

This course module introduces the basic physical models by which we explain the flow of electricity. The Bohr model of an atom – a nucleus surrounded by shells of electrons traveling in discrete orbits – is presented. Electrical current is described as a flow of electrons. Ohm's law – the relationship between voltage, current and electrical resistance – is introduced.

### **Learning Objectives**

Understanding the basic principles of electricity is a foundational skill for all branches of engineering. Understanding electricity is required to use electrical sensors, switches, digital and analog devices, and microcontrollers. In this course, students will use breadboards to assemble electronic components for reading data from sensors and controlling switches, lights, motors and other actuators. The larger purpose is to learn how to incorporate electronic components into solutions to engineering design problems.

Successful completion of this module will enable students to

1. Link basic model of an atom to the flow of electricity;
2. Understand the definition of fundamental quantities related to the flow of electricity: coulomb, amp, volt, ohm, joule and watt;
3. Apply Ohm's Law to single electronic components and to simple circuits.

### **Definition of Electricity and Electrical Charge**

According to the Concise Oxford English Dictionary, revised 10th edition, the first definition of electricity is

*a form of energy resulting from the existence of charged particles (such as electrons or protons), either statically as an accumulation of charge or dynamically as a current.*

Thus, to describe electricity we must introduce the idea of positive and negative electrical charge, which is stored energy associated with particles – electrons and protons. It is tempting to think of electrons and protons as discrete, hard objects, like marbles. However, the physical reality is much more complicated. Electrons are highly mobile concentrations of energy that hold the negative charge. Electrons moving around an atomic nucleus can only occupy discrete or quantized energy levels. Those levels are called electron shells. Protons are themselves composed of subatomic particles that give the entity called a proton its mass and charge.

We will use a somewhat crude and simple model of atoms, protons and electrons that allow us to develop a practical understanding of electricity. It is important to understand that this simple model is just that, a model, not a precisely accurate representation of the complex physical world. We will resist the temptation get lost in the fascinating and bewildering realm of atomic and subatomic physics.

When the arrangement or distribution of electrical charge does not change, it is called *static charge* or *static electricity*. The build-up of electrical charge creates the potential for the flow of electricity. When that flow is prevented, static charge accumulates. When you scuff your stocking feet across a synthetic carpet, you store charge on the surface of our body. The charge may cause the hairs on your body to prickle, or in extreme cases, stand on end. When the accumulated charge is suddenly released, for example, when you touch a light switch or other grounded metal object, you feel a shock as the electrical current surges between your body and the grounding object. The shock is the sudden release or discharge of the static electricity.

Similarly, lightning is the discharge of large amounts of charge accumulated in clouds during storms.

Static electricity is important, at least because the build-up of static charge can cause problems when that charge is released. However, much of modern technology is possible because of the controlled *flow* of electricity, i.e. the movement of charge between regions of positive and negative charge.

### **Conductors, Insulators and Semiconductors**

Materials can be classified as conductors, insulators, and semiconductors according to the ability of the material to allow the flow of electricity. All materials have a measurable property called electrical conductivity that indicates the ability of the material to either allow or impede the flow of electrons. Materials that easily conduct electricity have a high conductivity.

A **conductor** is a material that readily allows the flow of electricity. Metal wires are good conductors, though some metals are better conductors than others. Copper, aluminum, silver and gold are examples of good conductors. Compared to non-conductors, these materials have a high electrical conductivity.

An **insulator** is a material that is a poor conductor. Insulators inhibit the flow of electricity. Rubber, wood, ceramics and air are examples of good insulators. Compared to conductors, these materials have a low electrical conductivity.

If a positively charged region is separated from a negatively charged region by a conductor, then electrical current will flow between the regions. If instead the positively charged region is separated from a negatively charged region by an insulator, little or no electrical current will flow.

A **semiconductor** is a material that has an intermediate tendency to allow the flow of electrons, i.e. it is somewhere between an insulator and a conductor. The conductivity of semiconductor materials can be changed by the presence of an electrical field, exposure to light, or the application of mechanical pressure or heat. The ability to change the apparent electrical conductivity by introducing these stimuli allows semiconductors to be used as the building blocks of *semiconductor devices*.

Semiconductor devices are like switches that allow electricity to flow. Sometimes that switching is controlled intentionally to control the flow of electricity, for example in LEDs (light emitting diodes) and transistors. Other times the switching of the flow of electricity is passive and controlled by the environment, for example in photovoltaic solar cells or semiconductor sensors.

*Transistors* are semiconductor devices that can be used to switch or amplify electrical currents. Digital logic and computing devices like microprocessors, communication chips, and signal processing chips can have hundreds, thousands, millions or billions of transistors.

### **Atomic Structure and the Periodic Chart**

Electrical current is caused by the movement of electrons. The electrical characteristics of matter are determined by its atomic structure, which in turn determines how easily the electrons in the atoms can move.

Matter is made of molecules, which are stable arrangements of chemical elements. A chemical element is the essential constituent of pure substance. Each element has a characteristic atom, which consists of a core or *nucleus* with a fixed number of positively charged particles

called *protons* surrounded by a cloud of negatively charged particles called *electrons*. The nucleus also contains neutrons, particles that have mass, but no charge. Figure 1 is a model of the Helium atom, which has two protons and two neutrons in the nucleus and two electrons orbiting the nucleus.

Each chemical element may exist in several stable arrangements of protons and neutrons. These stable arrangements are called *isotopes*, which have slightly different mass because of the different numbers of neutrons in the nucleus. Isotopes of an element have the same chemical behavior when those elements are combined in molecules with elements of different type. For example, the chemical formula for common table salt is NaCl, which has one atom of sodium (Na) and one atom of chlorine (Cl). The molecules of NaCl are chemically equivalent for all combinations of Na isotopes and Cl isotopes.

An element is characterized by two quantities, its atomic number  $Z$  and its atomic mass  $A$ . The atomic number is the number of protons in the nucleus. Therefore,  $Z$  is always an integer. The atomic mass (or atomic weight) of an isotope is due to the number of protons and neutrons in the nucleus, plus a small contribution from the number of electrons. Because there may be two or more stable isotopes of an element, there may be two or more masses for the stable forms of an element. The atomic mass of an element is the *weighted average* of the masses of the isotopes, where the averaging accounts for the relative abundance of the isotopes on the planet earth. In other words, the atomic mass of an element is determined by the proportions of the isotopes that are found in nature.

The periodic chart is a graphical arrangement of the chemical elements. Each element is represented by a small box that provides a few key pieces of information about that element. Figure 2 is a typical example of a periodic table. The elements in the table are arranged in order of increasing atomic number from left to right and top to bottom. The table also groups elements according to their chemical properties, which explains why the table is not a neat rectangular array of elements.

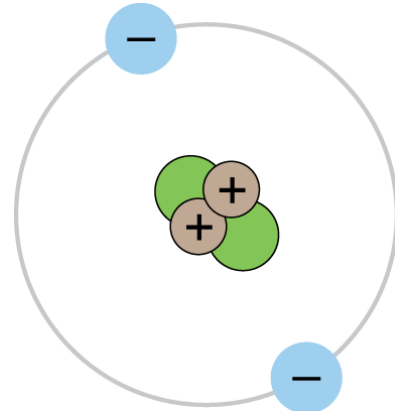


Figure 1. Model of a Helium atom.

## PERIODIC TABLE OF THE ELEMENTS

<http://www.periodni.com>

**GROUP NUMBERS IUPAC RECOMMENDATION (1985)**      **GROUP NUMBERS CHEMICAL ABSTRACT SERVICE (1986)**

**ATOMIC NUMBER**      **RELATIVE ATOMIC MASS (1)**

**SYMBOL**      **ELEMENT NAME**

**Example: Boron (B)**

13 IIIA 5 10.811 B BORON

**PERIOD** 1 2 3 4 5 6 7

**GROUP** 1 IA 2 IIA 3 IIIB 4 IVB 5 VB 6 VIB 7 VIIB 8 VIII 9 VIIIB 10 11 IB 12 IIB 13 IIIA 14 IVA 15 VA 16 VIA 17 VIIA 18 VIIIA

**Element Entries:**

1 1.0079 H HYDROGEN

2 4.0026 He HELIUM

3 6.941 Li LITHIUM

4 9.0122 Be BERYLLIUM

11 22.990 Na SODIUM

12 24.305 Mg MAGNESIUM

19 39.098 K POTASSIUM

20 40.078 Ca CALCIUM

21 44.956 Sc SCANDIUM

22 47.867 Ti TITANIUM

23 50.942 V VANADIUM

24 51.996 Cr CHROMIUM

25 54.938 Mn MANGANESE

26 55.845 Fe IRON

27 58.933 Co COBALT

28 58.693 Ni NICKEL

29 63.546 Cu COPPER

30 65.38 Zn ZINC

31 69.723 Ga GALLIUM

32 72.64 Ge GERMANIUM

33 74.922 As ARSENIC

34 78.96 Se SELENIUM

35 79.904 Br BROMINE

36 83.798 Kr KRYPTON

37 85.468 Rb RUBIDIUM

38 87.62 Sr STRONTIUM

39 88.906 Y YTTRIUM

40 91.224 Zr ZIRCONIUM

41 92.906 Nb NIObIUM

42 95.96 Mo MOLYBDENUM

43 (98) Tc TECHNETIUM

44 101.07 Ru RUTHENIUM

45 102.91 Rh RHODIUM

46 106.42 Pd PALLADIUM

47 107.87 Ag SILVER

48 112.41 Cd CADMIUM

49 114.82 In INDIUM

50 118.71 Sn TIN

51 121.76 Sb ANTIMONY

52 127.60 Te TELLURIUM

53 126.90 I IODINE

54 131.29 Xe XENON

55 132.91 Cs CAESIUM

56 137.33 Ba BARIUM

57-71 La-Lu Lanthanide

72 178.49 Hf HAFNIUM

73 180.95 Ta TANTALUM

74 183.84 W TUNGSTEN

75 186.21 Re RHENIUM

76 190.23 Os OSMIUM

77 192.22 Ir IRIIDIUM

78 195.08 Pt PLATINUM

79 196.97 Au GOLD

80 200.59 Hg MERCURY

81 204.38 Tl THALLIUM

82 207.2 Pb LEAD

83 208.98 Bi BISMUTH

84 (209) Po POLONIUM

85 (210) At ASTATINE

86 (222) Rn RADON

87 (223) Fr FRANCIUM

88 (226) Ra RADIUM

89-103 Ac-Lr Actinide

104 (267) Rf RUTHERFORDIUM

105 (268) Db DUBNIUM

106 (271) Sg SEABORGIUM

107 (272) Bh BOHRIUM

108 (277) Hs HASSIUM

109 (276) Mt MEITNERIUM

110 (281) Ds DARMSTADIUM

111 (280) Rg ROENTGENIUM

112 (285) Cn COPERNICIUM

**LANTHANIDE**

57 138.91 La LANTHANUM

58 140.12 Ce CERIUM

59 140.91 Pr PRASEODYMIUM

60 144.24 Nd NEODYMIUM

61 (145) Pm PROMETHIUM

62 150.36 Sm SAMARIUM

63 151.96 Eu EUROPIUM

64 157.25 Gd GADOLINIUM

65 158.93 Tb TERBIUM

66 162.50 Dy DYSPROSIUM

67 164.93 Ho HOLMIUM

68 167.26 Er ERBIUM

69 168.93 Tm THULIUM

70 173.05 Yb YTTERIUM

71 174.97 Lu LUTETIUM

**ACTINIDE**

89 (227) Ac ACTINIUM

90 232.04 Th THORIUM

91 231.04 Pa PROTACTINIUM

92 238.03 U URANIUM

93 (237) Np NEPTUNIUM

94 (244) Pu PLUTONIUM

95 (243) Am AMERICIUM

96 (247) Cm CURIUM

97 (247) Bk BERKELIUM

98 (251) Cf CALIFORNIUM

99 (252) Es EINSTEINIUM

100 (257) Fm FERMIUM

101 (258) Md MENDELEVIUM

102 (259) No NOBELIUM

103 (262) Lr LAWRENCIUM

(1) Pure Appl. Chem., 81, No. 11, 2131-2156 (2009)  
Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element. However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

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Figure 2. Periodic table of chemical elements. Downloaded 17 August 2010 from [www.periodni.com](http://www.periodni.com).

The display of data for each element varies somewhat according to the aesthetic design of the periodic table. The basic design includes three pieces of information: the atomic number of the element, the one or two-character symbol for the element, and the atomic mass of the element. Figure 3 shows the details of the entry for copper in the periodic table. Copper has the symbol Cu, and it has 29 protons, hence its atomic number is 29. The relative atomic mass of copper is 63.546, which means that on earth, the *average* composition of a sample of pure copper atoms would have a nucleus with 29 protons and approximately 35 (= 64 – 29) neutrons.

Atomic number	29	Relative atomic mass
= number of protons in the nucleus	63.546	
	Cu	Symbol
	COPPER	Element name

Figure 3. Entry in the periodic table for copper.

There are two dominant isotopes of copper,  $^{63}\text{Cu}$  and  $^{65}\text{Cu}$ . The left superscript number in the isotope symbol is the number of nucleons. A nucleon is either a proton or a neutron.  $^{63}\text{Cu}$  has 63 nucleons: 29 protons plus 34 neutrons.  $^{65}\text{Cu}$  has 65 nucleons: 29 protons plus 36 neutrons. On earth, pure copper consists of approximately 69 percent  $^{63}\text{Cu}$  and 31 percent  $^{65}\text{Cu}$ . Neutrons are discrete, so in a typical sample of copper atoms, 69 percent of the atoms would have 36 neutrons and 31 percent would have 34 neutrons. Therefore the average atomic mass is of copper is 63.546.

## Counting Atoms and Atomic Mass

The number of proton, neutrons and electrons determines the mass of an individual atom. The atomic mass of a substance is converted to a bulk, macroscopic mass with a constant known as *Avogadro's number* or *Avogadro's constant*

$$N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$$

The unit of  $N_A$  is 1/mol, where mol is the unit abbreviation for *mole*.  $N_A$  is the number of things – usually atoms or molecules or atomic particles – in a *mole*. A *mole* is the number of things necessary to have a mass in grams that is numerically equal to the atomic mass. For example, a mole of Hydrogen atoms has a mass of 1.0079 g. A mole of copper atoms has a mass of 63.456 g. A mole of NaCl has a mass of 58.442 g ( $22.98977 + 35.453 = 58.442$ ).

## Electrons in Shells: the Bohr Model of the Atom

In the early 1900s, quantum mechanics revolutionized our understanding of physics. Quantum mechanics is a theory of matter and energy that posits that energy only exists of discrete states or quanta. Physicist Niels Bohr hypothesized that electrons can only exist in discrete energy levels or shells as they orbit around the dense nucleus. Figure 4 is a highly simplified schematic of the electron shells for a copper atom. The 29 electrons of copper are arranged in four shells. The innermost (K) shell has two electrons. The next (L) shell has 8 electrons. The next (M) shell has 18 electrons. The outermost (N) shell has just one electron.

The outermost shell of any atom is called the *valence shell*. The electrons in the valence shell are the *valence electrons* and they determine the chemical and electrical properties of the atom. When there are few valence electrons, as in the case of copper, those electrons can be more easily displaced to a nearby atom. The movement of electrons causes an electrical current to flow. In general, the valence shell for metals contains relatively few electrons. Since the valence shell for metals is mostly empty, the exposed electrons can be removed relatively easily. In contrast, elements that are insulators have relatively full valence shells. The valence electrons in an insulator are hard to displace, so the electrons do not “flow” in the presence of an applied electrical potential.

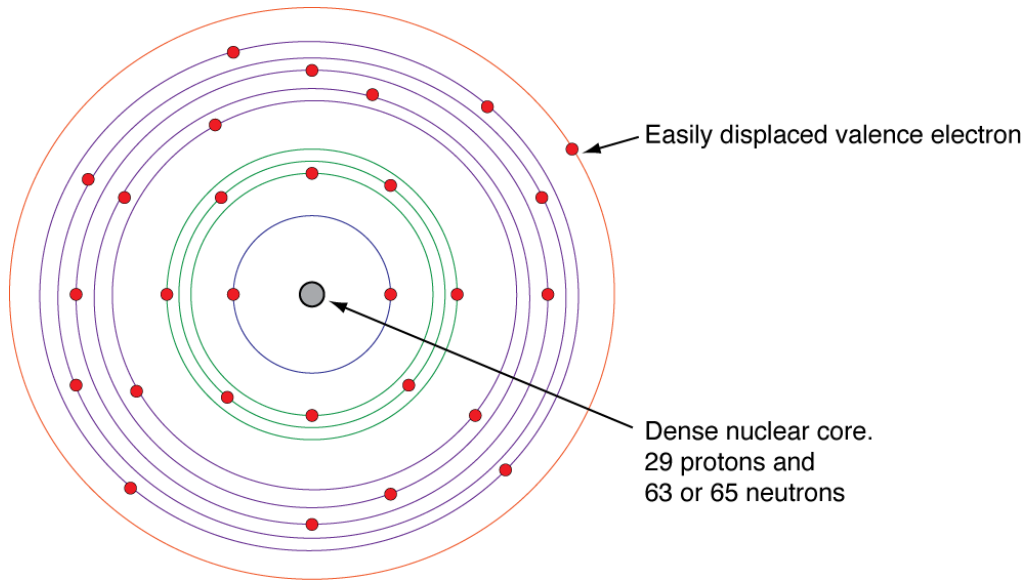


Figure 4. Schematic representation of electron shells for copper. The relative size of the nucleus and electrons is not accurate.

### Electrical Current: The Flow of Charge

Electrical current is the movement of charge. By convention, we say that current flows from the positive terminal to the negative. We could say that “current flows downhill”, from plus to minus, or from high to low. Figure 5 depicts the flow of electrical current from the positive to the negative terminal of a battery when the terminals are connected by a conducting loop. The positively charged terminal of the battery is caused by a deficit of electrons relative to the negatively charged terminal.

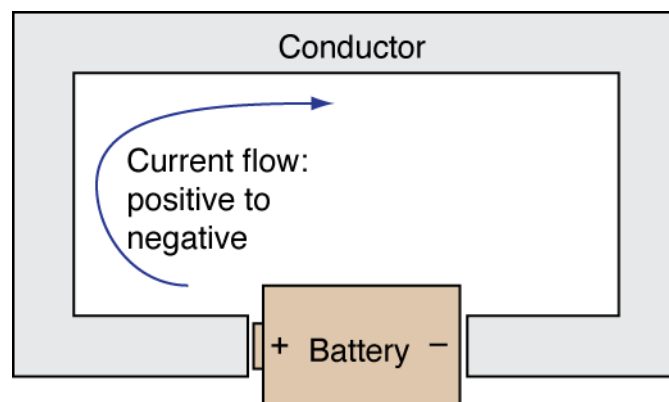


Figure 5. Current in the loop is from regions of positive charge to regions of negative charge.

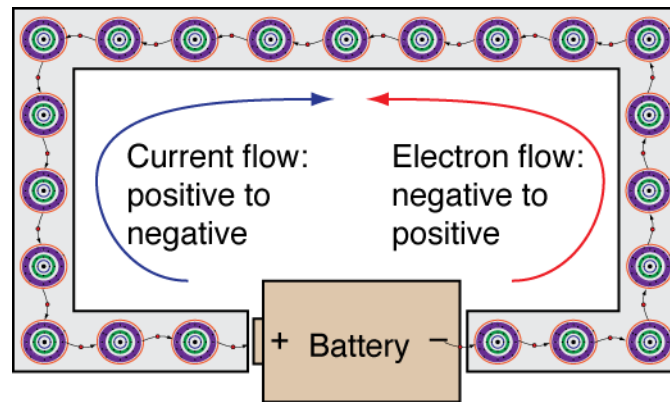
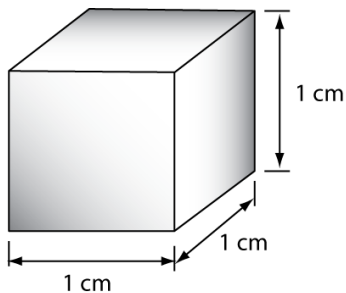


Figure 6. The electron flow is in the opposite direction of the current.  
The larger circles represent atoms and their electron shells.

The atoms in the conductor loop have mobile valence electrons. The valence electrons move between adjacent atoms in the solid resulting in an electrical current. The atoms and their nuclei do not move. Figure 6 is a graphical representation of the transfer of valence electrons between adjacent atoms. As with all of the images in these notes, the visual representation is only meant to suggest how the process works, it is not a literal picture of atoms and the flow of electrons.

Example: How many valence electrons are in a 1cm cube of copper?



*Useful data:*

Atomic mass = 63.55 g/mol

Density of pure copper = 8.94 g/cm<sup>3</sup>

Avogadro's number  $N_A = 6.022 \times 10^{23}$  atoms/mol

First compute the number of atoms,  $N$

$$N = 1 \text{ cm}^3 \times 8.94 \frac{\text{gm}}{\text{cm}^3} \times \frac{1 \text{ mol}}{63.55 \text{ g}} \times \frac{6.022 \times 10^{23} \text{ atoms}}{\text{mol}} = 8.5 \times 10^{22} \text{ atoms}$$

Since each copper atom has one valence electron, there are  $8.5 \times 10^{22}$  valence electrons in a 1 cm cube of copper.

Note:  $N$  is greater than the number of grains of sand on the earth. Compute the number of sand grains by assuming that 10 cm of sand covers all 200 million square miles of the earth's surface. Assume that each grain is 1 mm in diameter and are the packing efficiency is 68 percent.

## Model of Electrical Current

Electrical current is the movement of electrons. Conductors facilitate electrical current because good conductors have valence electrons that can move from atom to atom in the solid.

Figure 7 is a graphical representation of current in a conductor represented by a solid cylinder. The two ends of the conductor have different density of charge. The diagram represents a situation where there is a relative surplus of electrons on the right. Because the conductor connects the regions having a surplus and a deficit of electrons, a current flows.

The path of an individual electron is not straight. However, the number of electrons involved is enormous, so the net flow can be conceptualized as a continuous flow from the negative region having the electron surplus to the positive regions having the electron deficit.

In routine engineering work, we say that current flows from positive to negative. That convention is not a problem as long as we are consistent. However, the convention is actually inconsistent with the physical mechanism. Positively charged particles (protons) do not flow because they are bound in the nucleus of atoms that have a relatively fixed position in the solid.

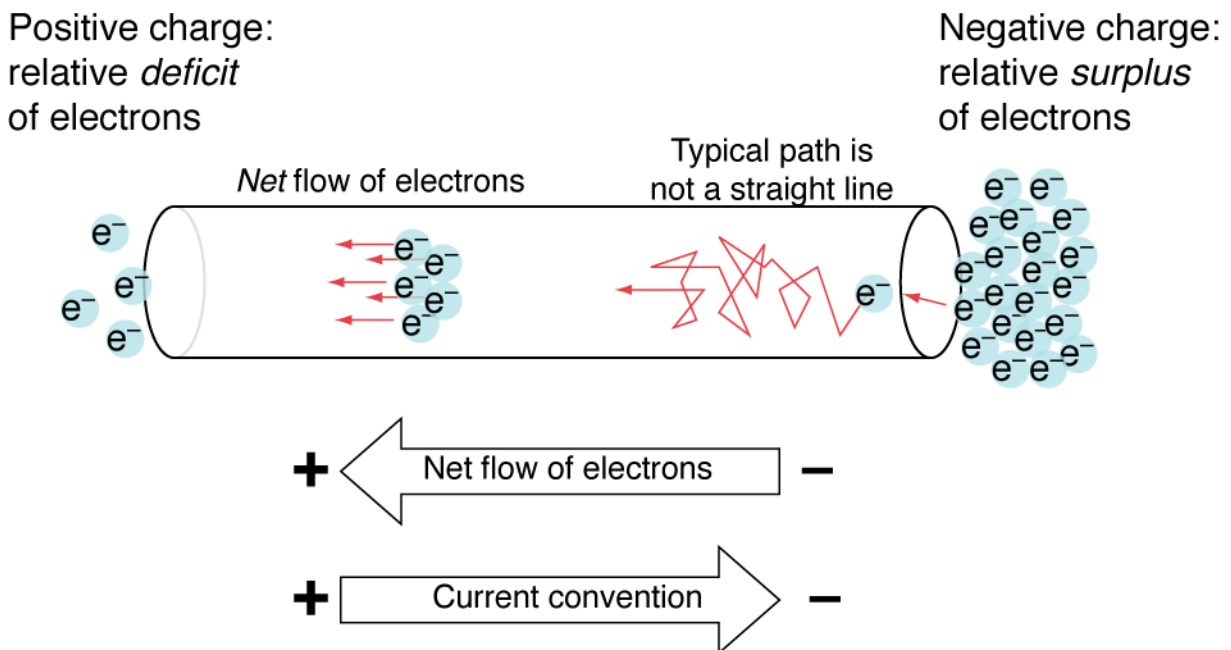


Figure 7. Electrons flow from a negatively charged region to a positively charged region. The common convention is that current flows from a region of positive charge to a region of negative charge.



## Definitions

*Electrical charge* is a fundamental electrical characteristic of matter that results in attraction or repulsion of other matter with electrical charge. Electrical charge is either positive or negative. Two objects with the same electrical charge (both positive or both negative) repel each other. Two objects with opposite electrical charge attract each other.

Electrical charge exists in discrete quantities. The smallest unit of charge is the charge associated with a single electron, which is called the elementary charge. The elementary charge is equal to  $1.602 \times 10^{-19}$  coulomb. This defines a coulomb, which is also given the unit symbol C

$$\text{electrical charge of one electron} = 1.602 \times 10^{-19} \text{ C.}$$

Instead of the number of coulombs associated with a single electron, we can invert the definition to find the number of electrons in a coulomb.

$$1 \text{ C} = 6.24 \times 10^{18} \text{ electrons}$$

*Electrical current* is the flow of electrons, and is expressed in terms of the number of electrons passing a point in a unit time. The symbol for current is  $I$ . The unit of current is *amps*, which has the symbol A. One amp is the flow of one coulomb per second.

$$1 \text{ A} = 1 \frac{\text{C}}{\text{s}}$$

*Voltage* is the force necessary to separate two objects with opposite charge. Voltage is also a measure of the potential energy that can cause the flow of electrons. Voltage has units of energy (Joules) per unit of charge (coulomb). One volt is the defined as energy (in Joule) necessary to separate one coulomb of positive charge from one coulomb of negative charge. It is also the amount of work done (in Joule) when a coulomb of charge moves across a potential of one volt. This last case is depicted in Figure 8. The symbol for voltage is  $V$ .

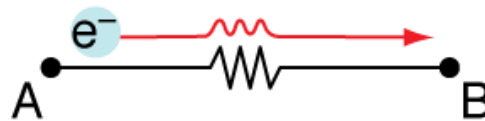


Figure 8. If the voltage between A and B is one volt, then one Joule of work is done when  $6.28 \times 10^{18}$  electrons move from A to B.

$$1 \text{ V} = 1 \frac{\text{J}}{\text{C}}$$

*Electrical resistance* (or just *resistance*) is a measure of the insulating effectiveness of materials. Materials with high resistance are good insulators. The unit of resistance is Ohm and is given the symbol  $\Omega$  (capital omega).

## Ohm's Law

Ohm's law is the fundamental relationship between voltage and current for a steady current through a fixed resistance. Consider the flow of current through a resistor as depicted in Figure 9. For current to flow, there must be a voltage potential  $V$ . The amount of current for a given potential is determined by how readily the material conducts electricity. Instead of working directly with the intrinsic property, the electrical conductivity, we use a macroscopic property  $R$ , which is the overall resistance. To sustain a current  $I$  through a connecting resistance  $R$ , there must be a voltage potential  $V$  given by Ohm's law

$$V = IR$$

This simple equation is the basis for much of the circuit analysis in this course.

Ohm's law can be applied to a single component in a circuit or a loop in a circuit. Figure 10 is a schematic of a simple conduction loop that connects a voltage source  $V_s$  with a resistor  $R$ .

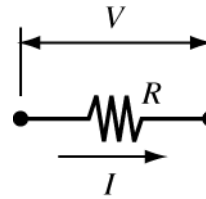
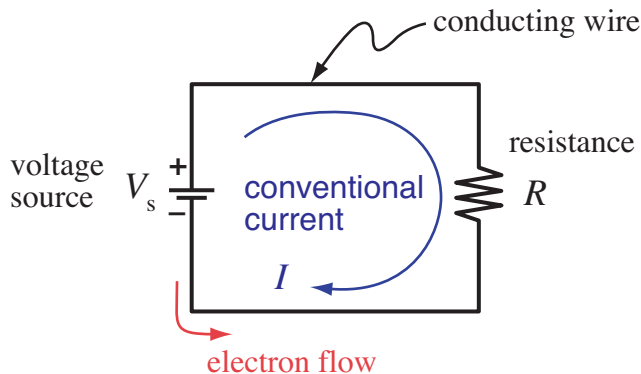


Figure 9. When current of  $I$  flows through a resistor  $R$ , the voltage drop across the resistor is  $V$ .



$$V = I \times R$$

voltage = current  $\times$  resistance  
volts = amps  $\times$  ohms

Figure 10. Ohm's Law applied to a simple loop.