Introduction to Faraday's Law of Induction

1

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Chapter 31-32

Thank You, Emily Rencsok, for these notes.

- Moving charges cause a B field
- Moving poles cause an E field
- If B field changes/time, charge flows + induced current + induced emf
- Faraday's Law of Induction

$$\mathcal{E} = -N \frac{d\Phi_B}{dt}$$

$\uparrow$ induced emf $\quad \uparrow$ # of loops

$$\Phi_B = BA\cos\theta \qquad \mathcal{E} = -N\frac{d}{dt}(BA\cos\theta)$$

Can induce emf by changing:

1) magnitude of B field
2) area enclosed by loop
3) θ btwn $\vec{A}$ + $\vec{B}$
4) Any combination of other 3

Introduction to Lenz' Law - The Direction of Faraday's Law of Induction (with Examples)

2

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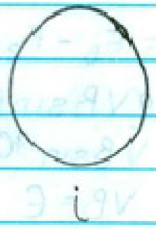
Thank You, Emily Rencsok, for these notes.

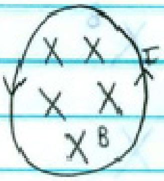
- Direction of induced current

Lenz' Law

$\mathcal{E} = -N \frac{d\Phi_B}{dt}$ induced emf is opposite the change in Φ_B

(electromagnetic intertia)

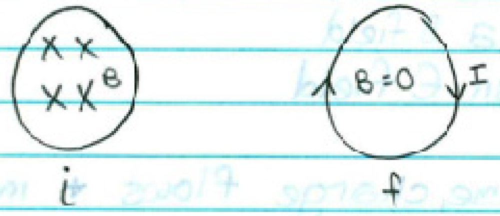




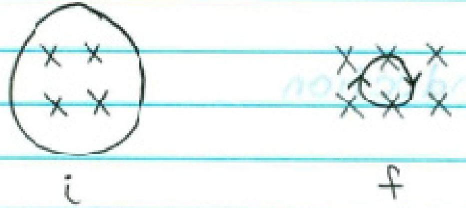
B_{in} + increasing

B_{ind} => out

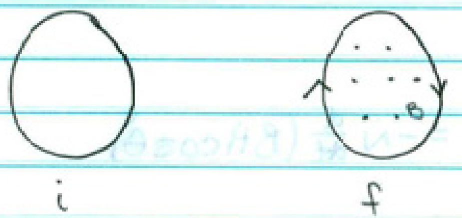
I_{ind} => counterclockwise



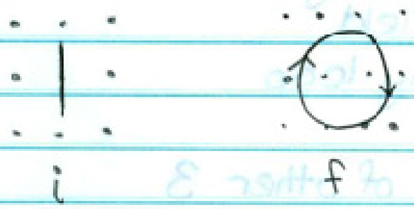
B_{in} + decreasing
B_{ind} ⇒ into board
I_{ind} ⇒ clockwise



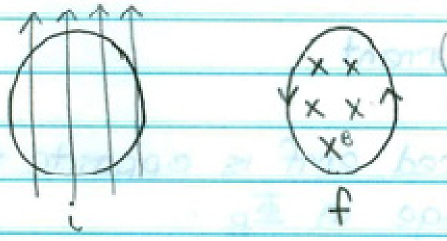
B_{in} Φ_B decreasing
B_{ind} ⇒ into board
I_{ind} ⇒ clockwise



B_{out} + increasing
B_{ind} ⇒ into board
I_{ind} ⇒ CW



(i) $\Phi_B = 0$
(f) Φ_B inc + out of board
B_{ind} ⇒ into board
I_{ind} ⇒ CW



(i) $\Phi_B = 0$
(f) Φ_B inc + into board
B_{ind} ⇒ out
I_{ind} ⇒ CCW

Derivation of Motional EMF using Net Force
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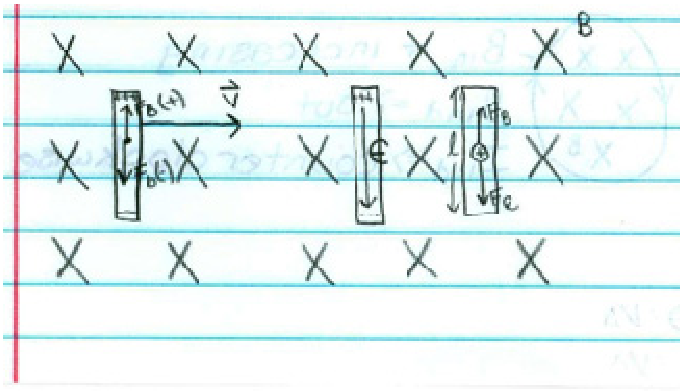

$$\Sigma F_y = F_B - F_e = \cancel{m a_y} = 0$$

$$\cancel{q} v B \sin\theta = \cancel{q} \mathcal{E}$$

$$v B \cancel{\sin 90°} = \mathcal{E}$$

$$v B = \mathcal{E}$$

$$\Delta V = \mathcal{E} d$$

$$\Delta V = v B \ell$$

$$\boxed{\mathcal{E} = v B \ell}$$

motional emf

Derivation of Motional EMF using Faraday's Law of Induction

4

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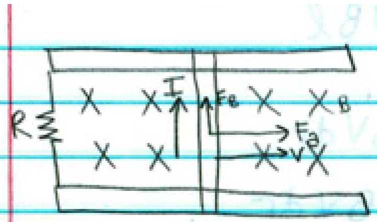
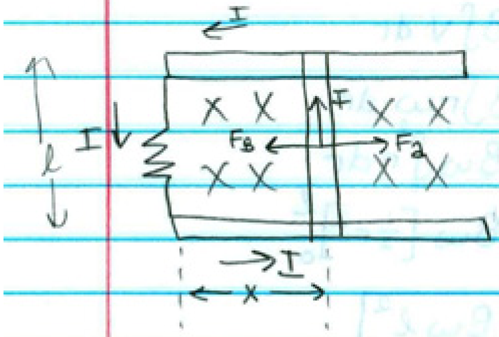


$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

Φ_B into board + increasing

$B_{ind} \Rightarrow$ out of board

$I_{ind} \Rightarrow$ CCW



$$\Phi_B = BA\cos\theta$$

$$\mathcal{E} = -N\frac{dI_B}{dt}$$

$$\mathcal{E} = -(1)\frac{d}{dt}(BA\cos\theta)$$

$$= -B\cos(180)\frac{d}{dt}(\ell x)$$

$$= B\ell\frac{dx}{dt} = B\ell v$$

Faraday's Law of Induction Example - Changing Current on a Resistance Loop
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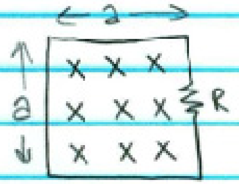
Ex



$R = 25.0\ \Omega$

$a = 5.00\text{ cm}$

$B_{\perp} = (45.0\cos(17t))\text{ T}$

$I(t) = \text{mag}?$

$f = ?$

$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

$$= -(1)\frac{d}{dt}(BA\cos\theta)$$

$$\mathcal{E} = -a^2\cos 0\frac{d}{dt}(45\cos(17t))$$

$$\mathcal{E} = \cancel{-}a^2 765(\cancel{-}\sin(17t))$$

$$\Delta V = IR$$

$$I = \frac{\Delta V}{R}$$

$$I = \frac{1}{R}(765a^2\sin(17t))$$

$$I = \frac{1}{25}(765(0.05)^2\sin(17t))$$

$$I = 0.0765\sin(17t)$$

$$\boxed{I(t) = 76.5\sin(17t)\text{ mA}}$$

$$A = 76.5\text{ mA}$$

$$\frac{1}{T} = f$$

$$\omega = 17 = \frac{\Delta\theta}{\Delta t} = \frac{2\pi}{T} = 2\pi f$$

$$f = \frac{\omega}{2\pi} = \frac{17}{2\pi} = \boxed{2.71\text{ Hz}}$$

Example - Rotating Metal Bar in Constant Magnetic Field (Motional EMF)

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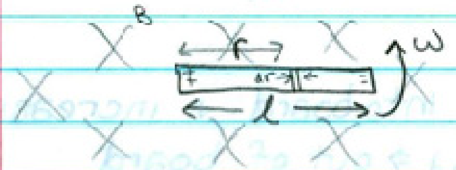
Ex

$v = r\omega$

$\Delta V = vB\ell$



$\Delta V = ?$

$$\int d\mathcal{E} = \int Bv\,dr$$

$$\mathcal{E} = \int Bv\,dr$$

$$\mathcal{E} = B\int v\,dr$$

$$\mathcal{E} = B\int r\omega\,dr$$

$$\mathcal{E} = B\omega\int_0^\ell r\,dr$$

$$\mathcal{E} = B\omega\left[\frac{1}{2}r^2\right]_0^\ell$$

$$\boxed{\mathcal{E} = \frac{B\omega\ell^2}{2}}$$

Introduction to Generators and Motors
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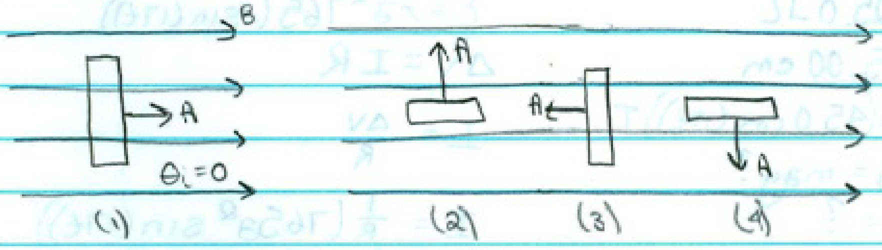
- Generators + motors

ME → EE   EE → ME
CE → ME

Generator



Φ_B max   0 Φ_B min   0

$$\Phi_B = BA\cos\theta$$

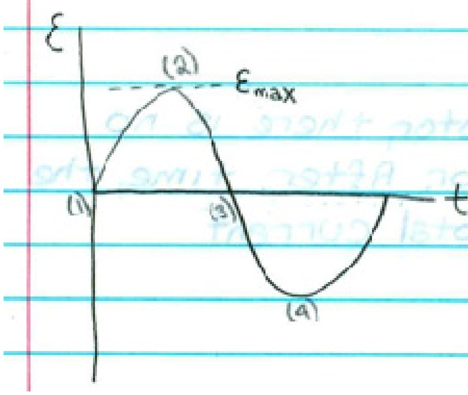
$$\omega = \frac{\Delta\theta}{\Delta t} = \frac{\theta}{t} \rightarrow \theta = \omega t$$

set $\theta_i = 0$ + $t_i = 0$

$$\Phi_B = BA\cos(\omega t)$$

$$\mathcal{E} = -N\frac{d\Phi_B}{dt} = -N\frac{d}{dt}(BA\cos(\omega t)) = -N.BA\frac{d}{dt}\cos(\omega t)$$

$$\mathcal{E} = -NBA(-\sin\omega t)\omega \rightarrow \mathcal{E} = \omega NBA\sin(\omega t) \quad \boxed{\mathcal{E}_{max} = \omega NBA}$$



for a generator

Derivation of Back EMF in an Electric Motor
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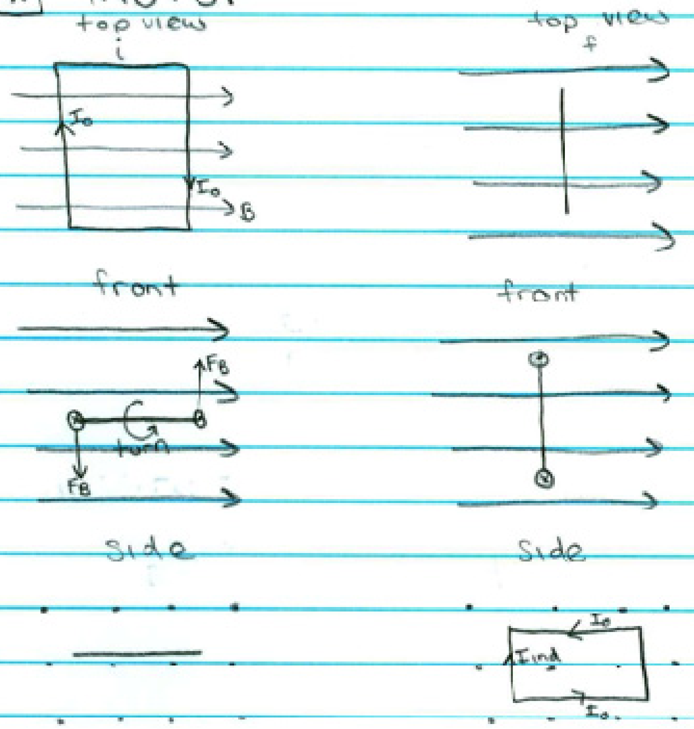
Ex] motor



$\Phi_{B\,initial} = 0$

Φ_B out + inc

$B_{ind} \Rightarrow$ into board

$I_{ind} \Rightarrow$ CW

$I_0 \Rightarrow$ current from motor

$I_{ind} \Rightarrow$ induced from loop turning in B field

- Back emf
  - When you start up a motor, there is no induced emf in the motor. After time, the back emf reduces the total current

Example - Back EMF in an Electric Motor

10

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Thank You, Emily Rencsok, for these notes.

(#9 was the Eddy Current Demo and there weren't any lecture notes to go along with that one, in case you were looking for them.)

Ex| motor 120 V circuit

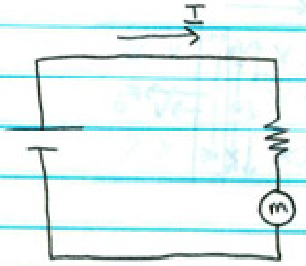
$R_m = 5.00\,\Omega$

@Full speed, $I = 2.40$ A

a) $\mathcal{E}_{back} = ?$

b) I @ start

c) $\frac{P_{start}}{P_{run}} = ?$



@ full speed

a) $\Delta V_{loop} = 0 = -\Delta V_R - \mathcal{E}_{back} + \Delta V_t$

$0 = -IR - \mathcal{E}_{back} + \Delta V_t$

$\mathcal{E}_{back} = \Delta V_t - IR$

$\mathcal{E}_{back} = 120 - 2.4(5)$

$\boxed{\mathcal{E}_{back} = 108 \text{ V}}$

@ beginning, no $\mathcal{E}_{back}$

b) $\Delta V_{loop} = 0 = -\Delta V_R + \Delta V_t$

$\Delta V_t = IR$

$120 = I(5)$ $\boxed{I_{start} = 24 \text{ A}}$

c) $\frac{(I_{start})^2 \cancel{R}}{(I_{run})^2 R} = \frac{24^2}{2.4^2} = \boxed{100}$

Example - Current Carrying Square Loop in a Solenoid
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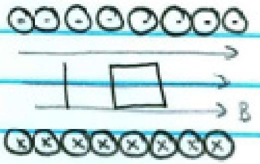
Ex



$n_s = 500$ turns/m
$I_s = 20.0$ A
$R_s = 10$ cm

Square loop in solenoid
- Turn by mechanical means

$N_L = 150$
$d_{side} = 0.020$ m
$\omega = 2\pi$ rad/s

$\mathcal{E}(t) = ?$

$$\mathcal{E} = -N_L \frac{d\Phi_B}{dt} \qquad \Phi_B = BA\cos\theta$$

$$\mathcal{E} = -N_L \frac{d}{dt}(\mu_0 n I d^2 \cos\omega t) \qquad B = \mu_0 n I$$

$$\mathcal{E} = -N_L \mu_0 n I d^2 \frac{d}{dt}(\cos\omega t) \qquad A = d^2$$

$$\omega = \frac{\Delta\theta}{\Delta t} = \frac{\theta_f - \cancel{\theta_i}}{t_f - \cancel{t_0}} = \frac{\theta}{t}$$

$$\mathcal{E} = \cancel{-}N_L \mu_0 n I d^2 \cancel{-}\omega \sin(\omega t) \qquad \theta = \omega t$$

$$\mathcal{E} = 150(4\pi\times10^{-7})(500)(20)(0.02)^2(2\pi)\sin(2\pi t)$$

$$\mathcal{E} = 0.0047732\sin(2\pi t)$$

$$\boxed{\mathcal{E} = 0.00473\sin(2\pi t)\ \text{V}}$$

Example - Power and Motional EMF
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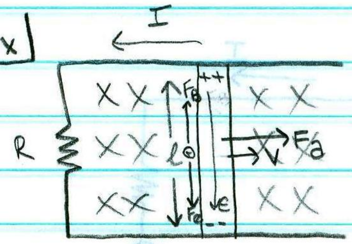
Ex



$\Sigma F_y = F_B - F_e = \cancel{ma_y} = 0$

$F_B = F_e$

$\theta = 90°$

$\cancel{q}vB\cancel{\sin\theta} = \cancel{q}E$

$E = vB$

$\Delta V = -Ed$

$\|\Delta V\| = Ed$

$\Delta V = vB\ell$

$B = 1.5\ T$

$V = 5.0\ m/s$

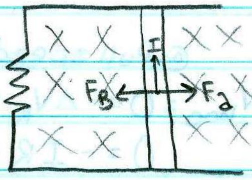
$R = 2.0\ \Omega$

$\ell = 25\ cm$

a) $F_a = ?$

b) $P_{F_a} = ?$

c) $P_R = ?$



$\Delta V = IR$

$I = \frac{\Delta V}{R} = \frac{vB\ell}{R}$

$\Sigma F_x = F_a - F_B = \cancel{ma_x} = 0$

$F_a = F_B$

$F_a = I\ell B \sin\theta$

$= I\ell B \cancel{\sin 90}$

$F_a = \frac{vB\ell}{R} \ell B$

$F_a = \frac{vB^2\ell^2}{R} = \boxed{0.35\ N}$

b) $P_{F_a} = F_a V \cos\theta$

$= \frac{VB^2\ell^2}{R} V \cos 0 = \boxed{1.8\ W}$

c) $P_e = I\Delta V$

$P_e = \left(\frac{vB\ell}{R}\right)(vB\ell)$

$P_R = \frac{V^2B^2\ell^2}{R}$

$\boxed{P_R = 1.8\ W}$

Demo Hand Crank Motor and Electric Generator and Prius
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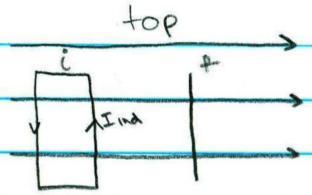
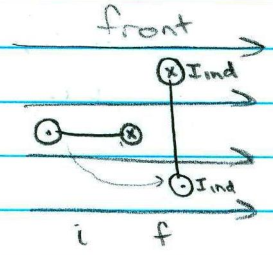
- Generator

$\frac{d\Phi_B}{dt}$





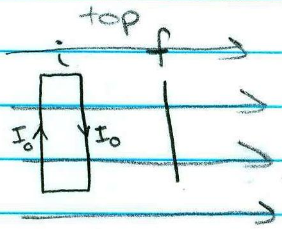
$\Phi_B = 0$ i

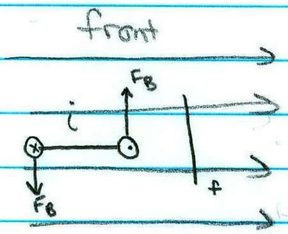
Φ_B right f + inc

B_{ind} ⇒ left

I_{ind} ⇒

- Motor





Torque in same direction as we turned it

Derivation of Inductance of a Coil and Self Inductance of a Solenoid
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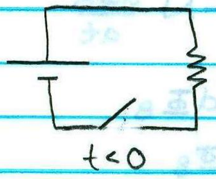

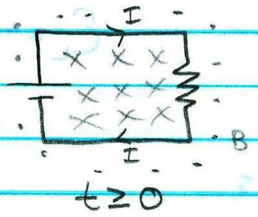

$\Phi_{B_i} = 0$
Φ_{B_f} = into board + inc
B_{ind} = out
I_{ind} = CCW

Self-inductance

$\mathcal{E}_{ind} = -N \frac{d\Phi_B}{dt}$

$\Phi_B = BA\cos\theta$
$B = \frac{\mu_0 I}{2\pi a}$

$\mathcal{E}_{ind} \propto \frac{dI}{dt}$

$\boxed{\mathcal{E}_L = -L \frac{dI}{dt}}$ L is the inductance of the coil

$\cancel{-}\int L \frac{dI}{\cancel{dt}} = \int \cancel{-} N \frac{d\Phi_B}{\cancel{dt}}$

$L\,dI = N\,d\Phi_B$
$LI = N\Phi_B$
$\boxed{L = \frac{N\Phi_B}{I}}$ not on eqn sheet

$L = \frac{-\mathcal{E}_L}{dI/dt}$

$L \Rightarrow \frac{V}{A/s} = \frac{V \cdot s}{A}$ = Henry, H

$R = \frac{\Delta V}{I} \rightarrow$ resistance to current

$L = -\frac{\mathcal{E}_L}{dI/dt} \rightarrow$ resistance to a change in current

Example - Inductance and Induced EMF on a Solenoid
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Ex| Solenoid

$\frac{dI}{dt} = 75.0 \text{ A/s}$

$N = 500.0$ turns

$\ell = 50.0$ cm

$r = 4.0$ cm

a) $L = ?$

b) $\mathcal{E}_{ind} = ?$

$$\mathcal{E}_L = -L\frac{dI}{dt} = -N\frac{d\Phi_B}{dt}$$

$$L\,dI = N\,d\Phi_B$$

$$LI = N\Phi_B$$

$$L = \frac{N\Phi_B}{I} = \frac{NBA\cos\theta}{I}$$

$$L = \frac{NBA\cancel{\cos\theta}}{I}$$

$$L = \frac{NA}{\cancel{I}}\left(\mu_0 \frac{N}{\ell}\cancel{I}\right)$$

$$L = \frac{\mu_0 A N^2}{\ell}$$

$$L = \frac{(4\pi\times10^{-7})(\pi(0.04)^2)(500)^2}{0.5}$$

$$L = 0.003158$$

$$\boxed{L = 3.16 \text{ mH}}$$

$$\mathcal{E}_{ind} = -L\frac{dI}{dt}$$

$$\mathcal{E}_{ind} = -(0.003158)(75)$$

$$\boxed{\mathcal{E}_{ind} = -237 \text{ mV}}$$

Derivation of Current as Function of Time in an RL Circuit (Putting Energy into the Inductor)

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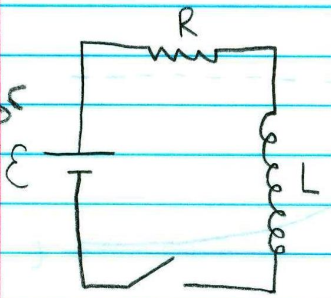
Energy into Inductor



$t < 0$

Close switch at $t = 0$

Limits

@$t=0$ $\left[I_i = 0 \quad \frac{dI}{dt} \max \right]$

$0 = \mathcal{E} - L\frac{dI}{dt}$

$L\frac{dI}{dt} = \mathcal{E}$

$\frac{dI}{dt} = \frac{\mathcal{E}}{L}$ (max)

@$t \approx \infty$

$\left[\frac{dI}{dt} = 0 \quad I_f \max \right]$

$0 = \mathcal{E} - IR$

$IR = \mathcal{E}$

$I = \frac{\mathcal{E}}{R}$ (max)

RL Circuit

$$\Delta V_{loop} = 0 = \mathcal{E} - \Delta V_R - \Delta V_L$$

$$0 = \mathcal{E} - IR - L\frac{dI}{dt}$$

$$0 = \underbrace{\frac{\mathcal{E}}{R} - I}_{x} - \frac{L}{R}\, dI/dt$$

let $x = \frac{\mathcal{E}}{R} - I$

$dx = -dI$

$$0 = x - \frac{L}{R}\frac{-dx}{dt}$$

$$0 = x + \frac{L}{R}\frac{dx}{dt}$$

$$-\frac{L}{R}\frac{dx}{dt} = x$$

$$\int \frac{dx}{x} = \int \frac{-R\,dt}{L}$$

$$\int_{x_i}^{x_f} \frac{1}{x}\,dx = -\int_0^t \frac{R}{L}\,dt$$

$$\left[\ln x\right]_{x_i}^{x_f} = \left[-\frac{R}{L}t\right]_0^t$$

$$\ln x_f - \ln x_i = -\frac{R}{L}t$$

$$e^{\ln \frac{x_f}{x_i}} = e^{-\frac{R}{L}t}$$

$$\frac{x_f}{x_i} = e^{-Rt/L}$$

$$x_f = x_i e^{-Rt/L}$$

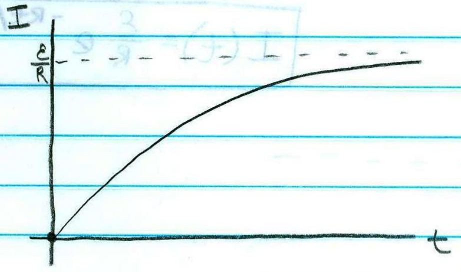
$x_f = \frac{\mathcal{E}}{R} - I_f$

$x_i = \frac{\mathcal{E}}{R} - \cancel{I_i}$

$$\frac{\mathcal{E}}{R} - I_f = \frac{\mathcal{E}}{R} e^{-Rt/L}$$

$$-I_f = \frac{\mathcal{E}}{R} e^{-Rt/L} - \frac{\mathcal{E}}{R}$$

$$\boxed{I_f = \frac{\mathcal{E}}{R}\left(1 - e^{-Rt/L}\right)}$$



$$\boxed{\tau = \frac{L}{R}}$$

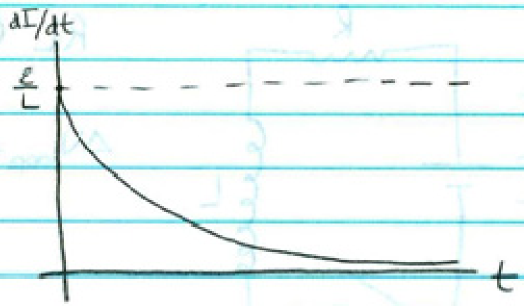
$$I(t) = \frac{\mathcal{E}}{R}\left(1 - e^{-t/\tau}\right)$$

63.2% change

$$I = \frac{\varepsilon}{R} - \frac{\varepsilon}{R} e^{-Rt/L}$$

$$\frac{dI}{dt} = \cancel{-}\frac{\varepsilon}{\cancel{R}}\frac{\cancel{-}\cancel{R}}{L} e^{-Rt/L}$$

$$\boxed{\frac{dI}{dt}(t) = \frac{\varepsilon}{L} e^{-Rt/L}}$$



Derivation of Current as Function of Time in an RL Circuit (Removing Energy from the Inductor) - 17
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Thank You, Emily Rencsok, for these notes.

Energy out of inductor

Remove battery

$$\Delta V_{loop} = 0 = \mathcal{E} - \Delta V_R - \Delta V_L$$

$$0 = \cancel{\mathcal{E}} - IR - L\frac{dI}{dt}$$

$$IR = -L\frac{dI}{dt}$$

$$-\frac{R}{L}\,dt = \frac{dI}{I}$$

$$-\int_0^t \frac{R}{L}\,dt = \int_{I_i}^{I_f}\frac{dI}{I}$$

$$\left[-\frac{Rt}{L}\right]_0^t = \left[\ln I\right]_{I_i}^{I_f}$$

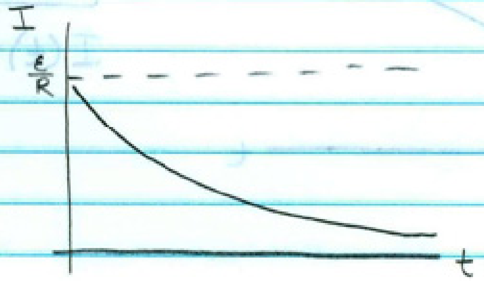
$$-\frac{Rt}{L} = \ln I_f - \ln I_i$$

$$e^{-\frac{Rt}{L}} = \cancel{\ln}\frac{I_f}{I_i}$$

$$\frac{I_f}{I_i} = e^{-Rt/L}$$

$$I_f = I_i\,e^{-Rt/L}$$

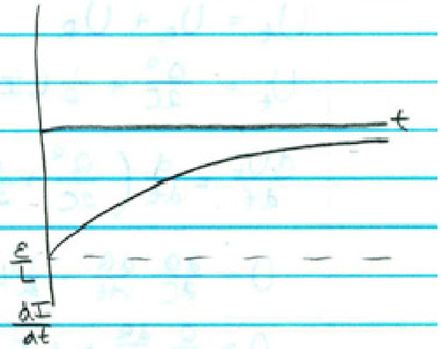
$$\boxed{I(t) = \frac{\mathcal{E}}{R}e^{-Rt/L}}$$



$$\frac{dI}{dt} = \frac{d}{dt}\left[\frac{\varepsilon}{R} e^{-Rt/L}\right]$$

$$\frac{dI}{dt} = \frac{\varepsilon}{\cancel{R}}\left(-\frac{\cancel{R}}{L}\right) e^{-Rt/L}$$

$$\boxed{\frac{dI}{dt}(t) = \frac{-\varepsilon}{L} e^{-Rt/L}}$$



Derivation of Energy stored in the Magnetic Field of an Inductor

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Thank You, Emily Rencsok, for these notes.

$$\Delta V = 0 = \mathcal{E} - IR - L\frac{dI}{dt}$$

$$\mathcal{E} = IR + L\frac{dI}{dt}$$

$$P = \underbrace{I\mathcal{E}}_{\text{Power delivered by battery}} = \underbrace{I^2 R}_{\text{power dissipated by resistor}} + \underbrace{LI\frac{dI}{dt}}_{\text{power stored in B field of inductor}}$$

$$P = \frac{dU}{\cancel{dt}} = LI\frac{dI}{\cancel{dt}}$$

$$\int dU = \int LI\,dI$$

$$U = \int_0^I LI\,dI$$

$$U_L = \left[L\frac{I^2}{2}\right]_0^I$$

$$\boxed{U_L = \frac{1}{2}LI^2}$$

energy stored in the B field of an inductor

The Last New AP Physics C - Derivation of Simple Harmonic Motion of an LC Circuit - 19
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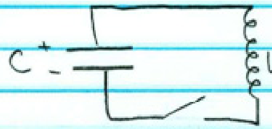
- The last new subject

LC circuit



$t<0$

Close switch @ $t=0$

$U_t = U_c + U_f$

$U_t = \frac{Q^2}{2C} + \frac{1}{2}LI^2$

Q + I change

$I_{max} \rightarrow Q = 0$

$Q_{max} \rightarrow I = 0$

$$\frac{dU_t}{dt} = \frac{d}{dt}\left(\frac{Q^2}{2C} + \frac{1}{2}LI^2\right) = 0$$

$$0 = \frac{2Q}{2C}\frac{dQ}{dt} + \frac{1}{\cancel{2}}L(\cancel{2}I)\frac{dI}{dt}$$

$$0 = \frac{Q}{C}\frac{dQ}{dt} + LI\frac{dI}{dt} \qquad I = \frac{dQ}{dt}$$

$$0 = \frac{Q}{C}\cancel{I} + L\cancel{I}\frac{d^2Q}{dt^2} \qquad \frac{dI}{dt} = \frac{d^2Q}{dt^2}$$

$$0 = \frac{Q}{C} + L\frac{d^2Q}{dt^2}$$

$$-\frac{Q}{C} = L\frac{d^2Q}{dt^2}$$

$$\boxed{\frac{d^2Q}{dt^2} = -\frac{1}{LC}Q} \qquad \frac{d^2x}{dt^2} = -\omega^2 x$$

$$\omega = \sqrt{\frac{1}{LC}} = \frac{1}{\sqrt{LC}}$$

$$Q(t) = Q_{max}\cos\left(\frac{1}{\sqrt{LC}}t + \phi\right) \qquad x(t) = A\cos(\omega t + \phi)$$

@ $t=0$, $Q_i = Q_{max}$, so $\phi = 0°$

$$\boxed{Q(t) = Q_{max}\cos\left(\frac{1}{\sqrt{LC}}t\right)}$$

$$I = \frac{dq}{dt} = \frac{d}{dt}\left(Q_{max}\cos\left(\frac{1}{\sqrt{LC}}t\right)\right)$$

$$\boxed{I(t) = \frac{-Q_{max}}{\sqrt{LC}}\sin\left(\frac{t}{\sqrt{LC}}\right)}$$

Example - Current and Potential Difference in an RL Circuit
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Ex) RL circuit

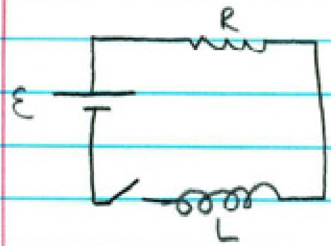
$L = 4.5\ H$

$R = 6.0\ \Omega$

$\mathcal{E} = 24\ V$

a) $\Delta V_L = ?$ @ $I = 1.50\ A$

b) $I_{max} = ?$



$\Delta V_{loop} = 0 = \mathcal{E} - \Delta V_R - \Delta V_L$

$\Delta V_L = \mathcal{E} - \Delta V_R = \mathcal{E} - IR$

$\Delta V_L = 24 - 1.5(6) = \boxed{15\ V}$

I_{max} @ $t = \infty$

when $\frac{dI}{dt} = 0$

$\Delta V_L = 0$

$0 = \mathcal{E} - \Delta V_R - \cancel{\Delta V_L}$

$0 = \mathcal{E} - IR$

$IR = \mathcal{E}$

$I = \frac{\mathcal{E}}{R} = \frac{24}{6} = \boxed{4.0\ A}$

Example - A Battery, Resistor, Capacitor and Inductor in a Circuit
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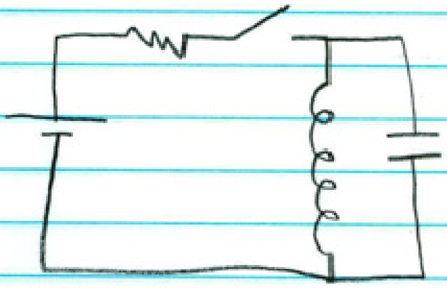
Ex



$\mathcal{E} = 12\ V$

$R = 4.0\ \Omega$

$L = 2.0\ H$

$C = 0.020\ F$

a) $U_{L(max)} = ?$

b) $Q_{(max)} = ?$

closed for long time, opened at t = 0

$Q_i = 0$

$U_{L_{max}} = \frac{1}{2} L I^2$

$I_{max} = ? = I_i$

$\Delta V = IR$

$I_L = \frac{\Delta V}{R} = \frac{\mathcal{E}}{R} = \frac{12}{4} = 3.0\ A$

$U_{L_{max}} = \frac{1}{\cancel{2}}(\cancel{2})(3)^2$

$\boxed{U_{L_{max}} = 9.0\ J}$

$Q_{max} = ?$

$U_{L_{max}} = U_{C_{max}}$

$9 = U_{C_{max}} = \frac{Q_{max}^2}{2C}$

$\sqrt{2(9)(0.02)} = Q_{max}$

$\boxed{Q_{max} = 0.60\ C}$

Chapter 31- 32 Review - 22
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- $\mathcal{E} = -N \frac{d\Phi_B}{dt}$

  $\mathcal{E} = -N \frac{d}{dt}(BA\cos\theta)$

  RHR = *change in flux (Lenz' Law)

- Motional emf

  $\Delta V = vB\ell$ -derive -memorize

  ↑ assumes θ btwn v + B is 90°

  $F_B = qvB\sin\theta$

- Generators

  $\mathcal{E}(t) = \omega NBA\sin(\omega t)$ $\omega = \frac{\Delta\theta}{\Delta t} = \frac{\theta}{t}$ $\theta_i + t_i = 0$ $\theta = \omega t$

  - derive
  - memorize

- Back emf = 0 when motor isn't spinning

- $L = \frac{N\Phi_B}{I}$ -derive -memorize

- RL Circuit

  $I(t) = \frac{\mathcal{E}}{R}(1 - e^{-t/\tau})$ $\tau = \frac{L}{R}$ (derive + know limits)

  $U_L = \frac{1}{2}LI^2$

- LC circuit → SHM (memorize + derive)

  $\omega = \frac{1}{\sqrt{LC}} = \frac{\Delta\theta}{\Delta t} = \frac{2\pi}{T}$