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Dept. of the electrical power
and Machine engineering
Subject / Electrical Eng. Fundamental I

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References:

1. Introductory_Circuit_Analysis-12th by Robert L Boylestad
2. Fundamental electrical circuits By Charles K. Alexander and matthew
3. Electric circuit By James W. Nilsson
4. ENGINEERING CIRCUIT ANALYSIS By William H. Hayt, Jr.
5. Theory and Problems of ELECTRIC CIRCUITS By MAHMOOD NAHVI and JOSEPH A. EDMINISTER.

SYSTEMS OF UNITS

TABLE 1

Comparison of the English and metric systems of units.

ENGLISH	METRIC		SI
	MKS	CGS	
Length: Yard (yd) (0.914 m)	Meter (m) (39.37 in.) (100 cm)	Centimeter (cm) (2.54 cm = 1 in.)	**Meter (m)**
Mass: **Slug** (14.6 kg)	Kilogram (kg) (1000 g)	Gram (g)	**Kilogram (kg)**
Force: **Pound** (lb) (4.45 N)	Newton (N) (100,000 dynes)	Dyne	**Newton (N)**
Temperature: Fahrenheit (°F) $\left(= \frac{9}{5}°C + 32\right)$	Celsius or Centigrade (°C) $\left(= \frac{5}{9}(°F - 32)\right)$	Centigrade (°C)	**Kelvin (K)** K = 273.15 + °C
Energy: Foot-pound (ft-lb) (1.356 joules)	Newton-meter (N•m) or joule (J) (0.7376 ft-lb)	Dyne-centimeter or erg (1 joule = 10^7 ergs)	**Joule (J)**
Time: Second (s)	Second (s)	Second (s)	**Second (s)**

TABLE 2

Multiplication Factors	SI Prefix	SI Symbol
1 000 000 000 000 000 000 = 10^{18}	exa	E
1 000 000 000 000 000 = 10^{15}	peta	P
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

ATOMS AND THEIR STRUCTURE

The orbiting electron carries a negative charge equal in magnitude to the positive charge of the proton

The atomic structure of any stable atom has an equal number of electrons and protons.

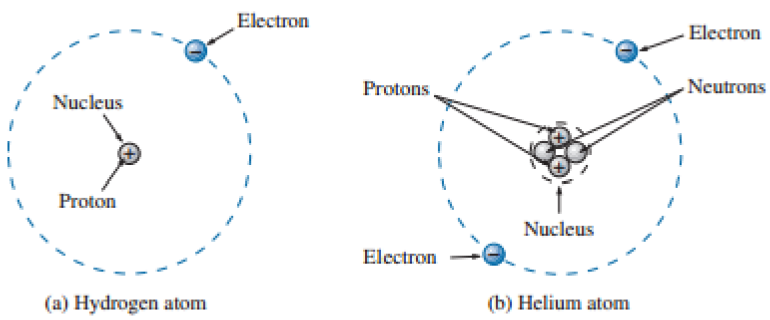

FIG. 1
Hydrogen and helium atoms.

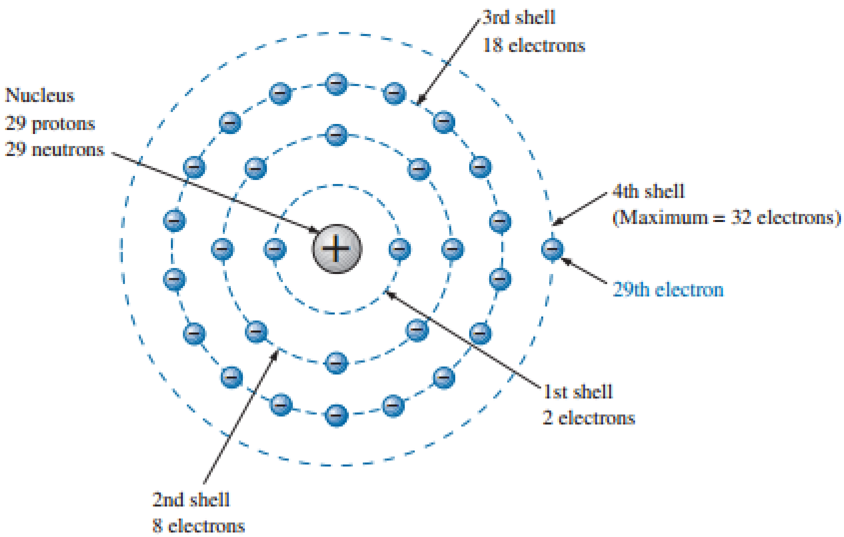

FIG. 2
The atomic structure of copper.

Coulomb's law is the force of attraction between the nucleus and the electron of atomic.

$$F = k\frac{Q_1 Q_2}{r^2} \quad \text{(newtons, N)}$$

where **F** is in newtons (N), **k** = a constant = 9.0 109 Nm^2 /C^2 , Q1 and Q2 are the charges in coulombs and r is the distance between the two charges in meters.

Other metals, that exhibit the same properties as copper, but to a different degree, are silver, gold, and aluminum, and some rarer metals such as tungsten. Additional comments on the characteristics of conductors are in the following sections.

VOLTAGE

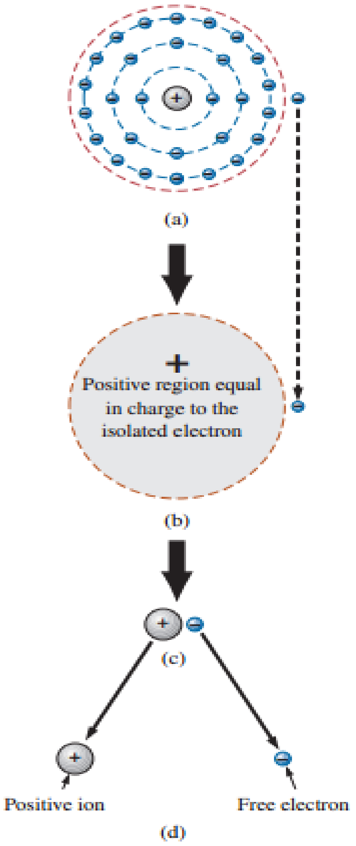

FIG. 4
Defining the positive ion.

every source of voltage is established by simply creating a separation of positive and negative charges.

- One coulomb of charge is the total charge associated with 6.242 1018 electrons.
- if a total of 1 joule (J) of energy is used to move the negative charge of 1 coulomb (C), there is a difference of 1 volt (V) between the two points.

The defining equation is

$$V = \frac{W}{Q} \qquad \begin{aligned} V &= \text{volts (V)} \\ W &= \text{joules (J)} \\ Q &= \text{coulombs (C)} \end{aligned} \qquad (2)$$

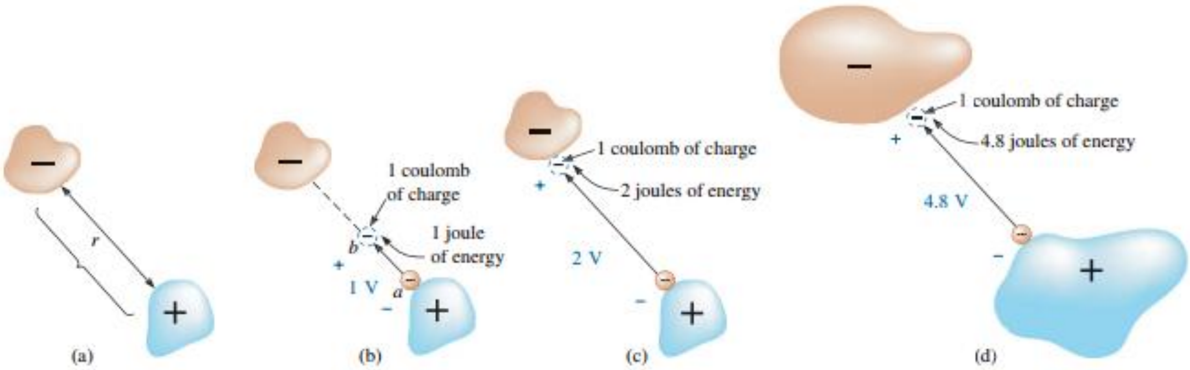

FIG. 5
Defining the voltage between two points.

CURRENT**;** the applied voltage is the starting mechanism—the current is a reaction to the applied voltage

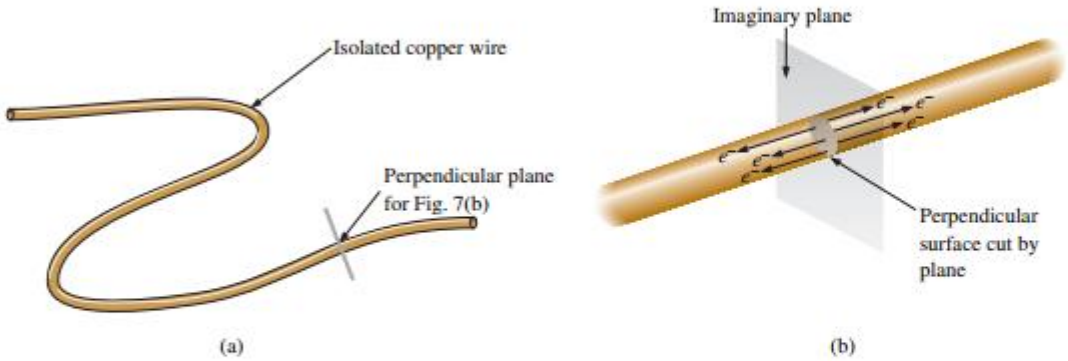

FIG. 7
There is motion of free carriers in an isolated piece of copper wire, but the flow of charge fails to have a particular direction.

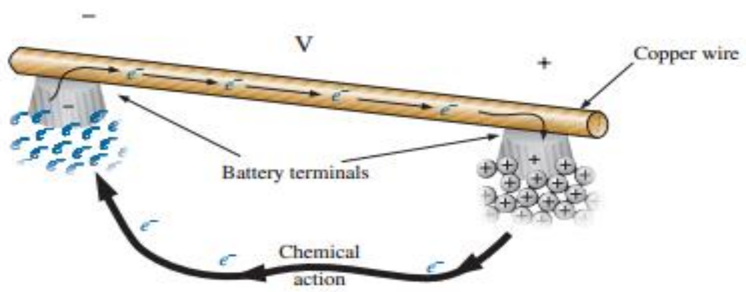

FIG. 8
Motion of negatively charged electrons in a copper wire when placed across battery terminals with a difference in potential of volts (V).

The instant the final connection is made, the free electrons of negative charge drift toward the positive terminal, while the positive ions left behind in the copper wire simply oscillate in a mean fixed position. The flow of charge (the electrons) through the bulb heats up the filament of the bulb through friction to the point that it glows red-hot and emits the desired light**.**

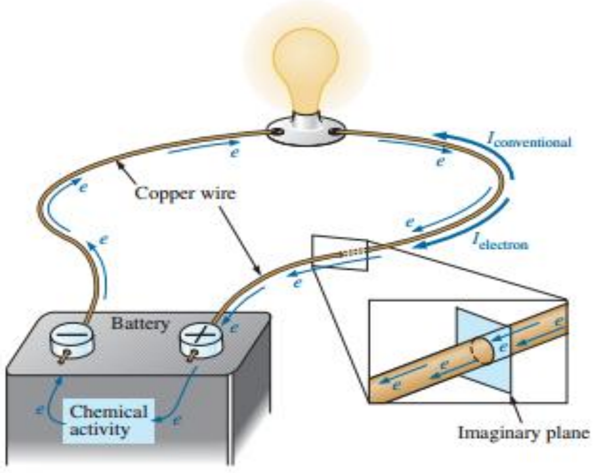

FIG. 9
Basic electric circuit.

if $6.242 * 10^{18}$ electrons (1 coulomb) pass through the imaginary plane in Fig. 9 in 1 second, the flow of charge, or current, is said to be 1 ampere (A).
Using the coulomb as the unit of charge, we can determine the current in amperes from the following equation

$$I = \frac{Q}{t}$$

I = amperes (A)
Q = coulombs (C)
t = time (s)

the applied voltage (or potential difference) in an electrical/electronic system is the "pressure" to set the system in motion, and the current is the reaction to that pressure.

VOLTAGE SOURCES

an electromotive force (emf) is a force that establishes the flow of charge (or current) in a system due to the application of a difference in potential.

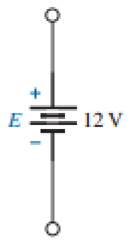

FIG. 11
Standard symbol for a dc voltage source.

In general, dc voltage sources can be divided into three basic types:

(1) batteries (chemical action or solar energy),

(2) Generators (electromechanical),

(3) Power supplies (rectification—a conversion process to be described in your electronics courses).

CONDUCTORS AND INSULATORS

conductors are those materials that permit a generous flow of electrons with very little external force (voltage) applied.

In addition, good conductors typically have only one electron in the valence (most distant from the nucleus) ring.

Insulators are those materials that have very few free electrons and require a large applied potential (voltage) to establish a measurable current level.

TABLE 1

Relative conductivity of various materials.

Metal	Relative Conductivity (%)
Silver	105
Copper	**100**
Gold	70.5
Aluminum	61
Tungsten	31.2
Nickel	22.1
Iron	14
Constantan	3.52
Nichrome	1.73
Calorite	1.44

RESISTANCE: CIRCULAR WIRES

The resistance of any material is due primarily to four factors:

1. Material (resistivity)
2. Length
3. Cross-sectional area
4. Temperature of the material

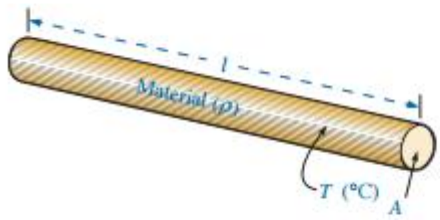

FIG. 2
Factors affecting the resistance of a conductor.

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

ρ = CM-Ω/ft at T = 20°C
l = feet
A = area in circular mils (CM)

Circular Mils (CM)

In Eq. (1), the area is measured in a quantity called **circular mils** (CM). It is the quantity used in most commercial wire tables, and thus it needs to be carefully defined. The *mil* is a unit of measurement for length and is related to the inch by

$$\mathbf{1\ mil = \frac{1}{1000}\ in.}$$

or

$$\mathbf{1000\ mils = 1\ in.}$$

In general, therefore, the mil is a very small unit of measurement for length. There are 1000 mils in an inch, or 1 mil is only 1/1000 of an inch. It is a length that is not visible with the naked eye, although it can be measured with special instrumentation. The phrase *milling* used in steel factories is derived from the fact that a few mils of material are often removed by heavy machinery such as a lathe, and the thickness of steel is usually measured in mils.

By definition,

a wire with a diameter of 1 mil has an area of 1 CM.

as shown in Fig. 4.

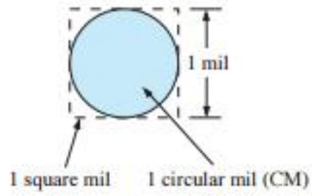

FIG. 4
Defining the circular mil (CM).

An interesting result of such a definition is that the area of a circular wire in circular mils can be defined by the following equation:

$$A_{CM} = (d_{mils})^2 \qquad \textbf{(2)}$$

Verification of this equation appears in Fig. 5, which shows that a wire with a diameter of 2 mils has a total area of 4 CM, and a wire with a diameter of 3 mils has a total area of 9 CM.

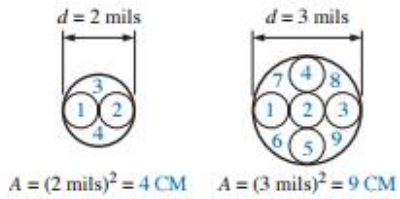

FIG. 5
Verification of Eq. (2): $A_{CM} = (d_{mils})^2$.

Remember, to compute the area of a wire in circular mils when the diameter is given in inches, first convert the diameter to mils by simply writing the diameter in decimal form and moving the decimal point three places to the right. For example,

$$\frac{1}{8}\text{ in.} = 0.\underbrace{125}_{3\text{ places}}\text{ in.} = 125\text{ mils}$$

Then the area is determined by

$$A_{CM} = (d_{mils})^2 = (125\text{ mils})^2 = \mathbf{15{,}625\ CM}$$

Sometimes when you are working with conductors that are not circular, you will need to convert square mils to circular mils, and vice versa. Applying the basic equation for the area of a circle and substituting a diameter of 1 mil results in

$$A = \frac{\pi d^2}{4} = \frac{\pi}{4}(1\text{ mil})^2 = \frac{\pi}{4}\text{ sq mils} \overset{\text{by definition}}{\equiv} 1\text{ CM}$$

from which we can conclude the following:

$$1\text{ CM} = \frac{\pi}{4}\text{ sq mils} \qquad \textbf{(3)}$$

or

$$1\text{ sq mil} = \frac{4}{\pi}\text{ CM} \qquad \textbf{(4)}$$

WIRE TABLES : The wire table was designed primarily to standardize the size of wire produced by manufacturers. As a result, the manufacturer has a larger market, and the consumer knows that standard wire sizes will always be available. The table was designed to assist the user in every way possible; it usually includes data such as the cross-sectional area in circular mils, diameter in mils, ohms per 1000 feet at 20°C, and weight per 1000 feet.

The American Wire Gage (AWG) sizes are given in Table 2 for solid, round copper wire. A column indicating the maximum allowable current in amperes, as determined by the National Fire Protection Association, has also been included. The chosen sizes have an interesting relationship.

TABLE 2
American Wire Gage (AWG) sizes.

	AWG #	Area (CM)	Ω/1000 ft at 20°C	Maximum Allowable Current for RHW Insulation (A)*
(4/0)	**0000**	211,600	0.0490	**230**
(3/0)	**000**	167,810	0.0618	**200**
(2/0)	**00**	133,080	0.0780	**175**
(1/0)	**0**	105,530	0.0983	**150**
	1	83,694	0.1240	**130**
	2	66,373	0.1563	**115**
	3	52,634	0.1970	**100**
	4	41,742	0.2485	**85**
	5	33,102	0.3133	—
	6	26,250	0.3951	**65**
	7	20,816	0.4982	—
	8	16,509	0.6282	**50**
	9	13,094	0.7921	—
	10	10,381	0.9989	**30**
	11	8,234.0	1.260	—
	12	6,529.9	1.588	**20**
	13	5,178.4	2.003	—
	14	4,106.8	2.525	**15**
	15	3,256.7	3.184	
	16	2,582.9	4.016	
	17	2,048.2	5.064	
	18	1,624.3	6.385	
	19	1,288.1	8.051	
	20	1,021.5	10.15	
	21	810.10	12.80	
	22	642.40	16.14	
	23	509.45	20.36	
	24	404.01	25.67	
	25	320.40	32.37	
	26	254.10	40.81	
	27	201.50	51.47	
	28	159.79	64.90	
	29	126.72	81.83	
	30	100.50	103.2	
	31	79.70	130.1	
	32	63.21	164.1	
	33	50.13	206.9	
	34	39.75	260.9	
	35	31.52	329.0	
	36	25.00	414.8	
	37	19.83	523.1	
	38	15.72	659.6	
	39	12.47	831.8	
	40	9.89	1049.0	

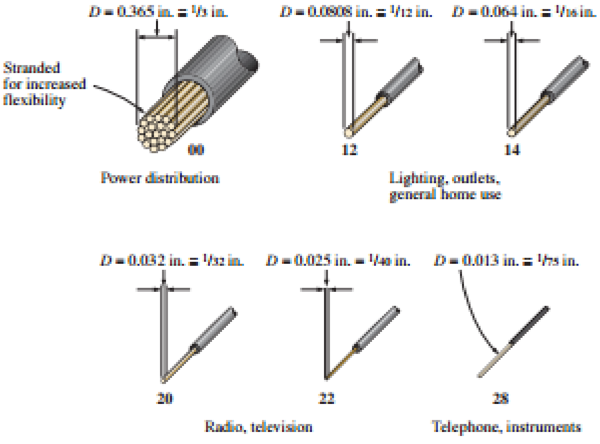

FIG. 8
Popular wire sizes and some of their areas of application.

EXAMPLE 6 For the system in Fig. 9, the total resistance of *each* power line cannot exceed 0.025 Ω, and the maximum current to be drawn by the load is 95 A. What gage wire should be used?

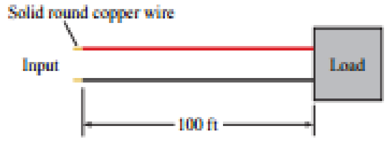

FIG. 9
Example 6.

Solution:

$$R = \rho\frac{l}{A} \Rightarrow A = \rho\frac{l}{R} = \frac{(10.37\ \text{CM-}\Omega/\text{ft})(100\ \text{ft})}{0.025\ \Omega} = \mathbf{41{,}480\ CM}$$

Using the wire table, we choose the wire with the next largest area, which is #4, to satisfy the resistance requirement. We note, however, that 95 A must flow through the line. This specification requires that **#3 wire** be used since the #4 wire can carry a maximum current of only 85 A.