NATIONAL UNIVERSITY OF PHARMACY
Department of Educational and Information Technologies

BIOPHYSICS, PHYSICAL METHODS OF ANALYSIS

Lecture 7

Electromagnetism. Biophysics of nerve impulses.

Plan of the Lecture

1. Electrostatics.
2. Introduction to Potential.
3. Conductors and Dielectrics.
4. Electric Current.
5. Electromotive Force.
6. Magnetic Fields.
7. Alternating Voltages and Currents.
8. Nerve Impulses.

Purpose of the lecture is

- **to obtain knowledge on the basics of electromagnetism that will understand interact of living organisms with electromagnetic fields.**

Point Charge Model basic concepts

Description

Point model (spatial distribution description)

Charged point (physical property of the point)

Extensible (continuous distribution can be built based on many points model)

Superposition principles for many points model

$$\vec{F}_i = \sum_{j \neq i} \vec{F}_{ji}$$

The force on a charge Q due to a single point charge q is given by Coulomb`s law

$$\vec{F} = \frac{1}{4\pi\varepsilon_0} \frac{qQ}{R^2} \hat{R} \qquad \vec{R} = \vec{r}_Q - \vec{r}_q = R\,\hat{R}$$

$$\varepsilon_0 = 8.85 \times 10^{-12} \frac{c^2}{N \cdot m^2}$$

Electric Field

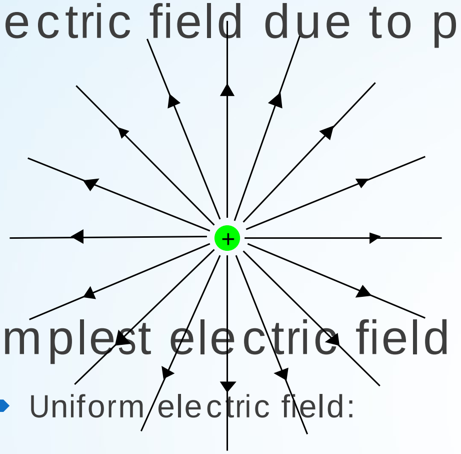
- *Need to introduce electric field:* ***Separating intrinsic and extrinsic factors***
  - Consider many point charges model

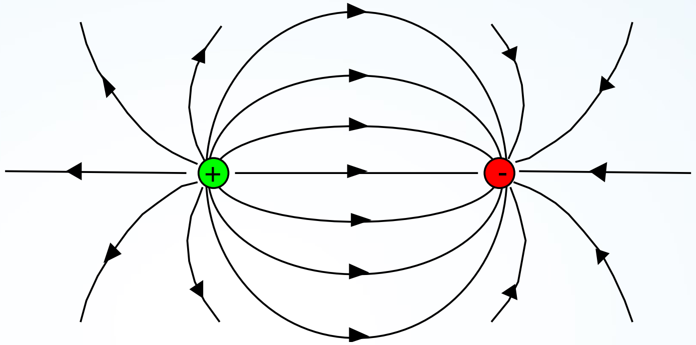
$$\vec{F}_i = \sum_{j\neq i} \vec{F}_{ji} = q_i \left\{ \sum_{j\neq i} \frac{q_j}{4\pi\varepsilon_0 r_{ji}^2} \hat{r}_{ji} \right\} = q_i \times \vec{E}(\vec{r}_i; \vec{r}_{j\neq i}; q_{j\neq i})$$

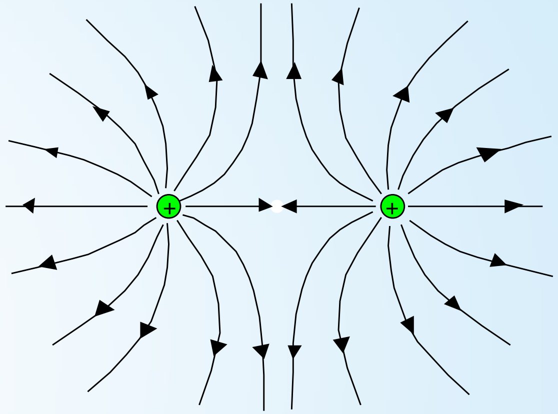
  - Electrostatic Force of *i*th point charge is equal to charge q_i (properties of the point: *intrinsic*) times a function *E* (property related to space and properties of other point charges: *extrinsic*)
  - Function *E* is called ***electric field*** which is a vector quantity at a space location due to charges

Examples

- Electric field due to point charge

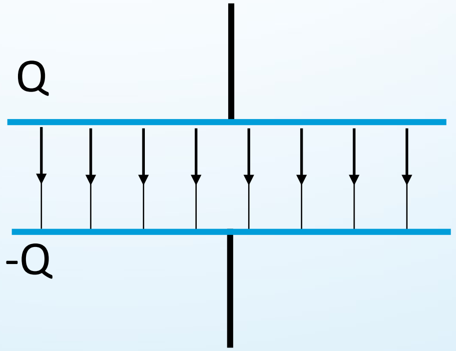






- Simplest electric field
  - Uniform electric field:

$$\vec{E}(\vec{r}) = \vec{E}$$



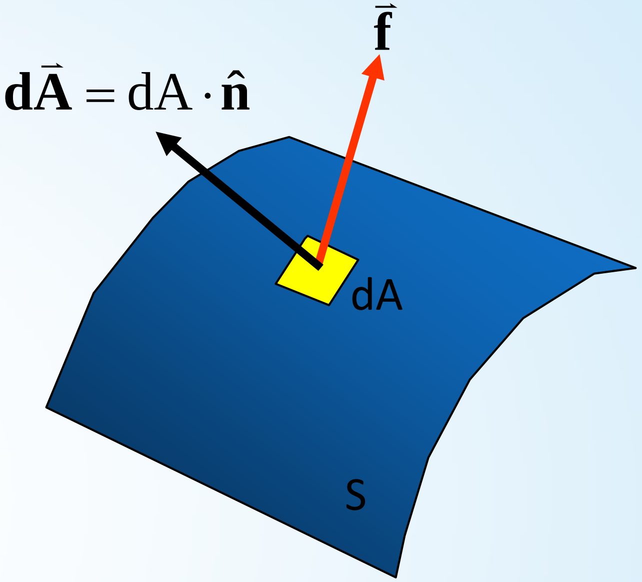
Properties of Electric Field

- *Distribution of vector* E *forms a vector field*
  - Curl of Electric Field: $\vec{\nabla} \times \vec{F} = 0 \Rightarrow \vec{\nabla} \times \vec{E} = 0$
  - Divergence of Electric Field: $\vec{\nabla} \bullet \vec{E} = \rho / \varepsilon_0$
  - Electron density ρ

- *Representation of Electric Field*
  - Line representation of vector field:
    - No cross-over (curl of electric field = 0)
    - Originate from positive charge/End at negative charge
    - Intensity proportional to line density

Electric Flux and Gauss's Law

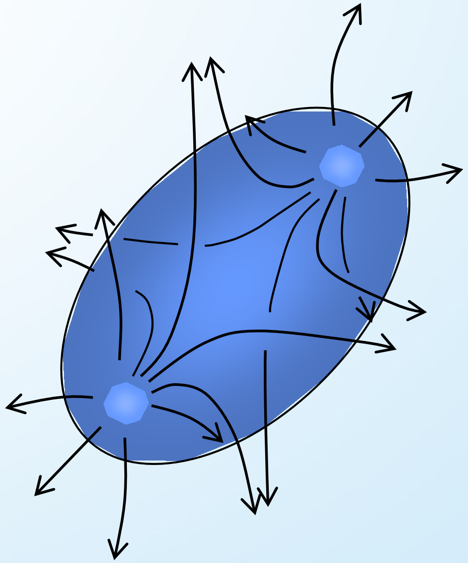
- *Flux Φ_E is a concept for vector field.*
  - In the line representation: flux is the number of field lines crossing over a given surface
  - Since the field line density is proportional to electric field, the number of field lines should be electric field integrate over the surface



$$\Phi_E = \int \vec{E} \bullet d\vec{A} = \int \vec{E} \bullet \vec{n} dA$$

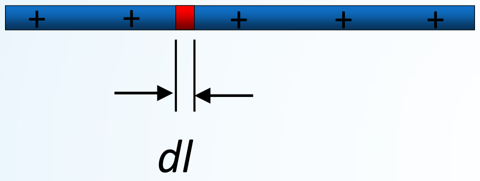
- *Gauss's Law for Enclosed Surface*
  - Φ_E of enclosed surface = charge enclosed divides free space permitivity

$$\Phi_E = \oint \vec{E} \bullet d\vec{A} = \oint \vec{E} \bullet \vec{n} dA = \frac{q}{\varepsilon_0}$$



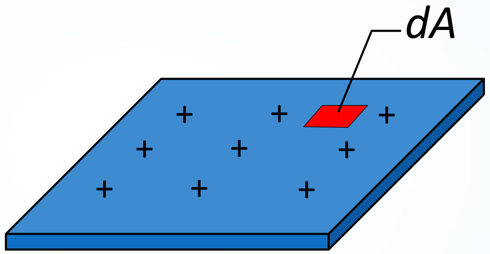
Simple Charge Distribution Models

If the charge is distributed over a volume, surface or a line, we can relate the geometrical size of the object with the charge.



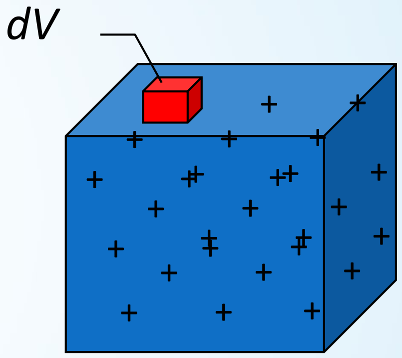
$$dQ = \lambda \cdot dl$$

linear charge density



$$dQ = \sigma \cdot dA$$

surface charge density



$$dQ = \rho \cdot dV$$

volume charge density

Introduction to potential

Any vector whose curl is zero is equal to the gradient of some scalar.
We define a function:

$$V(p) = -\int_a^b \vec{E} \cdot d\vec{l}$$

The fundamental theorem for gradients

$$V(b) - V(a) = \int_a^b (\nabla V) \cdot d\vec{l}$$

so $$\int_a^b (\nabla V) \cdot d\vec{l} = -\int_a^b \vec{E} \cdot d\vec{l} \quad \Rightarrow \quad \boxed{\vec{E} = -\nabla V}$$

Potential is not potential energy

$$\vec{F} = q\vec{E} = -q\nabla V \qquad \Delta U = \vec{F} \cdot \vec{X}$$

V : Joule/Coulomb $\quad$ U : Joule

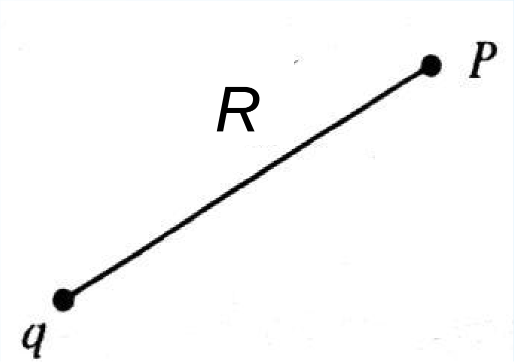
The Potential of a Localized Charge Distribution

$$\vec{E} = -\nabla V \qquad V - V_\infty = -\int_\infty^r E\,dr' \qquad V_\infty = 0$$

$$V(r) = \frac{-1}{4\pi\varepsilon_0}\int_\infty^r \frac{q}{r'^2}dr' = \frac{1}{4\pi\varepsilon_0}\frac{q}{r'}\bigg|_\infty^r = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$$

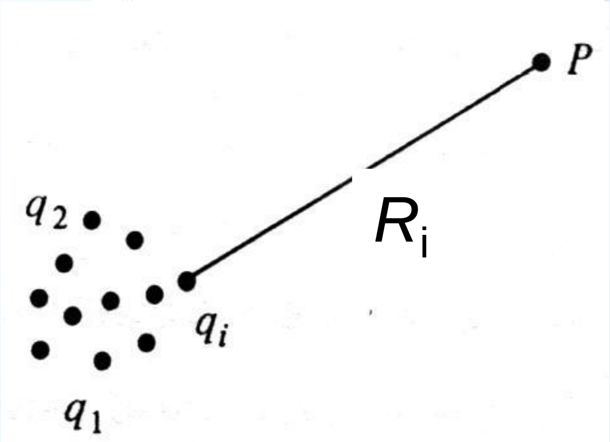
- Potential for a point charge

$$V(P) = \frac{1}{4\pi\varepsilon_0}\frac{q}{R} \qquad R = \left|\vec{r} - \vec{r}_p\right|$$



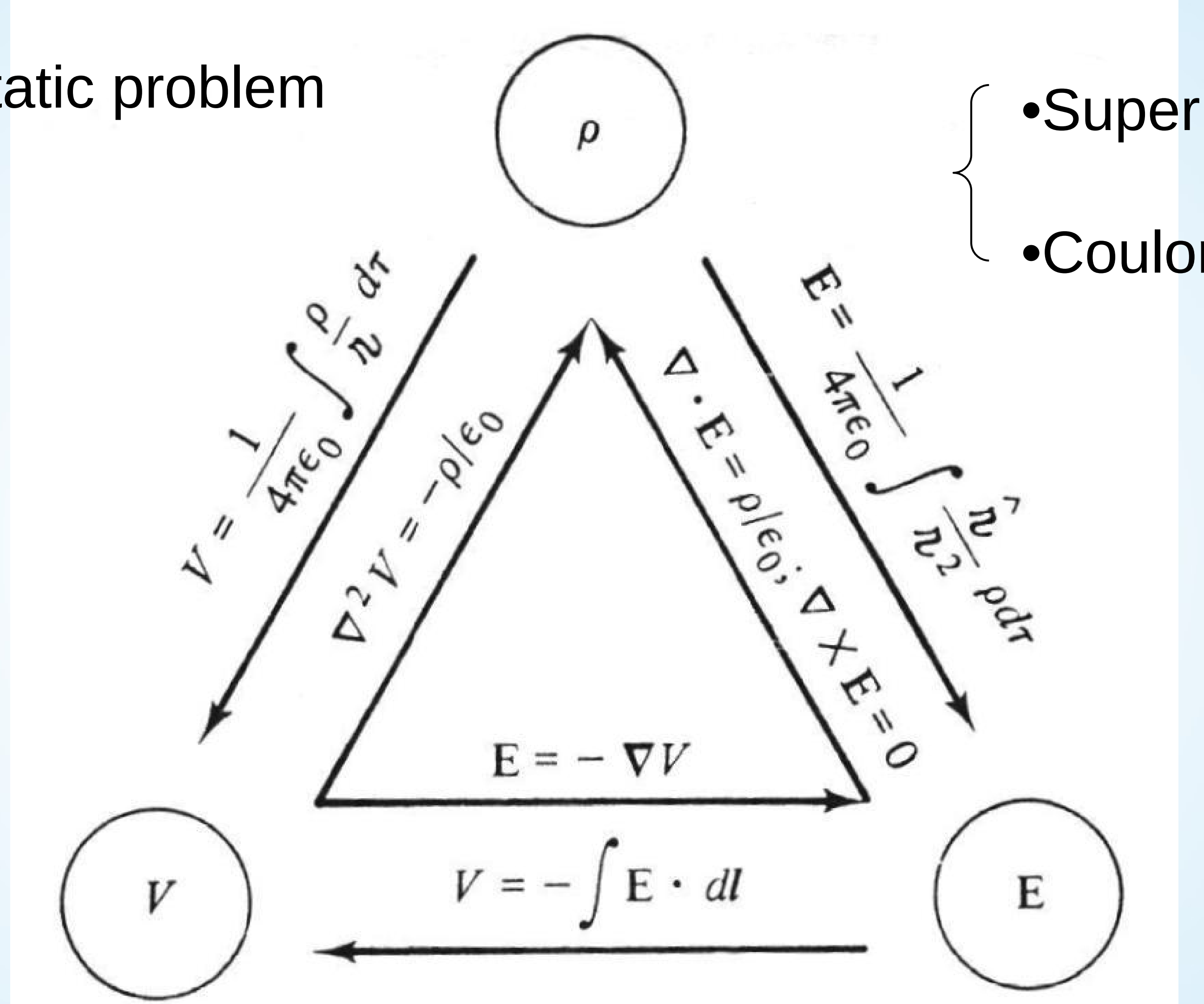
- Potential for a collection of charge

$$V(P) = \frac{1}{4\pi\varepsilon_0}\sum_{i=1}^{n}\frac{q_i}{R_i} \qquad R_i = \left|\vec{r}_i - \vec{r}_p\right|$$



Electrostatic Boundary Condition

Electrostatic problem



- Superposition
- Coulomb law

The above equations are differential or integral.
For a unique solution, we need boundary conditions. (e.q. , V(∞)=0)
(boundary value problem.)

The Work Done in Moving a charge

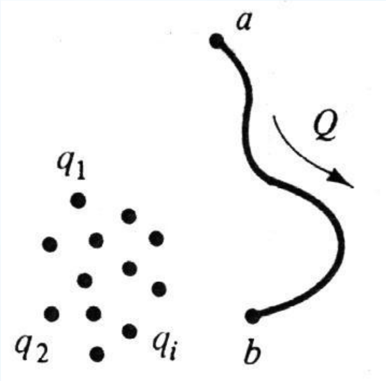
A test charge Q feels a force Q $\vec{E}$ (from the stationary source charges).

To move this test charge, we have to apply a force $\vec{F} = -Q\vec{E}$

↑ conservative

The total work we do is

$$W = \int_a^b \vec{F} \cdot d\vec{\ell} = -Q\int_a^b \vec{E} \cdot d\vec{\ell} = Q\left[V(b) - V(a)\right]$$



$$\boxed{V(b) - V(a) = \frac{W}{Q}}$$

So, bring a charge from ∞ to P, the work we do is

$$W = Q\left[V(P) - V(\infty)\right] = QV(P)$$

↑ $V(\infty) = 0$

The Energy of a Point Charge Distribution

It takes no work to bring in first charges

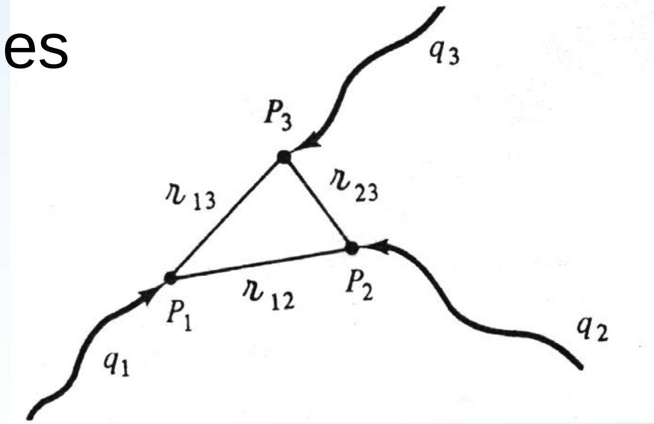


Figure 2.40

$W_1 = 0$ for q_1

Work needed to bring in q_2 is :

$$W_2 = q_2[\frac{1}{4\pi\varepsilon_0}\frac{q_1}{R_{12}}] = \frac{1}{4\pi\varepsilon_0}q_2(\frac{q_1}{R_{12}})$$

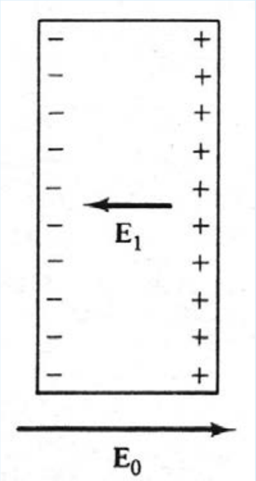
Work needed to bring in q_3 is :

$$W_3 = q_3[\frac{1}{4\pi\varepsilon_0}\frac{q_1}{R_{13}} + \frac{1}{4\pi\varepsilon_0}\frac{q_2}{R_{23}}] = \frac{1}{4\pi\varepsilon_0}q_3(\frac{q_1}{R_{13}} + \frac{q_2}{R_{23}})$$

Work needed to bring in q_4 is :

$$W_4 = \frac{1}{4\pi\varepsilon_0}q_4[\frac{q_1}{R_{14}} + \frac{q_2}{R_{24}} + \frac{q_3}{R_{34}}]$$

Basic Properties of Conductors



e^- are free to move in a conductor

(1) $\vec{E} = 0$ inside a conductor

otherwise, the free charges that produce $\vec{E}$ will move to make $\vec{E} = 0$ inside a conductor

(2) $\rho = 0$ inside a conductor

$$\because \nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \qquad \vec{E} = 0 \quad \Rightarrow \quad \rho = 0$$

(3) Any net charge resides on the surface

(4) V is constant, throughout a conductor.

$$V(b) - V(a) = -\int_a^b \vec{E} \cdot d\vec{l} = 0$$

$$\therefore V(b) = V(a)$$

Capacitors

Consider 2 conductors (Fig.)

The potential difference

$$V = V_+ - V_- = -\int_{(-)}^{(+)} \vec{E} \cdot d\vec{l}$$

(V is constant.)

$$\vec{E} = \frac{1}{4\pi\varepsilon_0} \int \frac{\hat{r}}{r^2} \rho \, d\tau$$

double $\rho \rightarrow$ double $Q \rightarrow$ double $\vec{E} \rightarrow$ double V

Define the ratio between Q and V to be capacitance

$$C = \frac{Q}{V}$$

a geometrical quantity

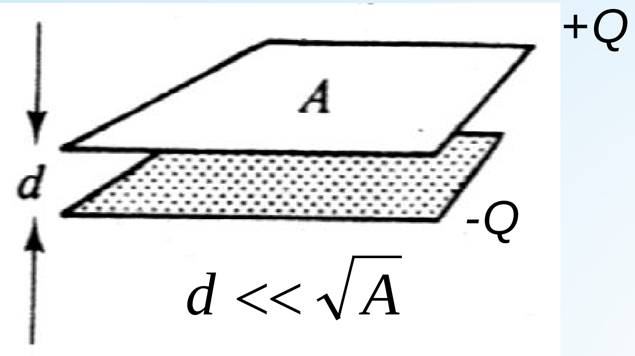
in SI 1 farad(F)= 1 Coulomb / volt

inconveniently large ;

$10^{-6} F : microfarad$

$10^{-12} F : picofarad$

Find the capacitance of a “parallel-plate capacitor”?



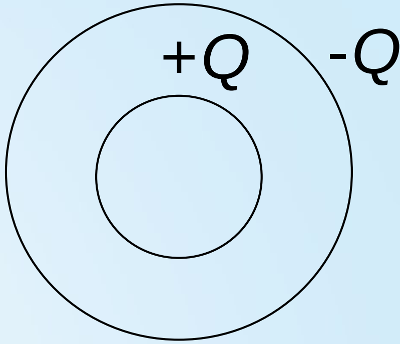
Solution:

$$E = \frac{\sigma}{\varepsilon_0} = \frac{Q}{A\varepsilon_0}$$

$$V = E \cdot d = \frac{Q}{A\varepsilon_0} d$$

$$C = \frac{A\varepsilon_0}{d}$$

Find capacitance of two concentric spherical shells with radii a and b .



Solution:

$$\vec{E} = \frac{1}{4\pi\varepsilon_0} \frac{Q}{r^2} \hat{r}$$

$$V = -\int_b^a \vec{E} \cdot d\vec{l} = -\frac{Q}{4\pi\varepsilon_0} \int_b^a \frac{1}{r^2} dr = \frac{Q}{4\pi\varepsilon_0} \left(\frac{1}{a} - \frac{1}{b} \right)$$

$$C = \frac{Q}{V} = 4\pi\varepsilon_0 \frac{ab}{(b-a)}$$

Energy Storage in Capacitors

$$V_b \equiv \frac{U_b}{q} \rightarrow V = \frac{dU}{dq} \quad \Rightarrow \quad dU = Vdq$$

Change in potential energy while charging capacitor

$$U = \int_{q=0}^{q=Q} Vdq$$

Parallel Plates $$V_{ba} = \frac{Qd}{A\varepsilon_o}$$

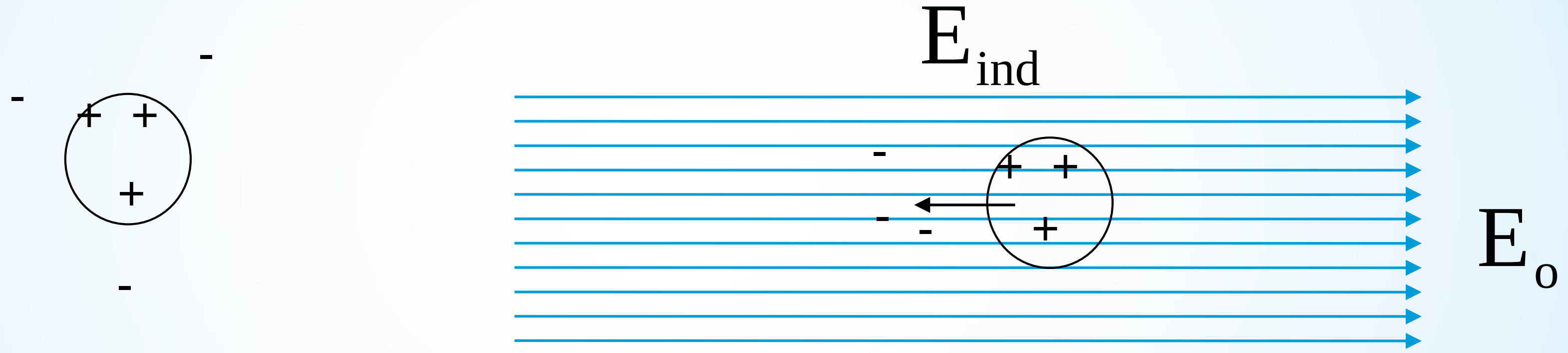
Concentric Cylinders $$V_{ba} = \frac{Q}{2\pi\varepsilon_o L}\ln\left(\frac{a}{b}\right)$$

In General $$V = \frac{Q}{C}$$

$$U = \int_{q=0}^{q=Q} \frac{q}{C}dq = \frac{1}{C}\frac{q^2}{2}\bigg|_0^Q = \frac{Q^2}{2C}$$

Dielectrics

- A *dielectric* is a nonconducting material that, when placed between the plates of a capacitor, increases the capacitance
  - Materials with Dipoles that can align with an external electric Field. Dielectrics include rubber, plastic, and waxed paper



$$E_{Dielectric} = E_o - E_{ind} = \frac{E_o}{K}$$

K is the Dielectric Constant

Measure of the degree of dipole alignment in the material

Effect of a dielectric on capacitance

$$E_{Dielectric} = \frac{E_o}{K}$$

$$\vec{E}_{Dielectric} \bullet d\vec{\ell} = \frac{\vec{E}_o}{K} \bullet d\vec{\ell}$$

$$V_{Dielectric} = \frac{V_o}{K}$$

Potential difference with a dielectric is less than the potential difference across free space

$$C = \frac{Q}{V} = K\frac{Q}{V_o} = KC_o$$

Results in a higher capacitance.

Allows more charge to be stored before breakdown voltage.

Effect of the dielectric constant

Parallel Plate Capacitor $C_o = \frac{\varepsilon_o A}{d} \rightarrow C = KC_o = \frac{K\varepsilon_o A}{d}$

Material permittivity measures degree to which the material permits induced dipoles to align with an external field

$$\varepsilon = K\varepsilon_o$$

$$C = \frac{\varepsilon A}{d}$$

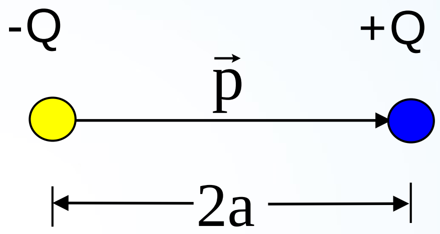
Example modifications using permittivity

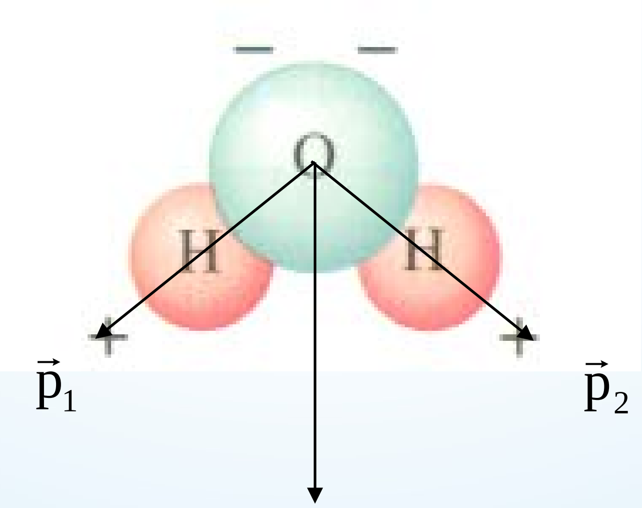
$$u_o = \frac{1}{2}\varepsilon_0 E^2 \rightarrow u = \frac{1}{2}K\varepsilon_0 E^2 = \frac{1}{2}\varepsilon E^2$$

Dipoles

The combination of two equal charges of opposite sign, +Q and –Q, separated by a distance *l*

$$|\vec{p}| = Q2a$$

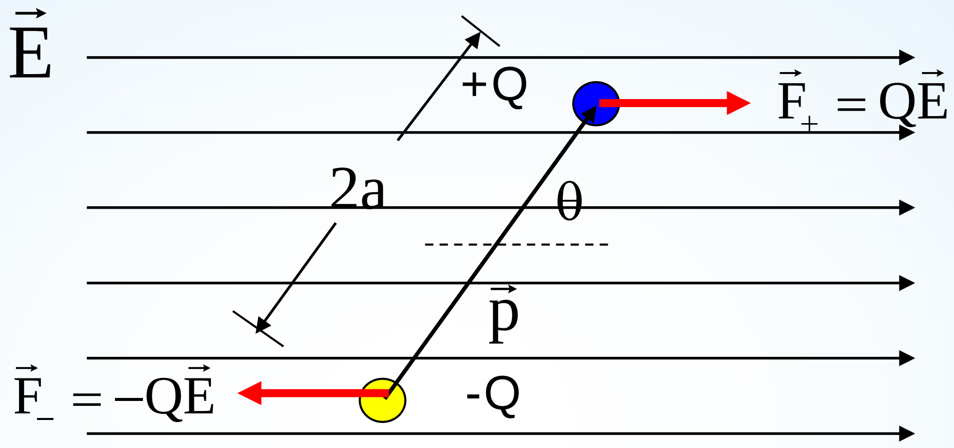




$$\vec{p} = \vec{p}_1 + \vec{p}_2$$

Dipoles in a Uniform Electric Field

the moment of force

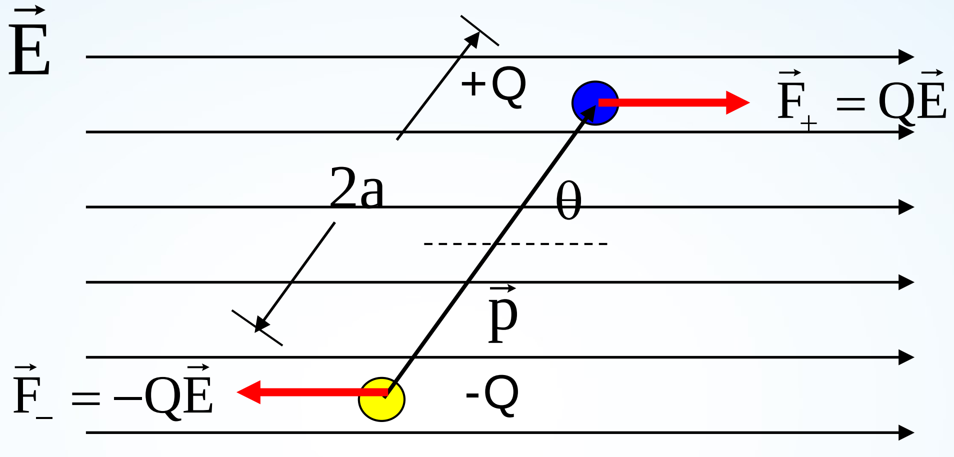


$$\vec{\tau} = \vec{r} \times \vec{F} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ x & y & z \\ F_x & F_y & F_z \end{vmatrix} \qquad |\vec{\tau}| = \tau = |\vec{r}||\vec{F}|\sin\theta$$

$$\tau = F_+ a \sin\theta + F_- a \sin\theta = QEa\sin\theta + QEa\sin\theta = Q2aE\sin\theta = pE\sin\theta$$

$$\vec{\tau} = \vec{p} \times \vec{E}$$

Work Rotating a Dipole in an Uniform Electric Field



$$dW = \tau d\theta = pE\sin\theta d\theta = dU$$

$$U = pE\int \sin\theta d\theta = -pE\cos\theta + U_0$$

Let: $U(\theta{=}90^o) = 0$ $\qquad U_0 = 0$ $\qquad U = -pE\cos\theta$

$$U = -\vec{p}\bullet\vec{E}$$

Electric Current I

- An electric current is the movement of positive and/or negative charges Q through a conductor.
- Current I is the rate of charge movement through a cross-sectional area of the conductor.

$$I = \frac{Q}{t} \qquad 1\,A = \frac{1\,C}{s}$$

- Charge is measured in coulombs C.
- The charge on an electron and a proton is: $Q = 1.602 \times 10^{-19}$ C
- Current is measured in amperes A;
- **DC current (direct current) is** a steady flow of current in one direction.
- **AC current (alternating current)** - direction of current flow changes many times a second. In the US, the frequency of change is 60 Hz. Therefore, the current changes direction 60 times per second.

Electromotive Force (EMF)

- Batteries, generators, and solar cells, transform chemical, mechanical, and radiant energy, respectively, into electric energy. These are examples of sources of EMF.
- EMF is measured in Volts V;

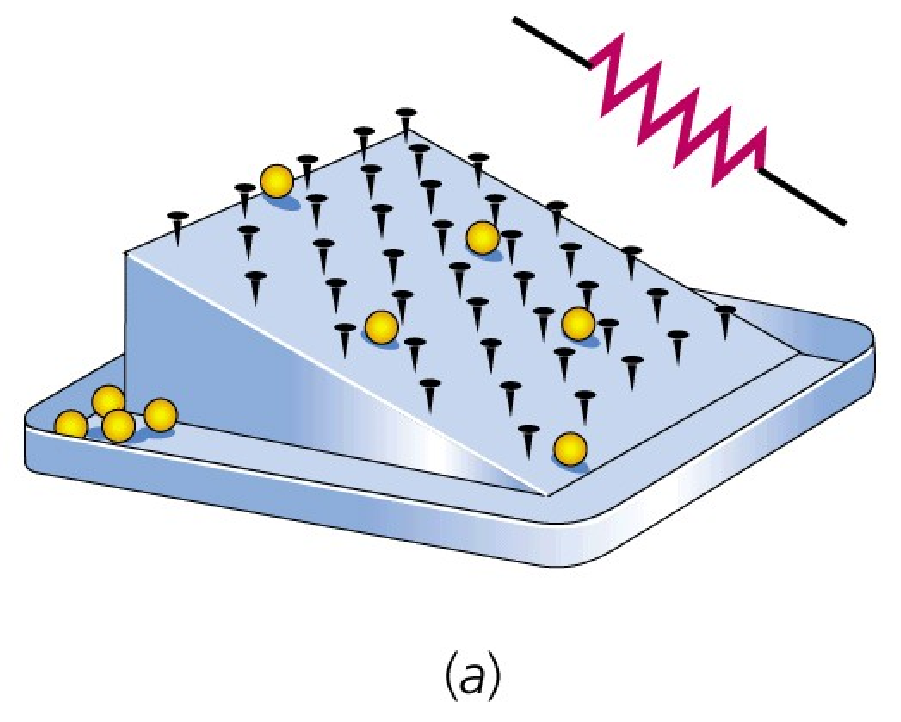
$$1\,\text{V} = \frac{1\,\text{J}}{1\,\text{C}}$$

- The source of EMF provides the energy the charge carriers will conduct through the electric circuit to the resistor.
- Current in a circuit moves from an area of high electric potential energy to an area of low potential energy. This difference in electric potential energy is necessary for current to move through a conductor.
- The positive terminal of a battery is the high electric potential energy terminal and the negative terminal is the low electric potential energy terminal.
- Potential difference V is also measured in volts.

Resistance R

- Resistance is the opposition to the flow of charge through the conductors.
- Resistance of a solid conductor depends upon:

1. nature of the material
2. length of the conductor
3. cross-sectional area of the conductor
4. temperature



Resistance

- Resistance is measured in ohms Ω. $$1\,\Omega = \frac{1\,\text{V}}{1\,\text{A}}$$
- Resistivity ρ is related to the nature of the material. Good conductors have low resistivity (or high conductivity). Poor conductors have high resistivity (or low conductivity).
- Unit for resistivity ρ is Ω·m.
- Resistance:

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

- Resistivity: $\rho = \rho_o + \rho_o \cdot \alpha \cdot (T - T_o)$

Current and its Effect on the Human Body

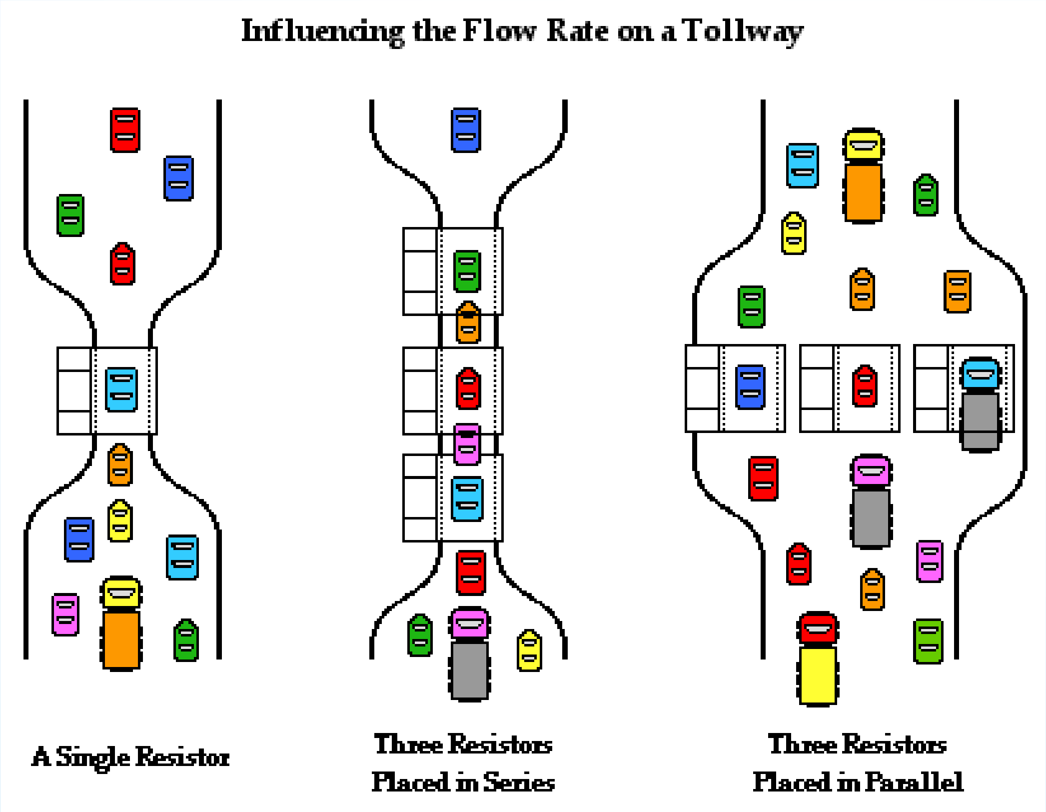
Current in Amps	Effect on human body
0.001 (1 mA)	Can be felt
0.005 (5 mA)	Painful
0.010 (10 mA)	Involuntary Muscle Spasms
0.015 (15 mA)	Loss of Muscle Control
0.070 (70 mA)	If through heart, serious disruption; probably fatal if > 1 second
0.1-0.2 (100-200 mA)	Uncontrolled "twitching" of heart
> 0.2 (> 200 mA)	Heart stops, but *may* be able to be revived easier than 0.1 – 0.2 A

Ohm's Law

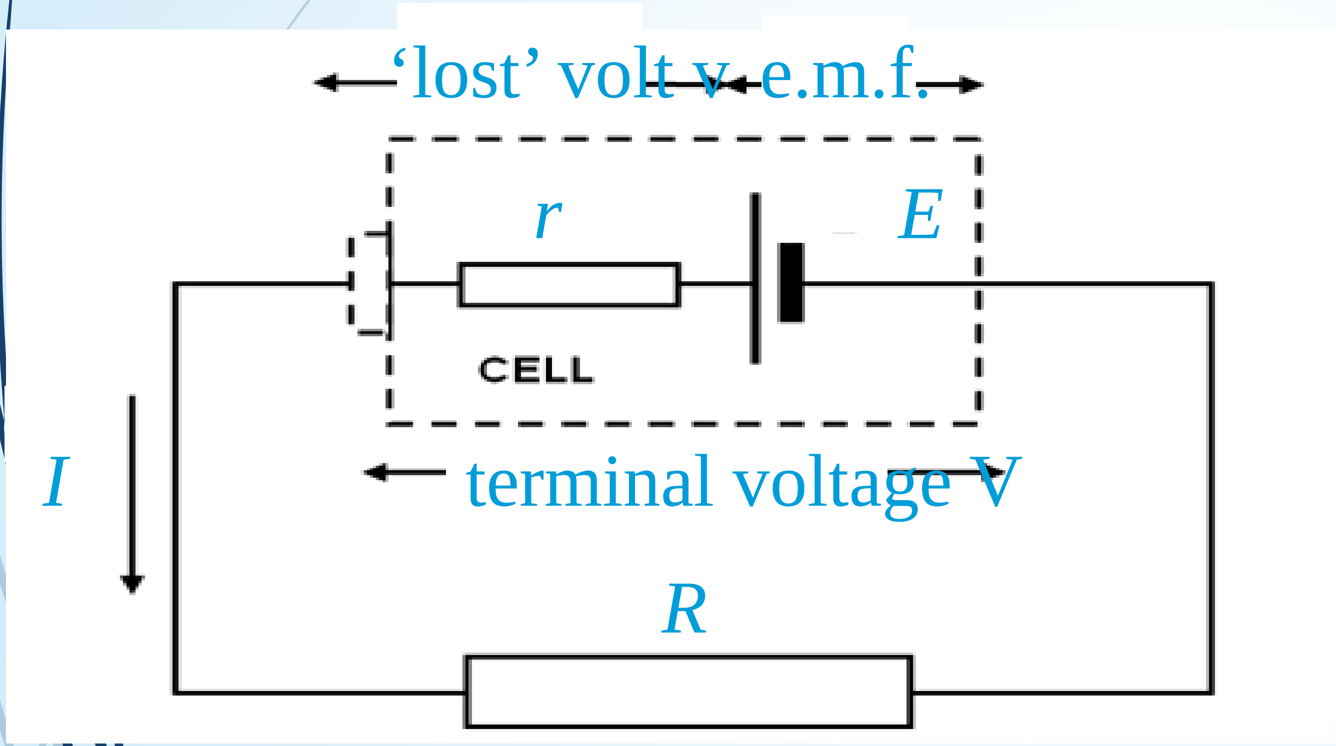
- **Ohm's Law** deals with the relationship between the voltage and current in a conductor with resistance R.
- Mathematically:

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

Toll Road—Circuit Analogy



- The deficiency is due to the cell itself having some resistance.
- All power supplies, including the batteries and low voltage power packs, have some resistance due to the way they are made. This is called **internal resistance**.



E = V + v

E = IR + Ir

For an open circuit,

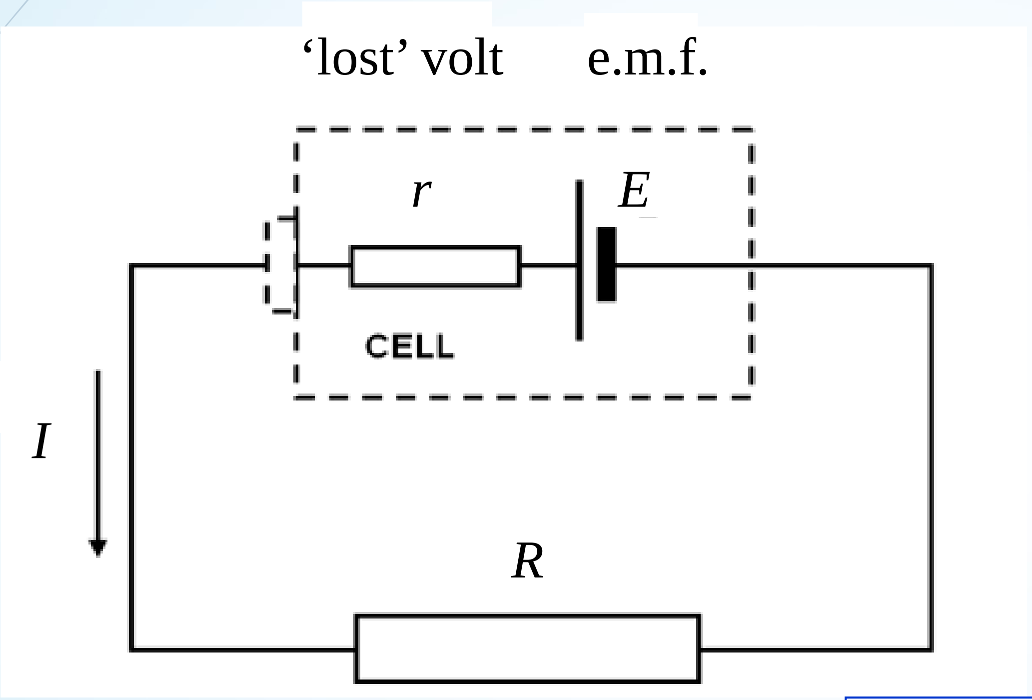
I = 0 ⇒ 'lost' volt v = 0.

e.m.f. E = terminal voltage V.

Electric Power

- Electric power P is the rate of doing electrical work.
- Power is the product of current and voltage.
- $P = V \cdot I$ $\qquad P = I^2 \cdot R$ $\qquad P = \frac{V^2}{R}$
- Unit: Watt, W
- 1 W = 1 Joule/sec = 1 Volt·Amp
- The total power in a series combination of light bulbs and in a parallel combination of light bulbs is the sum of the individual wattages. Ex.: two 60 W light bulbs will dissipate 120 W in a series combination as well as in a parallel combination.

Variation of power output with external resistance



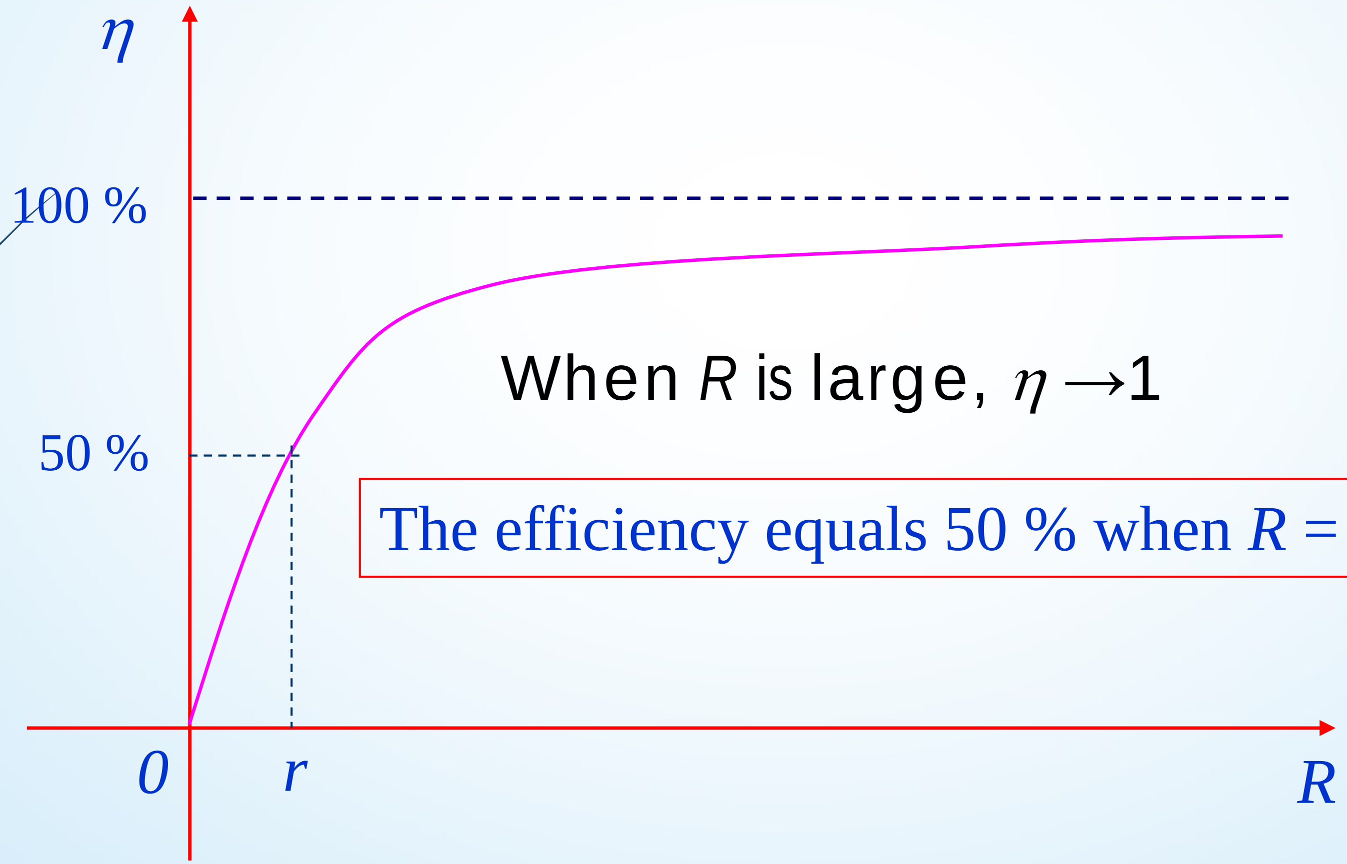
$I = E / (R + r)$

$$P_o = I^2 R = \frac{E^2 R}{(R+r)^2}$$

Power output to R is a maximum when R = r, internal resistance.

Variation of efficiency with the external resistance

$$\eta = \frac{P_o}{P_i} = \frac{I^2 R}{I^2 R + I^2 r} = \frac{R}{R + r} \times 100\%$$



When R is large, $\eta \to 1$

The efficiency equals 50 % when $R = r$

MAGNETIC FIELDS

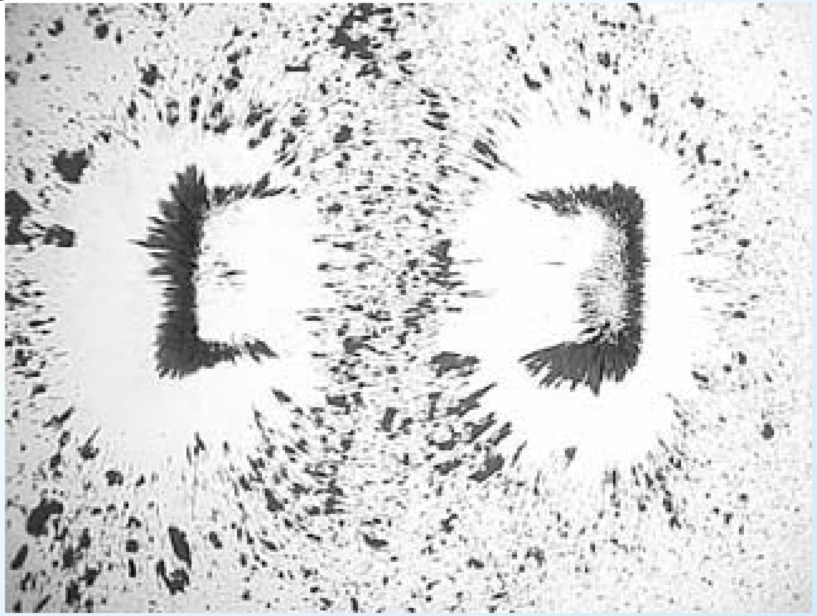
Produced by

-time varying electric fields

-permanent magnet (arises from quantum mechanical electron spin/ can be considered charge in motion=current)

-steady electric currents

$$[H]_{SI} = \frac{A}{m}$$



$F_m \sim q, u, B$ → $\overline{H} = \frac{1}{\mu}\overline{B}$

q –charge
u –velocity vector
B -strength of the field (magnetic flux density)
μ_r –relative permeability
μ –absolute permeability
μ_0-permeability of the free space $\mu_0 = 4\pi * 10^{-7} (H)$
$M=\chi_m H$- is the magnetization for linear and homogeneous medium

Lorentz's Force equation

$$\overline{F_e} = q\overline{E}$$

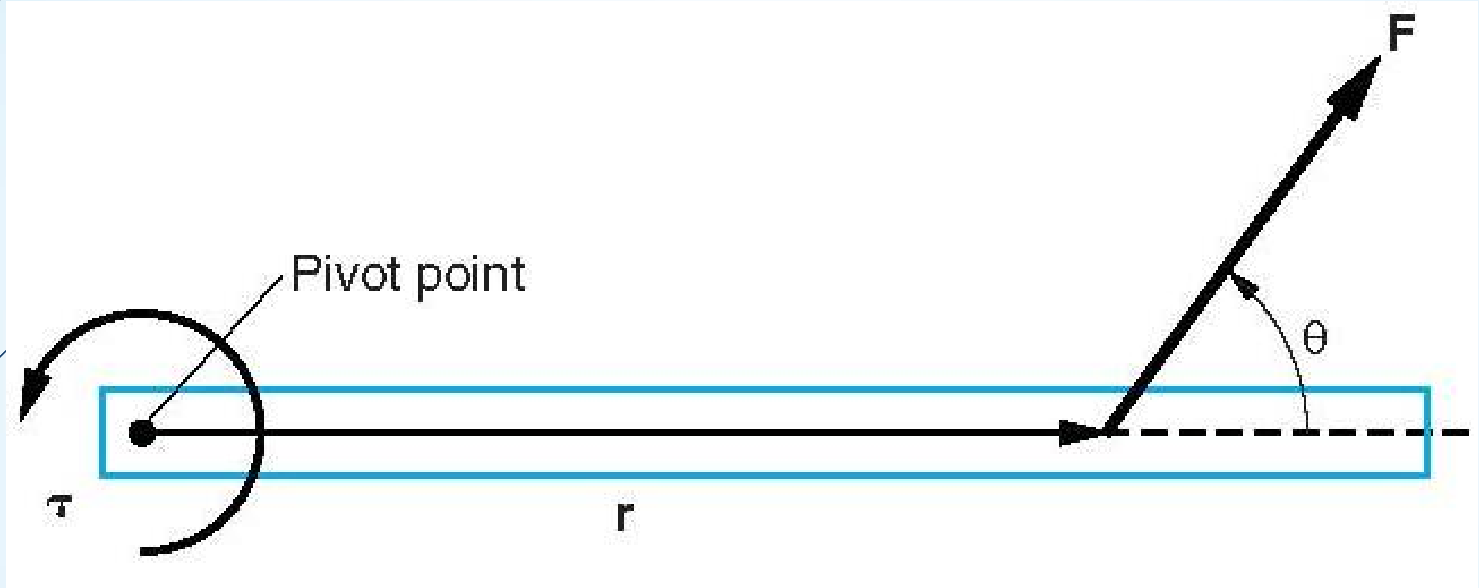
$$\overline{F_m} = q\overline{u} \times \overline{B}$$

$$\overline{F_e} + \overline{F_m} = F$$

$$\overline{F} = q(\overline{E} + \overline{u} \times \overline{B})$$

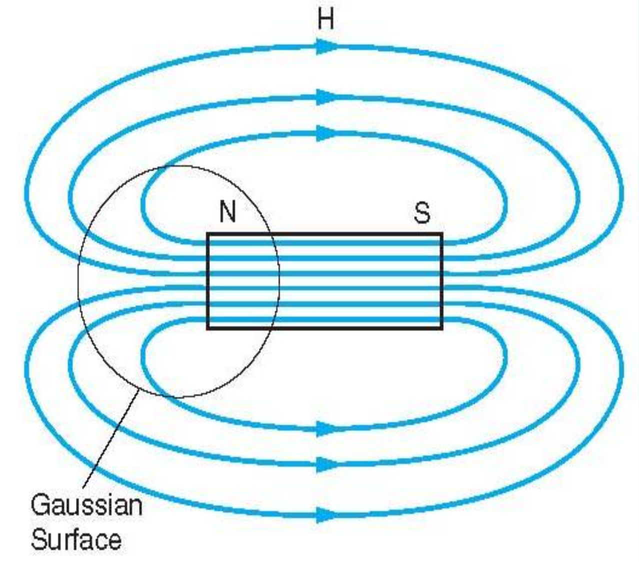
Note: Magnetic force is zero for q moving in the direction of the magnetic field (sin0=0)

The magnetic force is exerting a torque on the current carrying coil



$$\tau = \overline{r} \times \overline{F_m} = |r| \times |F_m| \sin\theta \, \overline{a_n}$$

Law of conservation of magnetic flux



$$\oint_s \overline{B} \bullet d\overline{s} = 0$$

Ampere's circuital law

$$\int_s \left(\nabla \times \overline{B}\right) \bullet d\overline{s} = \mu_0 \int_s \overline{J} \bullet d\overline{s}$$

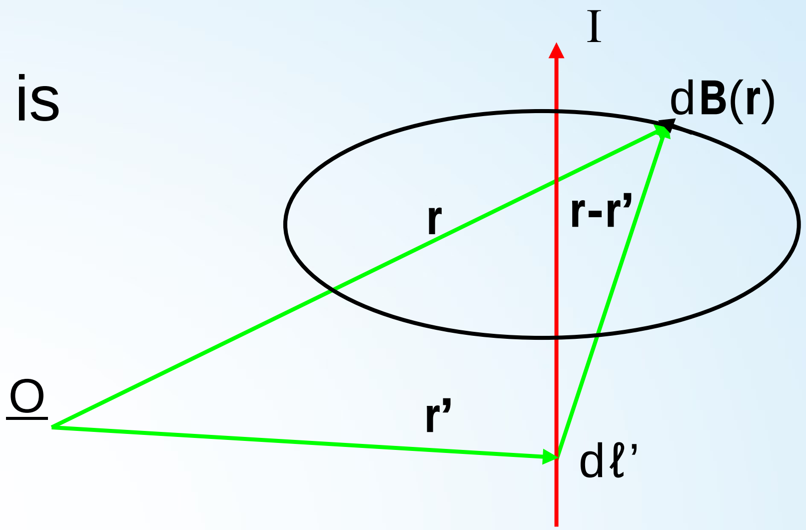
$$\oint_c \overline{B} \bullet d\overline{l} = \mu_0 I$$

The circulation of the magnetic flux density in free space around any closed path is equal to μ_0 times the total current flowing through the surface bounded by the path

Postulates of Magnetostatics in Free Space	
Differential Form	Integral Form
$\nabla \bullet \overline{B} = 0$	$\oint_s \overline{B} \bullet d\overline{s} = 0$
$\nabla \times \overline{B} = \mu_0 J$	$\oint_c \overline{B} \bullet d\overline{l} = \mu_0 I$

Biot-Savart Law

- The analogue of Coulomb's Law is the Biot-Savart Law
- Consider a current loop (I)
- For element d**ℓ** there is an associated element field d**B**



$$d\mathbf{B}(\mathbf{r}) = \frac{\mu_o I}{4\pi} \frac{d\ell' \mathrm{x} (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3}$$

d**B** perpendicular to both d**ℓ'** and **r-r'**
same $1/(4\pi r^2)$ dependence
μ_o is "permeability of free space"
defined as $4\pi \times 10^{-7}$ Wb A^{-1} m^{-1}

Integrate to get B-S Law

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_o I}{4\pi} \oint_{\ell} \frac{d\ell' \mathrm{x} (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3}$$

Magnetic dipole moment

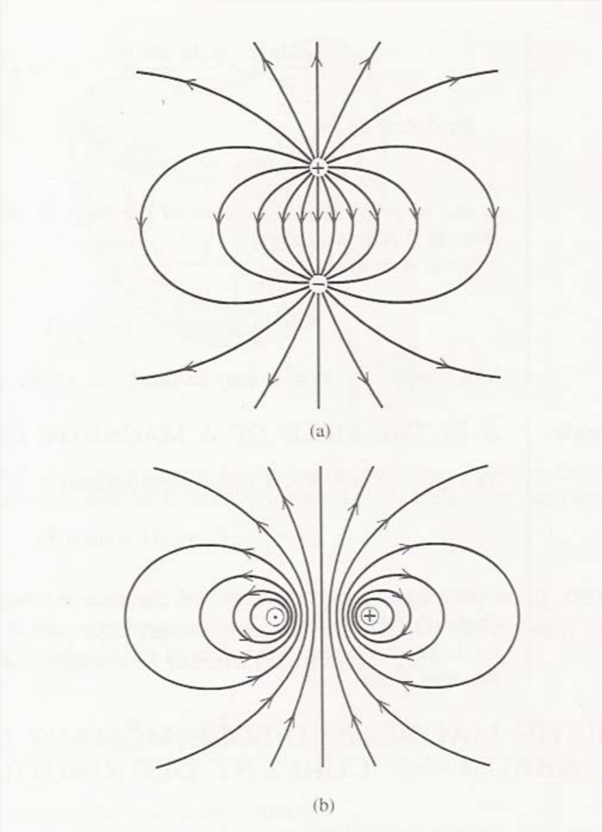
The off-axis field of circular loop is much more complex. For *z* >> *a* it is *identical* to that of the electric dipole

$$\mathbf{E} = \frac{p}{4\pi\varepsilon_o r^3}\left[2\cos\theta\,\hat{\mathbf{r}} + \sin\theta\,\hat{\theta}\right]$$

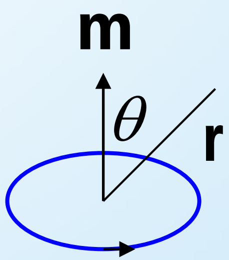
$$\Rightarrow \mathbf{B} = \frac{\mu_o m}{4\pi\, r^3}\left[2\cos\theta\,\hat{\mathbf{r}} + \sin\theta\,\hat{\theta}\right]$$

where $m = \pi\, a^2 I = \alpha\, I$ or $\mathbf{m} = \pi\, a^2 I\,\hat{z}$

α area enclosed by current loop

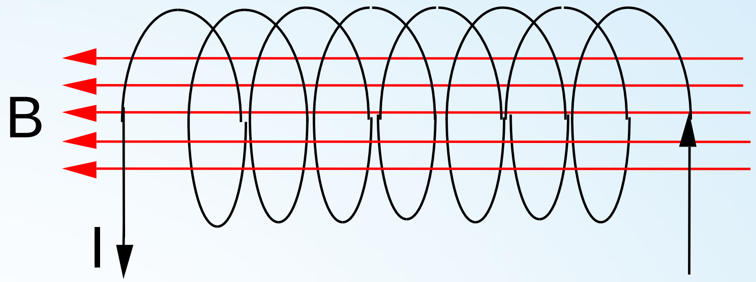


m "current times area" vs **p** "charge times distance"



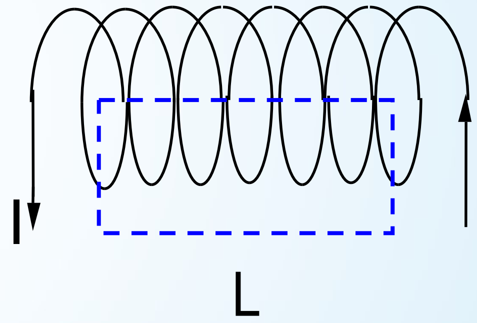
Solenoid

Distributed-coiled conductor
Key parameter: n loops/metre



If finite length, sum individual loops via B-S Law

If infinite length, apply Ampere's Law
B constant and axial inside, zero outside
Rectangular path, axial length L



$$\oint \mathbf{B}_{vac}.d\ell = \mu_o I_{encl} \Rightarrow B_{vac}L = \mu_o (nL) I \Rightarrow B_{vac} = \mu_o n I$$

(use label $\mathbf{B}_{vac}$ to distinguish from core-filled solenoids)

solenoid is to magnetostatics what capacitor is to electrostatics

Relative permeability

Recall how field in vacuum capacitor is reduced when dielectric medium is inserted; always *reduction*, whether medium is polar or non-polar:

$$\mathbf{E} = \frac{\mathbf{E}_{\mathbf{vac}}}{\varepsilon_{\mathbf{r}}} \Rightarrow \mathbf{B} = \mu_{\mathbf{r}}\mathbf{B}_{\mathbf{vac}}$$

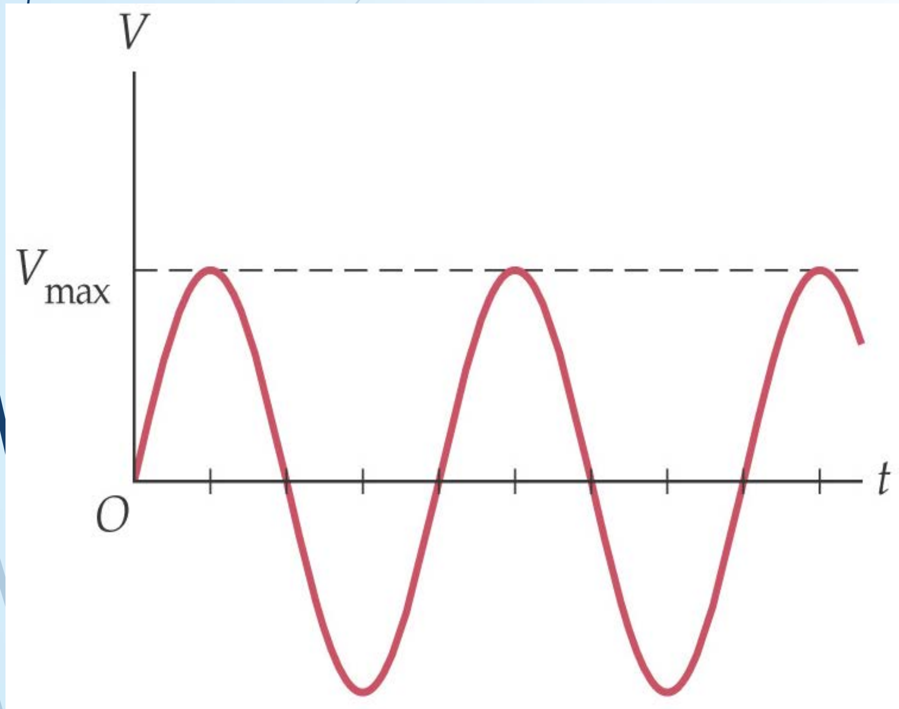
is the analogous expression when magnetic medium is inserted in the vacuum solenoid.

Complication: the **B** field can be reduced or increased, depending on the type of magnetic medium

Alternating Voltages and Currents

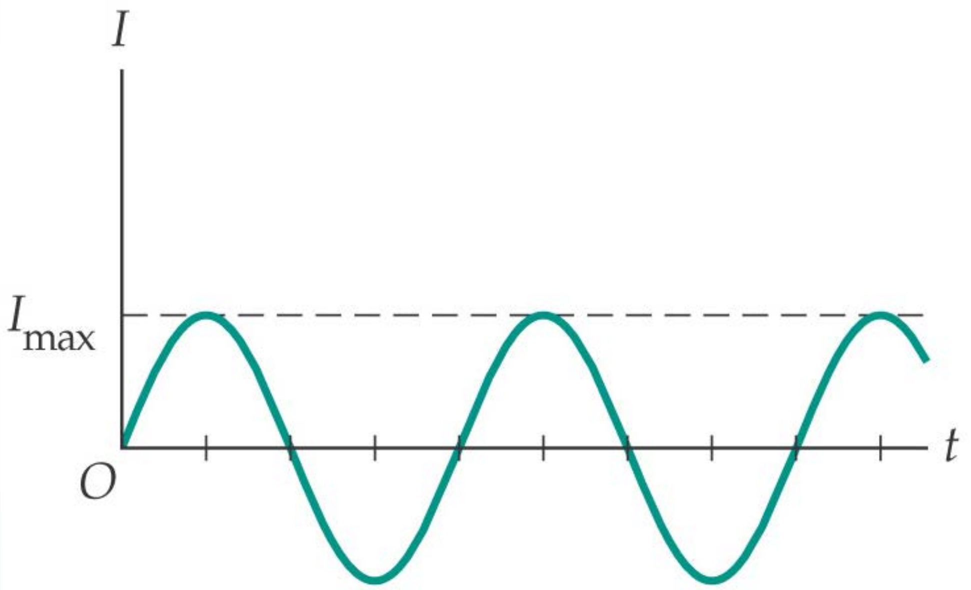
The voltage as a function of time is:

$$V = V_{max} \sin \omega t$$



Since this circuit has only a resistor, the current is given by:

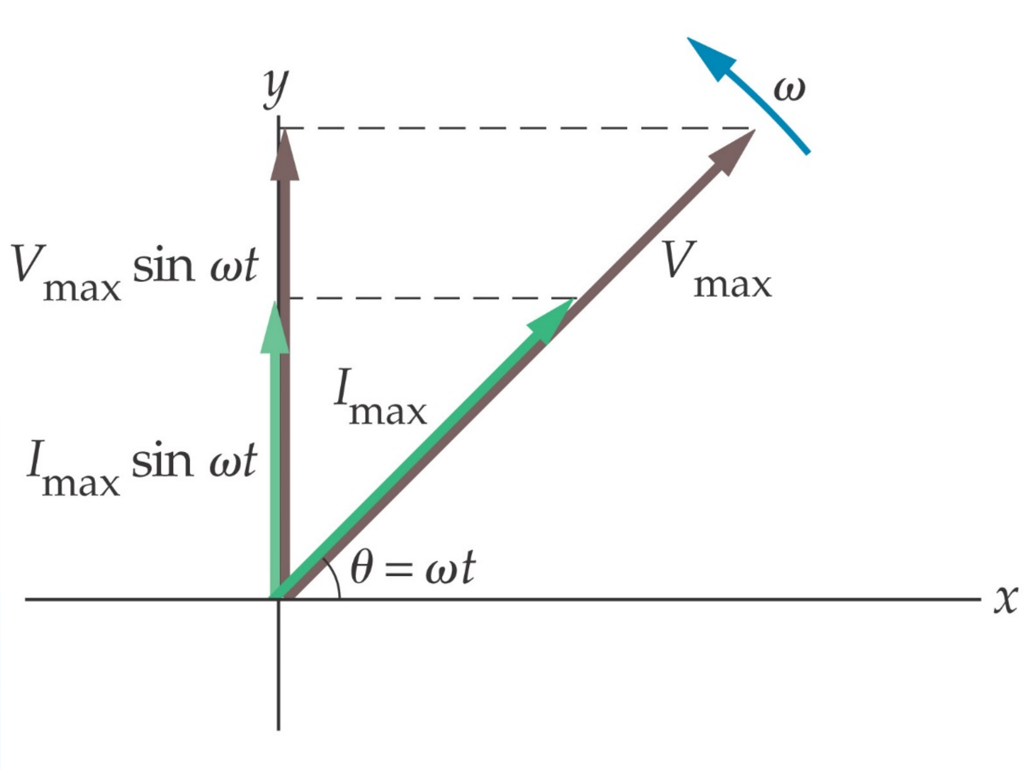
$$I = \frac{V}{R} = \left(\frac{V_{max}}{R}\right) \sin \omega t = I_{max} \sin \omega t$$



Here, the current and voltage have peaks at the same time – they are in phase.

In order to visualize the phase relationships between the current and voltage in ac circuits, we define phasors – vectors whose length is the maximum voltage or current, and which rotate around an origin with the angular speed of the oscillating current.

The instantaneous value of the voltage or current represented by the phasor is its projection on the *y* axis.



The voltage and current in an ac circuit both average to zero, making the average useless in describing their behavior.

We use instead the root mean square (rms); we square the value, find the mean value, and then take the square root:

RMS Value of a Quantity with Sinusoidal Time Dependence

$$(x^2)_{av} = \frac{1}{2} x_{max}{}^2$$

$$x_{rms} = \frac{1}{\sqrt{2}} x_{max}$$

220 volts is the rms value of household ac.

By calculating the power and finding the average, we see that:

$$P = I^2 R = I_{max}{}^2 R \sin^2 \omega t$$

$$P_{av} = I_{max}{}^2 R (\sin^2 \omega t)_{av} = \frac{1}{2} I_{max}{}^2 R = I_{rms}{}^2 R$$

Capacitors in AC Circuits

How is the rms current in the capacitor related to its capacitance and to the frequency? The answer, which requires calculus to derive:

$$I_{rms} = \omega C V_{rms}$$

In analogy with resistance, we write:

$$I_{rms} = \frac{V_{rms}}{X_C}$$

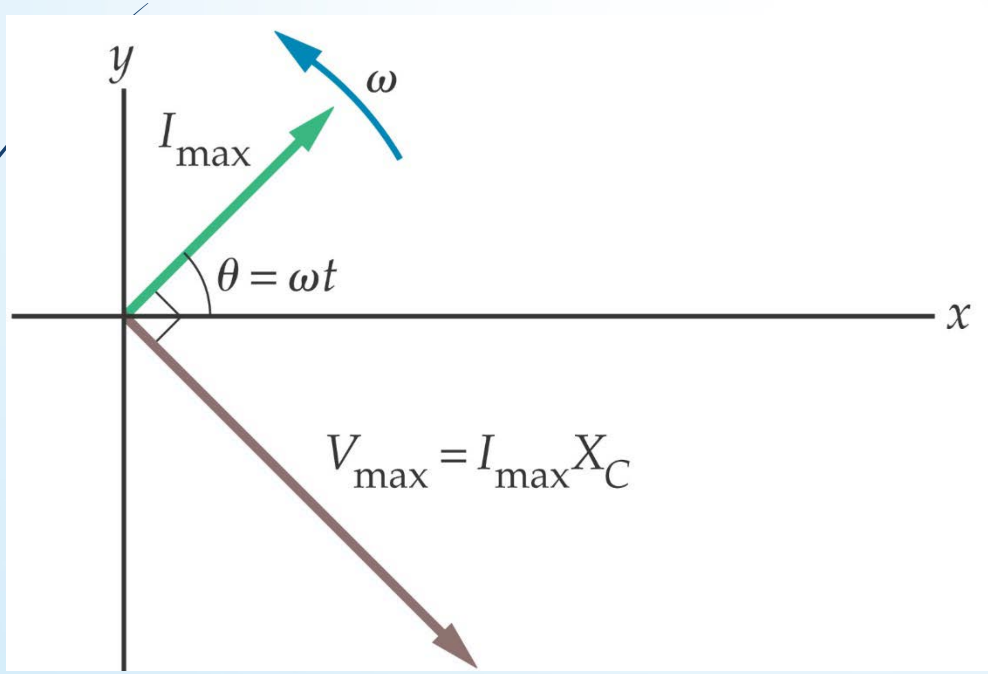
Capacitive Reactance, X_C

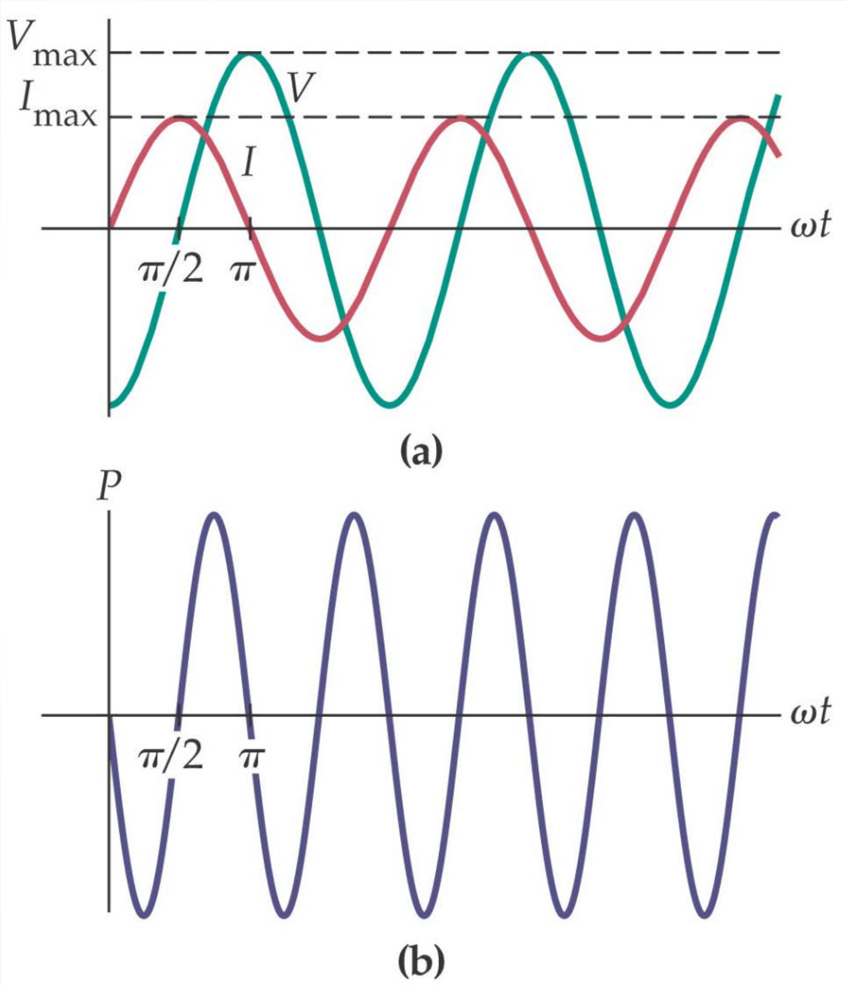
$$X_C = \frac{1}{\omega C}$$

SI unit: ohm, Ω

Capacitors in AC Circuits

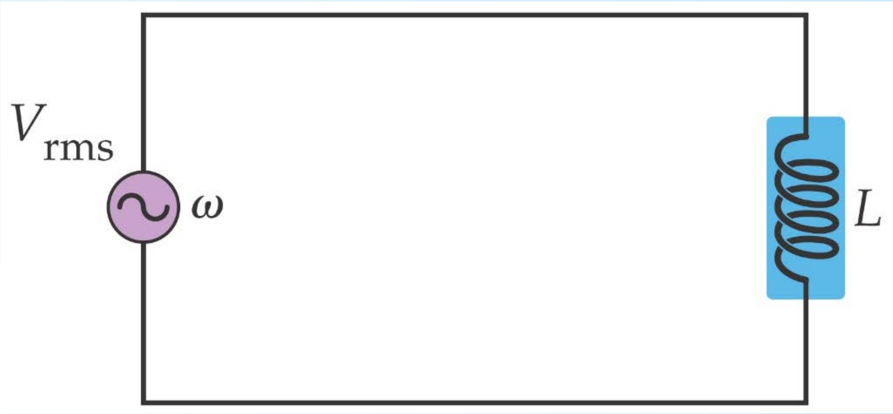
The voltage and current in a capacitor are not in phase. The voltage lags by 90°.





Inductors in AC Circuits

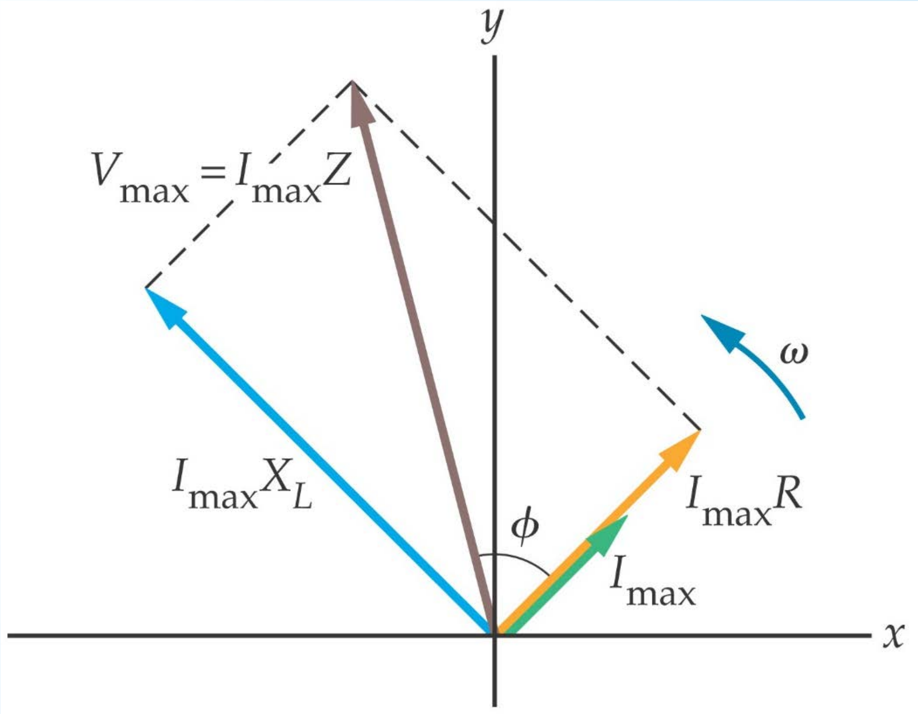
Just as with capacitance, we can define inductive reactance:



Inductive Reactance, X_L

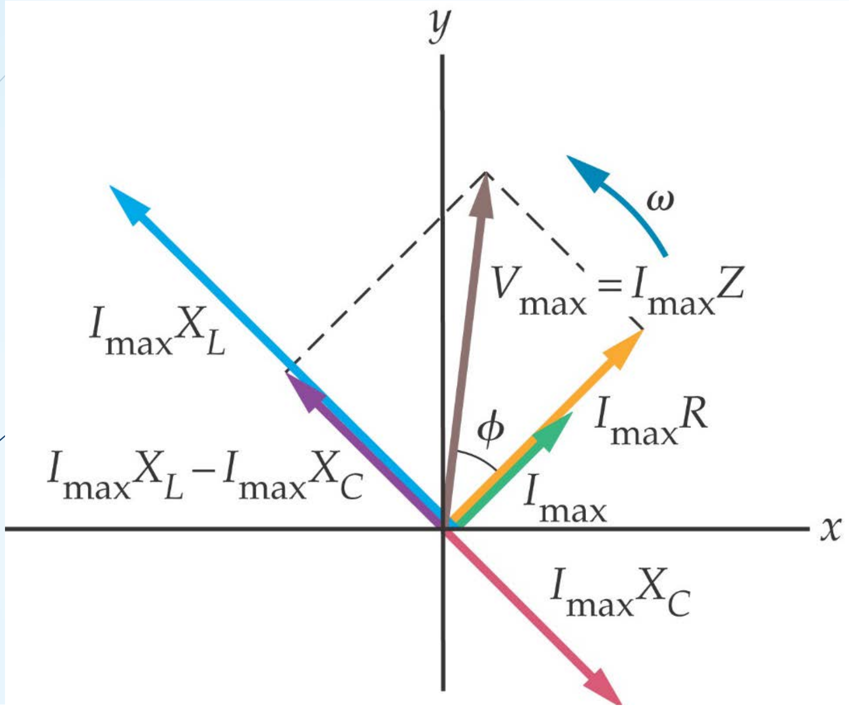
$$X_L = \omega L$$

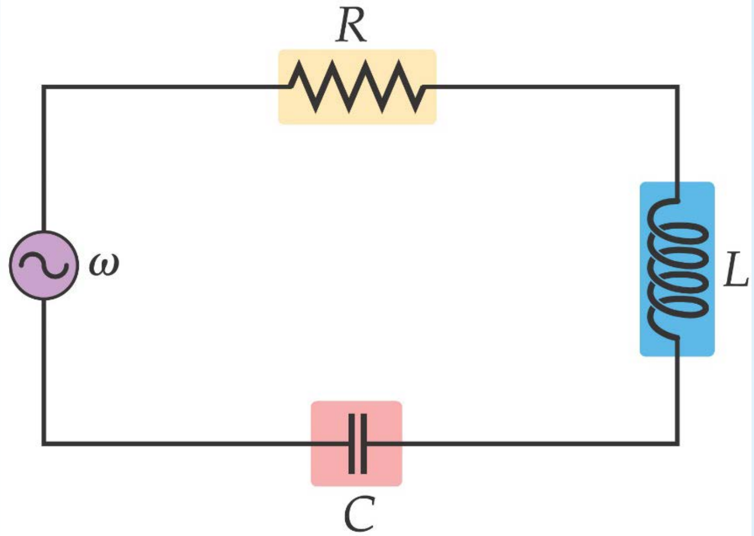
SI unit: ohm, Ω



RLC Circuits

A phasor diagram is a useful way to analyze an RLC circuit.





Impedance of an *RLC* Circuit

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

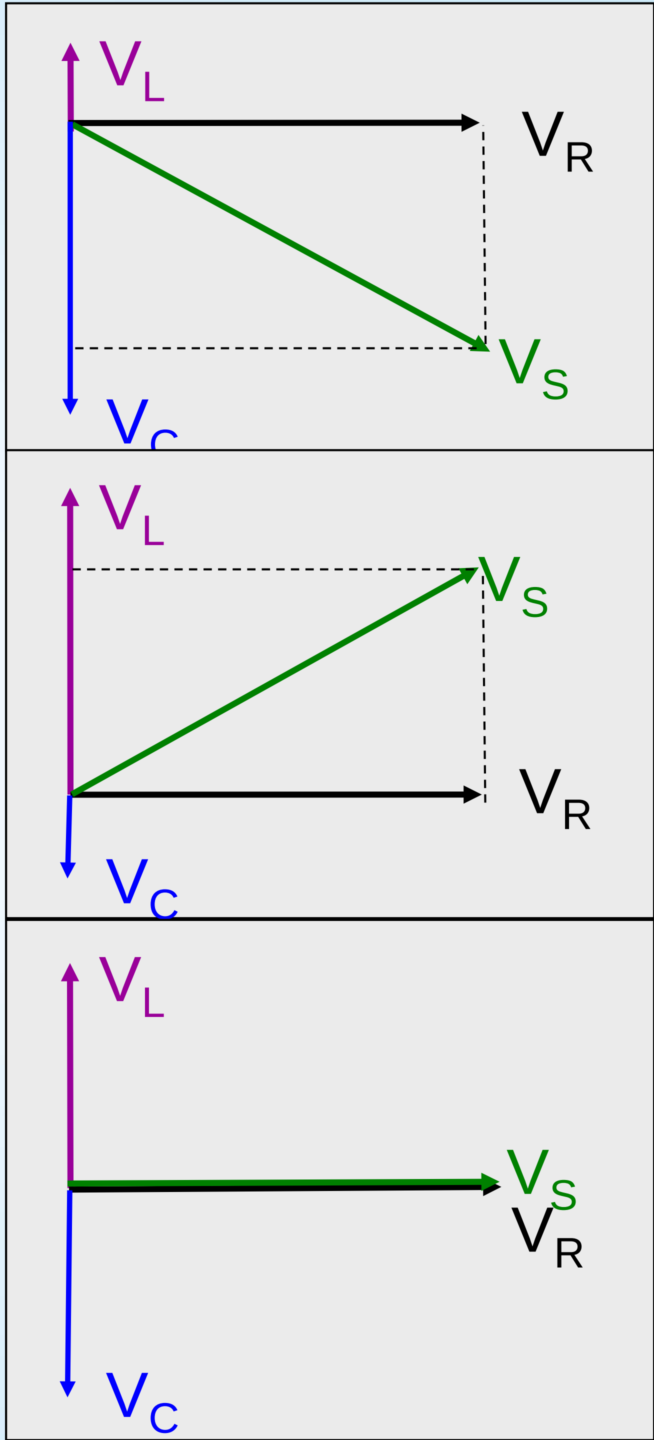
SI unit: ohm, Ω

Resonance

- At low f, $V_C > V_L$ so V_R (and therefore I) is small.
- ie. Capacitors limit the current better at low frequencies

- At high f, $V_L > V_C$ so V_R (and therefore I) is small.
- ie. Inductors limit the current better at high frequencies

- At resonance, $V_L = V_C$ and they cancel each other out. So $V_S = V_R$ and if V_R is at max then I is at max.



Resonant Frequency

- A circuit will have a resonant frequency f_0 which depends on L and C:

$$X_L = X_C$$

$$2\pi f_0 L = \frac{1}{2\pi f_0 C}$$

$$f_0^2 = \frac{1}{4\pi^2 LC}$$

$$\boxed{f_0 = \frac{1}{2\pi\sqrt{LC}}}$$

Control Questions

1. Ohm's Law.
2. Dipoles.
3. Lorentz's Force equation.
4. Solenoid.
5. Resonance in RLC Circuits.
6. Nerve Impulses.

Recommended literature:

Basic:

1. Vladimir Timanyuk, Elena Zhivotova, Igor Storozhenko. Biophysics: Textbook for students of higher schools / Kh.: NUPh, Golden Pages, 2011.- 576p.
2. Vladimir Timaniuk, Marina Kaydash, Ella Romodanova. Physical methods of analysis / Manual for students of higher schools/– Kharkiv: NUPh: Golden Pages, 2012. – 192 p.
3. Philip Nelson. Biological Physics. – W. H. Freeman, 1st Edition, 2007. – 600 p.
4. Biophysics, physical methods of analysis. Workbook: Study guide for the students of higher pharmaceutical educational institutions / Pogorelov S. V., Krasovskyi I. V., Kaydash M. V., Sheykina N. V., Frolova N. O., Timaniuk V. O., Romodanova E.O., Kokodii M.H. – Kharkiv., – 2018. – 130 p.
5. Center for distance learning technologies of NPhaU. Access mode: http://nuph.edu.ua/centr-distancijjnih-tehnologijj-navcha/

Support:

1. Eduard Lychkovsky. Physical methods of analysis and metrology: tutorial / Eduard Lychkovsky, Zoryana Fedorovych. – Lviv, 2012. – 107 p.
2. Daniel Goldfarb. Biophysics DeMYSTiFied. – McGraw-Hill Professional, 1st Edition, 2010. – 400 p.


Thanks for
your attention