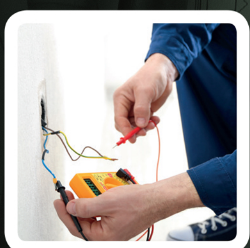
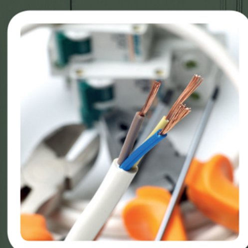
9TH EDITION

ELECTRICAL INSTALLATION WORK





COVERS LEVEL 2 AND 3 COURSES IN ELECTRICAL INSTALLATION WORK

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CHAPTER 2

Electricity

What is electricity? Where does it come from? How fast does it travel? In order to answer such questions, it is necessary to understand the nature of substances. The following paragraphs give a very simple explanation of the relationship between atomic particles as this area of physics and chemistry is extremely complex.

Molecules and atoms

Every known substance is composed of molecules which in turn are made up of atoms. Substances whose molecules are formed by atoms of the same type are called **elements**, of which there are known to be, at present, 118 (Table 2.1). Some of these are synthetic.

Table 2.1 Elements

Atomic Number	Name	Symbol	Atomic Number	Name	Symbol
1	Hydrogen	H	52	Tellurium	Te
2	Helium	He	53	Iodine	I
3	Lithium	Li	54	Xenon	Xe
4	Beryllium	Be	55	Caesium	Cs
5	Boron	B	56	Barium	Ba
6	Carbon	C	57	Lanthanum	La
7	Nitrogen	N	58	Cerium	Ce
8	Oxygen	O	59	Praseodymium	Pr
9	Fluorine	F	60	Neodymium	Na
10	Neon	Ne	61	Promethium	Pm
11	Sodium	Na	62	Samarium	Sm
12	Magnesium	Mg	63	Europium	Eu
13	Aluminium	Al	64	Gadolinium	Gd
14	Silicon	Si	65	Terbium	Tb
15	Phosphorus	P	66	Dysprosium	Dy
16	Sulphur	S	67	Holmium	Ho
17	Chlorine	Cl	68	Erbium	Er
18	Argon	A	69	Thulium	Tm
19	Potassium	K	70	Ytterbium	Yb
20	Calcium	Ca	71	Lutecium	Lu
21	Scandium	Sc	72	Hafnium	Hf

Table 2.1 (Continued)

Atomic Number	Name	Symbol	Atomic Number	Name	Symbol
22	Titanium	Ti	73	Tantalum	Ta
23	Vanadium	V	74	Tungsten	W
24	Chromium	Cr	75	Rhenium	Re
25	Manganese	Mn	76	Osmium	Os
26	Iron	Fe	77	Iridium	Ir
27	Cobalt	Co	78	Platinum	Pt
28	Nickel	Ni	79	Gold	Au
29	Copper	Cu	80	Mercury	Hg
30	Zinc	Zn	81	Thallium	Tl
31	Gallium	Ga	82	Lead	Pb
32	Germanium	Ge	83	Bismuth	Bi
33	Arsenic	As	84	Polonium	Po
34	Selenium	Se	85	Astatine	At
35	Bromine	Br	86	Radon	Rn
36	Krypton	Kr	87	Francium	Fr
37	Rubidium	Rb	88	Radium	Ra
38	Strontium	Sr	89	Actinium	Ac
39	Yttrium	Y	90	Thorium	Th
40	Zirconium	Zr	91	Protoactinium	Pa
41	Niobium	Nb	92	Uranium	U
42	Molybdenum	Mo	93	Neptunium	Np
43	Technetium	Tc	94	Plutonium	Pu
44	Ruthenium	Ru	95	Americium	Am
45	Rhodium	Rh	96	Curiam	Cm
46	Palladium	Pd	97	Berkelium	Bk
47	Silver	Ag	98	Californium	Cf
48	Cadmium	Cd	99	Einsteinium	Es
49	Indium	In	100	Fermium	Fm
50	Tin	Sn	101	Mendelevium	Md
51	Antimony	Sb	102	Nobelium	No
103	Lawrencium	Lr	111	Roentgenium	Rg
104	Rutherfordium	Rf	112	Ununbium	Uub
105	Dubnium	Db	113	Ununtrium	Uut
106	Seaborgium	Sg	114	Ununquadium	Uuq
107	Bohrium	Bh	115	Ununpentium	Uup
108	Hassium	Hs	116	Ununhexium	Uuh
109	Meitnerium	Mt	117	Ununseptium	Uus
110	Darmstadtium	Ds	118	Ununoctium	Uuo

Substances whose molecules are made up of atoms of different types are known as **compounds**. Hence, water, which is a compound, comprises two hydrogen atoms (H) and one oxygen atom (O), that is H_2O. Similarly, sulphuric acid has two hydrogen, one sulphur and four oxygen atoms: hence, H_2SO_4.

Molecules are always in a state of rapid motion, but when they are densely packed together this movement is restricted and the substance formed by these molecules is stable (i.e. a **solid**). When the molecules of a substance are less tightly bound there is much free movement, and such a substance is known as a **liquid**. When the molecule movement is almost unrestricted the substance can expand and contract in any direction and, of course, is known as a **gas**.

The atoms which form a molecule are themselves made up of particles known as protons, neutrons and electrons. Protons are said to have a positive (+ve) charge, electrons a negative (–ve) charge and neutrons no charge. Since neutrons play no part in electricity at this level of study, they will be ignored from now on.

So what is the relationship between protons and electrons; how do they form an atom? The simplest explanation is to liken an atom to our Solar System, where we have a central star, the Sun, around which are the orbiting planets. In the tiny atom, the protons form the central nucleus and the electrons are the orbiting particles. The simplest atom is that of hydrogen which has one proton and one electron (Fig. 2.1).

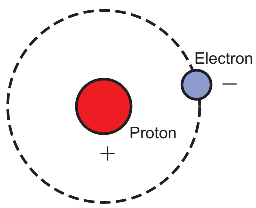

Figure 2.1 The hydrogen atom.

The atomic number (Table 2.1) gives an indication of the number of electrons surrounding the nucleus for each of the known elements. Hence, copper has an atomic number of 29, indicating that it has 29 orbiting electrons.

Electrons are arranged in layers or clouds at varying distances from the nucleus (like the rings around Saturn); those nearest the nucleus are more strongly held in place than those farthest away. These distant electrons are easily dislodged from their orbits and hence are free to join those of another atom whose own distant electrons in turn may leave to join other atoms, and so on. These wandering or **random** electrons that move about the molecular structure of the material are what makes up electricity.

So, then, how do electrons form electricity? If we take two dissimilar metal plates and place them in a chemical solution (known as an electrolyte) a reaction takes place in which electrons from one plate travel across the electrolyte and collect on the other plate. So one plate has an excess of electrons which makes it more –ve than +ve, and the other an excess of protons which makes it more +ve than –ve. What we are describing here, of course, is a simple cell or battery (Fig. 2.2).

Now then, consider a length of wire in which, as we have already seen, there are electrons in random movement (Fig. 2.3).

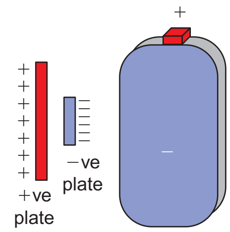

Figure 2.2 Battery.

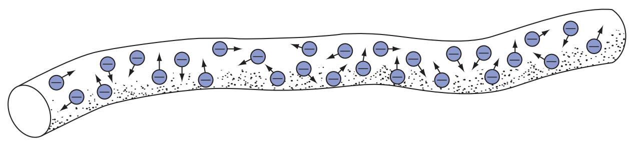

Figure 2.3 Conductor with random electrons.

If we now join the ends of the wire to the plates of a cell, the excess electrons on the –ve plate will tend to leave and return to the +ve plate, encouraging the random electrons in the wire to **drift** in the same direction (Fig. 2.4). This drift is what we know as electricity. The process will continue until the chemical action of the cell is exhausted and there is no longer a difference, +ve or –ve, between the plates.

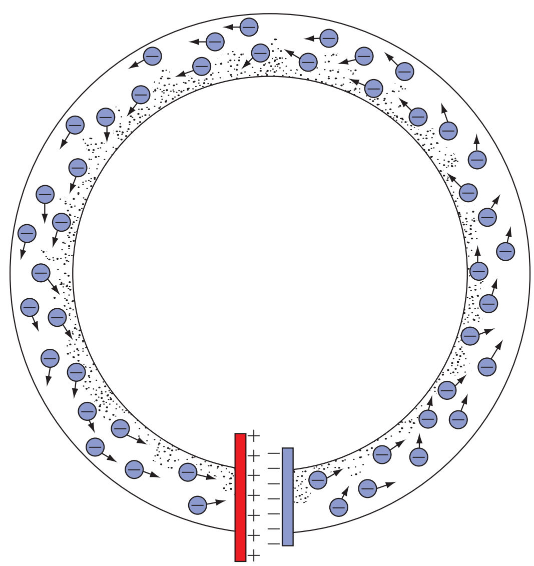

Figure 2.4 Conductor connected to battery (electron drift).

Potential difference

Anything that is in a state whereby it may give rise to the release of energy is said to have **potential**. For example, a ball held above the ground has potential in that, if it were let go, it would fall and hit the ground.

So, a cell or battery with its +ve and –ve plates has potential to cause electron drift. As there is a difference in the number of electrons on each of the plates, this potential is called the **potential difference** (p.d.).

Electron flow and conventional current flow

As we have seen, if we apply a p.d. across the ends of a length of wire, electrons will drift from –ve to +ve. In the early pioneering days, it was incorrectly thought that electricity was the movement of +ve protons and, therefore, any flow was from +ve to –ve. However, as the number of proton charges is the same as the number of electron charges, the convention of electric current flow from +ve to –ve has been maintained.

Conductors and insulators

Having shown that electricity is the general drift of random electrons, it follows that materials with large numbers of such electrons give rise to a greater drift than those with few random electrons. The two different types are known as conductors and insulators. Materials such as PVC, rubber, mica, etc., have few random electrons and therefore make good **insulators**, whereas metals such as aluminium, copper, silver, etc., with large numbers, make good **conductors**.

Electrical quantities

The units in which we measure electrical quantities have been assigned the names of famous scientific pioneers, brief details of whom are as follows. (Others will be detailed as the book progresses.)

André Marie Ampère (1775–1836)

French physicist who showed that a mechanical force exists between two conductors carrying a current.

Charles Augustin de Coulomb (1746–1806)

French military engineer and physicist famous for his work on electric charge.

Georg Simon Ohm (1789–1854)

German physicist who demonstrated the relationship between current, voltage and resistance.

Allessandro Volta (1745–1827)

Italian scientist who developed the electric cell, called the 'voltaic pile', which comprised a series of copper and zinc discs separated by a brine-soaked cloth.

Electric current: symbol, *I*; unit, ampere (A)

This is the flow or drift of random electrons in a conductor.

Electric charge or quantity: symbol, *Q*; unit, coulomb (C)

This is the quantity of electricity that passes a point in a circuit in a certain time. One coulomb is said to have passed when one ampere flows for one second:

$$Q = I \times t$$

Electromotive force (e.m.f.): symbol, *E*; unit, volt (V)

This is the total potential force available from a source to drive electric current around a circuit.

Potential difference (p.d.): symbol, *V*; unit, volt (V)

Often referred to as 'voltage' or 'voltage across', this is the actual force available to drive current around a circuit.

The difference between e.m.f. and p.d. may be illustrated by the **pay** analogy used in Chapter 1. Our gross wage (e.m.f.) is the total available to use. Our net wage (p.d.) is what we actually have to spend after deductions.

Resistance: symbol, *R*; unit, ohm (Ω)

This is the opposition to the flow of current in a circuit.

When electrons flow around a circuit, they do not do so unimpeded. There are many collisions and deflections as they make their way through the complex molecular structure of the conductor, and the extent to which they are impeded will depend on the material from which the conductor is made and its dimensions.

Resistivity: symbol, ρ; unit, μΩ mm
If we take a sample of material in the form of a cube of side 1 mm and measure the resistance between opposite faces (Fig. 2.5), the resulting value is called the **resistivity** of that material.

This means that we can now determine the resistance of a sample of material of any dimension. Let us suppose that we have a 1 mm cube of material of resistivity, say 1 Ω (Fig. 2.6a). If we double the length of that sample, leaving the face area the same (Fig. 2.6b), the resistance now measured would be 2 Ω (i.e.

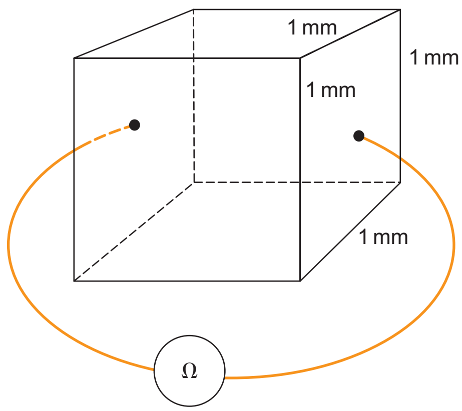

Figure 2.5 Resistivity of a unit cube.

the resistance has doubled). If, however, we leave the length the same but double the face area (Fig. 2.6c), the measured value would now be 0.5 | (i.e. the resistance has halved).

Hence, we can now state that whatever happens to the length of a conductor also happens to its resistance (i.e. **resistance is proportional to length**) and whatever happens to the cross-sectional area (c.s.a.) has the opposite effect on the resistance (i.e. **resistance is inversely proportional to area**).

So,

$$\text{Resistance } R = \frac{\text{resistivity } \rho \times \text{length } l}{\text{area } a}$$

$$R = \frac{\rho \times l}{a}$$

In practice, the resistance across a 1 mm cube of a material is extremely small, in the order of millionths of an ohm (μΩ) as shown in Table 2.2.

Table 2.2 Examples of resistivity

Material	Resistivity, ρ (μΩ mm at 20°C)
Copper, International Standard	17.2
Copper, annealed	16.9–17.4
Copper, hard drawn	17.4–18.1
Aluminium, hard drawn	28
Silver, annealed	15.8
Silver, hard drawn	17.5
Platinum	117
Tungsten	56
Eureka (constantan)	480
German silver (platinoid)	344
Manganin	480

Example

Calculate the resistance of a 50 m length of copper conductor of c.s.a. 2.5 mm², if the resistivity of the copper used is 17.6 μΩ mm.

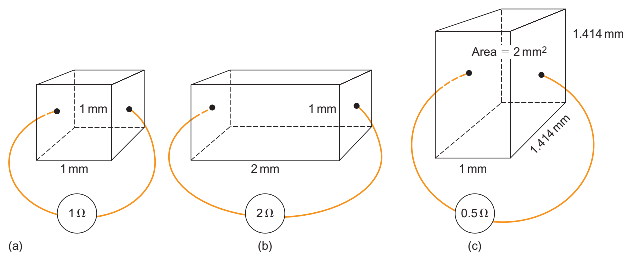

Figure 2.6 Change of resistivity with length and csa.

Note

All measurements should be of the same type, that is resistivity, microohm millimetres; length, millimetres; c.s.a., square millimetres. Hence 10^3 to convert metres to millimetres.

$$R = \frac{\rho \times l}{a}$$

$$\therefore R = \frac{17.6 \times 10^{-6} \times 50 \times 10^3}{2.5}$$

$$= \frac{17.6 \times 10^{-3} \times 50}{2.5}$$

$$= 17.6 \times 10^{-3} \times 20$$

$$= 352 \times 10^{-3}$$

$$= 0.352\,\Omega$$

Example

Calculate the resistivity of aluminium if a 100 m length of conductor of c.s.a. 4 mm² has a measured resistance of 0.7 Ω.

$$R = \frac{\rho \times l}{a}$$

$$\therefore \rho = \frac{R \times a}{l}$$

$$= \frac{0.7 \times 4}{100 \times 10^3}$$

$$= 7 \times 10^{-1} \times 4 \times 10^{-5}$$

$$= 28 \times 10^{-6}$$

$$= 28\,\mu\Omega\,\text{mm}$$

Reference to Table 2.2 will show that values of resistivity are based on a conductor temperature of 20°C which clearly suggests that other temperatures would give different values. This is quite correct. If a conductor is heated, the molecules vibrate more vigorously making the passage of random electrons more difficult (i.e. the conductor resistance increases). On the other hand, a reduction in temperature has the opposite effect, and hence a decrease in conductor resistance occurs. The amount by which the resistance of a conductor changes with a change in temperature is known as the temperature coefficient of resistance.

Temperature coefficient: symbol, α; unit, ohms per ohm per °C (Ω/Ω/°C)

If we were to take a sample of conductor that has a resistance of 1 Ω at a temperature of 0°C, and then increase its temperature by 1°C, the resulting increase in resistance is its temperature coefficient. An increase of 2°C would result in twice the increase, and so on. Therefore the new value of a 1 Ω resistance which has had its temperature raised from 0°C to *t*°C is given by $(1 + \alpha t)$. For a 2 Ω resistance the new value would be $2 \times (1 + \alpha t)$, and for a 3 Ω resistance, $3 \times (1 + \alpha t)$, etc. Hence we can now write the formula:

$$R_f = R_0(1 + \alpha t)$$

where R_f is the final resistance, R_0 is the resistance at 0°C, α is the temperature coefficient and *t*°C is the change in temperature.

For a change in temperature between any two values, the formula is:

$$R_2 = \frac{R_1(1 + \alpha t_2)}{(1 + \alpha t_1)}$$

where R_1 is the initial resistance, R_2 is the final resistance, t_1 is the initial temperature and t_2 is the final temperature.

The value of temperature coefficient for most of the common conducting materials is broadly similar, ranging from 0.0039 to 0.0045 Ω/Ω/°C, that of copper being taken as 0.004 Ω/Ω/°C.

Example

A sample of copper has a resistance of 10 Ω at a temperature of 0°C. What will be its resistance at 50°C?

$$\begin{aligned}
R_f &= R_0(1 + \alpha t) \\
R_f &= ? \\
R_0 &= 10 \\
t &= 50 \\
\alpha &= 0.004\,\Omega/\Omega/^\circ C \\
\therefore R_f &= 10(1 + 0.004 \times 50) \\
&= 10(1 + 0.2) \\
&= 10 \times 1.2 \\
&= 12\,\Omega
\end{aligned}$$

Example

A length of tungsten filament wire has a resistance of 200 Ω at 20°C. What will be its resistance at 600°C ($\alpha = 0.0045\,\Omega/\Omega/^\circ C$)?

$$\begin{aligned}
R_2 &= \frac{R_1(1 + \alpha t_2)}{(1 + \alpha t_1)} \\
R_2 &= ? \\
R_1 &= 200 \\
t_1 &= 20^\circ C \\
t_2 &= 600^\circ C \\
\alpha &= 0.0045\,\Omega/\Omega/^\circ C
\end{aligned}$$

$$\begin{aligned}
\therefore R_2 &= \frac{200(1 + 0.0045 \times 600)}{(1 + 0.0045 \times 20)} \\
&= \frac{200(1 + 2.7)}{(1 + 0.09)} \\
&= \frac{200 \times 3.7}{1.09} \\
&= 679\ \Omega
\end{aligned}$$

There are certain conducting materials such as carbon and electrolytes whose resistances display an **inverse** relationship with temperature, that is their resistances **decrease** with a rise in temperature, and vice versa. These conductors are said to have **negative** temperature coefficients. Carbon, for example, is used for the brushes in some types of motor, where friction causes the brushes to become very hot. In this way current flow to the motor is not impeded.

We have already learned that random electrons moving in the same direction (electric current) through the molecular structure of a conductor experience many collisions and deflections. The energy given off when this happens is in the form of heat; hence the more electrons the more heat and thus the greater the

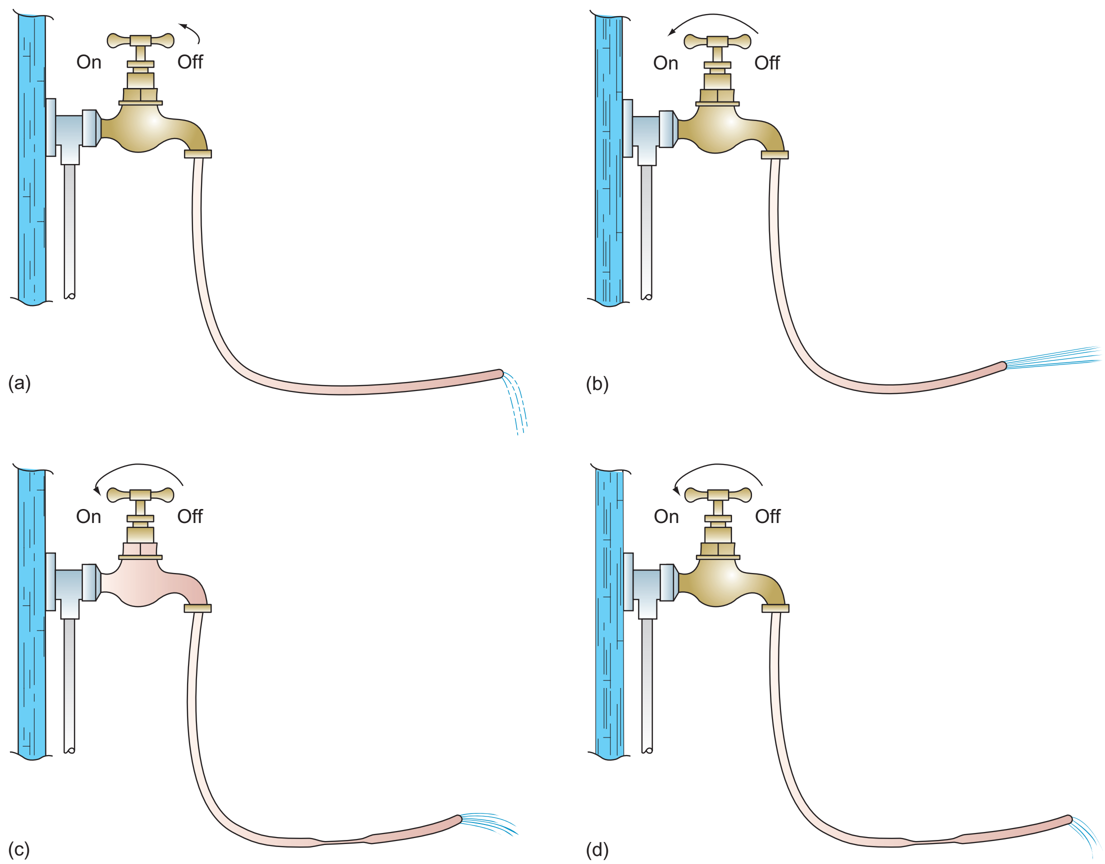

Figure 2.7 The water analogy.

resistance. So current flow can, itself, cause a change in conductor resistance.

The water analogy

Consider a tap and a length of hose. With the tap just turned on, only a trickle of water will issue from the hose (Fig. 2.7a). Turn the tap further and more water will flow (Fig. 2.7b). Hence pressure and flow are **proportional**. Leave the tap in this position and squeeze the pipe: less water will flow (Fig. 2.7c). Increase the opposition by squeezing more and even less water will flow (Fig. 2.7d). Hence opposition and flow are **inversely proportional**.

Now, for an electric circuit, replace the tap with some source of electricity supply, change the hose to a conductor and the constriction in the hose into added resistance. The flow of water becomes the current. We will now have the same effect, in that a small voltage will only give rise to a small current (Fig. 2.8a), an increase in voltage produces a greater current (Fig. 2.8b) and a constant voltage but with an increase in resistance results in reduced current flow (Fig. 2.8c and d).

Ohm's law

Georg Simon Ohm demonstrated the relationships we have just seen, and stated them in his famous law which is: 'The current in a circuit is proportional to the circuit voltage and inversely proportional to the circuit resistance, at constant temperature'.

So, we can show Ohm's law by means of the formula

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

Also, transposing,

$$R = \frac{V}{I} \text{ and } V = I \times R$$

Example

A 230 V electric heating element has a measured resistance of 19.2 Ω (Fig. 2.9). Calculate the current that will flow. (*Note*: Whenever possible, draw a diagram, no matter how simple; this will help to ensure that correct values are assigned to the various circuit quantities.)

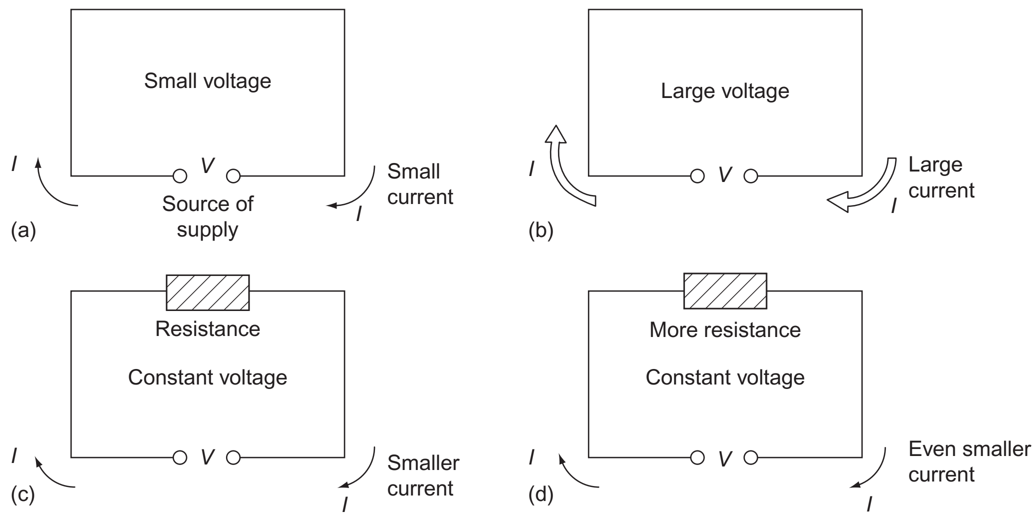

Figure 2.8 Ohm's Law.

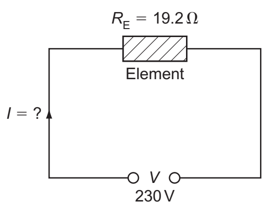

Figure 2.9

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

$$= \frac{230}{19.2}$$

$$= 11.9 \text{ A}$$

Example

What is the resistance of an electric lamp filament, if it draws a current of 0.625 A from a 230 V supply? (Fig. 2.10).

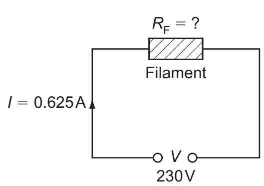

Figure 2.10

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

$$= \frac{230}{0.625}$$

$$= 368 \ \Omega$$

Example

What voltage would be required to cause a current of 2 A to flow through a resistance of 55 Ω? (Fig. 2.11).

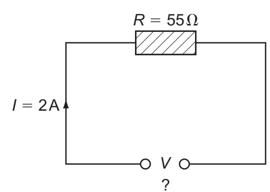

Figure 2.11

$$V = I \times R$$

$$= 2 \times 55$$

$$= 110 \text{ V}$$

Electricity and the human body

Water is a conductor of electricity and since the human body is made up of a high proportion of water, it follows that it also is a conductor. However, unlike other materials we have dealt with so far, there is no exact value for body resistivity, and therefore body resistance can vary, not only between individuals but between values for each person. Depending on whether the body is dry, moist or wet, the value measured between hands or between hands and feet can be anywhere between 1000 and 10 000 Ω. As we have just seen from Ohm's law, the current flowing through a body will depend on the voltage and the body resistance. Different levels of current will have different effects, the worst occurring when the heart goes out of rhythm and will not return to normal. This condition is known as ventricular fibrillation, and will

Table 2.3 Shock levels

Current (mA)	Effect
1–2	Perception level, no harmful effects
5	Throw-off level, painful sensation
10–15	Muscular contraction begins, cannot let go
20–30	Impaired breathing
50 and above	Ventricular fibrillation and death

often result in death. Table 2.3 is a guide to the various levels of shock current and their effects on the body.

It will be seen that 50 mA (0.05 A) is considered to be the minimum **lethal** level of shock current, so, if a person's body resistance was as low as 1000 Ω, the voltage required to cause this current to flow would be

$$V = I \times R$$
$$= 50 \times 10^{-3} \times 1000$$
$$= 50\ \text{V}$$

Note this voltage, it is important.

Types and sources of supply

There are only two types of electricity supply, **direct current** (d.c.) and **alternating current** (a.c.); d.c. is obtained from cells and batteries, d.c. generators or electronically derived from a.c. (rectification); a.c. is obtained from a.c. generators.

The methods of producing a.c. and d.c. supplies are discussed in later chapters.

Voltage bands

Extra low *Not* exceeding 50 V a.c. or 120 V d.c. between conductors or conductors and earth (Fig. 2.12a).

Low Exceeding extra low, but not exceeding 1000 V a.c. or 1500 V d.c. between conductors; or 600 V a.c. or 900 V d.c. between conductors and earth (Fig. 2.12b).

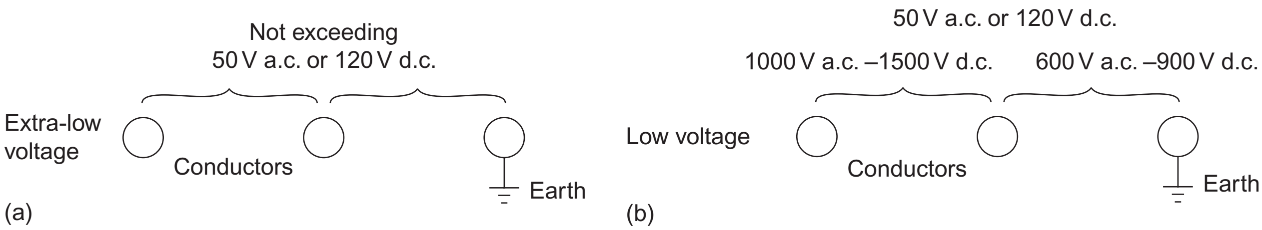

Figure 2.12 Voltage bands.

Measuring current and voltage

As current flows **through** a conductor, it seems logical to expect that any instrument used to measure current would need to have that current flowing **through** it. This is known as a **series** connection (Fig. 2.13).

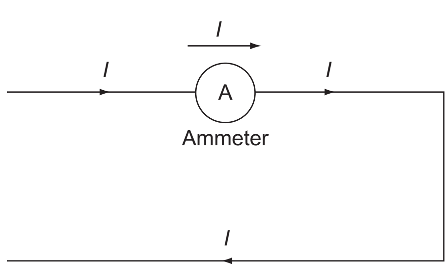

Figure 2.13 Ammeter connections.

Voltage, on the other hand, is a measure of potential difference **between** or **across** two points, and hence a voltage measuring instrument would need to be connected **between** or **across** two points in a circuit. This is known as a **parallel** connection (Fig. 2.14).

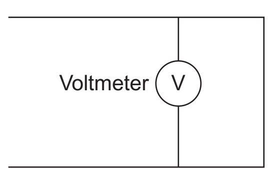

Figure 2.14 Voltmeter connections.

So, the arrangement of instruments to measure the current and voltage associated with a circuit supplying, say, a lamp would be as shown in Fig. 2.15.

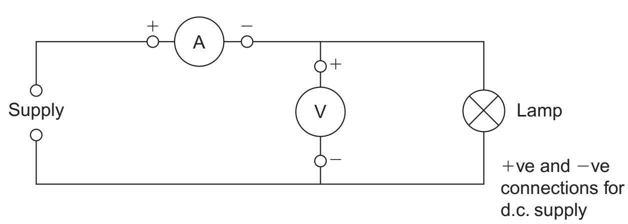

Figure 2.15 Ammeter and voltmeter connections.