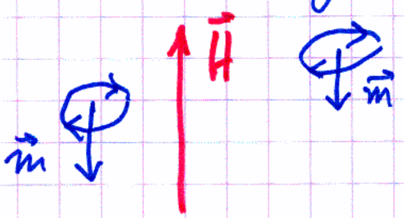
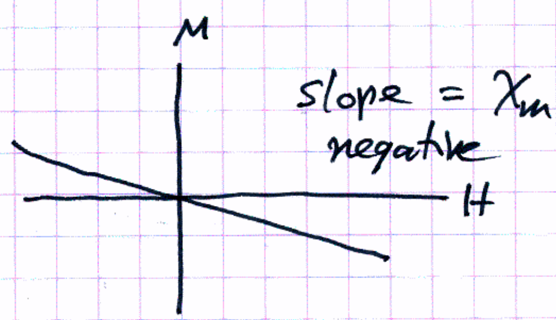
Ferromagnetism

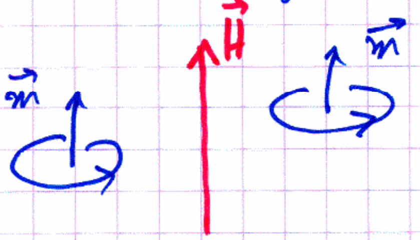
- Diamagnetism

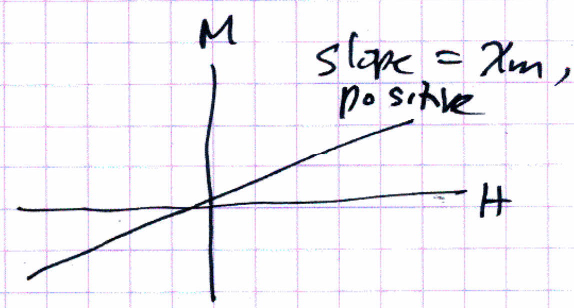




E.g., for Cu, $\chi_m = -9.6 \times 10^{-6}$

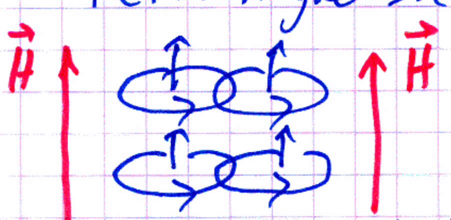
- Paramagnetism



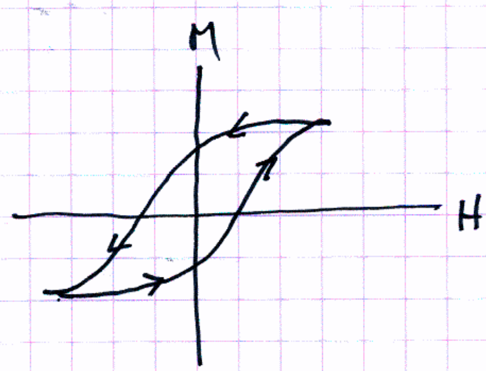


E.g., Al , $\chi = 2.1 \times 10^{-5}$

- Ferromagnetism



collective effects



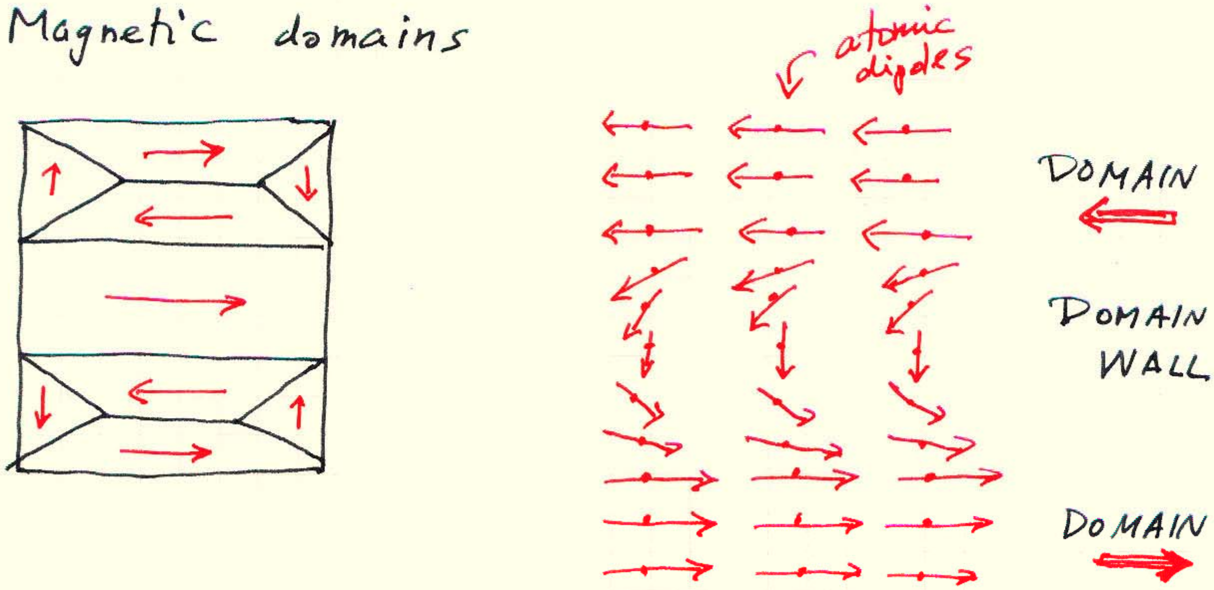
Magnetic Domains

Consider a non-magnetized bar of iron.

Macroscopically, $\vec{M}(\vec{x}) = 0$.

But in small domains, all the atomic dipoles are aligned by the "exchange interaction," a quantum effect.

Magnetic domains



How small is a magnetic domain?

At room temperature, with field $\vec{H} = 0$, the range is 10^{15} to 10^{20} atoms for pure crystalline iron; the typical mass is micrograms.

A macroscopic sample is many domains, with random orientations; so bulk $\vec{M} = 0$.

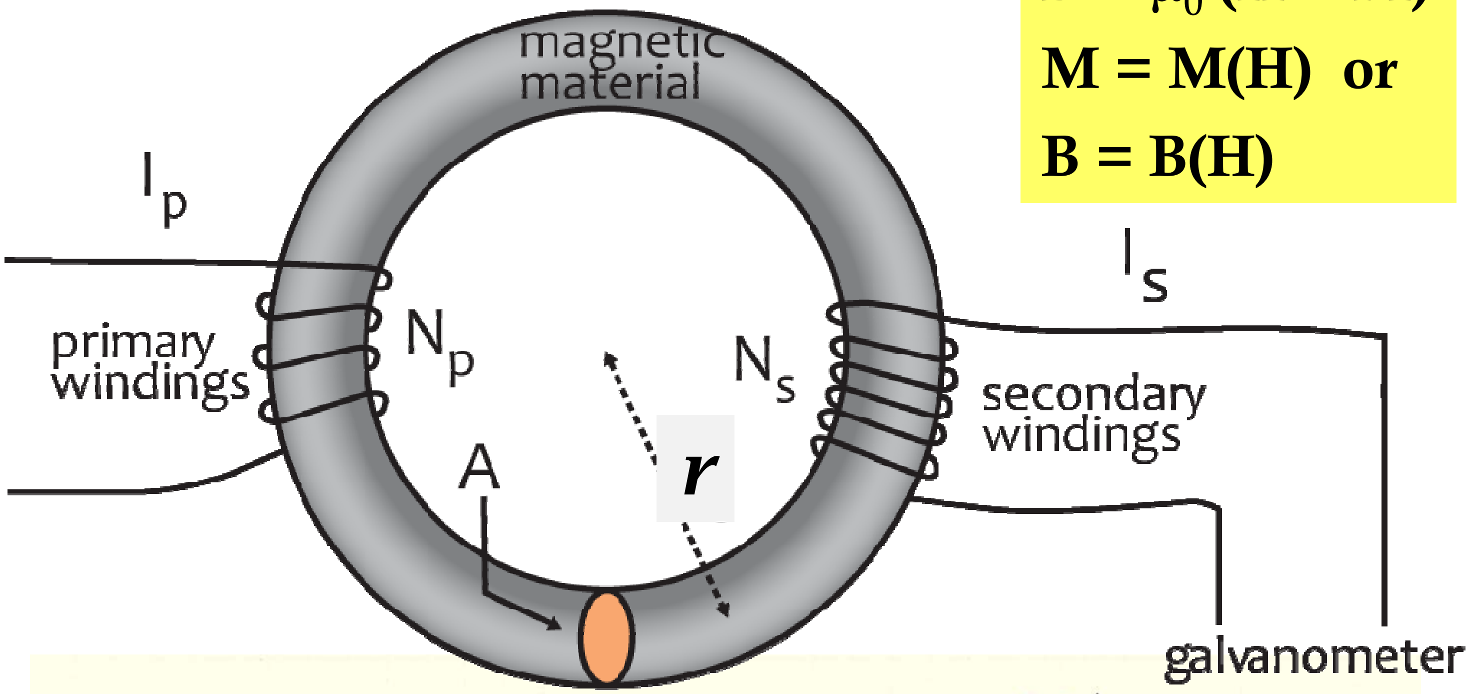
Now apply a magnetizing field $\vec{H}$.

Domain walls move; aligned domains grow and misaligned domains shrink.

$\vec{M}$ develops parallel to $\vec{H}$.

The Rowland Ring …
… for measuring **B** versus **H**

$B = \mu_0 (H + M)$
$M = M(H)$ or
$B = B(H)$



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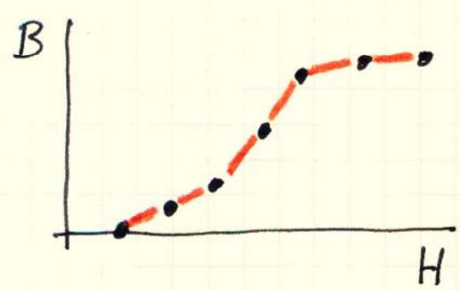
The primary current I_p creates a magnetizing field $\vec{H}$. When I_p changes, a current is induced in the secondary coil by electromagnetic induction. Observe ΔH and ΔB.

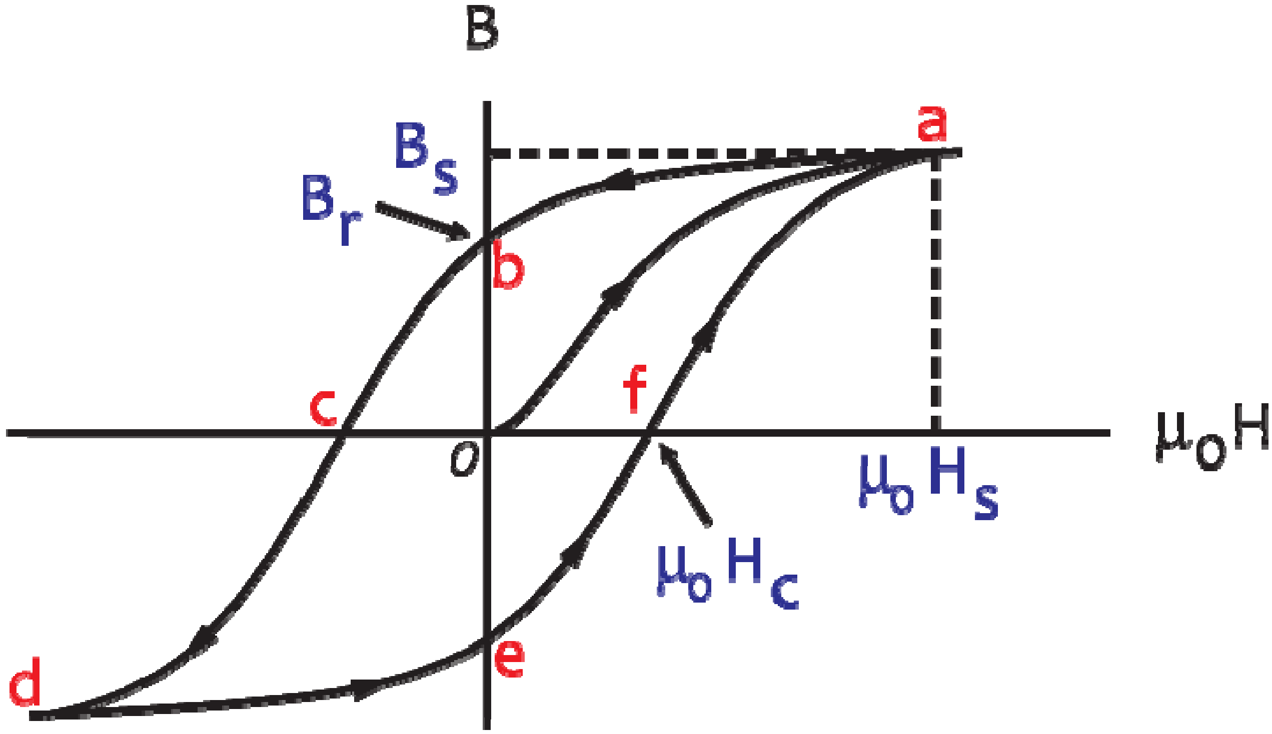
$$\oint \vec{H} \cdot d\vec{l} = I_{free}$$
$$H \cdot 2\pi r = N_p I_p$$
$$H = \frac{N_p I_p}{2\pi r}$$
$$\Delta H = \frac{N_p \Delta I_p}{2\pi r}$$

$$emf = -\frac{d\Phi}{dt}$$
$$I_s R = N_s \frac{dB}{dt} A$$
$$\Delta B = \frac{R \, \Delta Q_s}{N_s A}$$

Trace out B versus H



Magnetization Curve of a Ferromagnet



B_s = saturation field (all domains aligned)
B_r = remanent field (permanent magnet)
H_c = coercive force (static field required to demagnetize the sample)

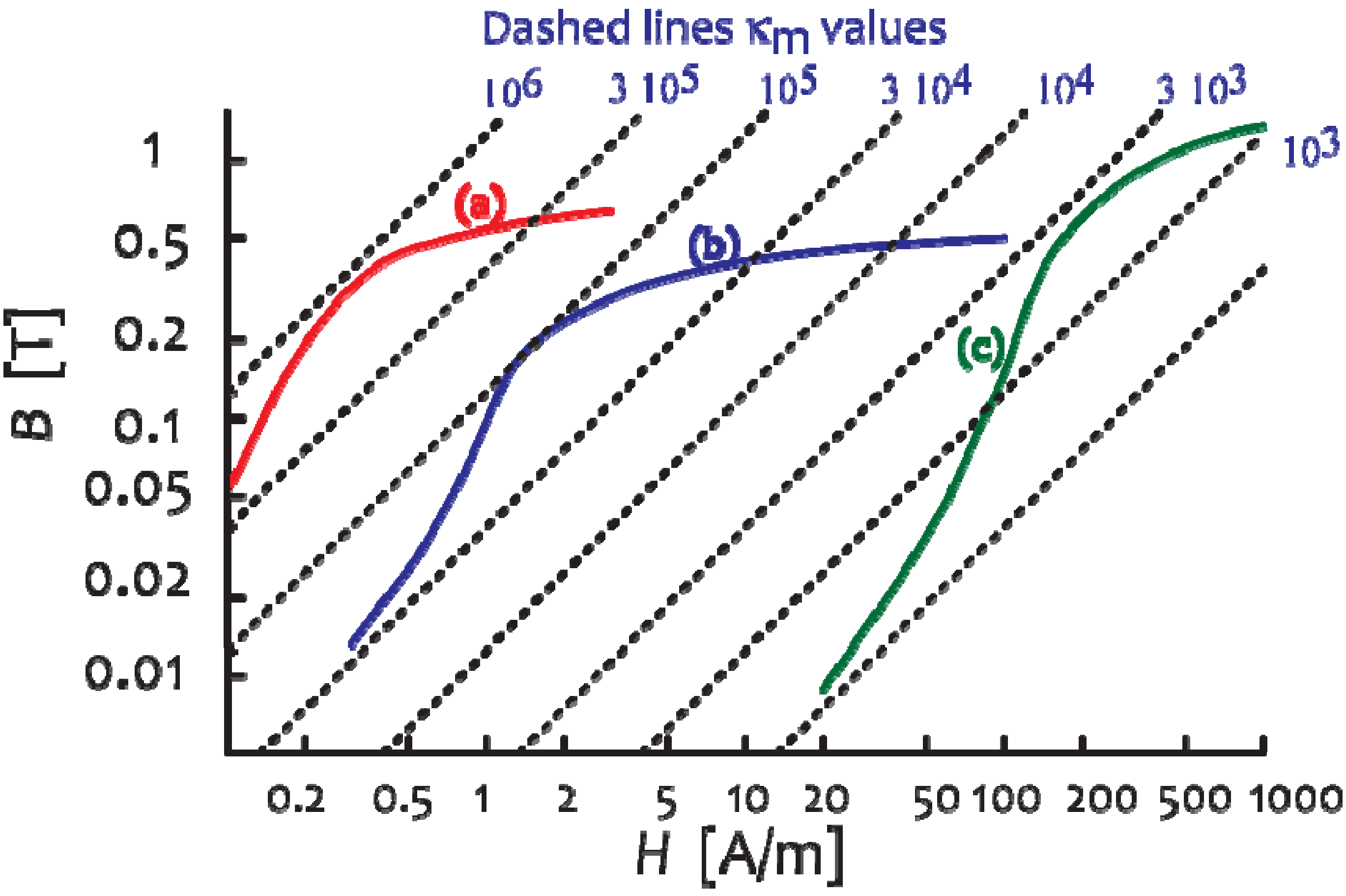
Hysteresis Loop

The energy per unit volume supplied for a cycle abcdefa is equal to the area enclosed in the (H,B) plane; this is ***heating*** the magnet.

Applications

Permeability **B** = μ **H**
For a ferromagnet, **B = μ**(H) **H**
Relative permeability κ_m

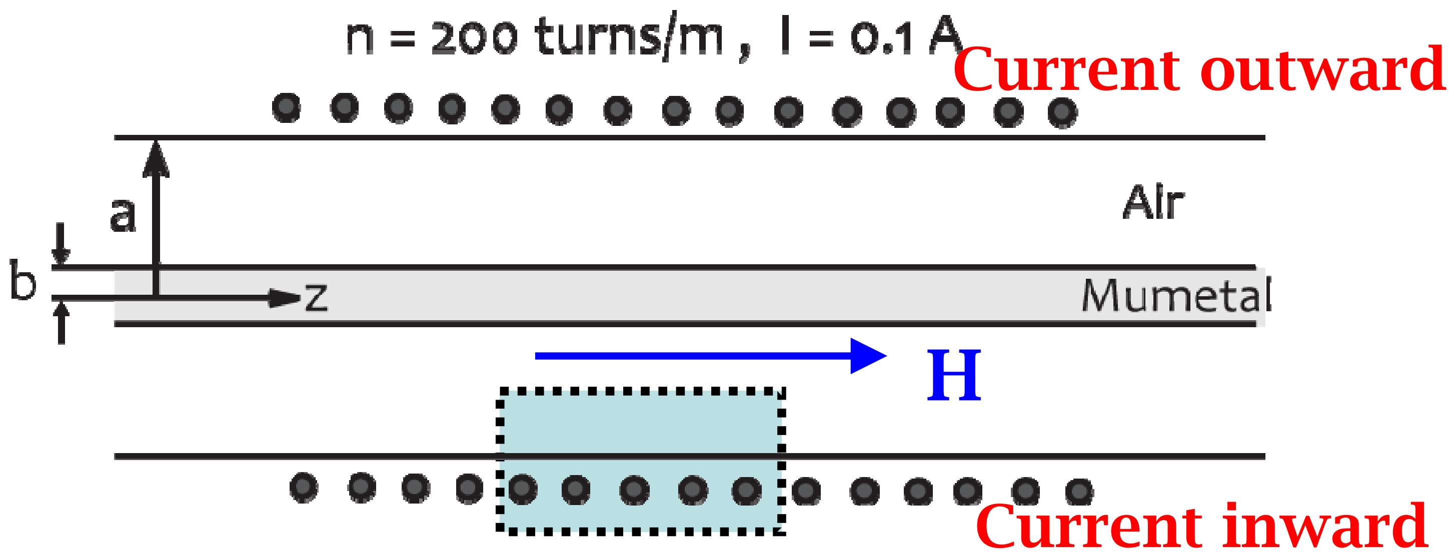
$$\kappa_m = \frac{\mu}{\mu_0} = \frac{B(H)}{\mu_0 H}$$



(a) Supermalloy; (b) Mumetal; (c) Iron
Ni(79%)Mo(5%)Fe(16%) Ni(77)Fe(15)Cu(4)Mo(4) Fe

Example

Consider a cylindrical solenoid with a thin core of mumetal on the axis of the cylinder. Determine **H, B and M.**



By symmetry $\vec{H} = H_z \hat{z}$ 9.5/6

Apply Ampère's law : $\oint \vec{H} \cdot d\vec{l} = I_{free}$

$$H L = n L I$$

$H = n I$ inside the solenoid

field	in the air	in the mumetal
H	$nI = 20$ A/m	$nI = 20$ A/m
B	$\mu_0 H = 2.5 \times 10^{-5}$ T	0.45 T (*)
M	0	3.6×10^{5} A/m (**)

(*) See curve (b)

(**) $M = \frac{B}{\mu_0} - H \approx \frac{B}{\mu_0}$

General Strategy for magnetic circuits 9.5/7

(1) $\oint_C \vec{H}\cdot d\vec{l} = I_{free} \Longrightarrow$ equations for $\vec{H}$

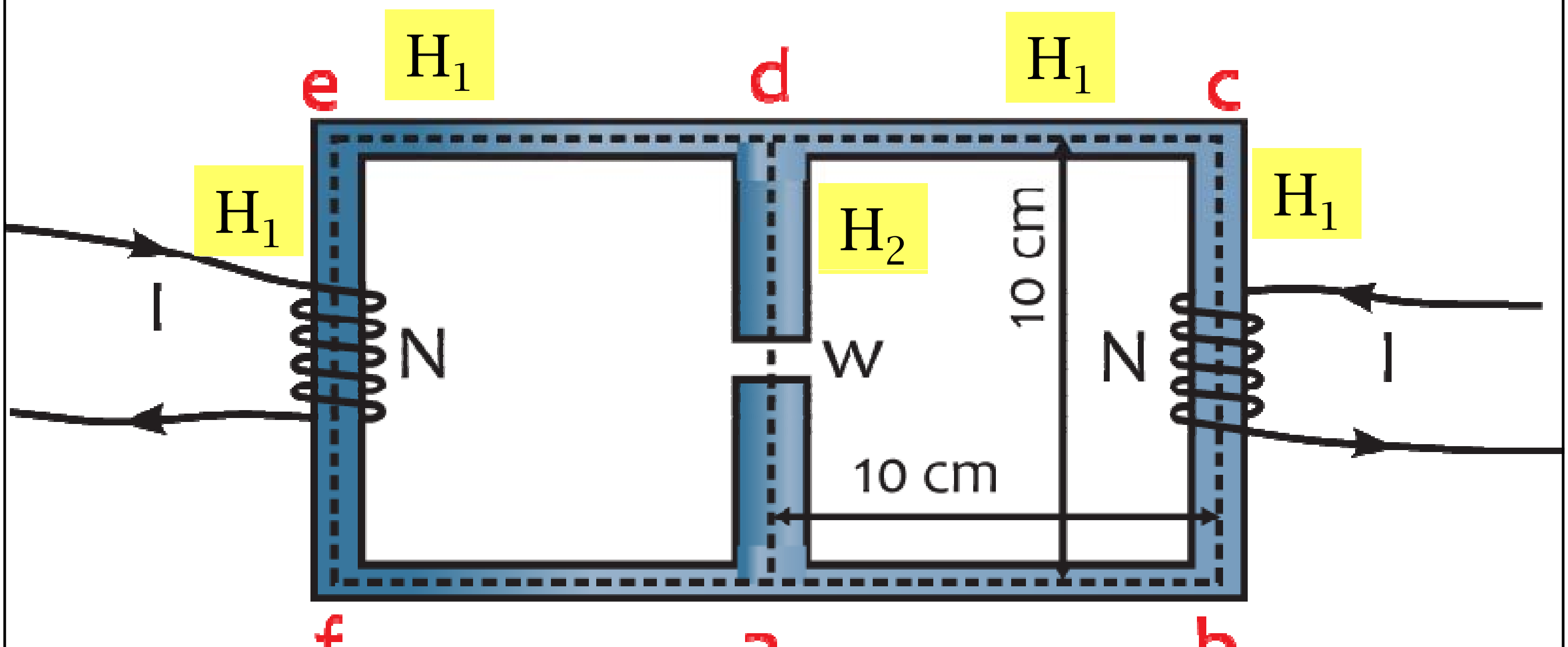
(2) • $\vec{B} = \mu_0 \vec{H}$ in free space ; or $\vec{H} = \vec{B}/\mu_0$

• Use $\vec{B}$ versus $\vec{H}$ graph for ferromagnetic material.

(3) B_n is continuous at any surface.

(4) Solve the coupled equations.

<u>Example</u> Consider the iron electromagnet in the figure. Calculate the current ***I*** such that ***B = 1*** tesla in the gap; w = 1 cm.



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- $\oint_{abcda} \vec{H}\cdot d\vec{\ell} = NI$

  $\hookrightarrow = 3H_1 L + H_2 (L-w) + H_{gap} w$

- $H_{gap} = \frac{B_{gap}}{\mu_0} = \frac{1\ T}{4\pi \times 10^{-7}\ \frac{Tm}{A}} = 8.0 \times 10^5\ A/m$

- B_n is continuous so $B_2 = B_{gap} = 1\ T$

$B_2 = 1\ T \Rightarrow H_2 = 500\ A/m$ (see the graph)

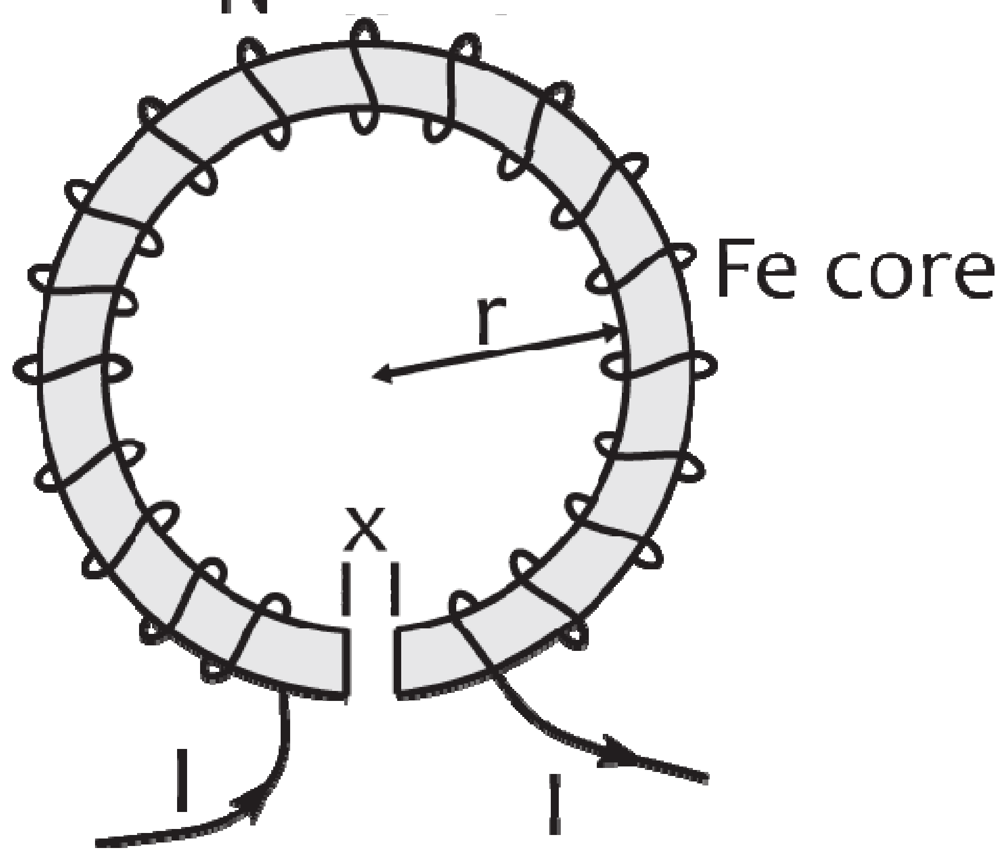
- Magnetic flux is conserved ($\oint_S \vec{B}\cdot d\vec{A} = 0$)

$\therefore B_1 + B_1 = B_2$ (points a and d)

$B_1 = 0{,}5\ T \Rightarrow H_1 = 185\ A/m$ (See the graph)

$$I = \frac{3H_1 L + H_2 (L-w) + H_{gap} w}{N} = 16\ A.$$

Quiz



Data:
N = 2000
$2\pi r = 1$ m
x = 1 cm.

Calculate the current ***I*** for which magnetic field in the gap would be 0.2 T.