BLM1612 - Circuit Theory

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Units with Prefixes and Significant Figures
Charge, Electric Current, Voltage, Power, and Energy
Ohm's Law

Objectives of the Lecture

- Introduce the electrical quantities or variables that are used in the field of Electrical and Computer Engineering.
- Present the prefixes to the units associated with the variables that will be used frequently in this course.
- Review significant figures.
- Explain how you should present the results of your calculations.

Objectives of the Lecture

- Discuss the mathematical relationships between charge, current, voltage, power, and energy.
- Explain the differences between positive and negative power using passive sign convention.
- Describe the application of the conservation of energy in electrical circuits.
- Introduce active and passive circuit elements.
- Describe a basic electric circuit, which may be drawn as a circuit schematic or constructed with actual components.

Units of Measurement

- As engineers, we deal with measurable quantities.
- Measurement must be communicated in a standard language.
- The International System of Units (SI),
  - adopted by the General Conference on Weights and Measures in 1960.
- In SI, there are seven principal units from which the units of all other physical quantities can be derived.

Units of Measurement

- Six basic SI units and one derived unit.

Quantity	Basic unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Charge	coulomb	C

More Units

Name	Symbol	Quantity	Expressed in terms of other SI units	Expressed in terms of SI base units
hertz	Hz	frequency		s^{-1}
newton	N	force		$kg{\cdot}m{\cdot}s^{-2}$
joule	J	energy, work	N·m	$kg{\cdot}m^{2}{\cdot}s^{-2}$
watt	W	power	J/s	$kg{\cdot}m^{2}{\cdot}s^{-3}$
coulomb	C	electric charge		s·A
volt	V	voltage	W/A or J/C	$kg{\cdot}m^{2}{\cdot}s^{-3}{\cdot}A^{-1}$
ohm	Ω	electric resistance	V/A	$kg{\cdot}m^{2}{\cdot}s^{-3}{\cdot}A^{-2}$
farad	F	electric capacitance	C/V	$kg^{-1}{\cdot}m^{-2}{\cdot}s^{4}{\cdot}A^{2}$
henry	H	inductance	Wb/A	$kg{\cdot}m^{2}{\cdot}s^{-2}{\cdot}A^{-2}$
weber	Wb	magnetic flux	V·s	$kg{\cdot}m^{2}{\cdot}s^{-2}{\cdot}A^{-1}$

- **joule**: fundamental unit of ***work or energy***
- 1 J = 2.78×10^{-7} kW·h = 2.39×10^{-4} kcal
- Since the **joule** is also a **watt-second** and the common unit for electricity sales to homes is the kWh (kilowatt-hour), a kWh is thus 1000 (kilo) × 3600 seconds = 3.6 MJ (megajoules).

Units of Measurement

- One great advantage of the SI unit is that it uses prefixes based on the power of 10 to relate larger and smaller units to the basic unit.
- For example, the following are expressions of the same distance in meters (m):
  - 600 000 000 mm
  - 600 000 m
  - 600 km

The SI prefixes.

Multiplier	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

Units of Measurement

- The numerical value substituted into an equation must have the unit of measurement specified by the equation.
- For example,
  - consider the equation for the velocity $v = d / t$.
    - v: velocity, d: distantance, t: time
  - Assume that the following data are obtained for a moving object: d = 4000 m, t = 1 min and v is desired in km per hour.
  - Incorrect answer:
    - v = 4000 / 1 = 4000 kmh
  - Correct answer:
    - $v = 4000\times10^{-3}$ / (1/60) = 240 kmh

Units of Measurement

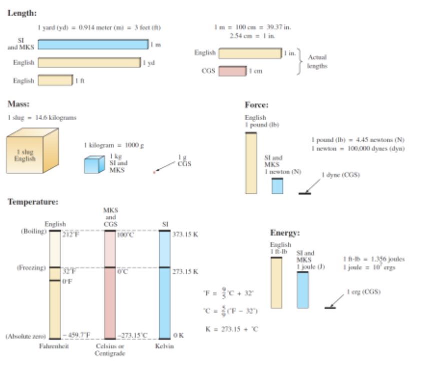
- Before substituting numerical values into an equation, be absolutely sure of the following:
  - Each quantity has the proper unit of measurement as defined by the equation.
  - The proper magnitude of each quantity as determined by the defining equation is substituted.
  - Each quantity is in the same system of units (or as defined by the equation).
  - The magnitude of the result is of a reasonable nature when compared to the level of the substituted quantities.
  - The proper unit of measurement is applied to the result.

Systems of Units

- Comparison of the English and metric systems of units.

English	Metric		
	MKS	CGS	SI
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)**

Comparison of units of the various systems of units



Standards of some units

- The meter is defined with reference to the speed of light in a vacuum, which is **299**792**458** m/s.
  - It was originally defined in 1790 to be 1/**10**000**000** the distance between the equator and either pole at sea level, a length preserved on a platinum-iridium bar at the International Bureau of Weights and Measures at Sèvres, France.
- The kilogram is defined as a mass equal to 1000 times the mass of one cubic centimeter of pure water at 4°C.
  - This standard is preserved in the form of a platinum-iridium cylinder in Sèvres.

Standards of some units

- The second is redefined in 1967 as 9**192**631**770** periods of the electromagnetic radiation emitted by a particular transition of cesium atom.
  - It was originally defined as 1/86**400** of the mean solar day.
  - However, Earth's rotation is slowing down by almost 1 second every 10 years.

13

Significant Figures, Accuracy, Round off

- Two types of numbers:
  - Exact
    - For example 12 apples
  - Approximate
    - Any reading obtained in the laboratory should be considered approximate
- The precision of a reading can be determined by the number of significant figures (digits) present.
- Accuracy refers to the closeness of a measured value to a standard or known value
- For approximate numbers, there is often a need to round off the result
  - that is, you must decide on the appropriate level of accuracy and alter the result accordingly.
    - For example, $3.186 \cong 3.19 \cong 3.2$

14

Powers of ten

- To express very large and very small numbers
- The notation used to represent numbers that are integer powers of ten is as follows:

$$1 = 10^0 \qquad 1/10 = 0.1 = 10^{-1}$$
$$10 = 10^1 \qquad 1/100 = 0.01 = 10^{-2}$$
$$100 = 10^2 \qquad 1/1000 = 0.001 = 10^{-3}$$
$$1000 = 10^3 \qquad 1/10{,}000 = 0.0001 = 10^{-4}$$

15

Powers of ten

- Some important mathematical equations and relationships pertaining to powers of ten:

$$\frac{1}{10^n} = 10^{-n} \qquad \frac{1}{10^{-n}} = 10^n$$

$$(10^n)(10^m) = (10)^{(n+m)}$$

$$\frac{10^n}{10^m} = 10^{(n-m)}$$

$$(10^n)^m = 10^{nm}$$

16

Powers of ten

- Addition and subtraction

$$A \times 10^n \pm B \times 10^n = (A \pm B) \times 10^n$$

- Multiplication

$$(A \times 10^n)(B \times 10^m) = (A)(B) \times 10^{n+m}$$

- Division

$$\frac{A \times 10^n}{B \times 10^m} = \frac{A}{B} \times 10^{n-m}$$

- Power

$$(A \times 10^n)^m = A^m \times 10^{nm}$$

17

Scientific notation vs. Engineering notation

- Scientific notation and engineering notation make use of powers of ten, with restrictions on the mantissa (multiplier) or scale factor (power of ten).
  - Scientific notation requires that the decimal point appear directly after the first digit greater than or equal to 1 but less than 10.
  - Engineering notation specifies that all powers of ten must be multiples of 3, and the mantissa must be greater than or equal to 1 but less than 1000.

18

Scientific notation vs. Engineering notation

- Scientific notation example:

$$\frac{1}{3} = 3.33333333333\text{E}-1 \quad \frac{1}{16} = 6.25\text{E}-2 \quad \frac{2300}{2} = 1.15\text{E}3$$

$$\frac{1}{3} = 3.33\text{E}-1 \quad \frac{1}{16} = 6.25\text{E}-2 \quad \frac{2300}{2} = 1.15\text{E}3$$

- Engineering notation example:

$$\frac{1}{3} = 333.333333333\text{E}-3 \quad \frac{1}{16} = 62.5\text{E}-3 \quad \frac{2300}{2} = 1.15\text{E}3$$

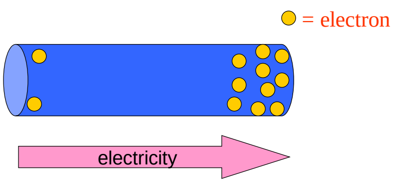
$$\frac{1}{3} = 333.33\text{E}-3 \quad \frac{1}{16} = 62.50\text{E}-3 \quad \frac{2300}{2} = 1.15\text{E}3$$

Example-01

- 1.2 kWh toaster takes roughly 4 minutes to heat four slices of bread.
  - Find the cost of operating the toaster once per day for 1 month (30 days).
    - Assume energy costs 0.5 TL/kWh.
  - Answer…
  - $(1.2/60) \times 4 \times 30 \times 0.5 = 1.2$ TL
- The clock speed of your computer is 2.6 GHz.
- This clock speed is equal to…
  - ……………MHz – 2.6×10^3 MHz
  - ……………KHz – 2.6×10^6 KHz
  - ……………HZ – 2.6×10^9 HZ

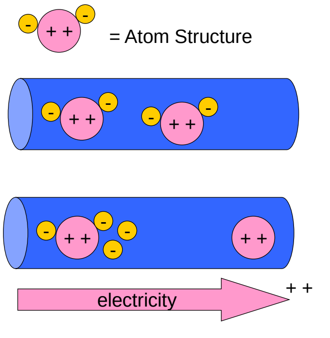
Electricity

- Electricity is a result from the flow of electrons.



  - Electricity flows in the opposite direction of electron flow.

Electric Current vs. Electron Current



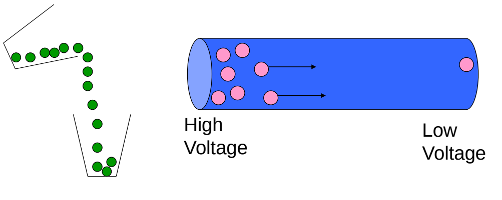
Electric current

- We cannot see electric current.
- We need a metaphor.
- Which thing has similar property with electricity??

Water

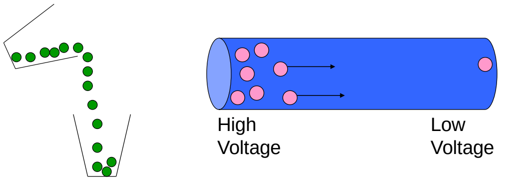
Electric current

- Electricity is similar to water flow.
  - Water flows from high level to low level.
  - Electricity flows from high voltage to low voltage.



Measurement of Electricity

- Since we use electricity to do work for us, how can we measure its energy?
- How can we measure the water power?
  - Think about a water gun.



- strong (fast, high kinetic energy) Voltage
- amount of water Current

25

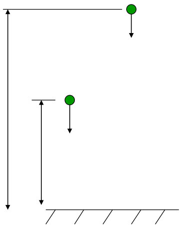
Measurement of Electricity

- Imagine the water power at the outlet

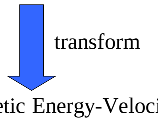
26

Electric Potential

- Which water drop has more impact force at the ground?



- Potential Energy-Height



- Kinetic Energy-Velocity
  - Electric potential can be compared with the height of the water drop from the reference ground

27

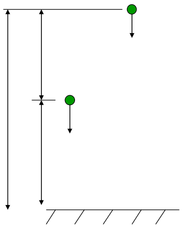
Ground: Reference Point

- Normally, we measure height compared to the sea level.
- Also, electric potential at a point can be measured compared to the electric potential at the ground.
- Electric potential, or voltage has a unit volt(V).
- Ground always has 0 volts.

28

Voltage

- Voltage is a difference of electric potential between 2 points



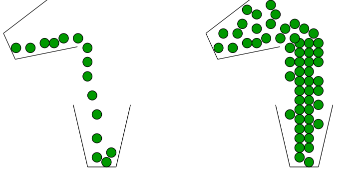
Unit: Volt

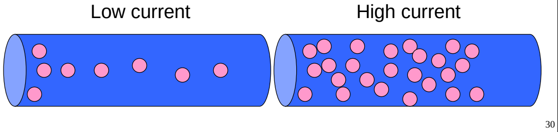
- Compare to the height of 2 water drops

29

Electric Current

Unit: Ampere, Amp (A)





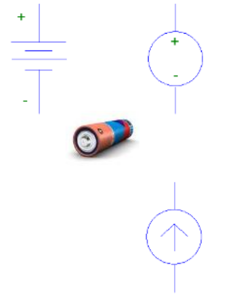
30

Circuit Components

- Active elements
  - Independent power sources
    - voltage, current
  - Dependent power sources
    - voltage, current
- Passive Elements
  - Resistors
  - Capacitors
  - Inductors
- Measurement Devices
  - Ampermeters:
    - measure current
  - Voltmeters:
    - measure voltage
- Ground
  - reference point
- Electric Wire
- Switches
- Protective devices
  - Fuse

Independent Power Sources

- Independent voltage source outputs a voltage, either dc or time varying, to the circuit no matter how much current is required.
- Independent current source outputs a dc or ac current to the circuit no matter how much voltage is required.

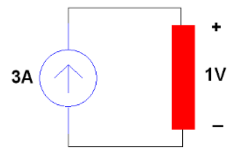


Independent Power Sources

- Current can flow in and out of an independent voltage source, but the polarity of the voltage is determined by the voltage source.
- There is always a voltage drop across the independent current source and the direction of positive current is determined by the current source.

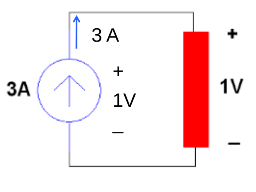
Example-02…

- 1V is dropped across some element (in red) and the wires to that element are connected directly to the independent current source.

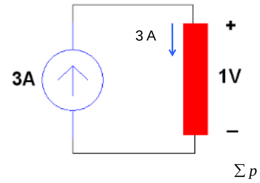


…Example-02…

- This means that 1V is also dropped across the independent current source. Therefore, the current source is generated 1 V(3 A) = 3 W of power.
- Passive sign convention: When current leaves the + side of a voltage drop across the independent current source, the power associated with the current source is: $p = -3\text{ A}(1\text{ V}) = -3\text{ W}$



…Example-02…



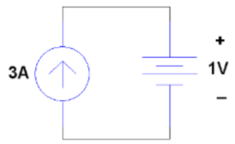
- Conservation of energy means that the other element in red must be dissipating 3 W of power.

$$\sum p = p_{current\,source} + p_{red\,element} = 0$$

$$p_{current\,source} = -3\text{ W; therefore } p_{red\,element} = 3\text{ W}$$

- Passive sign convention: When current enters the + side of a voltage drop across the element in red, the power associated with this element is: $p = 3\text{ A}(1\text{ V}) = 3\text{ W}$

…Example-02

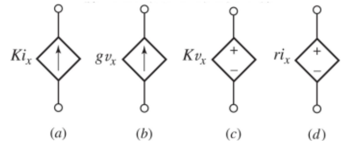


- Suppose the red element was an independent voltage source.

- This means is that the independent current source happens to be supplying power to the independent voltage source, which is dissipating power.
- This happens when you are charging a battery, which is considered to be an independent voltage source.

Dependent Power Sources

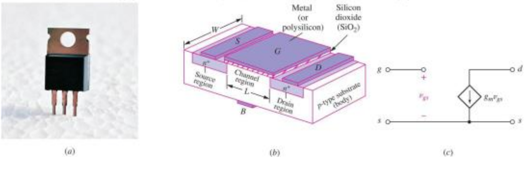
- Dependent V/C source
  - source whose V/C is dependent upon or controlled by some V/C at another point



- (a) current-controlled current source (CCCS)
- (b) voltage-controlled current source (VCCS)
- (c) voltage-controlled voltage source (VCVS)
- (d) current-controlled voltage source (CCVS)

Dependent Power Sources

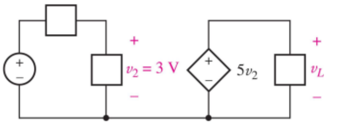
- useful for analyzing (simplifying) the behavior of complicated circuit elements (e.g. transistors, operational amplifiers)



  - Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

Example Dependent Sources

- If v_2 = 3 V, find the voltage v_L in the circuit below.
  - Assume that all points along a wire that do not cross a circuit element have the same voltage.

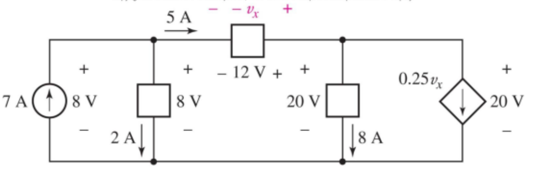


v_2 = 3 V

$v_L = 5 \times v_2 = 5 \times 3 = 15$ V

Example-03

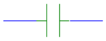
- Determine the power absorbed by each element in the circuit



Passive Elements

- The magnitude of the voltage drop and current flowing through passive devices depends on the voltage and current sources that are present and/or recently attached to the circuit.
  - These components can dissipate power immediately or store power temporarily and later release the stored power back into the circuit.

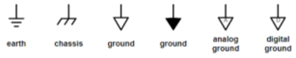
Passive Components

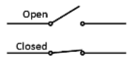
Component	Symbol	Basic Measure (Unit)
Resistor 		Ohm (Ω)
Inductor 		Henry (H)
Capacitor 		Farad (F)

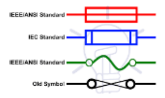
43

Other Basic Circuit Elements

Symbol

- Electric wire 
- Ground  

- Switch  

- Fuse  

44

Switches

- Switches are used to control whether a complete path is formed from an end of at least one power supply to the other end of the same power supply (closed circuit).
  - Current will only flow when there is a closed circuit.
- Switches can be mechanical, as are used on light switches in your home, or are electronic switches, which are semiconductor based.
- Electronic switches are used in TV sets, for example, to turn on the TV when an infrared optical signal from the remote control is detected.

45

Protective Devices

- Circuits that have carry dangerous levels of current and voltages are required to include fuses, circuit breakers, or ground fault detectors by federal and state electrical safety codes.
  - These protective devices are designed to create an open circuit, or a break in the round trip path in the circuit, when a malfunction of a component or other abnormal condition occurs.
  - The speed of response of the protective device, fast-acting or time-delay (slow-blow) is determine by the engineer, based upon the expected type of malfunction.

46

Wires

- Wires are assumed to have zero resistance; i.e., they are ideal conductors or short circuits.
  - The current carrying capability of a wire is determined by its diameter or cross-sectional area.
  - AWG, American wire gauge, is the standard followed in the US and is used to rate how much current a wire can safely carry.
  - The larger the gauge wire, the smaller its current carrying capability is.
    - The AWG standard includes copper, aluminum and other wire materials.
    - Typical household copper wiring is AWG number 12 or 14.
    - Telephone wire is usually 22, 24, or 26.
    - The higher the gauge number, the smaller the diameter and the thinner the wire.

47

AWG to square mm cross sectional area

American Wire Gauge (#AWG)	Diameter (inches)	Diameter (mm)	Cross Sectional Area (mm^2)
0000 (4/0)	0.460	11.7	107
000 (3/0)	0.410	10.4	85.0
00 (2/0)	0.365	9.27	67.4
0 (1/0)	0.325	8.25	53.5
1	0.289	7.35	42.4
2	0.258	6.54	33.6
3	0.229	5.83	26.7
4	0.204	5.19	21.1
5	0.182	4.62	16.8
6	0.162	4.11	13.3
7	0.144	3.67	10.6
8	0.129	3.26	8.36
9	0.114	2.91	6.63
10	0.102	2.59	5.26

American Wire Gauge (#AWG)	Diameter (inches)	Diameter (mm)	Cross Sectional Area (mm^2)
11	0.0907	2.30	4.17
12	0.0808	2.05	3.31
13	0.0720	1.83	2.63
14	0.0641	1.63	2.08
15	0.0571	1.45	1.65
16	0.0508	1.29	1.31
17	0.0453	1.15	1.04
18	0.0403	1.02	0.82
19	0.0359	0.91	0.65
20	0.0320	0.81	0.52
21	0.0285	0.72	0.41
22	0.0254	0.65	0.33
23	0.0226	0.57	0.26
24	0.0201	0.51	0.20
25	0.0179	0.45	0.16
26	0.0159	0.40	0.13

48

Ground

- Earth ground is a ground that is physically connected to the earth, itself.
  - All homes have an earth ground
    - a wire connected to a metal pipe that is driven into the ground immediately next to the house.
    - Wires that have a green jacket or are bare copper are connected to this pipe.
- Reference ground or common is used in a circuit to indicate a point where the voltage in the circuit is equal to zero.

49

General Rules

- All points on a same electric wire have the same voltage.
- A voltage source always have voltage difference of its pins equal to its value.
- A current source always have current pass through it equal to its value.
- Ground always has zero voltage. (0 volts)

50

Electric Flow Rule

- Electric current flows from high voltage to low voltage when there is a path.
- Electric current can freely pass through electric wire.
- Electric current can flow through a resistor with the amount according to Ohm's law.
- Electric current can flow through a voltage source with the amount depended on other components in the circuit.
- Electric current can flow pass a current source according to its value.

51

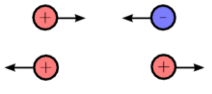
Charge

- is the fundamental property of matter that causes it to experience a force when placed in electro magnetic field and refers to electrons & protons
- The absolute value of the charge on an electron is 1.6×10^{-19} C
- The symbol used is Q or q
  - Uppercase is used to denote a steady-state or constant value
  - Lowercase is used to denote an instantaneous value or time-varying quantity

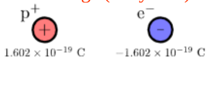
52

Charge

- Electrical property of atomic particles
  - Electrons are negatively charged
  - Protons are positivity charged
  - particles that attract each other (opposite "charge") or repel each other (same "charge")



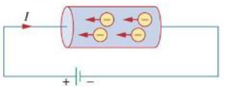
  - fundamental unit of charge (SI system) = coulomb



53

Current

- The movement of charge is called a current



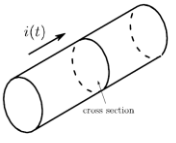
  - Historically the moving charges were thought to be positive
- The mechanism by which electrical energy is transferred
  - Send power from generation point to consumption point
  - Send signals from source to sink

54

Current

- Symbol used is i or I
- Current, i, is measured as charge moved per unit time through an element.

$$i = \frac{dq}{dt} \qquad Q = \int_{t_1}^{t_2} i\,dt$$

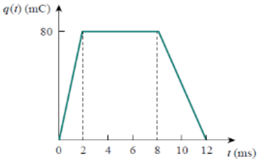


- Amount of charge that has passed a given point:

$$q(t) = \int_{t_0}^{t} i(\tau)d\tau + q(t_0)$$

Example-04

- The charge entering a certain element is shown in below Figure.



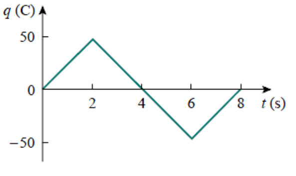
- Find the current at:
  - (a) $t = 1$ ms
  - (b) $t = 6$ ms
  - (c) $t = 10$ ms

$$i = \frac{dq}{dt}$$

  – The slope is defined as the ratio of the vertical change between two points, to the horizontal change between the same two points.

Example-05

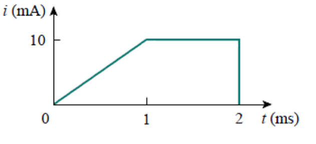
- The charge flowing in a wire is plotted in below Figure.
- Sketch the corresponding current.



$$i = \frac{dq}{dt}$$

Example-06

- The current flowing past a point in a device is shown in below Figure.
- Calculate the total charge through the point.



$$Q = \int_{t_1}^{t_2} i\,dt$$

DC vs. AC

- DC (or dc) is the acronym for direct current.
  – The current remains constant with time.
    - Uppercase variables are used when calculating dc values.
- AC (or ac) is the acronym for alternating current.
  – Specifically, AC current varies sinusoidally with time and the average value of the current over one period of the sinusoid is zero.
    - Lowercase variables are used when calculating ac values.
  – Other time-varying currents exist, but there isn't an acronym defined for them.

Voltage (Potential Difference)

- The electromotive force (emf) that causes charge to move.
- 1 Volt = 1 Joule/1 Coulomb

$$\text{v} = \frac{dw}{dq}$$

Power

- The change in energy as a function of time is power, which is measured in watts (W).

$$p = \frac{dw}{dt} = \frac{dw}{dq}\frac{dq}{dt} = \text{v}i$$

Energy

- Energy is the capacity to do work.

$$w = \int_{t_1}^{t_2} p\,dt = \int_{t_1}^{t_2} \text{v}\,i\,dt$$

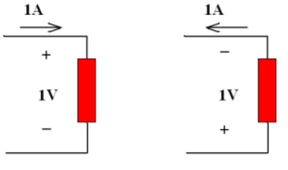
- Units for energy are kW-hr, which is what the electric company measures on your electric meter.

1 kW-hr = 3.6 MJ.

Positive vs. Negative Power

- Power consumed/dissipated by a component is positive power

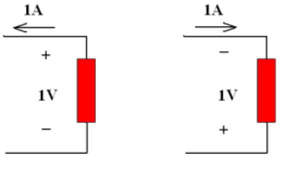
P = + 1W



Passive Sign Convention

- Generated power has a negative sign

P = -1W



Conservation of Energy (Tellegen's Theorem)

- All power instantaneously consumed by components must be instantly generated by other components within the circuit.
- For this reason, the algebraic sum of power in a circuit, at any instant of time, must be zero

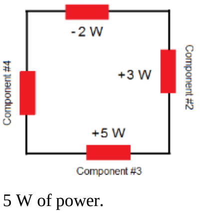
$$\sum p = 0$$

- The energy absorbed or supplied by an element from time t_0 to time t is

$$w = \int_{t_0}^{t} p\,dt = \int_{t_0}^{t} vi\,dt$$

Example-07

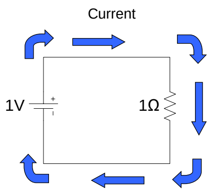
- There are 4 electrical components in the circuit shown to the right.
- Component #1 is generating 2 W of power and supplying this power to the circuit.
- Components #2 and #3 are consuming power.
- Component #2 is dissipating 3 W of power while Component #3 is dissipating 5 W of power.
- Component #4 must be generating 6 W of power in order to maintain the Conservation of Energy.



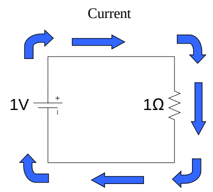
$$\sum p = p_{Component\#1} + p_{Component\#2} + p_{Component\#3} + p_{Component\#4} = 0$$

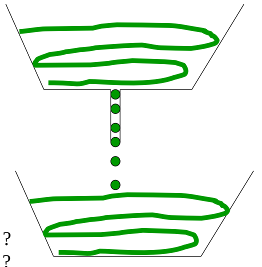
$$p_{Component\#4} = -(p_{Component\#1} + p_{Component\#2} + p_{Component\#3}) = -(-2\text{ W} + 3\text{ W} + 5\text{ W}) = -6\text{ W}$$

Simple DC Circuit



Metaphor



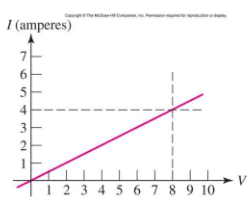


- Increasing V is compared to ?
- Increasing R is compared to ?

Ohm's Law

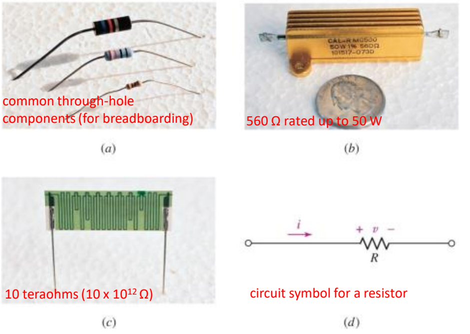
- first discussed by Georg Simon Ohm (German physicist) in a pamphlet describing voltage & current measurements

$$V = I \cdot R \qquad v = i \cdot r$$



- the voltage across a conducting material is linearly proportional to the current flowing through that material
- constant of proportionality = the resistance of the material
- unit of resistance = **ohm**
- 1 Ω = 1 V/A

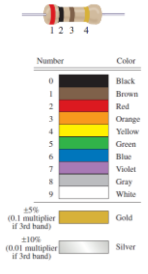
Resistors



(a) (b) (c) (d)

Resistors & Tolerance

- Real resistors are manufactured within a specific tolerance (5%, 10%, 20%).



- The first two bands represent the first and second digits, respectively.
  - They are the actual first two numbers that define the numerical value of the resistor.
- The third band determines the power-of-ten multiplier for the first two digits
- The fourth band is the manufacturer's tolerance, which is an indication of the precision by which the resistor was made.

Resistors & Tolerance

- Find the value of the following resistor 
  - Solution:
    - Reading from the band closest to the left edge, we find that the first two colors of brown and red represent the numbers 1 and 2, respectively.
    - The third band is orange, representing the number 3 for the power of the multiplier as follows:

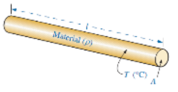
      $12 \times 10^3\ \Omega = 12\ \text{k}\Omega$

    - Now for the fourth band of gold, representing a tolerance of 5%
- Given a 50 Ω resistor with a tolerance of 10%, what is the minimum and maximum voltage across the resistor when a current of exactly 2 mA flows through it?

RESISTANCE: CIRCULAR WIRES

- The resistance of any material is due primarily to four factors:
  - Material
  - Length
  - Cross-sectional area
  - Temperature of the material

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



Resistivity (ρ) of various materials.

Material	ρ (CM · Ω/ft)@20°C
Silver	9.9
Copper	**10.37**
Gold	14.7
Aluminum	17.0
Tungsten	33.0
Nickel	47.0
Iron	74.0
Constantan	295.0
Nichrome	600.0
Calorite	720.0
Carbon	21,000.0

- the higher the resistivity, the greater the resistance of a conductor
- the longer the conductor, the greater the resistance
- the greater the area of a conductor, the less the resistance

Conductance & Open/Short Circuits

- For a linear resistor, the ratio of current to voltage is also a constant

$$\frac{i}{v} = \frac{1}{R} = G$$

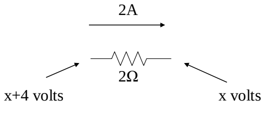
  - where G is called the conductance
  - units = siemens (S), 1 S = 1 A/V = Ω^{-1}
- open circuit: $R = \infty$, and $i = 0$ for any voltage across the open terminals
- short circuit: $R = 0$, and $v = 0$ for any current through the short
  - **For all of our circuits, wires are assumed to be perfect short circuits.**
    - i.e. since $v = i \times R$ and wires have $R = 0$, all neighboring points along a wire have the same voltage.

Ohm's Law

V = IR

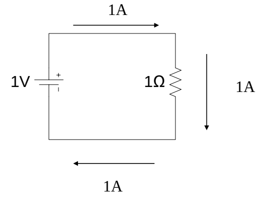
for using with a resistor only

Voltage (Volts) =
current (Amperes) x resistance (Ohms)



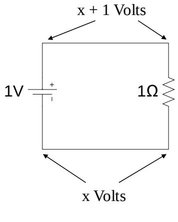
Note: (Theoretically) in our analysis ve assume that electric wire has a resistance of 0 ohms

Electric Current



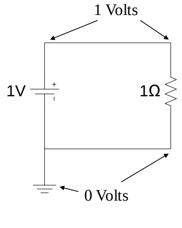
Every point in the circuit has current = 1A

Electric Voltage

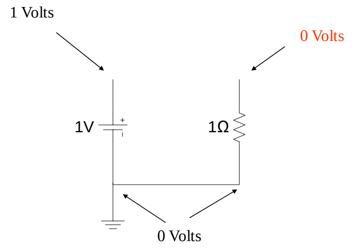


Ground

Ground = reference point always have voltage = 0 volts

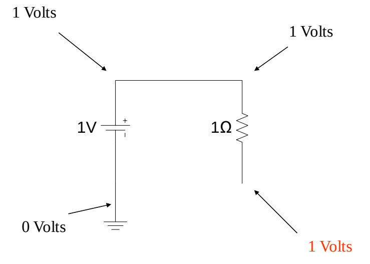


Electric Voltage (2)



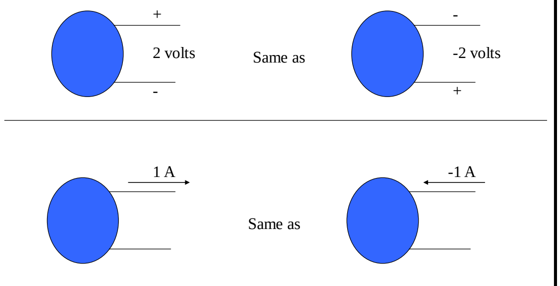
79

Electric Voltage (3)



80

Negative Voltage and Current

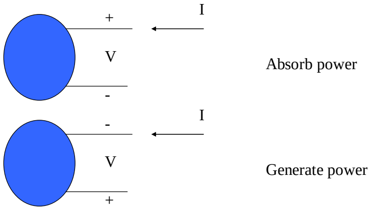


81

Power

Symbol P has a unit of Watt

P = VI



82

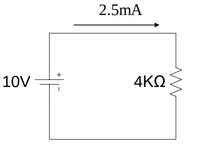
Passive Sign Convention

Absorb power: Power has a sign +

Generate power: Power has a sign -

83

Example-08



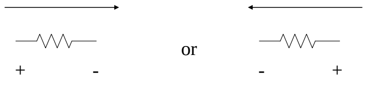
DC source generates power = 10V * -2.5mA = - 25mW

Resistor absorbs power = 10V * 2.5mA = 25mW

Note: Resistors always absorb power but DC source can either generate or absorb power

84

Direction of Voltage & Current on Resistors



- Resistor always absorb power.
- Therefore, it always have current flow through it from high voltage pin to low voltage pin.