Lecture 5: Electro-dynamics

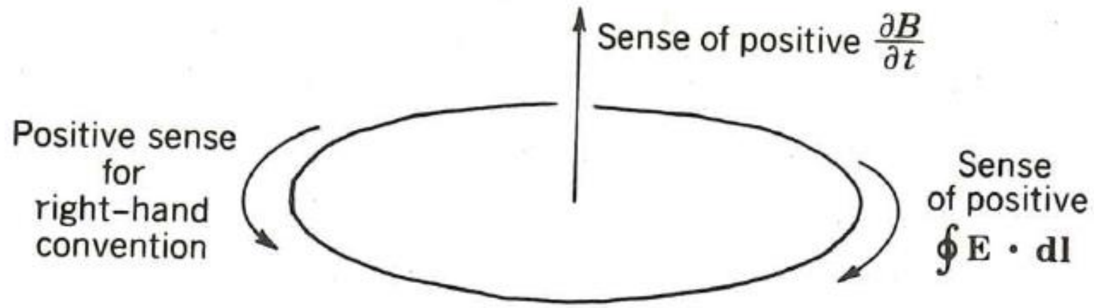
- A changing magnetic field and Faraday’s law
- A changing electrc field and displace current.
- Inductance and Lenz’ law
- Energy store in inductance

Changing magnetic field: Faraday's law

$\boldsymbol{\varepsilon} = -\frac{d\phi}{dt}$ **Faraday's law,** $\phi = \int_s \boldsymbol{B} \cdot d\boldsymbol{S}$ **is the magnetic flux.**

In static-electric field, $\nabla \times \boldsymbol{E} = 0$; and $\oint_c \boldsymbol{E}\, d\boldsymbol{l} = 0$, conservative vector field,

When $\frac{\partial B}{\partial t} \neq 0$, $\boldsymbol{\nabla} \times \boldsymbol{E} \neq \boldsymbol{0}$



$$\oint_c \boldsymbol{E}\, d\boldsymbol{l} = -\int_s \frac{\partial \boldsymbol{B}}{\partial t} \cdot d\boldsymbol{S} = -\frac{d}{dt}\left(\int_s \boldsymbol{B} \cdot d\boldsymbol{S}\right) = -\frac{d\phi}{dt}$$

$$\oint_c \boldsymbol{E}\, d\boldsymbol{l} = \int_s (\nabla \times \boldsymbol{E}) \cdot dS$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial B}{\partial t}$$

Electro-motive force (EMF): electric potential caused by changeint the magnetic filed.

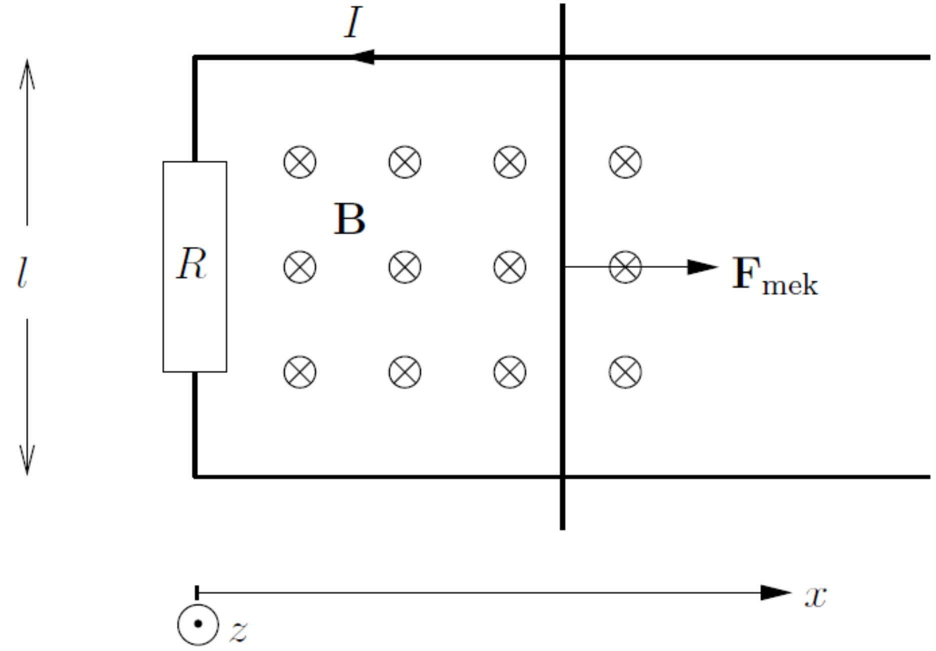
Example:

$$e = BLv$$

$$\mathbf{S} = (S_0 + lvt)\hat{\mathbf{z}}.$$

$$e = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} = -\frac{\mathrm{d}}{\mathrm{d}t}\int_S \mathbf{B}\cdot\mathrm{d}\mathbf{S} = -\frac{\mathrm{d}}{\mathrm{d}t}\left(\mathbf{B}\cdot\int_S \mathrm{d}\mathbf{S}\right) = -\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{B}\cdot\mathbf{S} = \frac{\mathrm{d}}{\mathrm{d}t}BS = Blv,$$

$$I = \frac{e}{R} = \frac{Blv}{R}.$$



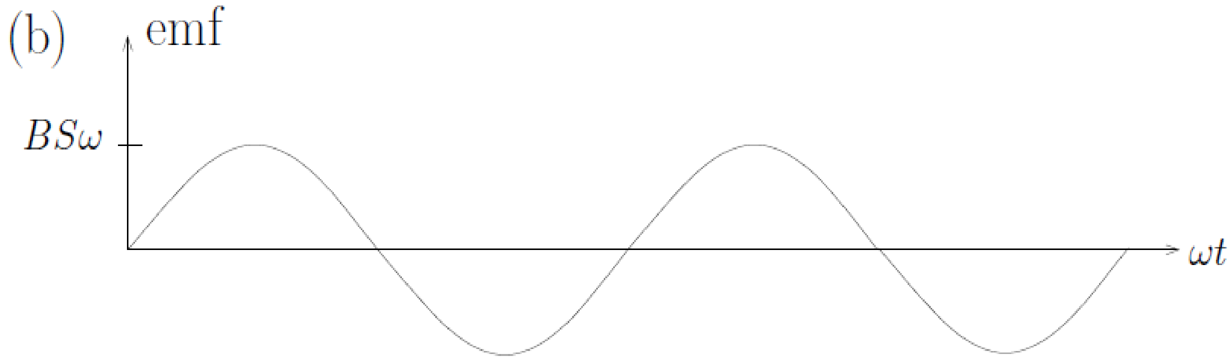
Faraday's law for a moving system: generator

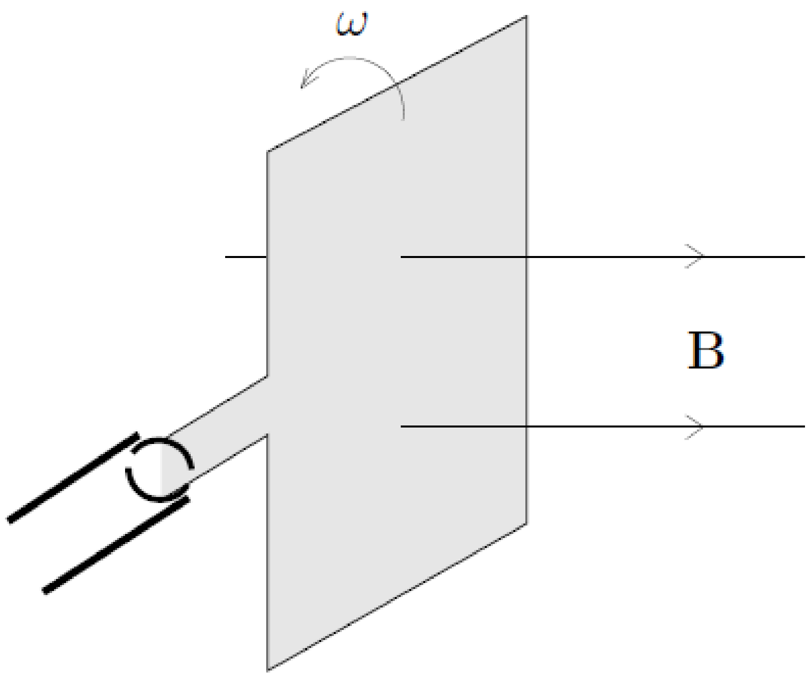
The angle between B and surface normal direction is: $\varphi = \omega t.$

What is the emf and its waveform with time.

$$\Phi = \int_S \mathbf{B} \cdot \mathrm{d}\mathbf{S} = \mathbf{B} \cdot \mathbf{S} = BS \cos \omega t.$$

$$e = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} = BS\omega \sin \omega t$$





Displacement current:

$\nabla \times H = J + \frac{\partial D}{\partial t}$; ($J = \sigma E$ is conduction current in materials)

Displacement current is defined in terms of the rate of change of electric displacement field.

$$J_D = \frac{\partial D}{\partial t}$$

$$\nabla \cdot \mathbf{J} = -\frac{\partial \rho}{\partial t}.$$

This addtional term solves some problems:

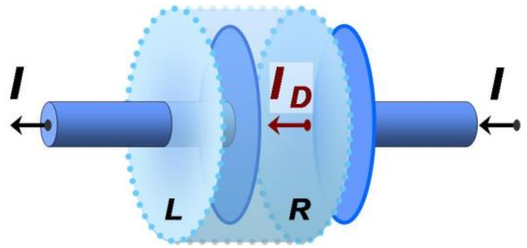
1) Charge conservation argument:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \Rightarrow \nabla \cdot (\nabla \times \mathbf{B}) = 0, \Rightarrow \nabla \cdot \mathbf{J} = 0.$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J},$$

2) Electro-magnetic wave propagates in vacuum, where there is no current J.
3) Current in Capacitor

When charging / discharging capacitor, there is current in the cable, this is no current between the two plates (assume vacuum medium), but electric field changing. (does not satisfy current continuty argument)



Capacitor

Capacitor and displacement current

Capcitor is charging with current I:

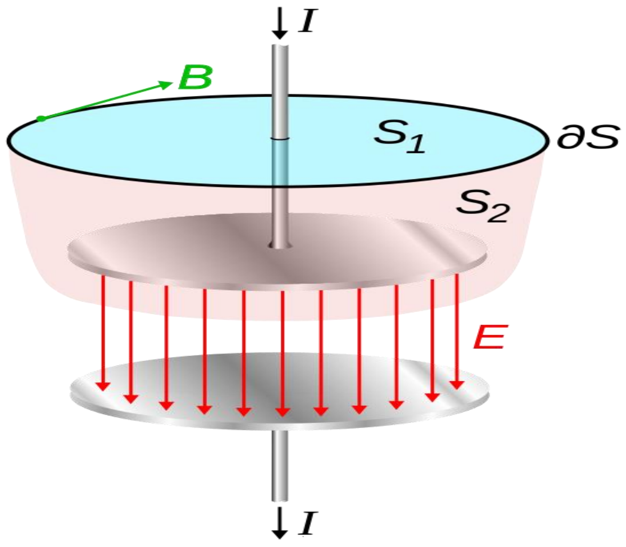
Capacitance : $C = \frac{\varepsilon A}{l}$, charge current is $I = C\frac{dV}{dt}$

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

Calculating the integral over surface S1,

$$\int_s \nabla \times H \cdot dS_1 = \int_s \left(J + \frac{\partial D}{\partial t}\right) \cdot dS_1 = \int_s J \cdot dS_1 = I \;\; (I = C\frac{dV}{dt} = \frac{\varepsilon A}{l}\frac{dV}{dt})$$

$\frac{\partial D}{\partial t}$=0, out of capacitor, the surface integration is zero



Calculating the integral over surface S2,

$$\int_s \nabla \times \boldsymbol{H} \cdot d\boldsymbol{S_2} = \int_s \left(\boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}\right) \cdot d\boldsymbol{S_2} = \int_s \frac{\partial \boldsymbol{D}}{\partial t} \cdot d\boldsymbol{S_2} = \int_s \frac{\varepsilon}{l}\frac{dV}{dt} d\boldsymbol{S_2} = \frac{\varepsilon A}{l}\frac{dV}{dt} = I$$

J=0 at surface S2,

$D = \varepsilon \boldsymbol{E} = \varepsilon\frac{\boldsymbol{V}}{l}$, only in the area of capacitor plate A.

Maxwell equations

$$\nabla \cdot \mathbf{E} = \frac{\rho_v}{\varepsilon} \qquad \text{(Gauss' Law)}$$

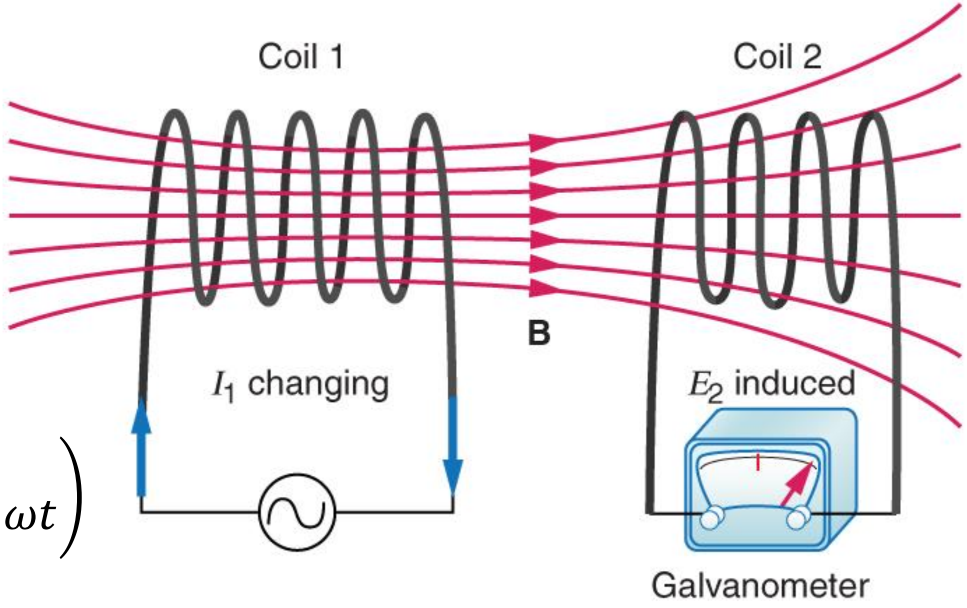
$$\nabla \cdot \mathbf{H} = 0 \qquad \text{(Gauss' Law for Magnetism)}$$

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \qquad \text{(Faraday's Law)}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \qquad \text{(Ampere's Law)}$$

Example:

Coil 1 : I(t)=$\hat{I}\sin(\omega t)$, coil cross − section area 1 and 2 is same A.
The flux produced form 1 going through coil 2: B(t)=$\hat{B}\sin(\omega t)$
1) What is the induced voltage in coil 2?
2) Assuming resistance in coil 2 is R, calculating the current in coil 2?



$\phi = N\int_s Bds$ (flux linkage between coil 1 and coil 2)

$$V_2(t) = -\frac{d\phi}{dt} = -\frac{N\int_s \hat{B}\sin(\omega t)\,ds}{dt} = -\frac{NA\hat{B}\sin(\omega t)}{dt} = -N\omega A\hat{B}\cos(\omega t)$$

$$I_2(t) = \frac{V_2(t)}{R} = -\frac{N\omega A\hat{B}\cos(\omega t)}{R}$$

Inductance definition : $L = \frac{\phi}{I}$;

Inductance and Lenz' law

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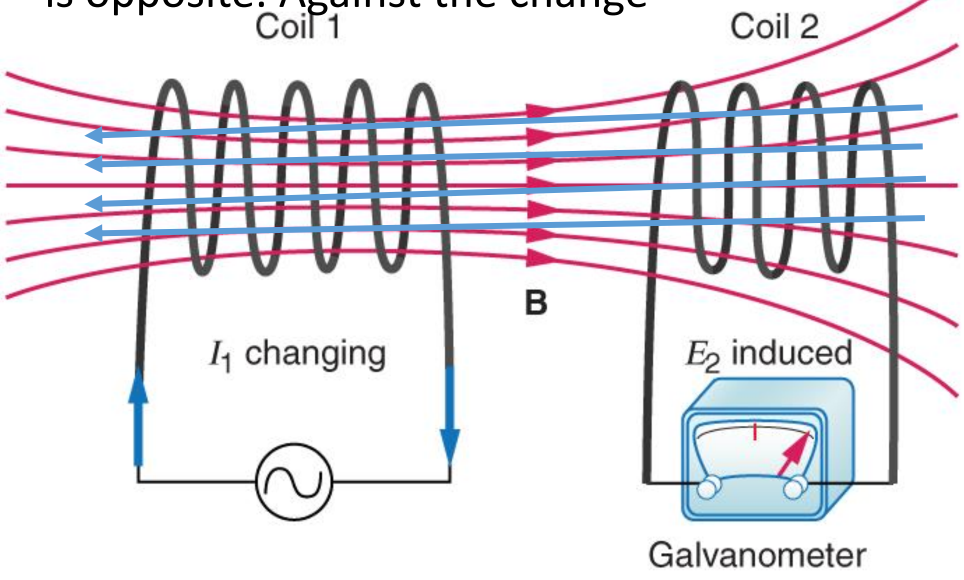
Slef-inductance: $L_1 = \frac{\phi_1}{I_1} = \frac{N_1 \int_{s_1} B_1 ds}{I_1}$

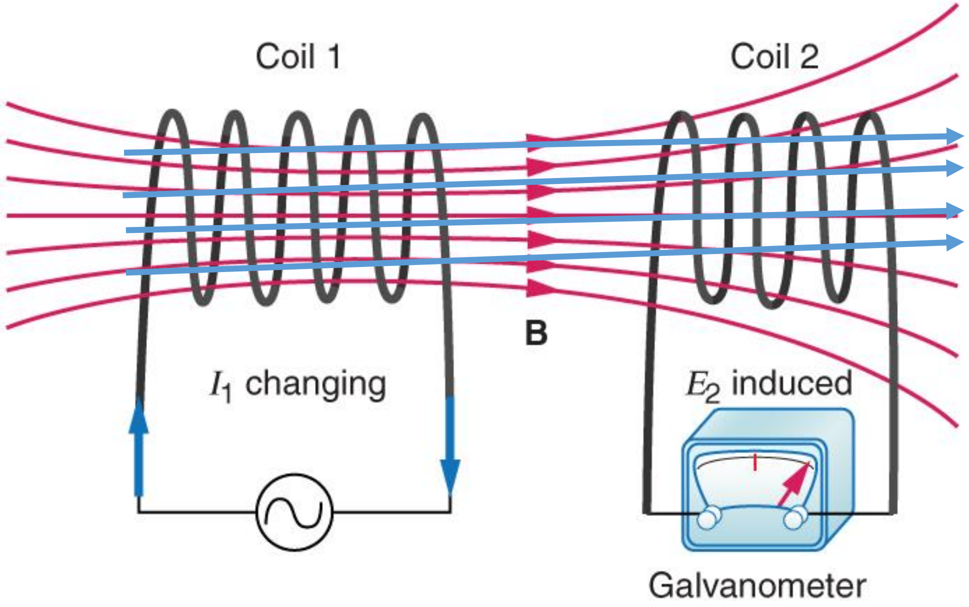
Mutual inductance: $L_{12} = \frac{\phi_{12}}{I_1} = \frac{N_2 \int_{s_2} B_2 dS}{I_1}$

$$I_2(t) = \frac{V_2(t)}{R} = -\frac{N\omega A\hat{B}\cos(\omega t)}{R} \qquad L_2 = \frac{\phi_2}{I_2} = \frac{N \int_{s_2} B_2 dS_2}{I_2}$$

Lenz's Law:
The induced magnetic field by a current that is caused from a change in magnetic flux (Faraday's **Law**) counteracts the change in flux.

When B1 increase, the direction of B2 is opposite. Against the change



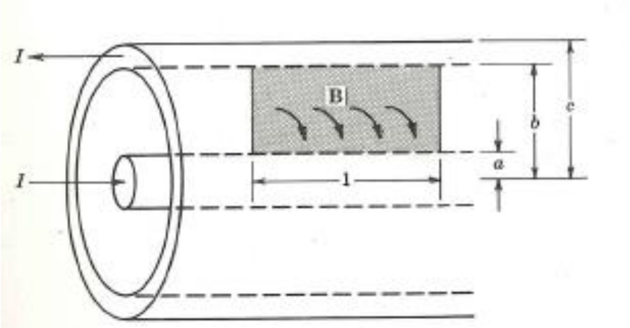


When B1 decreases, the direction of B2 is the same as B1. Against the change

Example : calculating inductance

A coaxial line carrying curent I on the inner conductor and –I on the outer .
Calculate the magnetic field H at r distance, (Current evenly distributed in the two conductors)
The

Calculating the external inductance of the coaxial line in unit length.



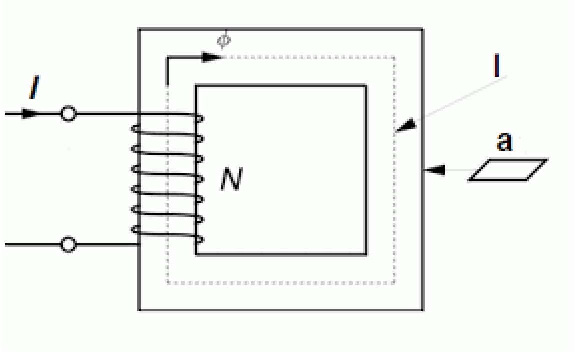
$$H_\phi = \frac{I}{2\pi r}$$

$$\int_S \mathbf{B} \cdot d\mathbf{S} = \int_a^b \mu\left(\frac{I}{2\pi r}\right) dr = \frac{\mu I}{2\pi} \ln \frac{b}{a}$$

$$L = \frac{\mu}{2\pi} \ln \frac{b}{a} \quad \text{H/m}$$

Inductance calculation:

Assum the total length is l and the cross-section area is a



$$L_1 = \frac{\phi_1}{I_1} = \frac{N_1 \int_{s_1} B_1 ds}{I_1}$$

$$\oint_c Hdl = \oint_s JdS = NI$$

$$R_m = \frac{l}{\mu a}$$

$$R_m \phi = NI$$

$$B = \frac{\phi}{a} = \frac{NI}{aR_m} = \frac{NI\mu}{l}$$

$$L = \frac{N^2 a\mu}{l} = \frac{N^2}{R_m}$$

$$P = \frac{1}{2} LI^2 = \frac{1}{2} \frac{N^2 \mu a}{l} I^2 = \frac{1}{2} \frac{N^2 I^2 \mu^2}{l^2} \frac{la}{\mu} = \frac{B^2}{2\mu} V_{vol}$$

$$\eta_m = \frac{p}{V_{vol}} = \frac{B^2}{2\mu}$$

Energy store in inductance

Energy stored in inductance:

$L = \frac{\int_s \boldsymbol{B} \cdot d\boldsymbol{S}}{I}$ difinition:

$$\mathbf{V}\,(\boldsymbol{t}) = -\frac{\boldsymbol{d}}{\boldsymbol{dt}}\left(\int_{\boldsymbol{s}} \boldsymbol{B}(\boldsymbol{t}) \cdot \boldsymbol{dS}\right) = -\frac{\boldsymbol{d}\phi}{\boldsymbol{dt}}$$

$$V(t) = \frac{d}{dt}(LI) = L\frac{dI}{dt} \Rightarrow dp = VI = LI\frac{dI}{dt}$$

$$P = \int_0^i LI\frac{dI}{dt}dt = \int_0^i LIdI = \frac{1}{2}LI^2$$

Energy stored in magnetic field

$$P = \frac{1}{2}LI^2 = \frac{1}{2}\frac{N^2\mu a}{l}I^2 = \frac{1}{2}\frac{N^2I^2\mu^2}{l^2}\frac{la}{\mu} = \frac{B^2}{2\mu}V_{vol}$$

$$L = \frac{N^2 a\mu}{l}$$

$$B = \frac{\phi}{a} = \frac{NI}{aR_m} = \frac{NI\mu}{l}$$

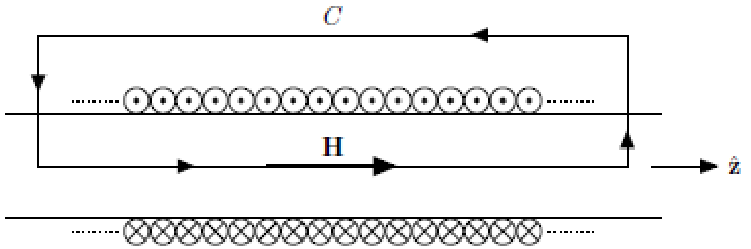
$$\eta_m = \frac{p}{V_{vol}} = \frac{B^2}{2\mu}$$

Example

Given a tightly wound toroid with radius a, and N number of turns that is conducting a constant direct current I. Use a = 10cm, N = 1000 and I = 1mA. Find the magnetic field B everywhere (both inside and outside the toriod) assuming the core consists of

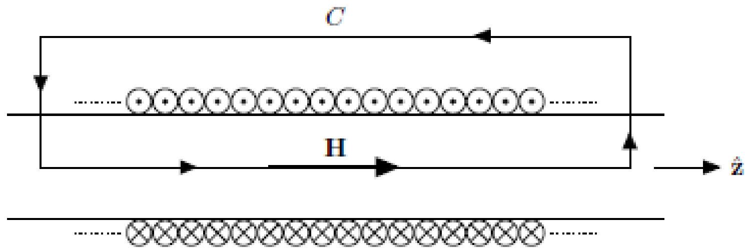
a) vacuum.

b) an iron core with $\mu_r = 5000$.



example

a) Find the self inductance L of a long, tightly wound solenoid.
b) If the number of turns is doubled (and everything else remains the same), what will happen with the self inductance?
c) Assume that the current is decaying from I_0 to 0 during the time T. Find the induced voltage as a function of I_0, T and L.



$$\mathbf{H} = H\hat{\mathbf{z}} = \frac{NI}{l}\hat{\mathbf{z}}. \qquad B = \mu\frac{NI}{l}$$

$$\Phi_{\rm cs} = \int_S \mathbf{B}\cdot \mathrm{d}\mathbf{S} = \int_S B\mathrm{d}S = B\int_S \mathrm{d}S = \mu\frac{NI}{l}\cdot \pi a^2.$$

$$L = \frac{\Phi}{I} = \frac{N\Phi_{\rm cs}}{I} = \frac{\mu\pi a^2 N^2}{l}.$$

$$e(t) = -L\frac{\mathrm{d}I(t)}{\mathrm{d}t},$$

$$I(t) = I_0\left(1-\frac{t}{\tau}\right), \quad \text{for } 0 \le t \le \tau.$$

$$\underline{\underline{e(t) = -L\frac{\mathrm{d}}{\mathrm{d}t}I_0\left(1-\frac{t}{\tau}\right) = \frac{LI_0}{\tau}.}}$$

Example

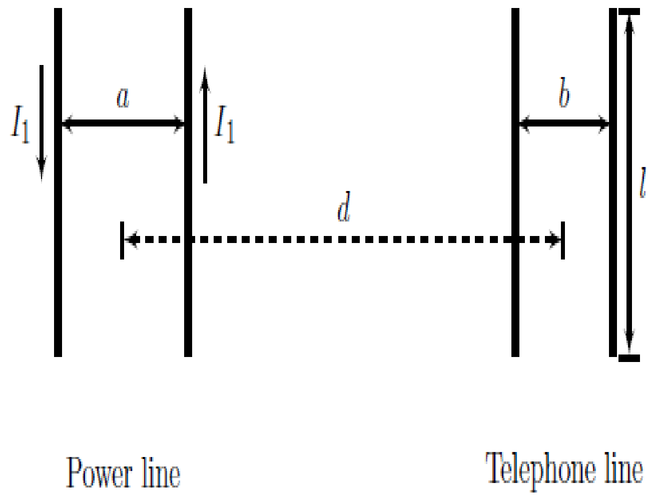
A telephone line and a power line is running parallel with each other. Both the power line and the telephone line consists of two thin, parallel conductors as shown in the figure below. The power line is assumed to be infinitely long, and the telephone line is assumed to be a closed, rectangular loop with length l and width b. Assume that the thickness of the conductor is negligible compared to the distances a, b, d, and l.

a) Find the mutual inductance between the to lines.
   Hint: Use $L_{12} = \Phi_{12}/I_1$.

b) Find the amplitude of the induced electromotive force in the telephone line when there is a harmonic alternating current with an amplitude I_0 and a frequency f in the power line. As a numerical example, we say that $f = 50\text{Hz}$, $I_0 = 100\text{A}$, $l = 500\text{m}$, $d = 10\text{m}$, $a = 50\text{cm}$, and $b = 10\text{cm}$.

   (Answer: 1.57mV.)

c) Why is it a good idea to twirl the conductors of the telephone line?



Solution: (a)

We have decided z = 0 at the left conductor of the telephone line

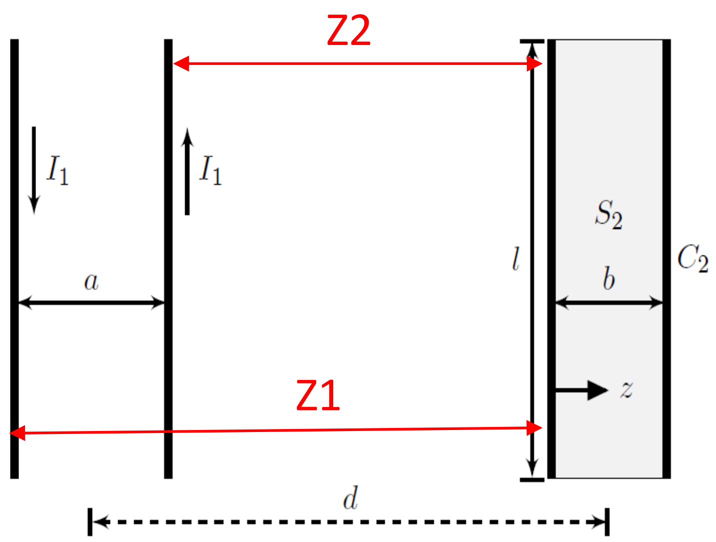
$$z_1 = -d - \frac{a}{2} + \frac{b}{2}$$

$$z_2 = -d + \frac{a}{2} + \frac{b}{2}$$

$$\begin{aligned} B(z) &= B_1(z) + B_2(z) \\ &= \frac{\mu_0 I_1}{2\pi r_1} - \frac{\mu_0 I_1}{2\pi r_2} \\ &= \frac{\mu_0 I_1}{2\pi}\left(\frac{1}{z - z_1} - \frac{1}{z - z_2}\right) \end{aligned}$$

the magnetic flux within C_2 is given by

$$\begin{aligned} \Phi_{12} &= \int_{S_2} \mathbf{B} \cdot \mathrm{d}\mathbf{S} = l \int_0^b B(z)\mathrm{d}z \\ &= \frac{\mu_0 I_1 l}{2\pi} \int_0^b \left(\frac{1}{z - z_1} - \frac{1}{z - z_2}\right) \\ &= \frac{\mu_0 I_1 l}{2\pi}\left[\ln\left(\frac{b - z_1}{-z_1}\right) - \ln\left(\frac{b - z_2}{-z_2}\right)\right] \end{aligned}$$



$$\underline{\underline{L_{12} = \frac{\Phi_{12}}{I_1} = \frac{\mu_0 l}{2\pi}\left[\ln\left(\frac{b - z_1}{-z_1}\right) - \ln\left(\frac{b - z_2}{-z_2}\right)\right].}}$$

Solution: b

$$e = -\frac{\mathrm{d}\Phi_{12}}{\mathrm{d}t}, \text{ Faraday's law}$$

$$I_1(t) = I_0 \cos(2\pi f t)$$

$$e = -\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mu_0 I_0 \cos(2\pi f t) l}{2\pi}\left[\ln\left(\frac{b-z_1}{-z_1}\right) - \ln\left(\frac{b-z_2}{-z_2}\right)\right]\right)$$

$$= \mu_0 I_0 f \sin(2\pi f t) l \left[\ln\left(\frac{b-z_1}{-z_1}\right) - \ln\left(\frac{b-z_2}{-z_2}\right)\right].$$

the amplitude e_0 of the induced electromotive force

$$e_0 = \left|\mu_0 I_0 f l \left[\ln\left(\frac{b-z_1}{-z_1}\right) - \ln\left(\frac{b-z_2}{-z_2}\right)\right]\right|.$$

$$e_0 = \left|4\pi \cdot 10^{-7} \cdot 100 \cdot 50 \cdot 500 \left[\ln\left(\frac{10.3}{10.2}\right) - \ln\left(\frac{9.8}{9.7}\right)\right]\right| \mathrm{V} = 1.57\mathrm{mV}.$$