows the NTC thermistor's resistance decreases and that allows normal load current to flow.



PTC THERMISTORS

PTC thermistors have low resistance at low temperatures, and higher resistances at high temperatures.

The curve at right shows a PTC thermistor that will suddenly transition into a high resistance state.

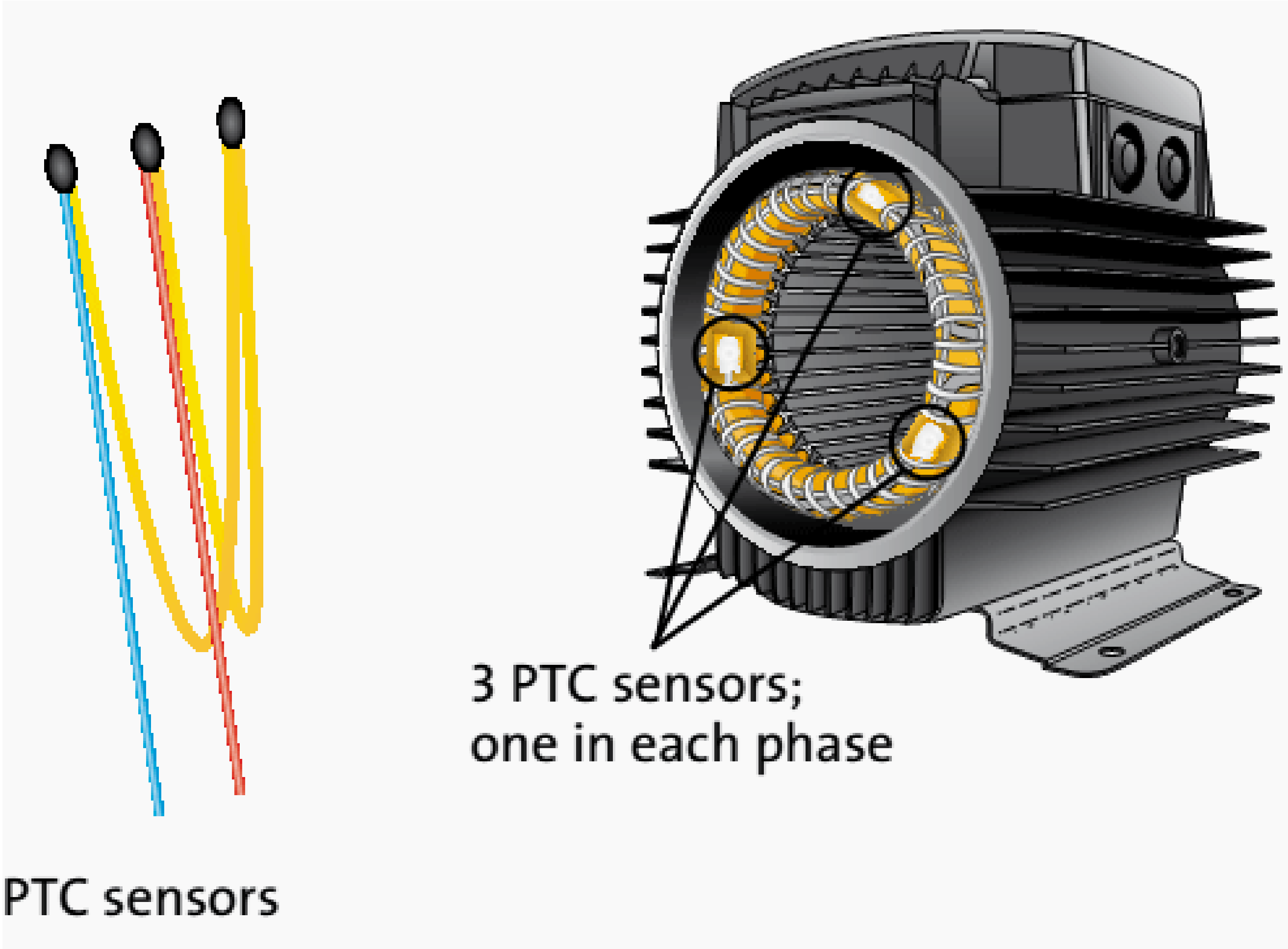


PTC APPLICATION – MOTOR WINDING PROTECTOR

PTC thermistors are used to protect motor windings from damage.

The thermistors are connected to a relay that senses their resistance, and when a resistance of about 3000 Ω is reached, the pilot relay triggers a thermal overload signal.

The thermistor transition temperature is selected to suit the motor e.g. 3000 Ω at 160°C.



PTC APPLICATION – SELF-REGULATING HEATER

The PTC thermistor has low resistance when cold. This causes current to flow, and the device to heat.

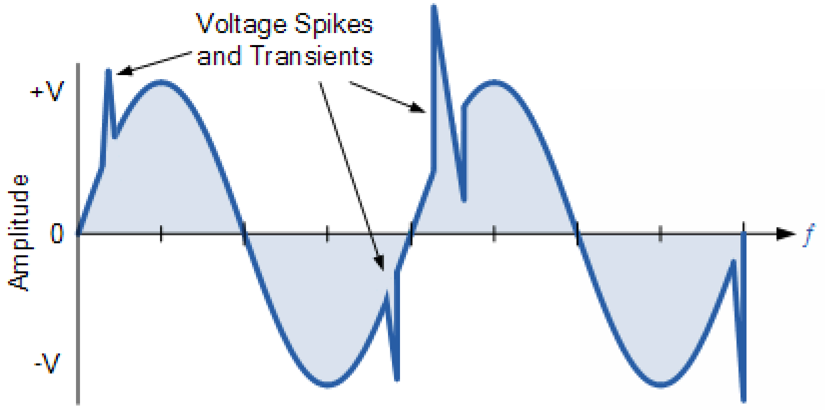
PTC heaters are designed to “flip” to a high resistance state at a certain temperature.

The lowered current reduces the heat output. A point will be reached where the current flow maintains the temperature.

The temperature can be tailored by changing the PTC material.

VOLTAGE DEPENDENT RESISTOR

INTRODUCTION



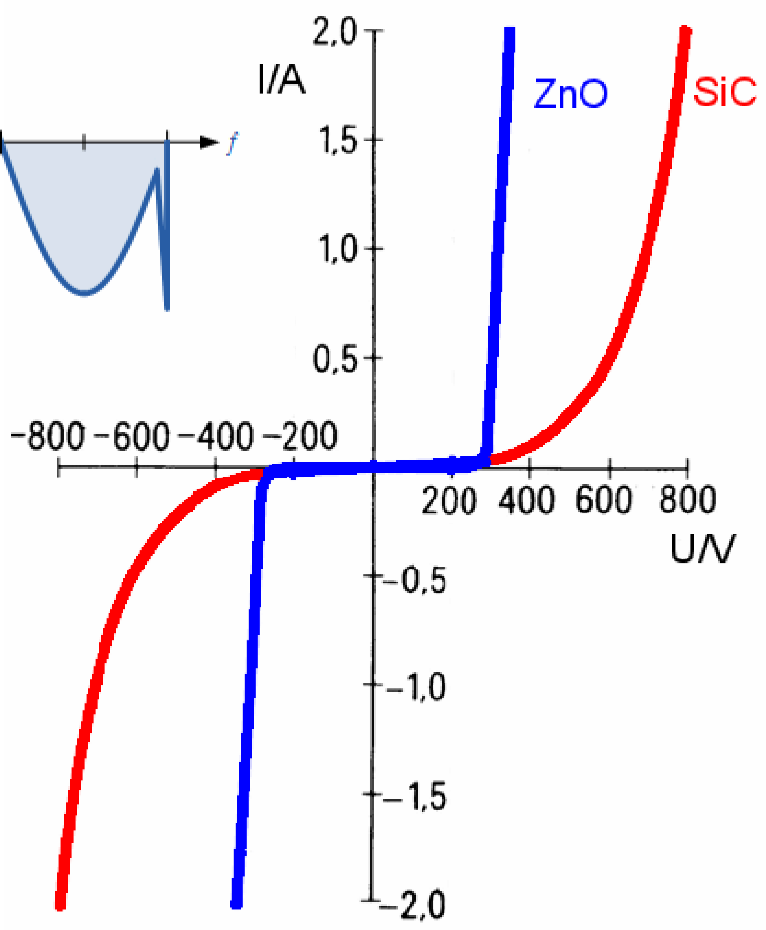
VDRs, or varistors, have a high resistance until a critical "knee point" or "breakover" voltage, where their resistance drops.

VDRs are widely used to protect electronic equipment against surges.

The chart on the left shows some example transients on the mains supply.

The chart on the right shows the current/voltage behavior of two types of varistors: zinc oxide (ZnO), and silicon carbide (SiC).

VDRs have a watt-second (or joule) rating which gives the maximum amount of energy they can absorb.

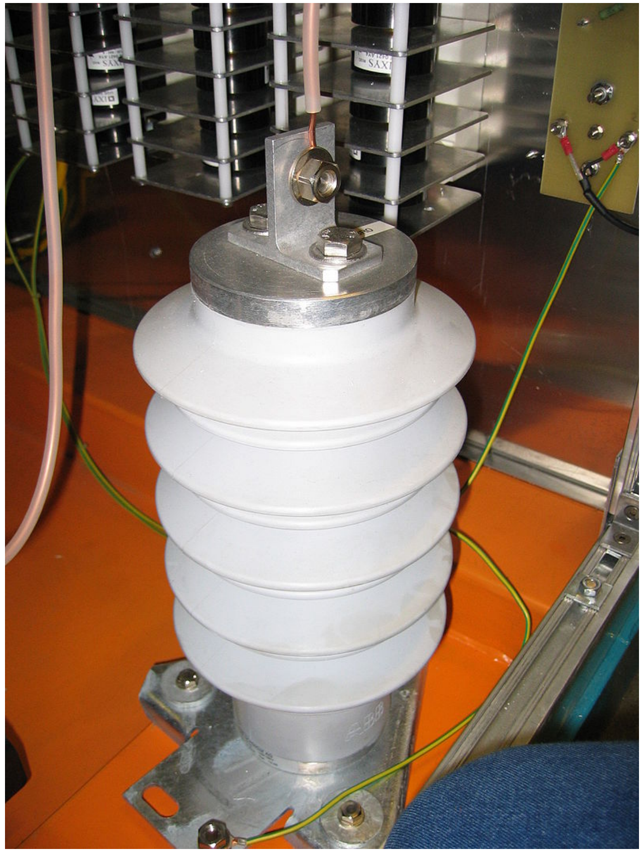


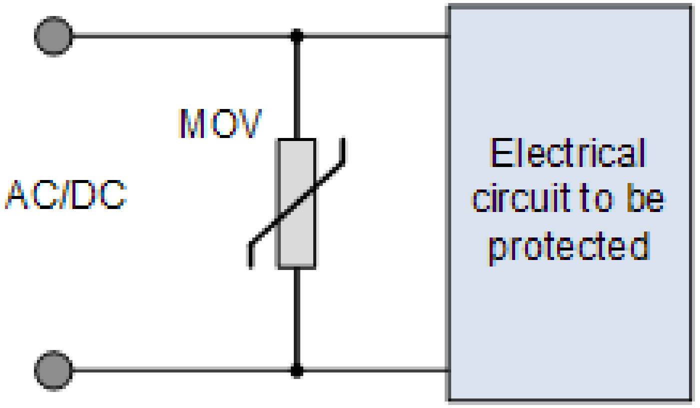
VARISTOR TYPES

Varistors come in many shapes and sizes.

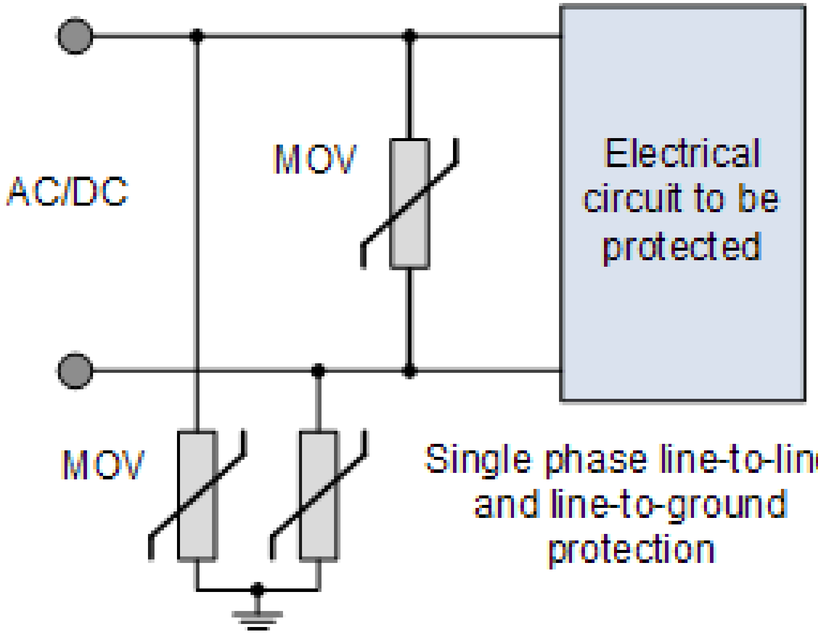
The varistor on the left is ~10 mm diameter, and is designed to protect mains-connected electronics.

The varistor on the right is designed to protect against lightning strikes, and is also referred to as a “surge protector” or “lightning arrester”.

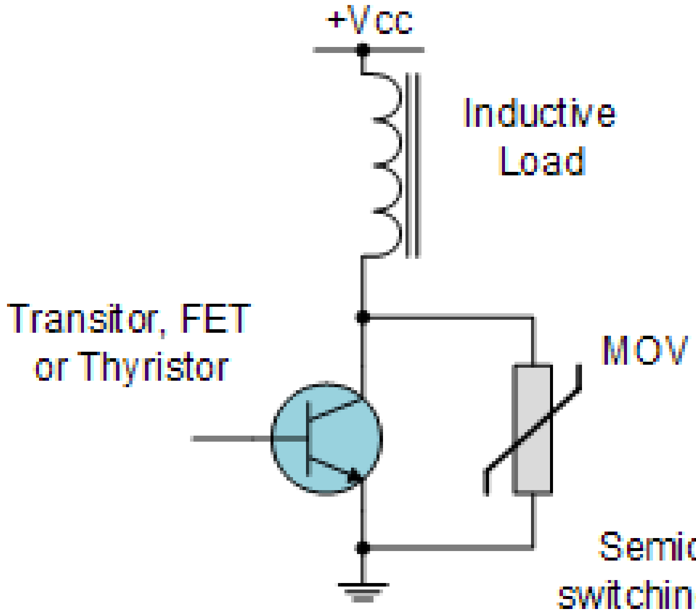




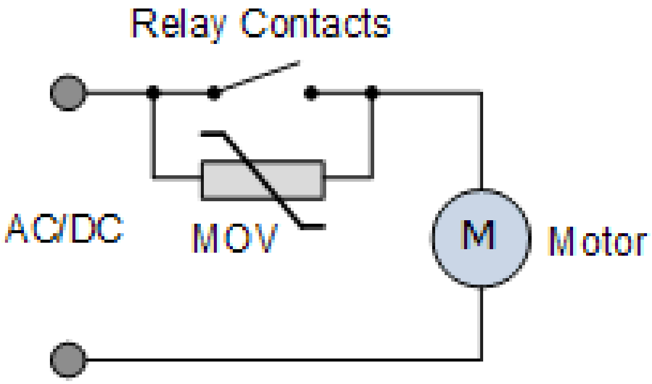
Single phase line-to-line protection



Single phase line-to-line and line-to-ground protection



Semiconductor switching protection



Contact arcing protection

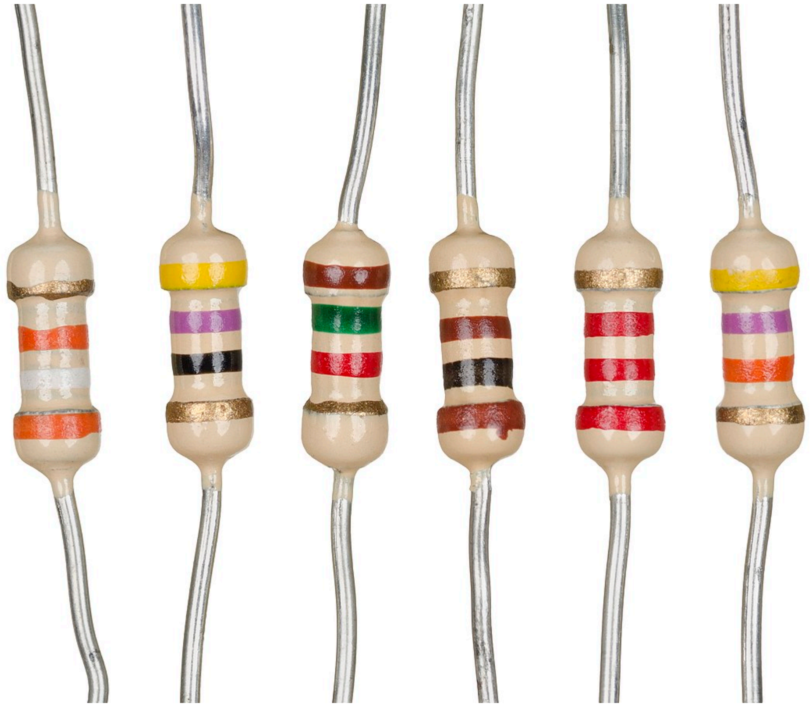
RESISTORS: SELECTION GUIDELINES

TOLERANCE

Resistors usually have a tolerance specified. The tolerance is given as a percentage, and tells the amount the resistor can vary.

The resistors on the right have a gold coloured tolerance band, meaning the tolerance is ±5%. The left-most resistor has a marked value of 39 kΩ, but its value could be from 37.05 kΩ to 40.95 kΩ.

The tolerance required is application dependent.



PREFERRED VALUES – E6, E12 ETC.

Resistors are available in preferred values, based on tolerance.

The main preferred values are based on 3, 6, and 12 values per decade, called E3, E6 and E12.

The basic preferred values are:

10 11 **12** 13 ***15*** 16 **18** 20

22 24 **27** 30 ***33*** 36 **39** 43

47 51 **56** 62 ***68*** 75 **82** 91

The E3, E6, E12, and E24 series values are as follows:

E3: bold, italic and underlined only.

E6: E3, and bold and italic only

E12: E6, and bold only

E24: all values.

The series values are based on the following tolerances:

E3: ±50%

E6: ±20%

E12: ±10%

E24: ±5%

STABILITY

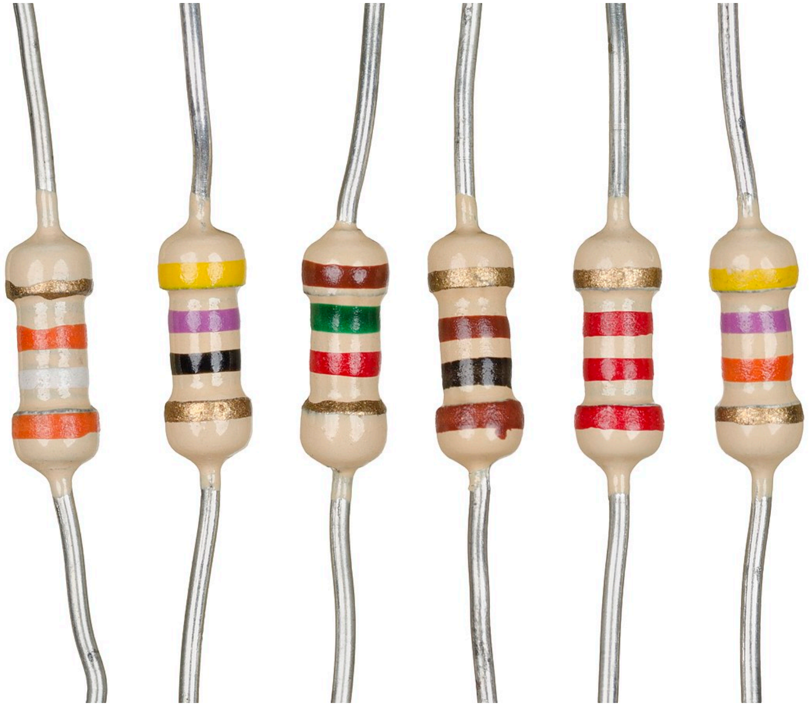
Resistance can change with temperature.

The usual unit for stability is a temperature coefficient given in ppm/°C. An ideal resistor would have a coefficient of 0 ppm/°C.

The stability may be indicated with an extra band, or indicated on the data sheet.

Copper has a stability of 4040 ppm/°C, nichrome 400 ppm/°C, and carbon -500 ppm/°C.

The stability required is application dependent.



POWER RATING

All resistors dissipate power as heat.

Resistors have a maximum power rating. Exceeding this power rating can damage or destroy the resistor, or shorten its life.

The picture on the right shows a burnt-out resistor.

Resistor ratings can range from milliwatts to hundreds of thousands of watts. Resistors commonly used in electronics have a power rating of about 0.25 W.

The power rating required is application dependent.

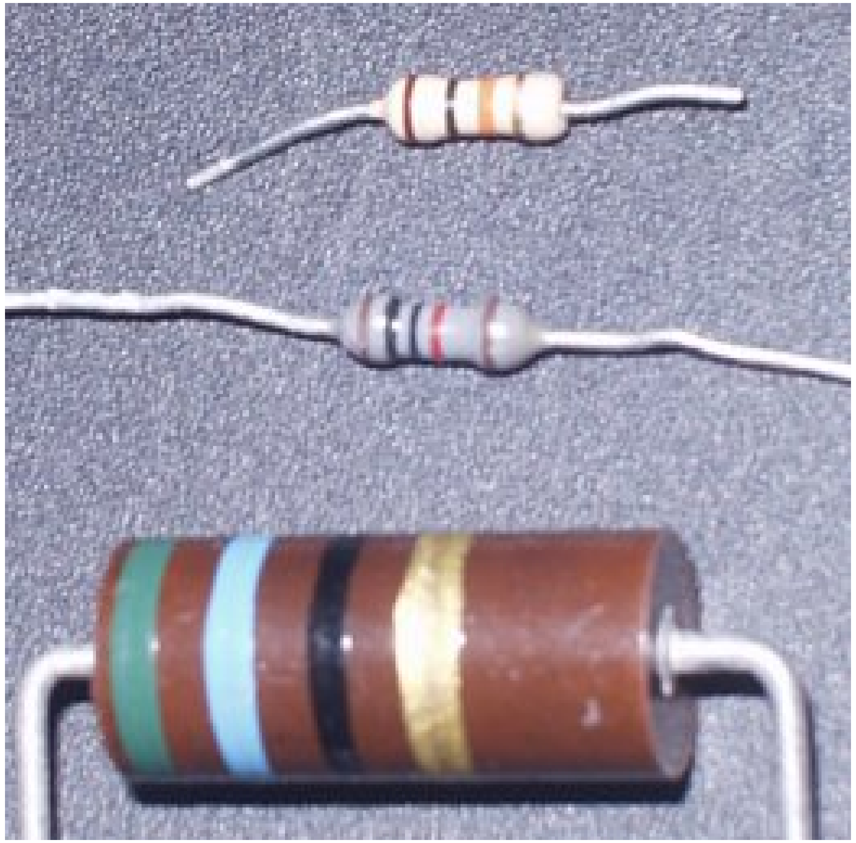
VOLTAGE AND CURRENT RATING

Resistors may have a maximum current and/or voltage rating.

A 0.25 W resistor may have a maximum voltage rating of 250 V. Even if an excessive voltage would not cause excessive power dissipation, applying excessive voltage could still cause the resistor to fail.

Current rating tends to flow "naturally" from the maximum power dissipation. However, a resistor may have some ability to absorb surge currents without damage. The carbon composition resistor (at bottom) has better surge absorbing abilities as the resistive element is the entire mass of the resistor rather than a thin external film.

These requirements are application dependent.



FUSIBLE RESISTORS

Some resistors are designed to act as fuses. Many electronic power supplies (e.g. for LED lamps) have a fusible resistor.

Under normal conditions, the fusible resistor acts as an inrush current limiter (e.g. 47 Ω will limit inrush current to ~6 A) .

Under fault conditions (e.g. a shorted filter capacitor causing a continuous 6 A draw), the resistor will burn out in a manner similar to a fuse.

READING RESISTORS

RESISTOR COLOUR CODE

Small resistors are marked with colour bands.

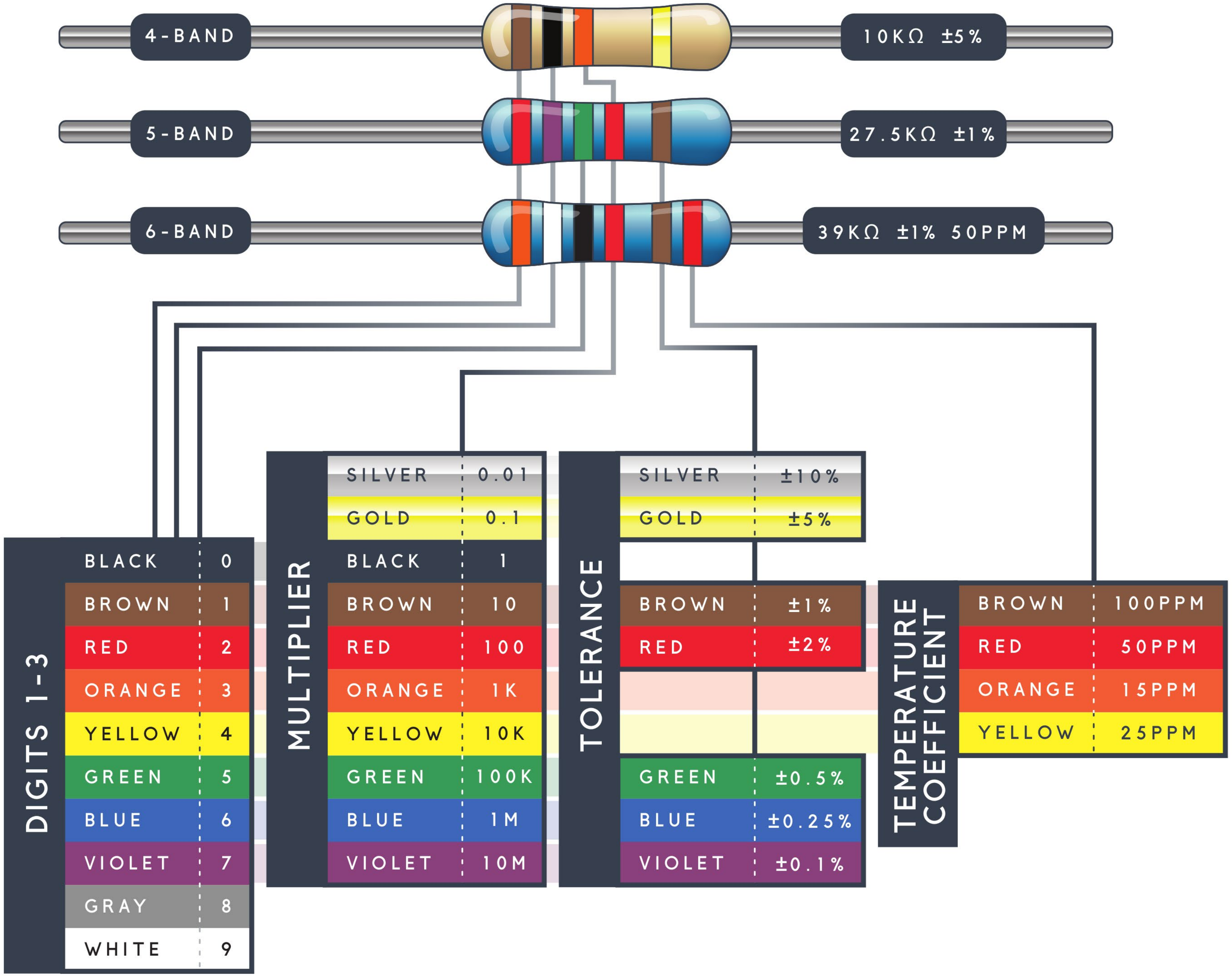
Two (or three) bands gives the value of the resistor.

A third (or fourth) band is the *multiplier*, it tells what power of 10 to multiply the value bands by.

A fourth (or fifth) band is the *tolerance*, it tells the tolerance of the resistor as a percentage.

If there is no tolerance band, the tolerance is $\pm$20%.

Colour	Name	Value	Mul	Tol
	Black	0	**1**	-
	Brown	1	**10**	**1%**
	Red	2	**100**	2%
	Orange	3	**10^3**	3%
	Yellow	4	**10^4**	4%
	Green	5	**10^5**	0.5%
	Blue	6	10^6	0.25%
	Violet	7	-	0.1%
	Grey	8	-	-
	White	9	-	-
	Gold	-	0.1	**5%**
	Silver	-	0.01	10%


4-BAND
10KΩ ±5%
5-BAND
27.5KΩ ±1%
6-BAND
39KΩ ±1% 50PPM
DIGITS 1-3
BLACK 0
BROWN 1
RED 2
ORANGE 3
YELLOW 4
GREEN 5
BLUE 6
VIOLET 7
GRAY 8
WHITE 9
MULTIPLIER
SILVER 0.01
GOLD 0.1
BLACK 1
BROWN 10
RED 100
ORANGE 1K
YELLOW 10K
GREEN 100K
BLUE 1M
VIOLET 10M
TOLERANCE
SILVER ±10%
GOLD ±5%
BROWN ±1%
RED ±2%
GREEN ±0.5%
BLUE ±0.25%
VIOLET ±0.1%
TEMPERATURE COEFFICIENT
BROWN 100PPM
RED 50PPM
ORANGE 15PPM
YELLOW 25PPM

RESISTORS EXAMPLE, 4-BAND

What are the values of these resistors? Beware, some read right-to-left! The tolerance band is always the last band to be read.

RESISTORS EXAMPLE, 4-BAND (ANSWERS)

Orange-White-Orange-Gold → 39 kΩ ± 5%

Yellow-Violet-Black-Gold → 47 Ω ± 5%

Brown-Green-Red-Gold → 1.5 kΩ ± 5%

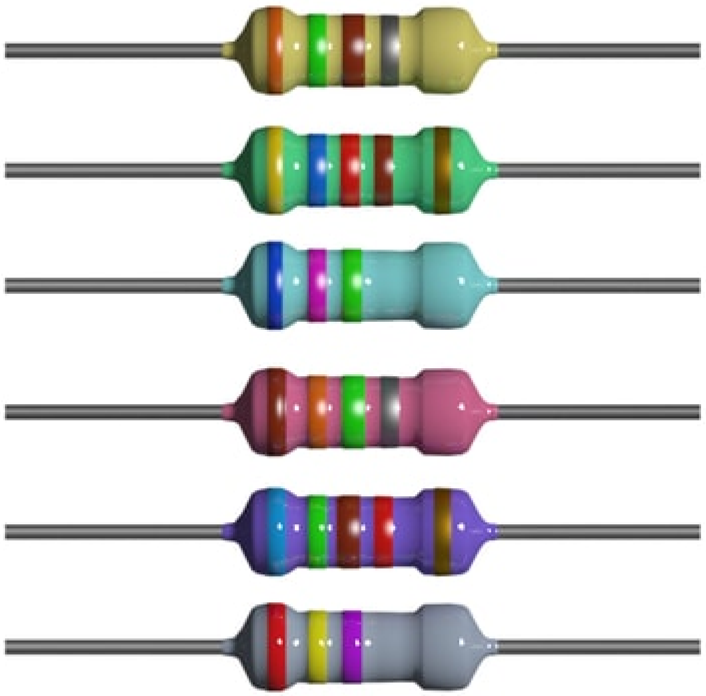
Brown-Green-Red-Gold → 100 Ω ± 5%

Red-Red-Red-Gold → 2.2 kΩ ± 5%

Yellow-Violet-Orange-Gold → 47 kΩ ± 5%

RESISTORS EXAMPLE, 4- AND 5-BAND

What are the values of these resistors? The first value band is always closer to the end of the resistor, and has a narrow gap to the next value band. The tolerance band is always the last band to be read, and may have a wider gap too.



RESISTORS EXAMPLE, 4- AND 5-BAND (ANSWERS)

Orange-Green-Brown-Silver → 35 kΩ ± 10%

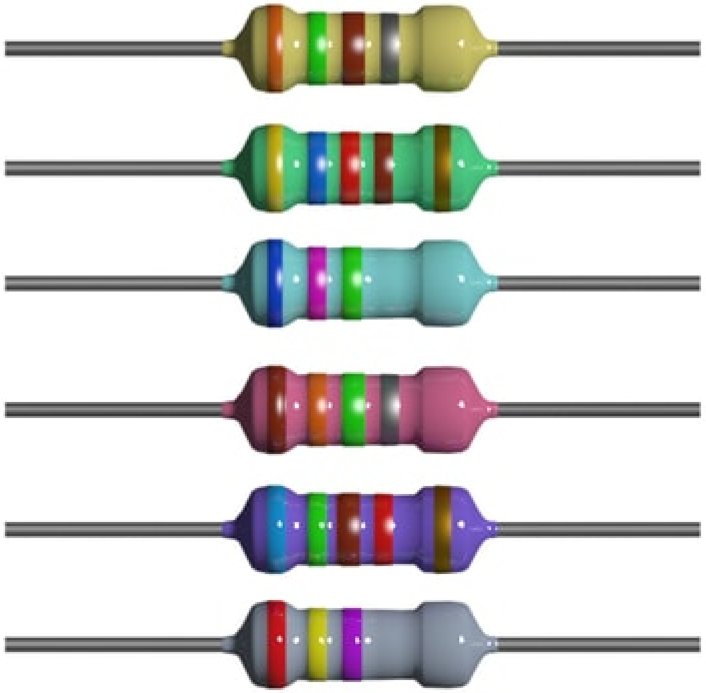
Yellow-Blue-Red-Brown-Gold → 462 Ω ± 5%

Blue-Violet-Green → 6.7 MΩ ± 20%

Brown-Orange-Green-Silver → 1.3 MΩ ± 10%

Blue-Green-Brown-Red-Gold → 65.1 kΩ ± 5%

Red-Yellow-Violet → 240 MΩ ± 20%



CABLE CONDUCTOR AND INSULATION RESISTANCE

INTRODUCTION

It is required to test all new wiring for insulation resistance, to ensure the wiring (and fittings connected to it) is electrically safe.

In particular, insulation resistance testing can be used to detect incorrect connections, cable damage and defective fittings.

The minimum insulation resistance value for most situations is 1 MΩ.

INSULATION RESISTANCE INTRODUCTION

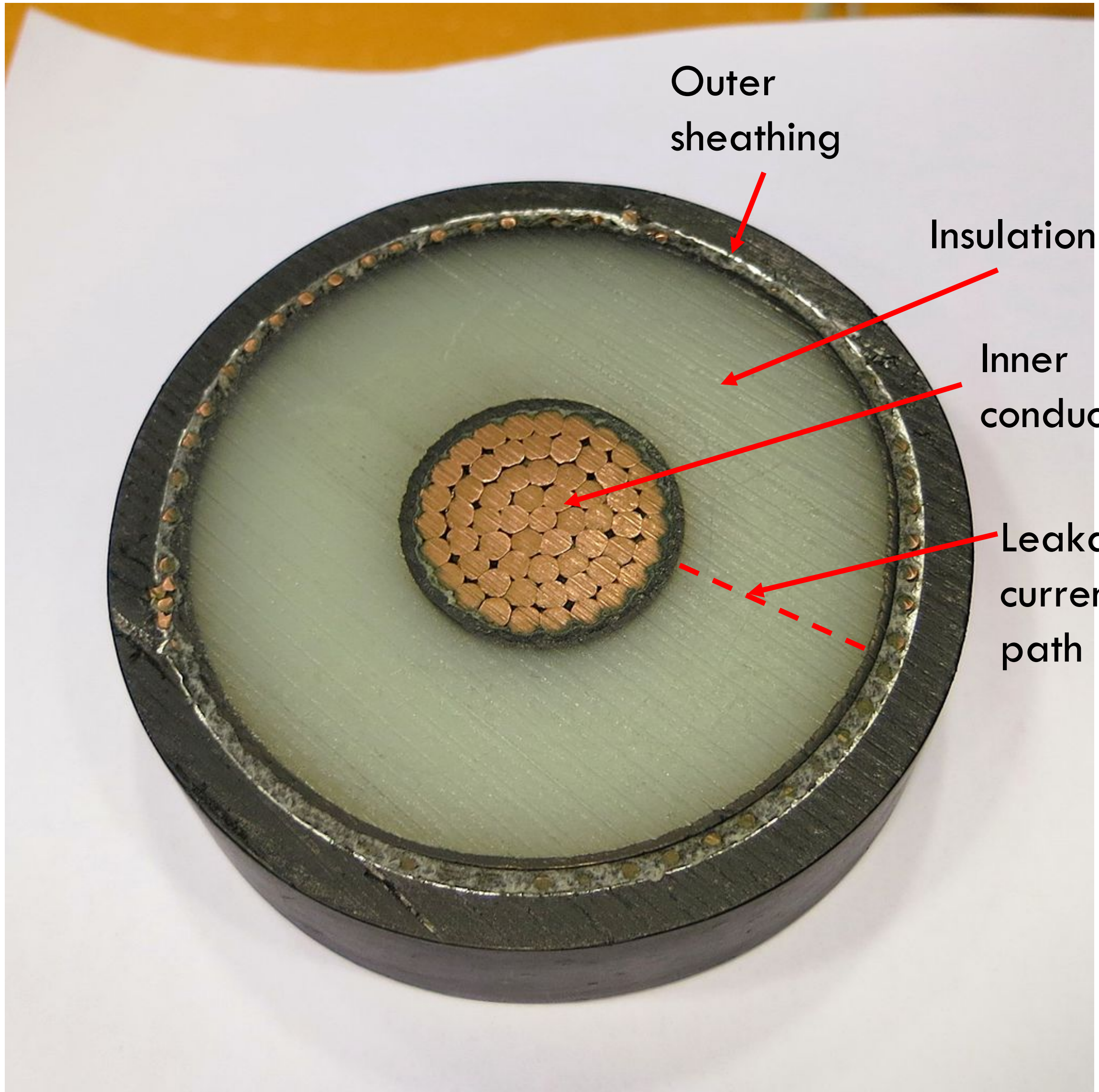
Insulation resistance is part of all conductor behaviour.

Unlike conductor resistance, which is a *series* phenomenon, insulation resistance is a *parallel* phenomenon.

If the cable is imagined as a series of slices, each 'slice' of the insulation is in parallel with each other 'slice'.

$$R_{\text{ins}} = \frac{\text{Constant}}{L}$$

Where R_{ins} is the insulation resistance, and L is the length of the cable, and constant is a value determined by the cable properties.



CALCULATING INSULATION RESISTANCE

The insulation resistance of any length of cable may be calculated if the insulation resistance of a sample length is known.

$$R_{\text{ins}} = R_{\text{sample}} \cdot \frac{L_{\text{sample}}}{L_{\text{ins}}}$$

Where R_{ins} is the insulation resistance of the cable with length L_{ins}, and R_{sample} and L_{sample} are the insulation resistance and length of the sample cable respectively.

A 100 m length of cable has an insulation resistance of 50 MΩ. What is the insulation resistance of a 25 m length?

For this problem, the following applies:
R_{sample} = 50 MΩ
L_{sample} = 100 m
L_{ins} = 25 m

$$R_{\text{ins}} = 5 \cdot 10^7 \cdot \frac{100}{25} = 2 \cdot 10^8$$

i.e. R_{ins} = 200 MΩ

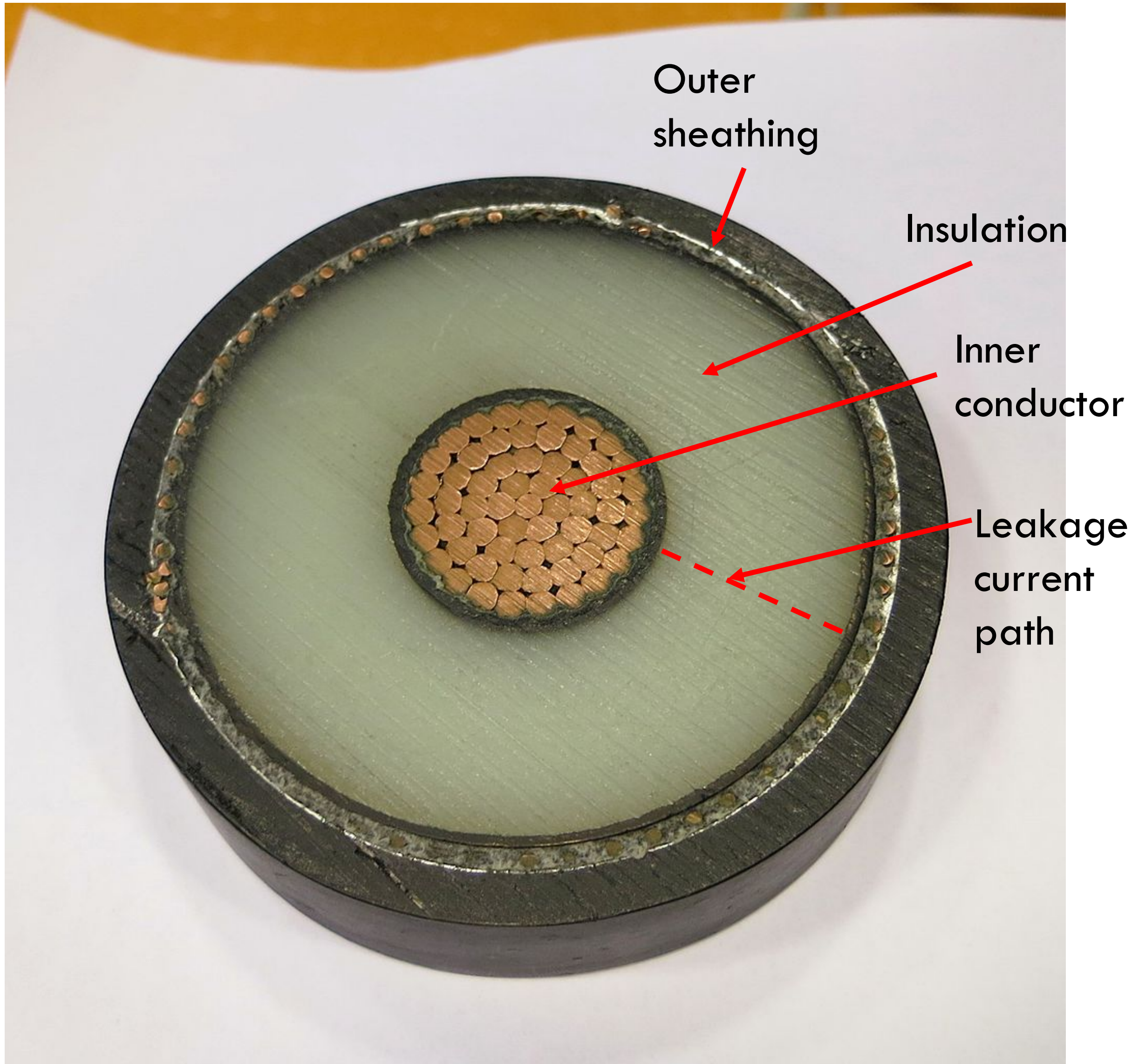
CONDUCTOR RESISTANCE INTRODUCTION

Conductor resistance is a *series* phenomenon.

If the cable is imagined as a series of slices, each 'slice' of the conductor is in parallel with each other 'slice'.

$$R_{\text{cond}} = \text{Constant} \cdot L$$

Where R_{cond} is the conductor resistance, and L is the length of the cable, and constant is a value determined by the cable properties.



CALCULATING CONDUCTOR RESISTANCE

The conductor resistance of any length of cable may be calculated if the conductor resistance of a sample length is known.

$$R_{\text{cond}} = R_{\text{sample}} \cdot \frac{L_{\text{cond}}}{L_{\text{sample}}}$$

Where R_{cond} is the conductor resistance of the cable with length L_{cond}, and R_{sample} and L_{sample} are the conductor resistance and length of the sample cable respectively.

A 100 m length of 1mm^2 copper conductor has a resistance of 1.72 Ω. What is the resistance of a 25 m length?

For this problem, the following applies:
R_{sample} = 1.72 Ω
L_{sample} = 100 m
L_{ins} = 25 m

$$R_{\text{cond}} = 1.72 \cdot \frac{25}{100} = 0.43$$

i.e. R_{cond} = 0.43 Ω

USING CONDUCTOR RESISTANCE

While we could calculate the resistance from scratch every time, *AS/NZS 3008 (Electrical Installations – Selection of Cables)* has tables of standardised conductor resistance for different cable sizes. The units are given in $mV.A^{-1}m^{-1}$. This is the same unit as $m\Omega.m^{-1}$, or $\Omega.km^{-1}$.

e.g. For 1 mm^2 2C+E cable we use table 42. The value given at 75°C is 44.7 $mV.A^{-1}m^{-1}$, which is multiplied by 1.155 ($\frac{2}{\sqrt{3}}$) to convert it to a single phase ac resistance of 51.62 $\Omega.km^{-1}$.

The calculation on the previous page implies that the resistance is 17.2 $\Omega.km^{-1}$.

First, we have to *double* the value, since current that flows one way must have a return path → 34.2 $\Omega.km^{-1}$.

Then, the resistivity figure we used has a base temperature of 20°C, but our resistance figure is at 75°C. We use $\alpha = 0.00393$, and a temperature rise of 55°C → 41.6 $\Omega.km^{-1}$ at dc.

The resistance of 51.62 $\Omega.km^{-1}$ is the ac resistance – it takes into account certain eddy current effects and losses that do not occur with dc.

EFFECT OF CABLE SIZE ON CONDUCTOR RESISTANCE

In general, the conductor resistance is given by:

$$R_{\text{cond}} = \frac{\text{Constant}}{\pi r^2}$$

Where r is the radius of the inner conductor, and the Constant is a value (unit: Ωm^2) determined by the properties of the cable.

Assuming the constant stays the same, the relationship between conductor resistances for different conductor radii is given below:

$$\frac{R_{\text{cond2}}}{R_{\text{cond1}}} = \frac{r_1^2}{r_2^2}$$

where r_1 and r_2 are the respective first and second conductor radii.

If the conductor radius is doubled, the conductor resistance will be ¼ of what it was before.

EFFECT OF CABLE SIZE ON INSULATION RESISTANCE

In general, the conductor resistance is given by:

$$R_{\text{ins}} = \frac{\text{Constant}}{2\pi r}$$

Where r is the radius of the inner conductor, and the Constant is a value (unit: Ωm) determined by the properties of the cable insulation.

The insulation resistance is inversely proportional to r, as the available path the leakage current flows through is proportional to the *external area* of the conductor.

Assuming the constant stays the same, the relationship between conductor resistances for different conductor radii is given below:

$$\frac{R_{\text{ins2}}}{R_{\text{ins1}}} = \frac{r_1}{r_2}$$

where r_1 and r_2 are the respective first and second conductor radii.

If the conductor radius is doubled, the insulation resistance will halve.

CABLE FAILURE MODES

INTRODUCTION

Electrical cables can fail for a variety of reasons. Some reasons, such as poor cable selection are foreseeable at the time of installation.

Others, such as rodent damage, are not so foreseeable.

The conductors do not generally fail, as they are on the inside of the cable and protected by insulation. The failures here are failures of insulation.

Insulation damage is generally not reversible, and the cable must be repaired or replaced.

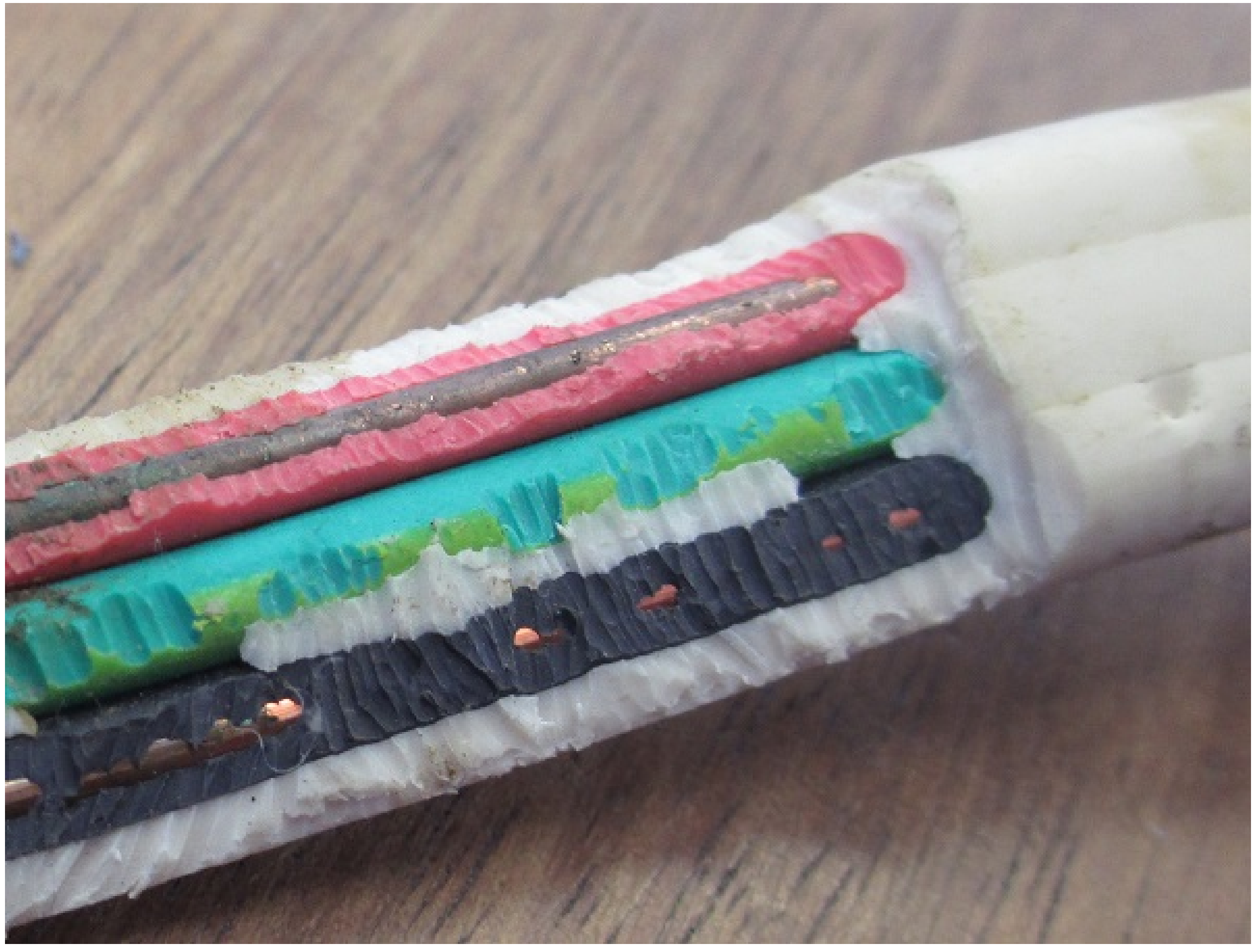
ANIMAL DAMAGE

Rodents are common offenders.

Insects living in cable points of entry.

Animal waste products filling junction boxes.

Sometimes these faults are very difficult to diagnose.



MECHANICAL DAMAGE

Underground cables are subject to mechanical damage, due to them being effectively invisible.

Cables are usually laid with warning tapes, but people digging may not be aware of where the cables are, or have inaccurate information.

Earthquakes, high ground temperatures and land movement may also damage cables.

The cable on the right has had its insulation pierced. The damage has resulted in the cable failing.

It may be some time between the damage being done, and the cable actually failing.

HEAT DAMAGE

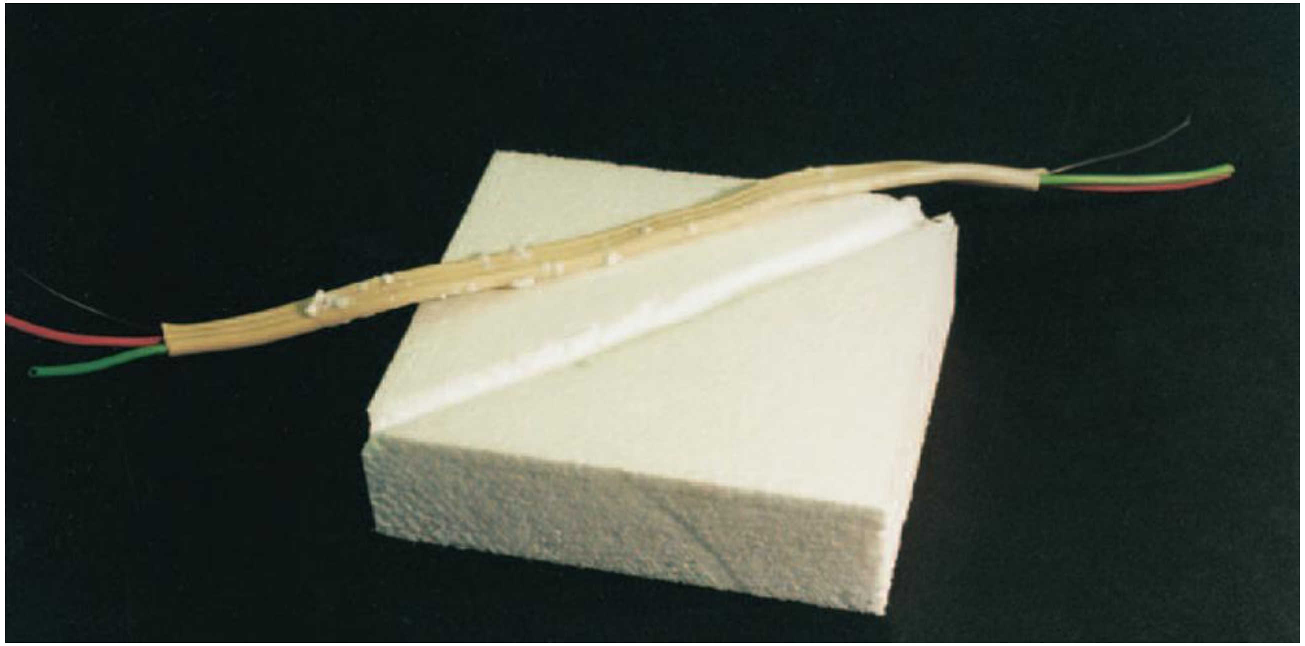
Most insulation is sensitive to heat. Too much heat, and the insulation will begin to deform and deteriorate. In the worst case, the insulation may fail completely.

Excluding poor cable selection, insulation failure can be caused by loose connections, such as shown.

CHEMICAL DAMAGE

Some types of PVC are incompatible with polystyrene insulation. The polystyrene “sucks up” the plasticisers in the PVC. The polystyrene dissolves away, and the PVC becomes brittle.

There may be other situations (e.g. factories) where special cable insulation is required.



INCORRECT CABLE SELECTION

These factors are mainly due to incorrect selection of cables:

Very thin insulation, and/or an excessive length conductor.

High ambient temperature e.g. using cable rated for 75°C in a 90°C ambient environment.

UV deterioration, from either sunlight or UV light emitted from light fixtures. UV resistant cable is required.

EXCESSIVE VOLTAGE

Excessive voltage, usually caused by lightning.

Excessive voltage can cause insulation failure.

The cable on the right is actually a communications cable, but the idea is the same.

ELECTRICAL TRACKING

Cables can fail due to electrical tracking, causing the insulation to fail over time. These factors include:

Poor insulation material or defects.

Poorly constructed cable or terminations.

High surface contact area e.g. underground cable buried below water table.

Moisture, especially if moisture penetrates the insulation.