PHY 316M

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1 Capacitors

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

2 Current

Is the flow of charge in on direction. Current:

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

Current Density (current per unit area): $J = \frac{I}{A}$
$n =$ charge carriere density, $q =$ charge per carrier, $v_d =$ drift velocity This can give us, $\boxed{J = nqv_d}$

2.1 Ohm's Law

Usually we see Ohm's law in different forms, i.e. for a particular chunk.
Consinder some block with volume $A \cdot l$, some source of energy(battery) forces current thorugh by applying an electric field.
For a uniform electric field: $\boxed{V = E \cdot l}$

$$\begin{aligned} J &= \frac{I}{A} \\ &= \sigma E \\ &= \sigma \frac{V}{l} \end{aligned}$$

$$\boxed{\frac{V}{I} = \frac{1}{\sigma}\frac{l}{A} = \rho\frac{l}{A} = R = \text{resistance}}$$

$\boxed{\frac{V}{I} = R}$ Resistance is not resistivity (opisiton of current flow of a particular material[ρ]) Ohmic material is a material that has a constant slope on Voltage to Current graph. Most common materials like copper behave like this.

Example The resistivity of nichrome wire(heaters, toasters) is $1.5 \times 10^{-6}\Omega m$. If a household voltage of $115V$ is applied acros a $0.2mm$ radius write, $1.0m$ long, what current flows?

$R = \rho\frac{l}{A} = \rho\frac{l}{\pi r^2} = \frac{1.5\times10^{-6}\Omega m \cdot 1.0m}{(\pi(2\times10^{-4}m)^2))} = 11.9\Omega$

2.2 Model for electric conduction

- electron unergo many rapid ocllision when $E = 0$
- when $E \neq 0$, the electrons accelrate between collisions
- $F = ma = qE => a = \frac{qE}{m}$
- $v = v_0 + at = v_0 + \frac{qE}{m}t$

Let τ = average collision time $= R \cdot C$
the $v_d = v_{avg} =< v_0 > + \frac{qE}{m}\tau$
so, $J = nqv_d = nq = \frac{qE}{m}\tau = \sigma E$
so conducitvity $\sigma = \frac{nq^2\tau}{m}$
Called the Drude model or free electron mode

$$\boxed{\sigma = \frac{nq^2\tau}{m}}$$

$$\boxed{\frac{1}{\sigma} = \rho}$$

Example Assume for copper that each atom donates one free electron. What is the average time between collision for electrons in copper.?
Given:

- Density= $8.98\frac{g}{cm^3}$
- Atomic Weight $= 63.54\frac{g}{mole}$
- $\rho = 1.7 \times 10 -^{-8}\ \Omega \cdot m$

$\tau = \frac{m}{nq^2\rho} = \frac{9.14\times10^{-31}kg}{(8.5\times10^22)(1.6\times10^{-19})^2 1.7\times10^{-8}\Omega m} = 2.5 \times 10^{-14}s$

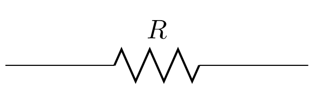
2.3 Temerature Dependence of resistivity

- resistivities tabulated for 20 °celsius
- for metals, ρ is higher and T is higher
- α = linear temprature coefficient
- over some range, $\boxed{\rho = \rho_0(1 + \alpha(T - T_0))}$

As T increases, the scattering time decreases due to collisions with vibrating atoms
At higher temperatures the ρ to temprature graph is linear. But at the beginning there is residual resistvity due to impurities.

Semiconductors The number of carriers decreases as the temperature decreases, this means that all the electrons are sticking to their atoms.

3 Resistors in Series and Parallel

Circuit symbol: 

3.1 Resistors in series

For resistors in series the resistivities add

$$R_{tot} = R_1 + R_2 + ...$$

$$R_{tot} = \frac{V}{I} = \frac{V_1}{I_1} + \frac{V_2}{I_2} = R_1 + R_2$$

The current (I) is the same everywhere too. **Resistors don't add in parallel. Capacitors do.**

$$V = V_1 + V_2$$

The voltage divider

$$V_1 = I \cdot R_1 = \frac{V}{R_1 + R_2} \cdot R_1$$

3.2 Resistors in parallel

For resisitors in parallel halve the resistance if two exact resistors are put in parallel

- In parallel have the same voltage across each element
- In parallel also the current divides among branches

$$I = I_1 + I_2 = \frac{V}{R_1} + \frac{V}{R_2} => R_{tot} = \frac{V}{I} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$

Superconductors Electrons pair up and when electron jumps to the lattice another electrons pulls it right back.

3.3 Resistors Disipate Energy

Electrons undergo collisions, and give up energy as heat. A steady release of current (I) causes a steady realease of energy.

$$\Delta U = \Delta Q V$$

Better to discess the rate, which is really known as:

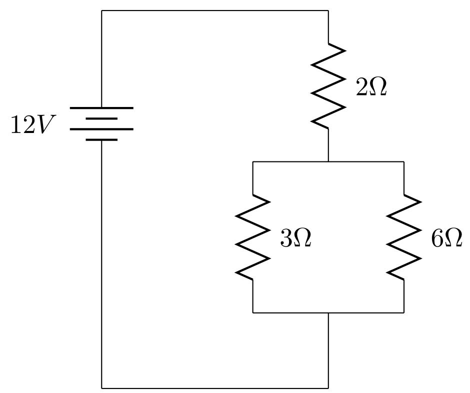
$$\text{Power} = P = \frac{\Delta U}{\Delta t} = \frac{\Delta U}{\Delta t} V = IV$$

$$\boxed{P = IV = I^2 R = \frac{V^2}{R}}$$

This power is also known as Joule heating.

Putting this into practice: many circuits can be analyzed with just Ohm's Law and Resistance.

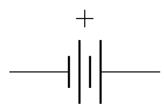
- What is the total power delivered?
- What is the power dissipated in each R?



$$P_{\text{dissapated in } 3\Omega} = \frac{V_3^2}{R} = \frac{(6V)^2}{3\Omega} = 12W$$

3.4 Direct Current Circuits

Real battery is an ideal $\mathscr{E}$MF plus intended resistance

Batteries are a source of voltage 

Source of voltage = "electromotive force" $= \mathscr{E}$MF$= \mathscr{E}$

$$\boxed{V = \mathscr{E} - Ir}$$

"Open-circuit voltage", where $I = 0$

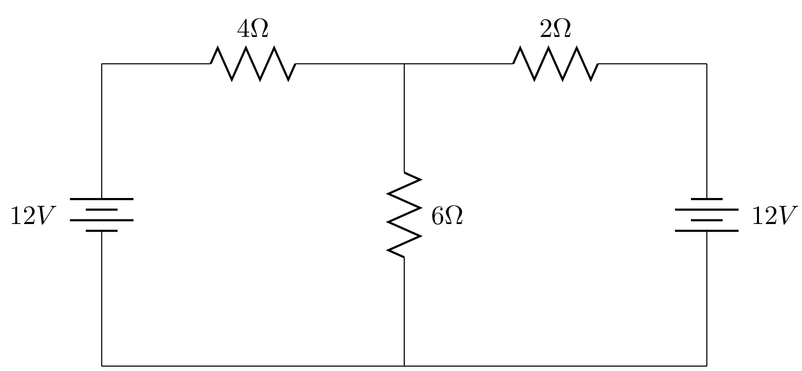
Analysis of circuits Any circuit can be analyzed with Kirchhoffs Rules:

- Junction Rule, algebraic sum of currents into a junction = sum of currents $\Sigma i_{in} = \Sigma i_{out}$
- Loop Rule, algebraic sum of voltages around any closed loop is zero. Where voltage rises are positive (- to +) and votlage drops are negative (+ to -)

For resistors the current directino determines voltage drop(negative)

Example

- What is the current in the 6Ω resisitor?
- Is it flowing up or down?



(I) Junction at A: $i_1 = i_2 + i_3$

(II) Loop A: $12V - i_1(4\Omega) - i_3(6\Omega) = 0$

(III) Loop B: $I_3(6\Omega) - i_2(2\Omega) + 12V = 0$

$i_3 = \frac{-12V}{22\Omega} = -\frac{6}{11}A$

2 other techniques:

i) same, except use ficticious "loop currents"

ii) Source suppressing - can look at effects of sources seperately

Next: Circuits with Capacitors will see time-depedent behavior Before "transient phenomena", look at *Steady-state*: "after a long time". The capacitor starts acting like the current is 0.

4 Magnetism

We saw:

$$F = qv\frac{\mu_0 I}{2\pi r} = 0$$

for $\vec{v}$ tangent to circle. where $\mu_0 = 4\pi \times 10^{-7}\frac{Ns^2}{C^2}$
Rewrite this as

$$\boxed{\vec{F} = q\vec{v} \times \vec{B}}$$

where $\boxed{B = \frac{\mu_0 I}{2\pi r}}$ magentic field due to a long wire where direciton of $\vec{B}$ is tangent to circle.
If also electric force, combination of electric and magnetic force is called "Lorentz Force"

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

$\vec{F} = q\vec{v} \times \vec{B}$

- Like $\vec{E}, \vec{F}$ opposite for $+q, -q$
- Depends on $\vec{v} : \vec{F} = 0$ for $\vec{v} = 0$
- Depends on angle : $\boxed{|\vec{F}| = |q|vBsin\Theta}$
  notice $\vec{F} = 0$ for $\vec{v} \parallel \vec{B}$
- Direction $\vec{F} = q\vec{v} \times \vec{B}$ given by right hand rule

Magnetic field does no work because the magnetic force is perpendcular to displacement.
So $\vec{B}$ changes direction of $\vec{v}$ but not its magnitude ($KE = \frac{1}{2}mv^2$)
Unit of B = $\frac{Ns}{Cm}$ = tesla = T also gauss = $G = 10^{-4}T$

4.1 Evaluating Cross Products

1. Get general equation by expaning determinant $\begin{vmatrix} i & j & k \\ v_x & v_y & v_z \\ B_x & B_y & B_z \end{vmatrix} =$
   $\vec{v} \times \vec{B} = i(v_y B_z - v_z B_y) - j(v_x B_z - v_z B_x) + k(v_x B_y - v_y B_x)$
2. Just multiply out.
   know that $i \times j = k$ and that $j \times i = -k$

5. Magnetic field does no work

4.2 Two ways to Find $\vec{B}$

1. Ampere's Law: for high symmetry
2. Biot Savart Law

In general we will only look at: center of arcs and circles, or due to straight segments, or on axis of loop.

4.2.1 $\vec{B}$ at the center of a circle

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{Id\vec{s}\times\hat{r}}{r^2}$$

$$B = \int dB = \int \frac{\mu_0 I}{4\pi r^2}ds = \frac{\mu_0 I}{2R}$$

Since $r = R$, the integral is constant and is easy to integrate with respect to s.

Also: for a fraction f of a circle $\boxed{\vec{B} = fB_{\text{full circle}}}$

4.2.2 $\vec{B}$ near a finite straight wire

$$\begin{aligned} d\vec{B} &= \frac{\mu_0 I}{4\pi}\frac{d\vec{s}\times\hat{r}}{r^2} \\ &= \frac{\mu_0 I}{4\pi}\frac{dssin\theta}{r^2} \end{aligned}$$

1. $sin\theta = sin\theta' = cos\phi$
2. $cos\phi = \frac{R}{r} \rightarrow r\frac{R}{cos\phi}$
3. $tan\phi = \frac{s}{R} \rightarrow s = R \cdot tan\phi \rightarrow \frac{R}{cos^2\phi d\phi}$

$$\begin{aligned} B &= \int dB \\ &= \int \frac{\mu_0 I \frac{R}{cos^2\phi}d\phi cos\phi}{4\pi(\frac{R}{cos\phi})^2} \\ &= \frac{\mu_0 I}{4\pi R}\int_{-\phi_1}^{+\phi^2} cos\phi d\phi \\ &= \frac{\mu_0 I}{4\pi R} sin\phi|_{-\phi_1}^{+\phi^2} \\ &= \frac{\mu_0 I}{4\pi R}[sin\phi_2 + sin\phi_1] \end{aligned}$$

4.2.3 B field due to a square loop of side a

$$B_{loop}$$

$$\frac{2\sqrt{2}\mu_0 I}{\pi a}$$

4.2.4 B on axis of loop

Off axis compnents cancel around circle.
ϕ is the angle at the bottom right of triangle formed by circle and axis

$$r = \sqrt{x^2 + R^2} \qquad \text{Using pythagorean theorem}$$

$$sin\phi = \frac{R}{\sqrt{x^2 + R^2}} \qquad \text{So we can define } sin\phi$$

We only have to integrate along the x compnents

$$\begin{aligned} dB_x &= dBsin\phi \\ &= \frac{\mu_0 I ds}{4\pi r^2} sin\phi \end{aligned}$$

We can say that $\int ds = 2\pi R$ since the radius is constant

$$\begin{aligned} B &= \int \frac{\mu_0 I}{4\pi r^2} sin\phi \, ds \\ &= \frac{\mu_0 IR}{4\pi (x^2 + R^2)^{3/2}} \int ds \\ &= \frac{\mu_0 IR^2}{2(x^2 + R^2)^{3/2}} \end{aligned}$$

Also, consider yourself very close to the field, $x >> R$ $\frac{1}{x^3}$ dipole field

4.3 Motion in a uniform B

$$|\vec{F}| = |q\vec{v} \times \vec{B}| = qvB$$

$\vec{F}$ is $\perp$ to $\vec{v}$ centripetal with accelarations $a_r = \frac{v^2}{r}$ We saw that

$$\begin{aligned} B_{\text{long wire}} &= \frac{\mu_0 I}{2\pi r} \\ B_{\text{solonoid}} &= \mu_0 n I \\ B_{\text{loop center}} &= \frac{\mu_0 I}{2R} \end{aligned}$$

angular velocity $\omega = ?$

$$r = \frac{mv}{qB}$$

Example: Mass Spectrometer *Note: Electrons travel in a semi-circle in a spectrometer* Electrons are accelarated through potential of $10^3 V$ ("a 1 keV electron"). They enter a region of uniform $B = 10^{-2} T$. What is the distance they are displaced?

$$x = 2r = 2\frac{mv}{qB}$$

Know m, q, B need to find v

$$\begin{aligned} \Delta KE = \Delta PE \rightarrow \frac{1}{2}mv^2 = eV_0 = \sqrt{\frac{2eV}{m}} \\ x = 2\frac{m}{eB}\sqrt{\frac{2eV_0}{m}} = \frac{2}{B}\sqrt{\frac{2mV_0}{e}} = \frac{2}{(10^{-2}T)}\sqrt{\frac{2(9.11 \times 10^{-31})(10^3 V)}{(1.6 \times 10^{-19} C)}} \end{aligned}$$

In practice however, we are given v,B,x to get $(\frac{q}{m})$

Example: Velocity Selector region of crossed $\vec{E} + \vec{B}$
All we have to consider is qE *-vs-* qvB
if $qE = qvB$ then $\boxed{v = \frac{E}{B}}$

4.4 Force on a current

Consider positive charge travelling along x axis with v_0 with a $-\vec{B}\hat{y}$

$$\begin{aligned}
F_{\text{on wire}} &= q\vec{v} \times \vec{B} \\
&= \frac{1}{n}\vec{j} \times \vec{B} \\
F_{\text{on wire}} &= (\#\text{ charges})F_{\text{on 1 charge}} \\
&= (nAl)\frac{1}{n}\hat{\vec{j}} \times \hat{\vec{B}} \\
&= lA\vec{j} \times \vec{B} \\
&= I\vec{l} \times \vec{B}
\end{aligned}$$

Example Net force on a current loop in a uniform $\vec{B}$ is **zero**. This is true for any loop.

Example A current I flows from the origin to $(x, y, z) = (1m, 1m, 0)$ and then straight to $(2m, 0, 0)$. In a uniform field of $\vec{B} = 5T\hat{\imath}$

$$\begin{aligned}
\vec{F}_1 &= (10N)(-\hat{\jmath} + \hat{\imath}) \\
\vec{F}_2 &= (10N)(-\hat{\jmath} - \hat{\imath}) \\
\vec{F} &= (20N) - \hat{\jmath}
\end{aligned}$$

Example Force on a wire segment due to a large $\|$ wire

$$\begin{aligned}
B &= \frac{\mu_0 I}{2\pi r} \\
\vec{F} &= I_2\vec{l} \times \frac{\mu_0 I_1}{2\pi r} \\
&= I_2 \times \frac{l\mu_0 I_1}{2\pi r} \\
\frac{\text{force}}{\text{length}} &= \frac{\mu_0 I_1 I_2}{2\pi r}
\end{aligned}$$

Definition: Magnetic Moment
Dipole moment ($\mu = IA$) due to a magnetic loop.

4.5 Torque on a current

We saw: $\vec{F} = I\vec{l} \times \vec{B}$

Magnetic Moment $\vec{\mu} = I\vec{A}$
and for N loops we have $\vec{\mu} = NI\vec{A}$

we also saw that for a loop in uniform $B \to \vec{F} = 0$. There is no force, but there is a **net torque**.

Torque on a current
Loop in a uniform B

$$\vec{\tau} = \Sigma \vec{r} \times \vec{F}$$
$$|\vec{\tau}| = \Sigma r F sin\theta$$
$$= (z)(\frac{l}{z}) I l B sin\theta$$
$$= I l^2 B sin\theta$$
$$= \mu B sin\theta$$
$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

Where μ is the magnetic moment and $\vec{B}$ is the magnetic field.

5 Magnetism in Matter

Comes from some sort of current loop in matter. Perhaps an electron traveling around a proton, that is a current loop.

Example Consider the oribting elctron as current:

$$I = \frac{\Delta Q}{\Delta t} = \frac{e}{T} = \frac{e}{(2\pi r)/v} = \frac{e \cdot v}{2\pi r}$$

$$\mu = IA = \frac{e \cdot v}{2\pi r} \cdot \pi r^2 = \frac{1}{2} evr$$

Recall that angular momentum is $\vec{l} = \vec{r} \times \vec{p}$ and therefore $\boxed{l = mvr}$

$$\mu = \frac{e}{2m} mvr = \frac{e}{2m} l$$

An atom can have many electrons $\vec{L} = \Sigma \vec{l_i}$ and that $\mu = -\frac{e}{2m}\vec{L}$

5.1 Quantum Mechanics

$\vec{l}$ is quantized: $l = 0, \hbar, 2\hbar, ...$ When $\hbar = \frac{h}{2\pi} = 1.06 \times 10^{-34} J$ where h = Planck's constant = $6.63 \times 10^{-34} J$. Ultimately, the spin of atom does not really exist, but it behaves like it is. Its "spin" would be $s = \frac{\hbar}{2}$

Adding total angular momentum $\vec{J} = \vec{L} + \vec{S}$

When $l = \hbar$ we have the smallest possible moment. $\mu = \frac{e\hbar}{2m}$ = Bohr magneton = $9.27 \times 10^{-24} J/T$

5.2 Magnetization

Definition Magnetization = $M = \frac{\mu}{(volume)}$ = magnetic moment per unit volume.

The total field In an external lfield, some moments align and they produce their own field, $\vec{B}_{matter}$. With our definitions, $B_{\text{matter}} = \mu_0 M$, so the total field $\vec{B} = \vec{B}_{ext} + \mu_0 \vec{M}$. For many field $\vec{B} \propto \vec{B}_{ext}$. Really we can say that $\vec{B} = K_m \vec{B}_{ext}$ where K_m = magnetic permeability or just the permeability constant.

Vaccum $K_m = 1$

Diamagnet in most materials $K_m - 1 \approx 10^{-6} - 10^{-4} \approx -10^{-5}$ because they have closed shells

Ferromagnet $K_m >> 1$ have locked moments due to Pauli exclusion principle.

Superconductors Type I superconductors have a $K_m = 0$, which means they shield the cternal field.

Magnetic Susceptibility $\chi_m = K_m - 1 \boxed{\frac{\mu_0 M}{B_{ext}}}$