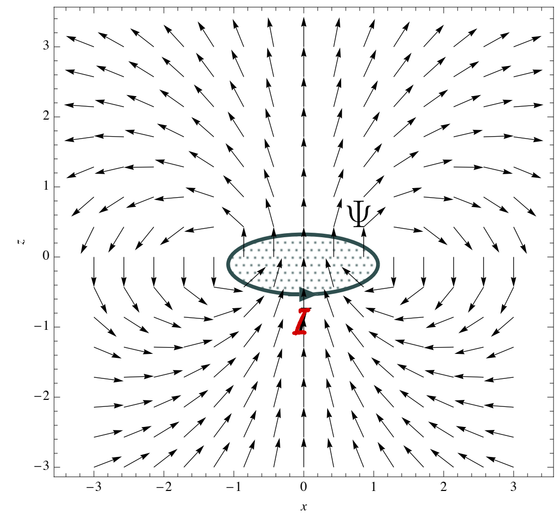
15 Inductance — solenoid, shorted coax



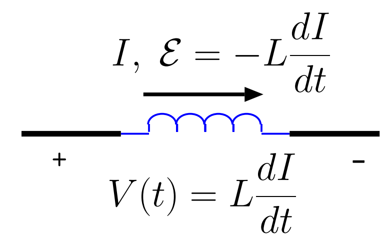
- Given a current conducting path C, the magnetic flux Ψ linking C can be expressed as a function of current I circulating around C.
- If the function is linear, i.e., if we have a *linear flux-current relation*

$$\Psi = LI,$$

then constant

$$L = \frac{\Psi}{I}$$

is termed the **self-inductance**[1] of path C, an elementary **inductor**.



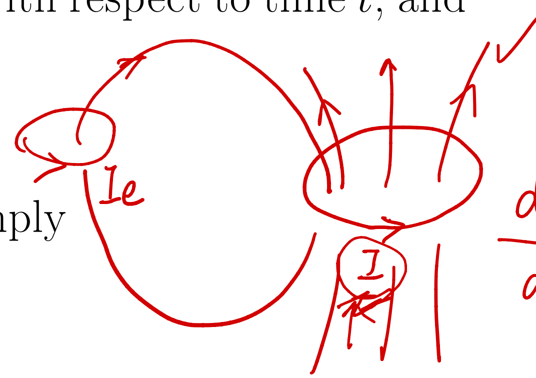
  - Differentiating the flux-current relation with respect to time t, and using the fact that

$$\mathcal{E} = -\frac{d\Psi}{dt},$$

we find that the emf of inductor L is simply

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

which is a voltage rise across the inductor in the direction of current I (with $L\frac{dI}{dt}$ denoting the voltage drop in the same direction as used in circuit courses).



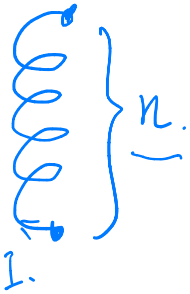
$$\frac{d\psi}{dt} = L\frac{dI}{dt} = -\mathcal{E}.$$

$$\psi = L\,I + M\,I_e$$

$$\frac{d\psi}{dt} = L\frac{dI}{dt} + M\frac{dI_e}{dt} = -\mathcal{E}.$$

$$\mathcal{E} = RI.$$

[1] A mutual inductance M_{12}, by contrast, relates the flux linking coil C_2 to a current I_1 flowing in a second coil C_1.



– For an inductor consisting of n-loops, the emf $\mathcal{E}$ measured around n-loops is naturally

$L = \frac{\Psi}{I}.$ single.

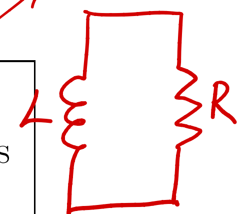
$$\mathcal{E} = n(-\frac{d}{dt}\Psi) = -\frac{d}{dt}n\Psi \equiv -L\frac{dI}{dt}$$

implying an inductance

$$L \equiv \frac{n\Psi}{I}. \leftarrow n\psi = LI.$$

$L\frac{dI}{dt} + M\frac{dI_e}{dt} = -RI.$

$L\frac{dI}{dt} + RI = -M\frac{dI_e}{dt}.$



$L\frac{dI}{dt} + RI = 0.$

source free

$I_e \uparrow$ $M \uparrow$ $L \downarrow$.

✓ $RI = -M\frac{dI_e}{dt}.$

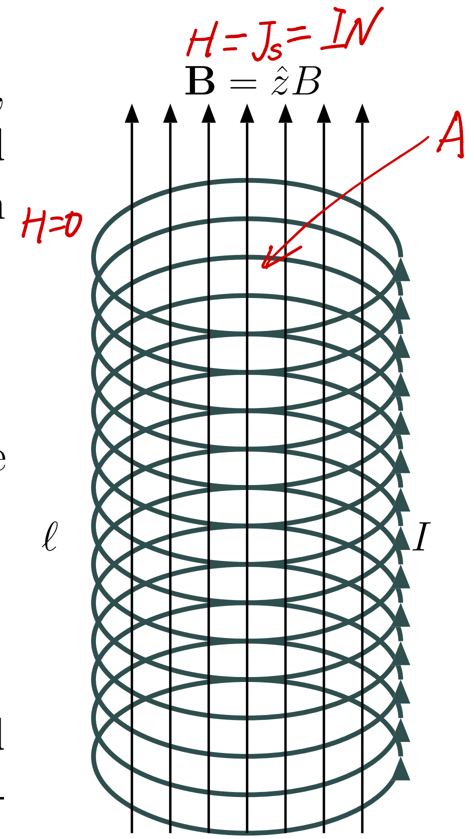
Example 1: An n-turn coil has a resistance $R = 1\,\Omega$ and inductance of $1\,\mu$H. If it is conducting 3 A of current at $t = 0$, determine $I(t)$ for $t > 0$.

Solution: Current flow in the resistive n-turn coil will be driven by emf $\mathcal{E} = -L\frac{dI}{dt}$ matching the voltage drop RI. Hence

$$-L\frac{dI}{dt} = RI \quad \leftrightarrow \quad \frac{dI}{dt} + \frac{R}{L}I = 0 \quad \Rightarrow \quad I(t) = I(0)e^{-\frac{R}{L}t} = 3e^{-10^6 t}\ \text{A}.$$

- As illustrated by above example, current I around a resitive loop C will in general be obtained by solving a *differential equation* constructed using the emf of the loop.
  - $I = \frac{\mathcal{E}}{R}$ used last lecture assumes that emf produced by the induced current is small compared to an externally produced emf.
- We continue with typical inductance calculations.

Inductance of long solenoid: Consider a long solenoid with length ℓ, cross-sectional area A, and a density of N loops per unit length as examined in Example 3 of Lecture 12 (see figure in the margin). As determined in Example 3, the magnetic flux density in the interior of the solenoid is



$B = \mu_o I N$

$$\mathbf{B} = \mu_o I N \hat{z}$$

B_z.

$A\mu_o I N = \Psi$

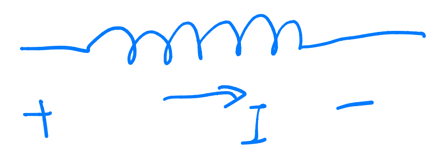
while $n = N\ell$ is the number of turns of the solenoid. Thus, the inductance of the solenoid with $n = N\ell$ turns is

$$L = \frac{n\Psi}{I} = \frac{N\ell(\mu_o I N)A}{\cancel{I}} = N^2\mu_o A\ell.$$

$N^2\mu A\ell.$

- As we know from our circuit courses, an inductor L such as the solenoid coil considered above can be used to store energy. An inductor connected to an external circuit with a quasi-static current I develops a voltage drop $V = L\frac{dI}{dt}$ across its terminals[2] and absorbs power at an instentaneous rate

$\frac{1}{2}CV^2$



$$P = VI = L\frac{dI}{dt}I = \frac{d}{dt}(\frac{1}{2}LI^2),$$

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

implying a stored energy of

volume

$$W = \frac{1}{2}LI^2 = \frac{1}{2}N^2\mu_o A\ell I^2 = \frac{|B_z|^2}{2\mu_o}A\ell = \frac{1}{2}\mu_o|H_z|^2 A\ell$$

$\vec{B} = \mu_o \vec{H}$

in an inductor in a conducting state.

[2]Assuming a physical size much smaller than a wavelength $\lambda = c/f$ for the highest frequency in $I(t)$.

- Notice that the stored energy of the solenoid is

$$\frac{1}{2}\mu_o|H_z|^2 = \frac{1}{2}\mu_o\mathbf{H}\cdot\mathbf{H}$$

times its volume $A\ell$ occupied by the field $\mathbf{H}$ inside the solenoid. That suggests that

$$w = \frac{1}{2}\mu_o\mathbf{H}\cdot\mathbf{H}$$

u J/m³ W — J. $\frac{1}{2}\varepsilon_0\vec{E}\cdot\vec{E}$. ↑ $\mathcal{E}$.

can be interpreted as stored magnetostatic energy per unit volume in general.

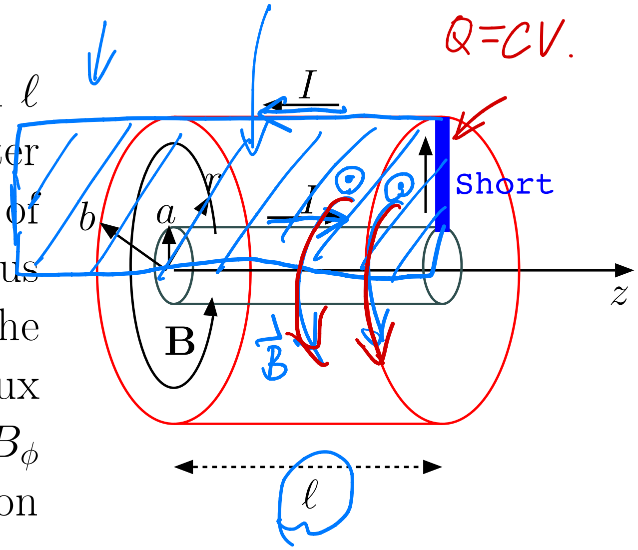
  - Also both inductance L and stored energies W and w would have μ replacing μ_o in material media with permeabilities

$$\mu = (1+\chi_m)\mu_o$$

    and magnetic susceptibilities χ_m, in analogy with the concepts of permittivity $\epsilon = (1+\chi_e)\epsilon_o$ and electrical susceptibility χ_e.

    - Permeability and magnetic susceptibility notions will be examined in a future lecture.

Inductance of shorted coax: Consider a coaxial cable of some length ℓ which is "shorted" at one end (with a wire connecting the inner and outer conductors), so that a steady current I can flow on the inner conductor of radius a to return on the interior surface of the outer conductor at radius b after having circulated through the short. We will next determine the inductance L of such an inductor after first computing the magnetic flux density B_ϕ that will be produced by the inner conductor current I. In B_ϕ calculation we will assume $\ell \gg b$ so that an "infinite coax" approximation can be invoked.

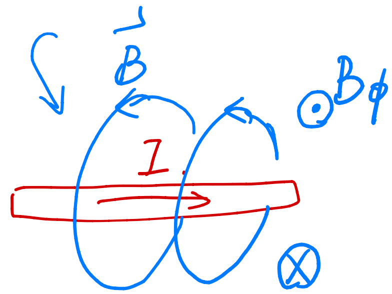


Shorted coax circulates a current I linking a magnetic flux Ψ confined to a region bounded by the outer conductor of the coax.

$\Psi = LI$.

$L = \frac{\Psi}{I}$.

- Expanding the integral form of Ampere's law



$$\oint_C \mathbf{B} \cdot d\mathbf{l} = \mu_o I_C$$

as

$$B_\phi 2\pi r = \mu_o I$$

over a circular integration contour C of a radius $r > a$, we find that the magnetic flux density in the interior of the coax cable is

$$B_\phi = \frac{\mu_o I}{2\pi r}.$$

- Therefore, the magnetic flux linked by the closed current path I (see figure in the margin) is

$\ln r$.

$$\Psi = \int_S \mathbf{B} \cdot d\mathbf{S} = \ell \frac{\mu_o}{2\pi} I \int_a^b \frac{dr}{r} = \ell \frac{\mu_o}{2\pi} \ln \frac{b}{a} I.$$

Clearly, we have a linear relation $\Psi = LI$, with

$$\rightsquigarrow \quad L \equiv \frac{\ln \frac{b}{a}}{2\pi} \ell \mu_o, \qquad \text{H}.$$

which is the inductance of a shorted coax of a finite length ℓ.

– The inductance of the coax per unit length is

$$\rightsquigarrow \quad \mathcal{L} = \frac{\ln \frac{b}{a}}{2\pi} \mu_o, \qquad \text{H/m}.$$

which should be contrasted with capacitance per unit length

$$\mathcal{C} = \frac{2\pi}{\ln \frac{b}{a}} \epsilon_o \qquad \rightsquigarrow \quad G = \frac{2\pi}{\ln \frac{b}{a}} \sigma.$$

σ.

of the same coax configuration.

Notice how $\mathcal{L}$ and $\mathcal{C}$ are proportional to ϵ_o and μ_o, respectively, having proportionality constants which are inverses of one another.

Inductance of shorted parallel plates: If a pair of parallel plates of areas $A = W\ell$ and separation d were shorted at one end, we would obtain effectively an inductor with a per length inductance

$$\mathcal{L} = \frac{d}{W}\mu_o$$

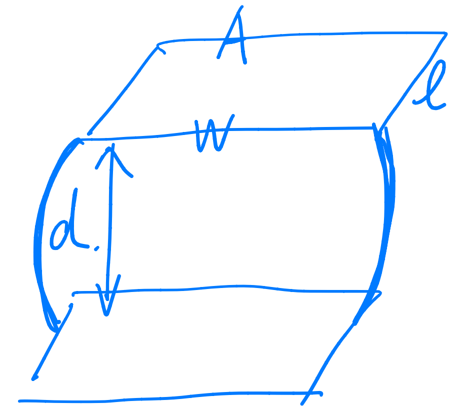
μ

that accompanies per length capacitance

$$\mathcal{C} = \frac{W}{d}\epsilon_o.$$

ε

$C = \frac{A}{d}\varepsilon_o.$



of the same parallel plate configuration. This follows from a generalization of our finding above that the proportionality constants of $\mathcal{L}$ and $\mathcal{C}$ are arithmetic inverses of one another.