PHYS 1444 – Section 001
Lecture #12

Monday, June 24, 2019
Dr. Jaehoon Yu

- Chapter 25
  - Microscopic View of Electric Current
  - Ohm's Law in Microscopic View
  - EMF and Terminal Voltage
- Chapter 26
  - Resistors in Series and Parallel
  - Kirchhoff's Rules
  - EMFs in Series and Parallel

Today's homework is homework #9, due 11pm, Thursday, June 27!!

Announcements

- 2nd Term Exam
  - First 80min this Wednesday, June 26
  - Covers CH25.1 through what we learn tomorrow
  - BYOF: You may bring one 8.5x11.5 sheet (front and back) of **handwritten** formulae and values of constants for the exam
  - No derivations, word definitions, setups or solutions of any problems!
  - No additional formulae or values of constants will be provided!

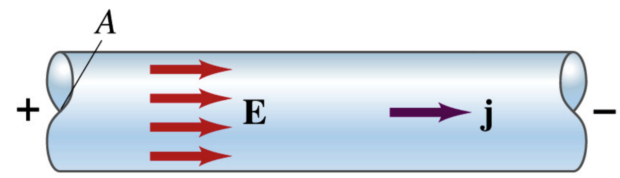
Reminder: Special Project #4

- Make a list of the power consumption and the resistance of all electric and electronic devices at your home and compile them in a table. (10 points total for the first 10 items and 0.5 points each additional item.)
- Estimate the cost of electricity for each of the items on the table using your own electric cost per kWh (if you don't find your own, use \$0.12/kWh) and put them in the relevant column. (5 points total for the first 10 items and 0.2 points each additional items)
- Estimate the the total amount of energy in Joules and the total electricity cost per day, per month and per year for your home. (8 points)
- Due: Beginning of the class Thursday, June 27

Item Name	Rated power (W)	Number of devices	Number of Hours per day	Daily Power Consumption (kWh)	Energy Cost per kWh (cents)	Daily Energy Consumption (J).	Daily Energy Cost ($)	Monthly Energy Consumption (J)	Monthly Energy Cost ($)	Yearly Energy Consumption (J)	Yearly Energy Cost ($)
Light Bulbs	30	4									
	40	6									
	60	15									
Heaters	1000	2									
	1500	1									
	2000	1									
Fans											
Air Conditioners											
Fridgers, Freezers											
Computers (desktop, laptop, ipad)											
Game consoles											
Total				0		0	0	0	0	0	0

Microscopic View of Electric Current

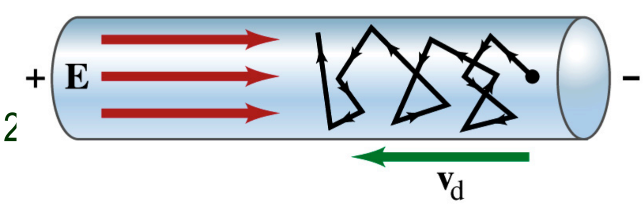
- When a potential difference is applied to the two ends of a wire w/ a uniform cross-section, the direction of the electric field is parallel to the walls of the wire, this is possible since the charges are moving
- Let's define a microscopic vector quantity, the current density, **j**, the electric current per unit cross-sectional area
  - j=I/A or I= jA if the current density is uniform
  - If not uniform $I = \int \vec{j} \cdot d\vec{A}$
  - The direction of **j** is the direction the positive charge would move when placed at that position, generally the same as E



- The current density exists on any point in space while the current I refers to a conductor as a whole so a macroscopic

Microscopic View of Electric Current – II

- The direction of j is the direction of a positive charge. So in a conductor, since negatively charged electrons move, the direction is $-\mathbf{j}$.
- Let's think about the current in a microscopic view again:
  - When voltage is applied to the end of a wire
  - Electric field is generated by the potential difference
  - Electrons feel force and get accelerated
  - Electrons soon reach to a steady average speed due to collisions with atoms in the wire, called drift velocity, $\mathbf{v}_d$
  - The drift velocity is normally much smaller than electrons' average random speed.



Microscopic View of Electric Current

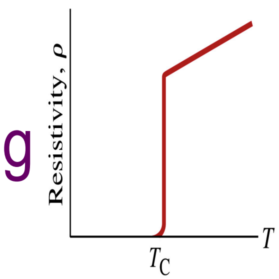
- The drift velocity of electrons in a wire is only about 0.05mm/s. How could we get light turned on immediately then?
  - While the electrons in the wire travels slow, the electric field travels essentially at the speed of light. Then what is all the talk about electrons flowing through?
    - It is just like water. When you turn on the facet, water flows right off the facet despite the fact that the water travels slow.
    - Electricity is the same. Electrons fill the conductor wire and when the switch is flipped on or a potential difference is applied, the electrons close to the positive terminal flows into the bulb.
    - Interesting, isn't it? Why is the field travel at the speed of light then?

Ohm's Law in Microscopic View

- Ohm's law can be written in microscopic quantities.
  - Resistance in terms of resistivity is $R = \rho \frac{l}{A}$
  - We can rewrite the potential V and current I as: I=jA, V=El.
  - If electric field is uniform, from V=IR, we obtain
  - $V = IR$
  - $El = (jA)\left(\rho \frac{l}{A}\right) = j\rho l$
  - So
  - $\boxed{j = \frac{E}{\rho} = \sigma E}$
  - In a metal conductor, ρ or σ does not depend on V, thus, the current density j is proportional to the electric field E ➔ Microscopic statement of Ohm's Law
  - In vector form, the density can be written as $\boxed{\vec{j} = \frac{\vec{E}}{\rho} = \sigma \vec{E}}$

Superconductivity

- At the temperature near absolute 0K, resistivity of certain material becomes 0.
  - This state is called the “superconducting” state.
  - Observed in 1911 by H. K. Onnes when he cooled mercury to 4.2K (-269^{o}C).
    - Resistance of mercury suddenly dropped to 0.
  - In general superconducting materials become superconducting below a transition temperature (T_c).



  - The highest temperature superconductivity seen is 160K
    - First observation above the boiling temperature of liquid nitrogen is in 1987 at 90k observed from a compound of yttrium, barium, copper and oxygen.
- Since much smaller amount of material can carry just as much current more efficiently, superconductivity can make electric cars more practical, computers faster, and capacitors store higher energy

Critical Temperature of Superconductors

Critical temperature (T_c), crystal structure and lattice constants of some high-T_c superconductors

Formula	Notation	T_c (K)	No. of Cu-O planes in unit cell	Crystal structure
$YBa_2Cu_3O_7$	123	92	2	Orthorhombic
$Bi_2Sr_2CuO_6$	Bi-2201	20	1	Tetragonal
$Bi_2Sr_2CaCu_2O_8$	Bi-2212	85	2	Tetragonal
$Bi_2Sr_2Ca_2Cu_3O_{10}$	Bi-2223	110	3	Tetragonal
$Tl_2Ba_2CuO_6$	Tl-2201	80	1	Tetragonal
$Tl_2Ba_2CaCu_2O_8$	Tl-2212	108	2	Tetragonal
$Tl_2Ba_2Ca_2Cu_3O_{10}$	Tl-2223	125	3	Tetragonal
$TlBa_2Ca_3Cu_4O_{11}$	Tl-1234	122	4	Tetragonal
$HgBa_2CuO_4$	Hg-1201	94	1	Tetragonal
$HgBa_2CaCu_2O_6$	Hg-1212	128	2	Tetragonal
$HgBa_2Ca_2Cu_3O_8$	Hg-1223	134	3	Tetragonal

Electric Hazards: Leakage Currents

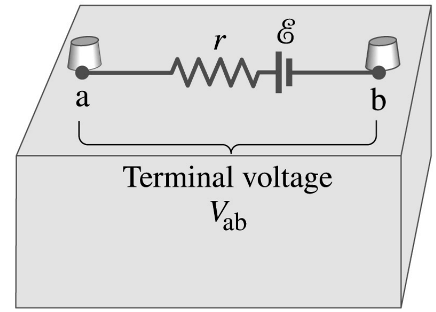
- How does one feel shock by electricity?
  - Electric current stimulates nerves and muscles, and we feel a shock
  - The severity of the shock depends on the amount of current, how long it acts and through what part of the body it passes
  - Electric current heats the tissue and can cause burns
- Currents above 70mA on a torso for a second or more is fatal, causing heart to function irregularly, "ventricular fibrillation".
- A dry human body between two points on the opposite side of the body is about 10^4 to 10^6 Ω.
- But when wet, it could be $10^3\Omega$.
- A person in good contact with the ground who touches 120V DC line with wet hands can get the current:
  - Could be lethal

$$I = \frac{V}{R} = \frac{120V}{1000\Omega} = 120mA$$

EMF and Terminal Voltage

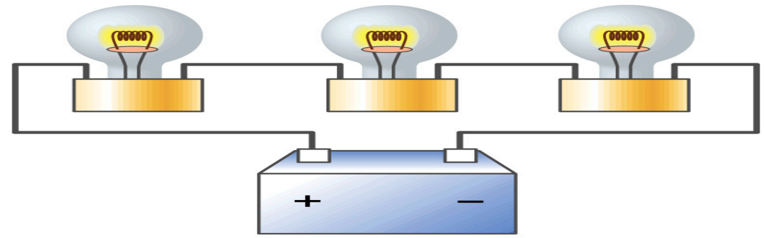
- What do we need to have current in an electric circuit?
  - A device that provides a potential difference, such as a battery or a generator
    - They normally convert some types of energy into the electric energy
    - These devices are called source of electromotive force (emf)
      - This is does NOT refer to a real "force".
- Potential difference between terminals of an emf source, when no current flows to an external circuit, is called the emf ($\mathscr{E}$) of the source.
- The battery itself has some **internal resistance** (r) due to the flow of charges in the electrolyte
  - Why does the headlight dim when you start the car?
    - The starter needs a large amount of current but the battery cannot provide charge fast enough to supply current to both the starter and the headlight

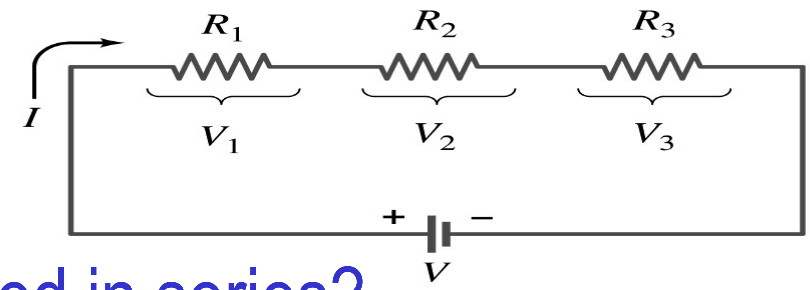
EMF and Terminal Voltage



- Since the internal resistance is inside the battery, we can never separate them out.
- So the terminal voltage difference is $V_{ab}=V_a-V_b$.
- When no current is drawn from the battery, the terminal voltage equals the emf which is determined by the chemical reaction; $V_{ab}= \mathscr{E}$.
- However when the current I flows naturally from the battery, there is a voltage drop due to the internal resistance which is equal to Ir. Thus the actual **delivered** terminal voltage is $\boxed{V_{ab} = \varepsilon - Ir}$

Resistors in Series





- Resistors are in series when two or more resistors are connected end to end
  - These resistors represent simple resistors in circuit or electrical devices, such as light bulbs, heaters, dryers, etc
- What is common in a circuit connected in series?
  - Current is the same through all the elements in series
- Potential difference across every element in the circuit is
  - $V_1=IR_1$, $V_2=IR_2$ and $V_3=IR_3$
- Since the total potential difference is V, we obtain
  - $V=IR_{eq}=V_1+V_2+V_3=I(R_1+R_2+R_3)$
  - Thus, $R_{eq}=R_1+R_2+R_3$

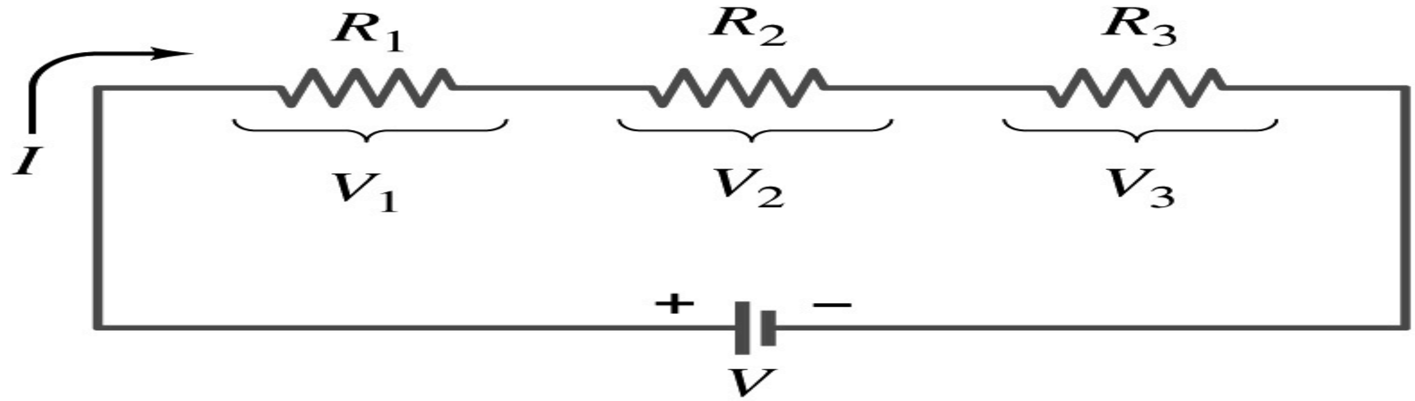
$$\boxed{R_{eq} = \sum_i R_i}$$

Resistors in series

When resistors are connected in series, the total resistance increases and the current decreases.

Energy Losses in Resistors

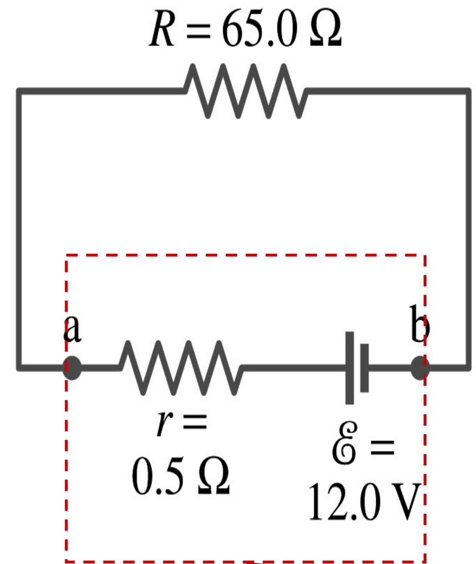
- Why is it true that $V=V_1+V_2+V_3$?



- What is the potential energy loss when charge q passes through resistors R_1, R_2 and R_3
  - $\Delta U_1=qV_1$, $\Delta U_2=qV_2$, $\Delta U_3=qV_3$
- Since the total energy loss should be the same as the total energy provided to the system, we obtain
  - $\Delta U=qV=\Delta U_1+\Delta U_2+\Delta U_3=q(V_1+V_2+V_3)$
  - Thus, $V=V_1+V_2+V_3$

Example 26 – 1

Battery with internal resistance. A 65.0-Ω resistor is connected to the terminals of a battery whose emf is 12.0V and whose internal resistance is 0.5-Ω. Calculate (a) the current in the circuit, (b) the terminal voltage of the battery, V_{ab}, and (c) the power dissipated in the resistor R and in the battery's internal resistor.



What is this?

A battery or a source of emf.

(a) Since $V_{ab} = \varepsilon - Ir$ We obtain $V_{ab} = IR = \varepsilon - Ir$

Solve for I

$$I = \frac{\varepsilon}{R + r} = \frac{12.0V}{65.0\Omega + 0.5\Omega} = 0.183A$$

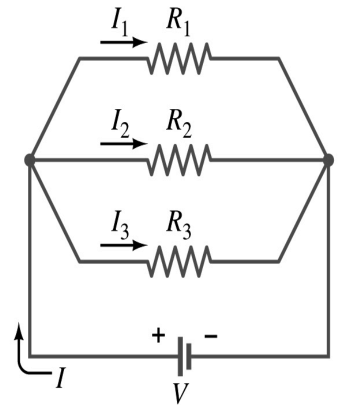
(b) The terminal voltage V_{ab} is $V_{ab} = \varepsilon - Ir = 12.0V - 0.183A \cdot 0.5\Omega = 11.9V$

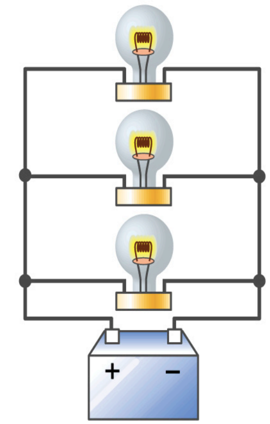
(c) The power dissipated in R and r are

$$P = I^2 R = (0.183A)^2 \cdot 65.0\Omega = 2.18W$$

$$P = I^2 r = (0.183A)^2 \cdot 0.5\Omega = 0.02W$$

Resistors in Parallel





- Resistors are in parallel when two or more resistors are connected in separate branches
  - Most the house and building wirings are arranged this way.
- What is common in a circuit connected in parallel?
  - The voltage is the same across all the resistors.
  - The total current that leaves the battery, is however, split.
- The current that passes through every element is
  - $I_1=V/R_1$, $I_2=V/R_2$, $I_3=V/R_3$
- Since the total current is I, we obtain
  - $I=V/R_{eq}=I_1+I_2+I_3=V(1/R_1+1/R_2+1/R_3)$
  - Thus, $1/R_{eq}=1/R_1+1/R_2+1/R_3$

$$\boxed{\frac{1}{R_{eq}}=\sum_i \frac{1}{R_i}}$$

Resistors in parallel

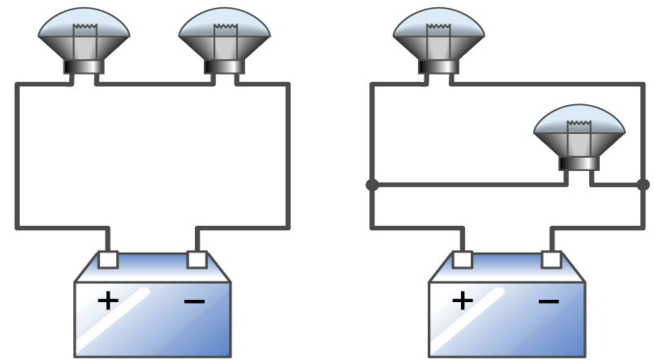
When resistors are connected in parallel, the total resistance decreases and the current increases.

Resistor and Capacitor Arrangements

- Parallel Capacitor arrangements $$C_{eq} = \sum_i C_i$$
- Parallel Resistor arrangements $$\frac{1}{R_{eq}} = \sum_i \frac{1}{R_i}$$
- Series Capacitor arrangements $$\frac{1}{C_{eq}} = \sum_i \frac{1}{C_i}$$
- Series Resistor arrangements $$R_{eq} = \sum_i R_i$$

Example 26 – 2

Series or parallel? (a) The light bulbs in the figure are identical and have identical resistance R. Which configuration produces more light? (b) Which way do you think the headlights of a car are wired?



(1) Series (2) Parallel

(a) What are the equivalent resistances for the two cases?

Series $R_{eq} = 2R$ **Parallel** $\frac{1}{R_{eq}} = \frac{2}{R}$ **So** $R_{eq} = \frac{R}{2}$

The bulbs get brighter when the total power transformed is larger.

series $P_S = IV = \frac{V^2}{R_{eq}} = \frac{V^2}{2R}$ parallel $P_P = IV = \frac{V^2}{R_{eq}} = \frac{2V^2}{R} = 4P_S$

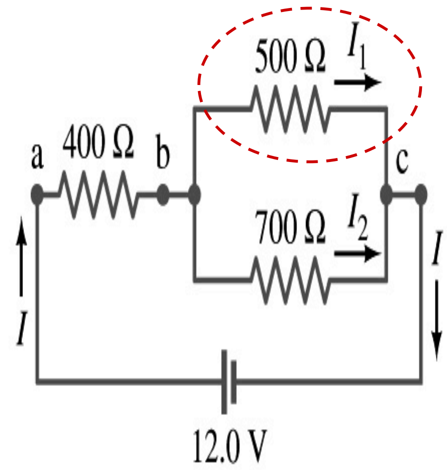
So parallel circuit provides brighter lighting.

(b) Car's headlights are in parallel to provide brighter lighting and also to prevent both lights going out at the same time when one burns out.

So what is bad about parallel circuits? Uses more energy in a given time.

Example 26 – 5

Current in one branch. What is the current flowing through the 500-Ω resistor in the figure?



What do we need to find first?

We need to find the total current.

To do that we need to compute the equivalent resistance.

R_{eq} of the small parallel branch is: $\frac{1}{R_P} = \frac{1}{500} + \frac{1}{700} = \frac{12}{3500}$ $\quad R_P = \frac{3500}{12}$

R_{eq} of the circuit is: $R_{eq} = 400 + \frac{3500}{12} = 400 + 292 = 692\Omega$

Thus the total current in the circuit is $I = \frac{V}{R_{eq}} = \frac{12}{692} = 17mA$

The voltage drop across the parallel branch is $V_{bc} = IR_P = 17 \times 10^{-3} \cdot 292 = 4.96V$

The current flowing across 500-Ω resistor is therefore

$$V_{bc} I_{500} = \frac{V_{bc}}{R} = \frac{4.96}{500} = 9.92 \times 10^{-3} = 9.92mA$$

What is the current flowing 700-Ω resistor? $I_{700} = I - I_{500} = 17 - 9.92 = 7.08mA$