CONTENTS

INTRODUCTION

- Magnetism plays an integral part in almost every electrical device used today in industry, research, or the home.

- Generators, motors, transformers, circuit breakers, televisions, computers, tape recorders, and telephones all employ magnetic effects to perform a variety of important tasks.

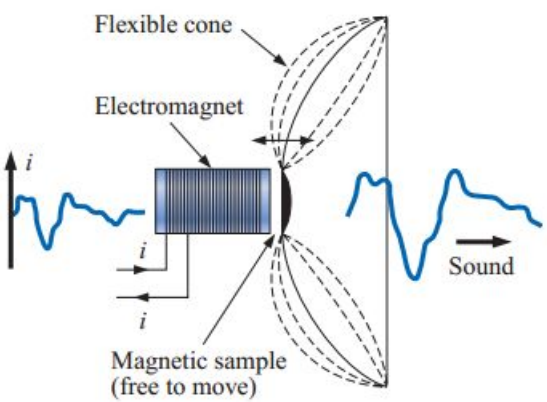


Fig: Speaker

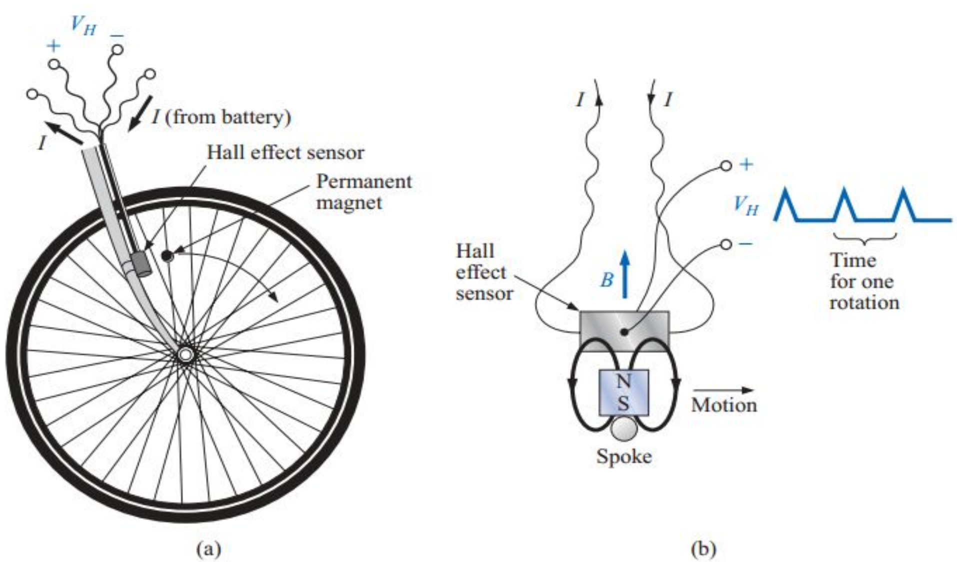


Fig:Obtaining a speed indication for a bicycle using a Hall effect sensor: (a) mounting the components; (b) Hall effect response.

For the first time it was demonstrated that electricity and magnetism were related, and the French physicist André-Marie Ampère performed experiments in this area and developed what is presently known as **Ampère's circuital law.**

MAGNETIC FIELDS

- In the region surrounding a permanent magnet there exists a magnetic field, which can be represented by **magnetic flux lines**

- Magnetic flux lines, do not have origins or terminating points. The symbol for magnetic flux is the Greek letter φ (phi).

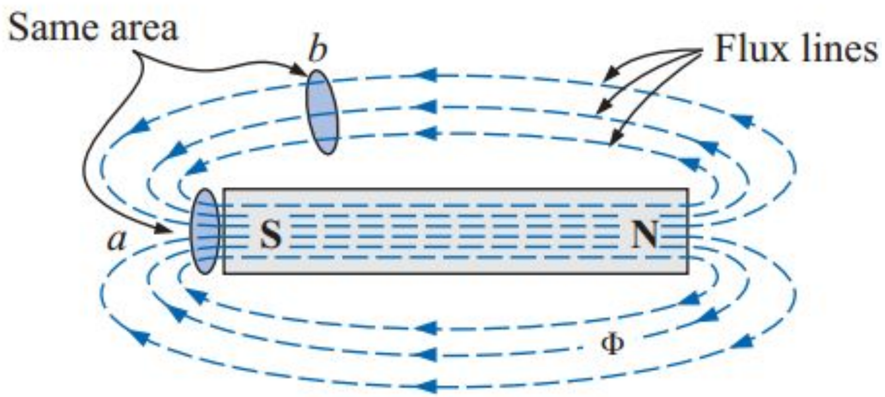


Fig. Flux distribution for a permanent magnet.

MAGNETIC FIELDS

- When the nonmagnetic material (glass or copper), and magnetic material (soft iron) are placed in the flux paths surrounding a permanent magnet,

there will be an almost unnoticeable change in the flux distribution in non magnetic materials as seen in Fig.

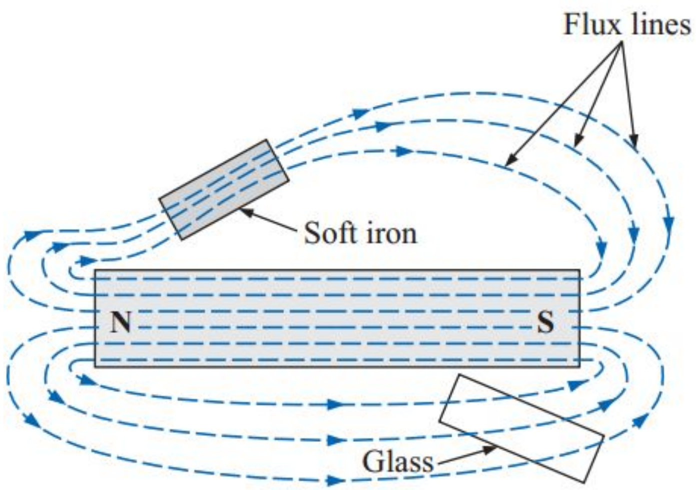
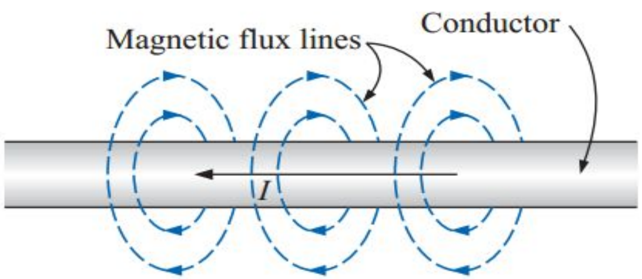
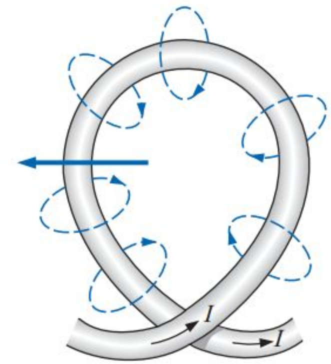


Fig: Effect of a ferromagnetic sample on the flux distribution of a permanent magnet.

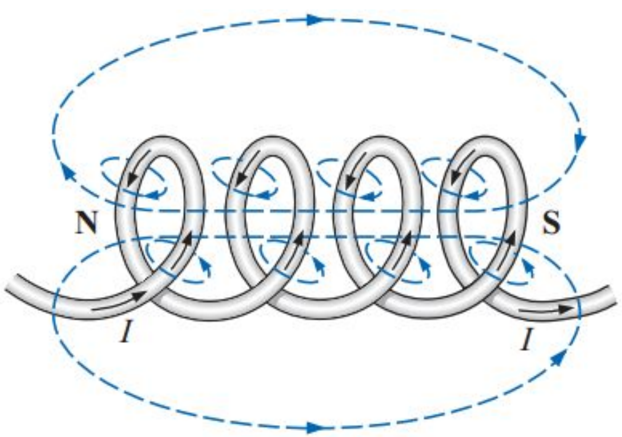
MAGNETIC FIELDS



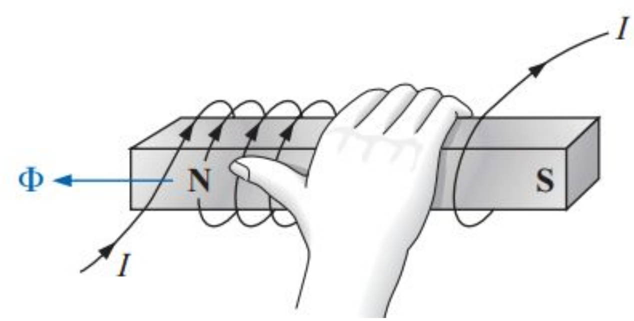
(a) Magnetic flux lines around a current-carrying conductor



(b) Flux distribution of a single-turn coil.



(c) Flux distribution of a current-carrying coil.

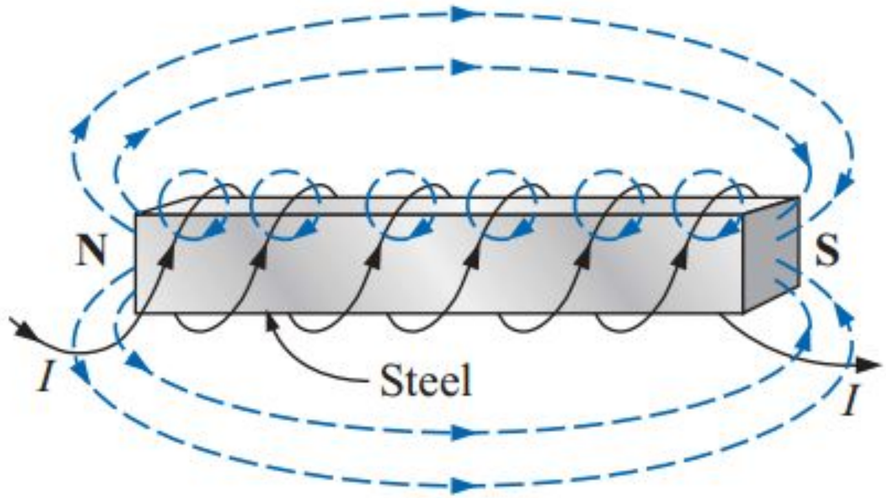


Right-hand rule

The direction of the magnetic flux lines can be found simply by placing the thumb of the *right* hand in the direction of *conventional* current flow and noting the direction of the fingers.

Electromagnet

Electromagnet has all the properties of a permanent magnet, also has a field strength that can be varied by changing one of the component values (current, turns, and so on).



FLUX DENSITY

- The number of flux lines per unit area is called the **flux density,** is denoted by the capital letter *B.*

$$\boxed{B = \frac{\Phi}{A}}$$

B = teslas (T)
Φ = webers (Wb)
A = square meters (m^2)

EXAMPLE.1: For the core of Fig, determine the flux density B in teslas.

$\Phi = 6 \times 10^{-5}$ Wb
$A = 1.2 \times 10^{-3}$ m^2

PERMEABILITY

- The **permeability (μ)** is a measure of the ease with which magnetic flux lines can be established in the material

- It is similar in many respects to conductivity in electric circuits.

- The ratio of the permeability of a material to that of free space is called its **relative permeability**

$$\boxed{\mu_r = \frac{\mu}{\mu_o}}$$

Permeability of free space $\mu_o = 4\pi \times 10^{-7}$

RELUCTANCE

- The resistance of a material to the flow of charge (current) is determined for electric circuits by the equation

$$R = \rho\frac{l}{A} \qquad \text{(ohms, } \Omega\text{)}$$

- The **reluctance** of a material to the setting up of magnetic flux lines in the material is determined by the following equation

$$\boxed{\mathcal{R} = \frac{l}{\mu A}} \qquad \text{(rels, or At/Wb)}$$

Where l is the length of the magnetic path, and *A* is the cross-sectional area

OHM'S LAW FOR MAGNETIC CIRCUITS

$$\boxed{\Phi = \frac{\mathscr{F}}{\mathscr{R}}}$$

The magnetomotive force $\mathscr{F}$ is proportional to the product of the number of turns around the core (in which the flux is to be established) and the current through the turns of wire

$$\boxed{\mathscr{F} = NI} \qquad \text{(ampere-turns, At)}$$

MAGNETIZING FORCE

The magnetomotive force per unit length is called the **magnetizing force** (*H*).

$$\boxed{H = \frac{\mathscr{F}}{l}} \qquad \text{(At/m)}$$

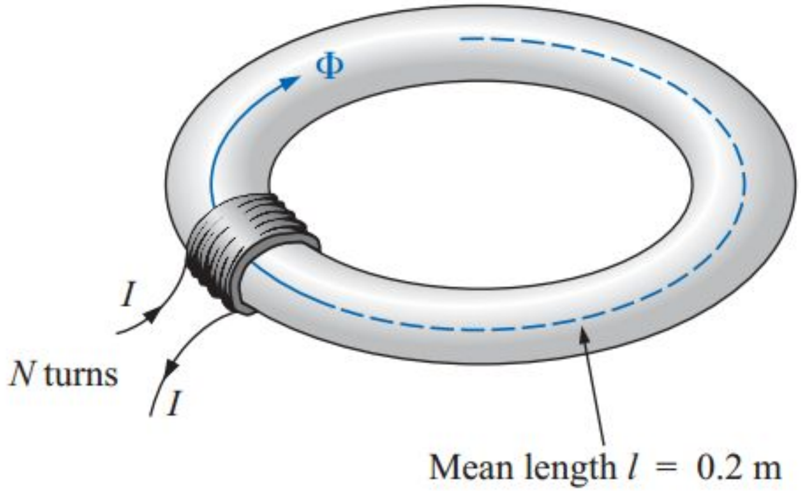
Substituting for the magnetomotive force will result in

$$\boxed{H = \frac{NI}{l}} \qquad \text{(At/m)}$$

MAGNETIZING FORCE

EXAMPLE.2:

For the magnetic circuit of Fig, if *NI* = 40 At and *length l*=0.2 m, then H=?



The magnetizing force is independent of the type of core material. It is determined solely by the number of turns, the current, and the length of the core.

MAGNETIZING FORCE

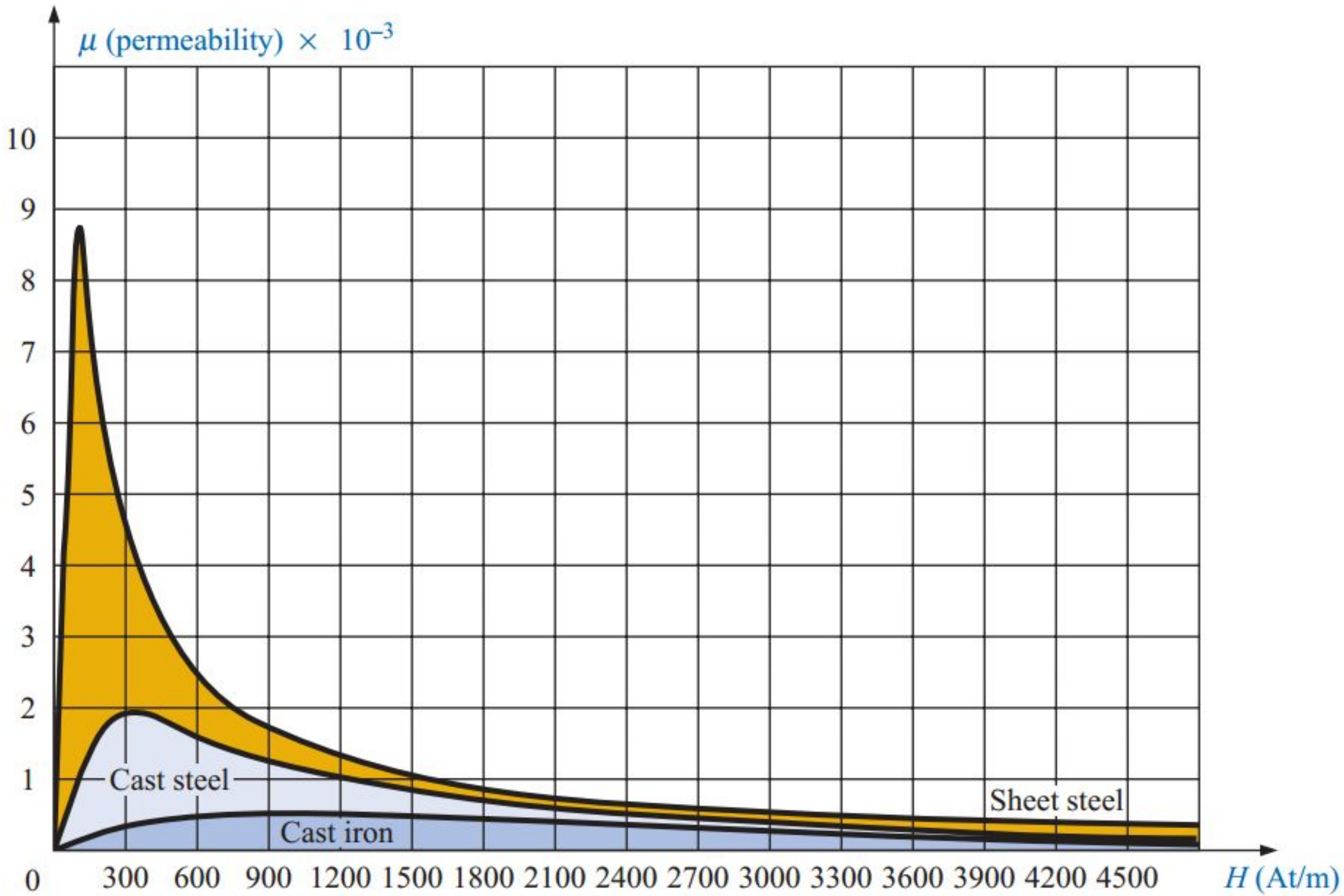
- The relation between the flux density and the magnetizing force is

$$\boxed{B = \mu H}$$

- The applied magnetizing force has a pronounced effect on the resulting permeability of a magnetic material.

- As the **magnetizing force increases**, the **permeability rises to a maximum** and then **drops to a minimum**

MAGNETIZING FORCE



Magnetizing force (H) vs Permeability

HYSTERESIS

- A curve of the flux density *B* versus the magnetizing force *H* of a material is of particular importance to the engineer.

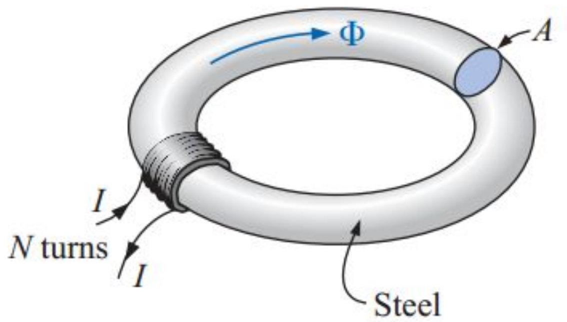


Fig.1

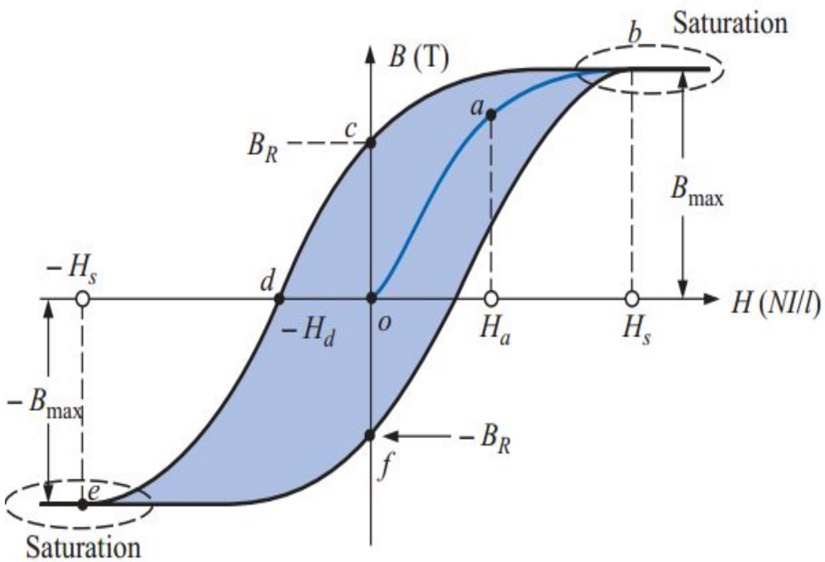
- The core is initially unmagnetized and **the current *I* = 0**. If the current I is increased to some value above zero, the **magnetizing force H** will increase to a value determined by

$$\boxed{H\uparrow = \frac{NI\uparrow}{l}}$$

- The flux and the flux density will also increase with the current I (or H)

HYSTERESIS

- When saturation occurs, any further increase in current through the coil increasing H will result in a very small increase in flux density B.

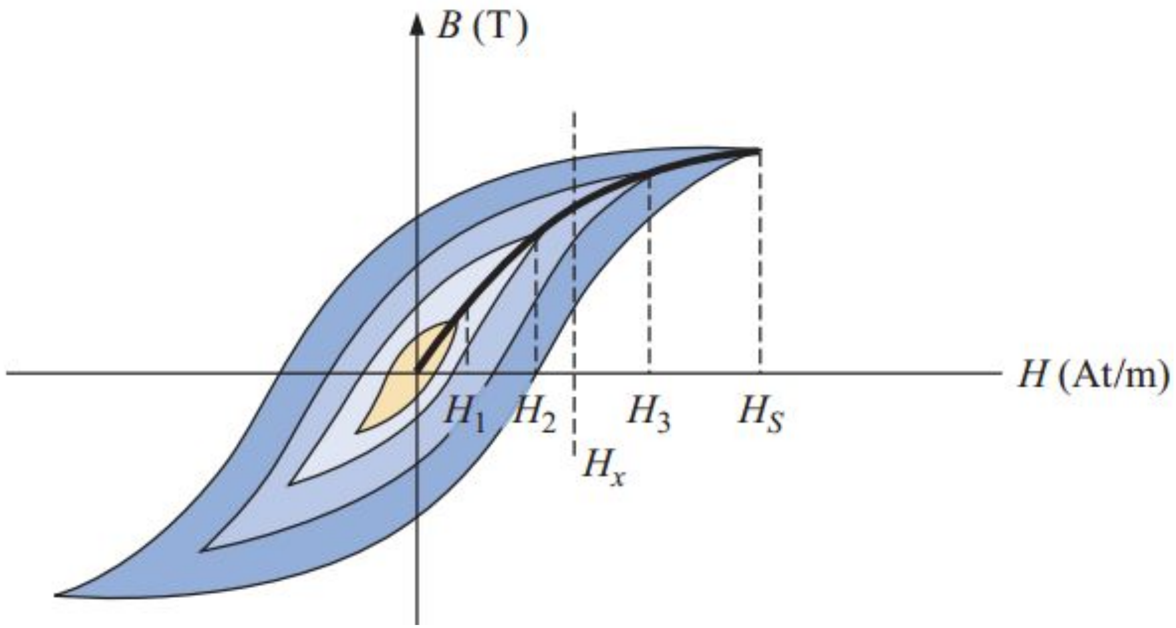


- The flux density B_R, which remains when the magnetizing force is zero, is called the *residual flux density.*

- The magnetizing force $-H_d$ required to "coerce" the flux density to reduce its level to zero is called the *coercive force,* a measure of the coercivity of the magnetic sample.

HYSTERESIS

- Three hysteresis loops for the same material for maximum values of *H,* less than the saturation value are shown in Fig.



- Note from the various curves that for a particular value of *H,* say, H_x, the value of *B* can vary widely, as determined by the history of the core.

HYSTERESIS

- A comparison of Figs. (A) and (B) shows that for the same value of *H*, the value of *B* is higher in Fig. (B) for the materials with the higher μ in fig. (A).

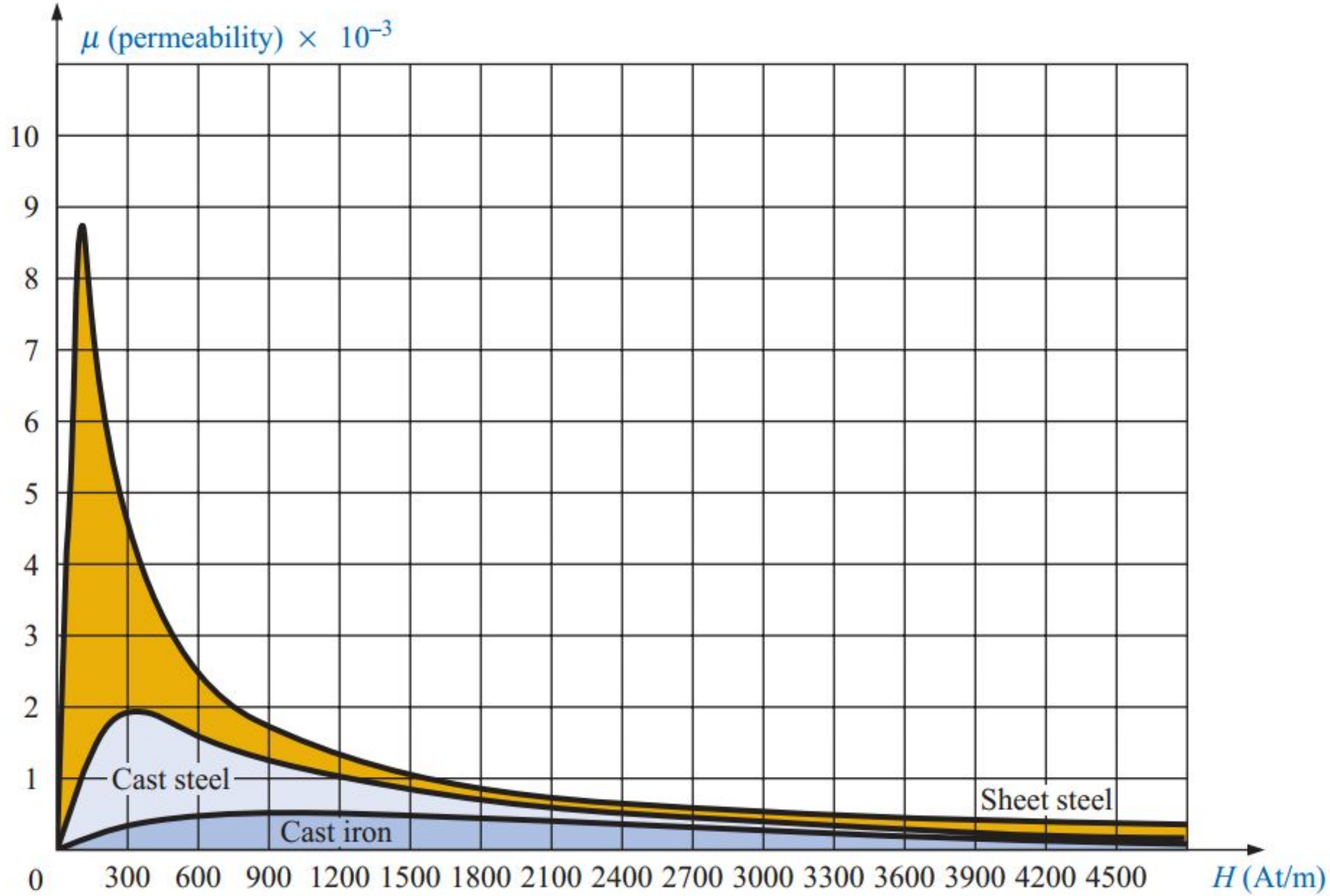


Fig. (A).

HYSTERESIS

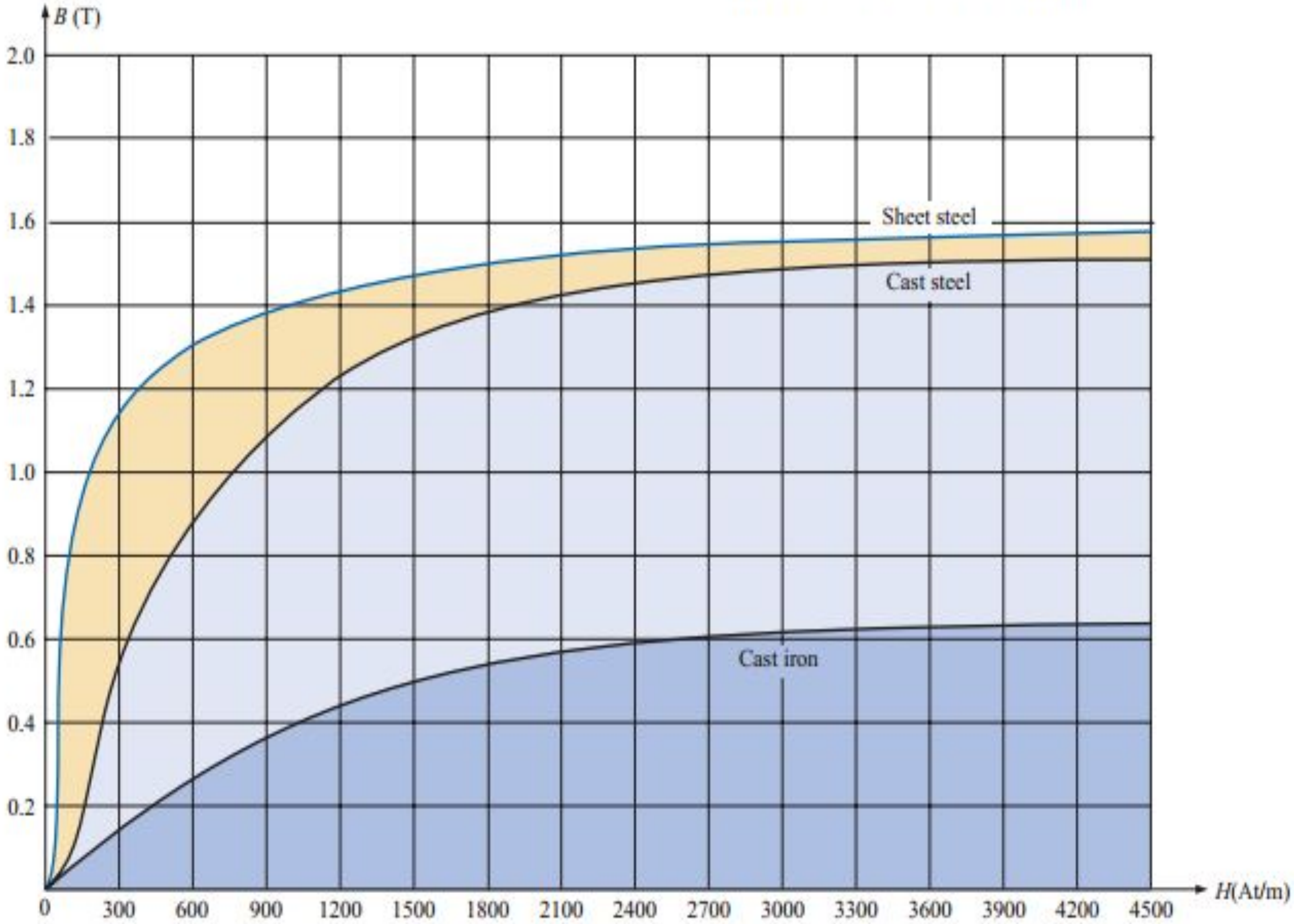


Fig. (B)

AMPERE'S CIRCUITAL LAW

There is a broad similarity between the analyses of electric and magnetic circuits

	Electric Circuits	**Magnetic Circuits**
Cause	E	$\mathscr{F}$
Effect	I	Φ
Opposition	R	$\mathscr{R}$

Kirchhoff's voltage law:

The algebraic sum of the rises and drops of the mmf around a closed loop of a magnetic circuit is equal to zero; that is, the sum of the rises in mmf equals the sum of the drops in mmf around a closed loop.

$$\boxed{\Sigma_{\circlearrowright}\, \mathscr{F} = 0} \qquad \text{(for magnetic circuits)}$$

AMPERE'S CIRCUITAL LAW

$$\boxed{\Sigma_{\circlearrowright} \mathcal{F} = 0} \qquad \text{(for magnetic circuits)}$$

This equation is referred to as **Ampère's circuital law**

When it is applied to magnetic circuits,

- The sources of mmf are expressed by the equation is

$$\boxed{\mathcal{F} = NI} \qquad \text{(At)}$$

- The drop mmf across a portion of a magnetic circuit is expressed by the equation

$$\boxed{\mathcal{F} = \Phi\mathcal{R}} \quad \text{(At)} \qquad \textbf{or} \qquad \boxed{\mathcal{F} = Hl} \quad \text{(At)}$$

AMPERE'S CIRCUITAL LAW

EXAMPLE.3:

consider the magnetic circuit appearing in Fig. constructed of three different ferromagnetic materials.

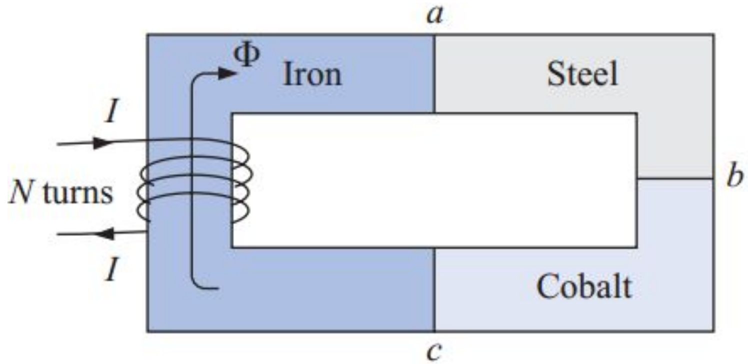


FIG. *Series magnetic circuit of three different materials.*

- Applying Ampère's circuital law, we have $\Sigma_{\circlearrowright}\ \mathscr{F} = 0$

$$\underbrace{+NI}_{\text{Rise}} - \underbrace{H_{ab}l_{ab}}_{\text{Drop}} - \underbrace{H_{bc}l_{bc}}_{\text{Drop}} - \underbrace{H_{ca}l_{ca}}_{\text{Drop}} = 0$$

$$\underbrace{NI}_{\substack{\text{Impressed}\\ \text{mmf}}} = \underbrace{H_{ab}l_{ab} + H_{bc}l_{bc} + H_{ca}l_{ca}}_{\text{mmf drops}}$$

AMPERE'S CIRCULAL LAW

Kirchhoff's current law:

The sum of the fluxes entering a junction is equal to the sum of the fluxes leaving a junction

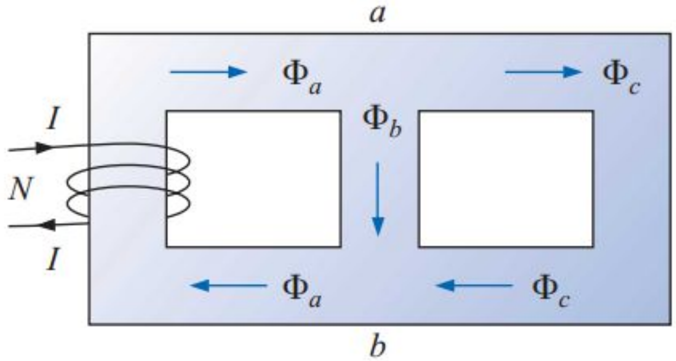


FIG. *Flux distribution of a series-parallel magnetic network*

$$\Phi_a = \Phi_b + \Phi_c \qquad \text{(at junction } a\text{)}$$

$$\Phi_b + \Phi_c = \Phi_a \qquad \text{(at junction } b\text{)}$$

Both of which are equivalent.

SERIES MAGNETIC CIRCUITS

Series magnetic circuits in which the flux φ is the same throughout

- An approach frequently employed in the analysis of magnetic circuits is the table method.

- Before a problem is analyzed in detail, a table is prepared listing in the extreme left-hand column the various sections of the magnetic circuit.

- The columns on the right are reserved for the quantities to be found for each section.

- Now we will see some of the series magnetic circuits and find the magnitude of the magnetomotive force of magnetic circuit.

SERIES MAGNETIC CIRCUITS

EXAMPLE.4:

For the series magnetic circuit of Fig. (i):

a. Find the value of *I* required to develop a magnetic flux of $\varnothing = 4 \times 10^{-4}$ Wb.

b. Determine μ and μ_r for the material under these conditions.

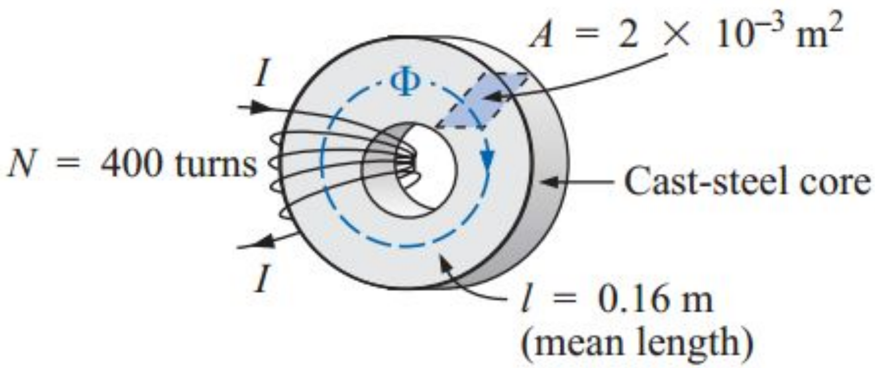
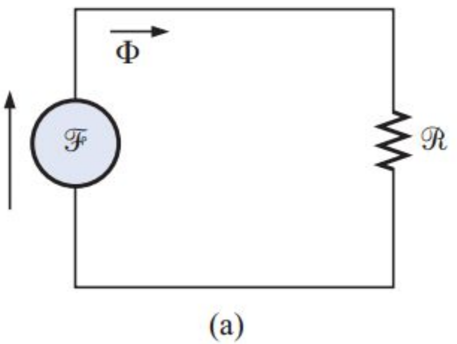


Fig. (i)

Solution:



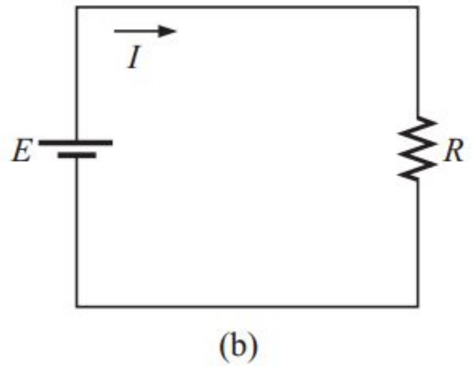


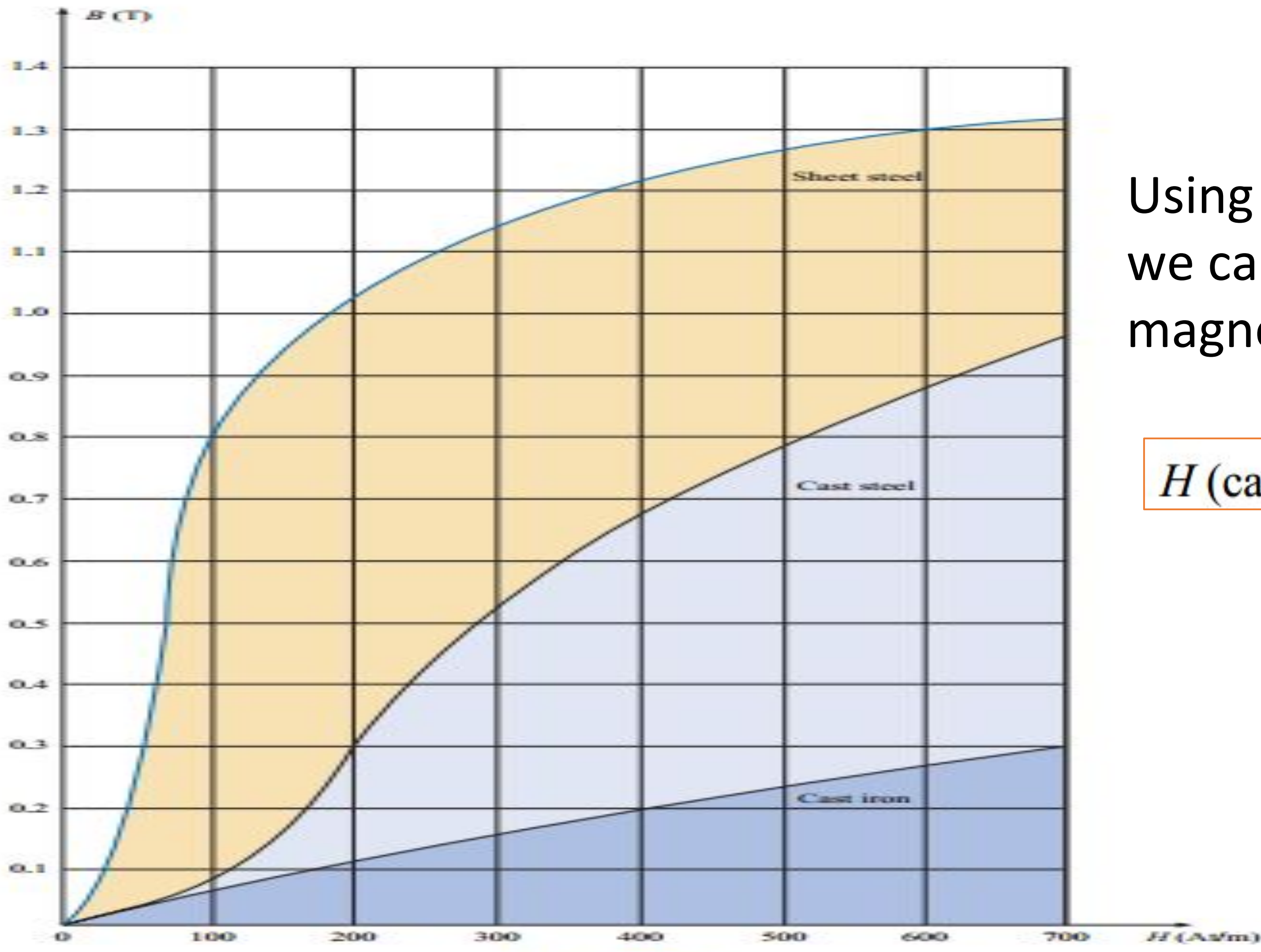
Fig:(a) Magnetic circuit equivalent and (b) electric circuit analogy.

Section	**Φ (Wb)**	***A*** **(m²)**	***B*** **(T)**	***H*** **(At/m)**	***l*** **(m)**	***Hl*** **(At)**
One continuous section	4×10^{-4}	2×10^{-3}			0.16	

(a) The flux density *B* is

SERIES MAGNETIC CIRCUITS

$$B = \frac{\Phi}{A} = \frac{4 \times 10^{-4}\,\text{Wb}}{2 \times 10^{-3}\,\text{m}^2} = 2 \times 10^{-1}\,\text{T} = 0.2\,\text{T}$$



Using the *B-H* curves, we can determine the magnetizing force *H;*

$$\boxed{H\,(\text{cast steel}) = 170\ \text{At/m}}$$

Applying Ampère's circuital law yields $\boxed{NI = Hl}$

$$I = \frac{Hl}{N} = \frac{(170\text{ At/m})(0.16\text{ m})}{400\text{ t}} = \mathbf{68\ mA}$$

(Recall that t represents turns.)

(b) The permeability of the material

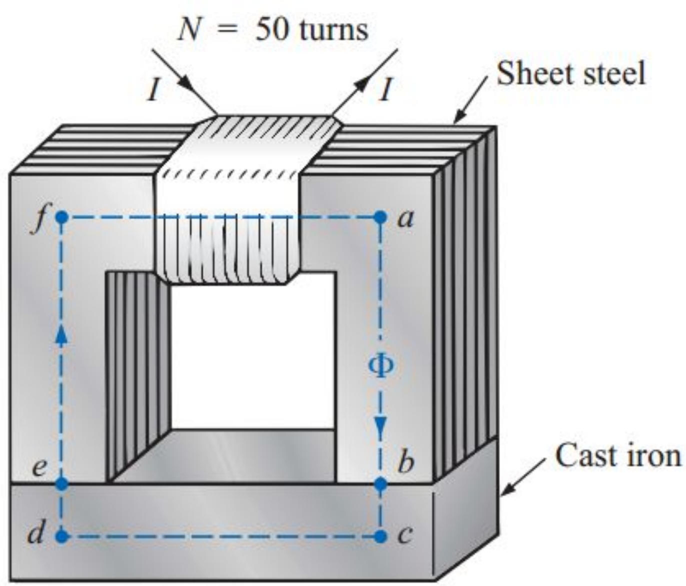
$$\mu = \frac{B}{H} = \frac{0.2\text{ T}}{170\text{ At/m}} = \mathbf{1.176 \times 10^{-3}\ Wb/A \cdot m}$$

the relative permeability is

$$\mu_r = \frac{\mu}{\mu_o} = \frac{1.176 \times 10^{-3}}{4\pi \times 10^{-7}} = \mathbf{935.83}$$

PROBLEM.1:

The electromagnet of Fig. has picked up a section of cast iron. Determine the current *I* required to establish the indicated flux in the core.



$l_{ab} = l_{cd} = l_{ef} = l_{fa} = 4$ in.
$l_{bc} = l_{de} = 0.5$ in.
Area (throughout) $= 1$ in.^{2}
$\Phi = 3.5 \times 10^{-4}$ Wb

To solve this problem, Use these B-H curve to get H values for corresponding B values

H (sheet steel, Fig. 11.24) $\cong$ 70 At/m

H (cast iron, Fig. 11.23) $\cong$ 1600 At/m

AIR GAPS

- The spreading of the flux lines outside the common area of the core for the air gap in Fig. (a) is known as *fringing.*

- For our purposes, we shall neglect this effect and assume the flux distribution to be as in Fig.(b).

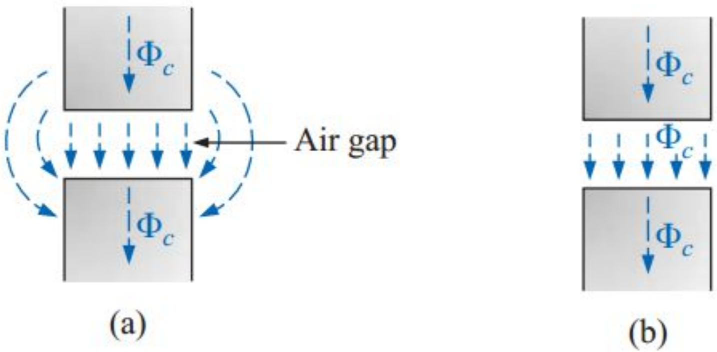


Fig. Air gaps: (a) with fringing; (b) ideal

- The average flux density in the air-gap is slightly less than the flux density in the core i.e., $(B_g)_{(av)} < B_c$.

$$\boxed{B_g = \frac{\Phi_g}{A_g}}$$

AIR GAPS

- The flux density of the air gap in Fig.(b) is given by

$$\Phi_g = \Phi_{\text{core}}$$

$$A_g = A_{\text{core}}$$

- For most practical applications, **the permeability of air** is taken to be equal to that of **free space**. The magnetizing force of the air gap is then determined by

$$\boxed{H_g = \frac{B_g}{\mu_o}}$$

- The mmf drop across the air gap is equal to $\boldsymbol{H_g l_g}$. An equation for $\boldsymbol{H_g}$ is as follows:

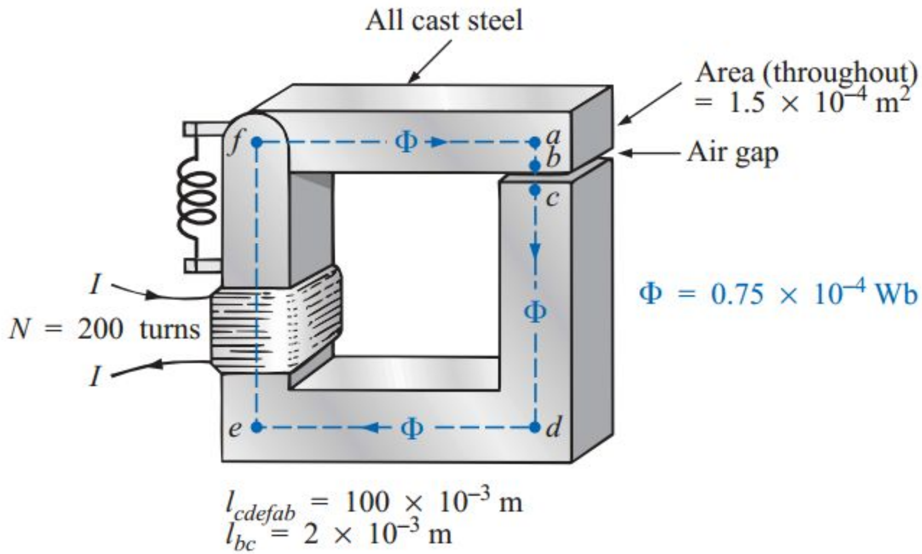
$$H_g = \frac{B_g}{\mu_o} = \frac{B_g}{4\pi \times 10^{-7}}$$

$$\boxed{H_g = (7.96 \times 10^5)B_g} \qquad \text{(At/m)}$$

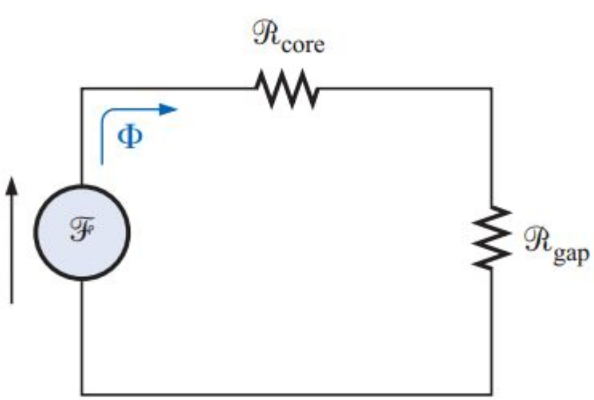
AIR GAPS

EXAMPLE.5:

Find the value of *I* required to establish a magnetic flux of $\emptyset = \mathbf{0.75} \times \mathbf{10^{-4}}$ Wb in the series magnetic circuit of Fig.

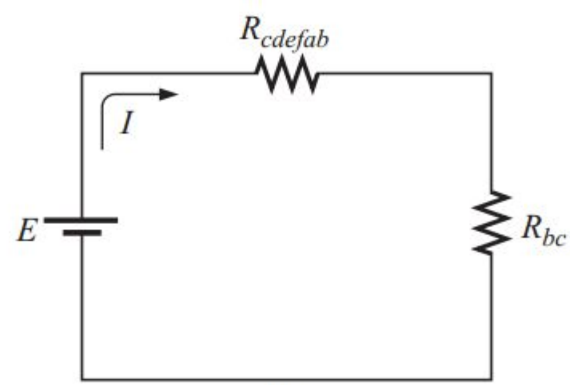


Solution:



(a)

Magnetic circuit equivalent



(b)

Electric circuit analogy

AIR GAPS

The flux density for each section is $B = \frac{\Phi}{A} = \frac{0.75 \times 10^{-4}\ \text{Wb}}{1.5 \times 10^{-4}\ \text{m}^2} = 0.5\ \text{T}$

From the *B-H* curves, $\boxed{H\ (\text{cast steel}) \cong 280\ \text{At/m}}$

An equation for H_g $\boxed{H_g = (7.96 \times 10^5)B_g}$ (At/m)

$$H_g = (7.96 \times 10^5)B_g = (7.96 \times 10^5)(0.5\ \text{T}) = 3.98 \times 10^5\ \text{At/m}$$

The mmf drops are

$$H_{\text{core}}l_{\text{core}} = (280\ \text{At/m})(100 \times 10^{-3}\ \text{m}) = 28\ \text{At}$$

$$H_g l_g = (3.98 \times 10^5\ \text{At/m})(2 \times 10^{-3}\ \text{m}) = 796\ \text{At}$$

Applying Ampere's circuital law,

$$NI = H_{core} l_{core} + H_g l_g \quad = 28 \text{ At} + 796 \text{ At}$$

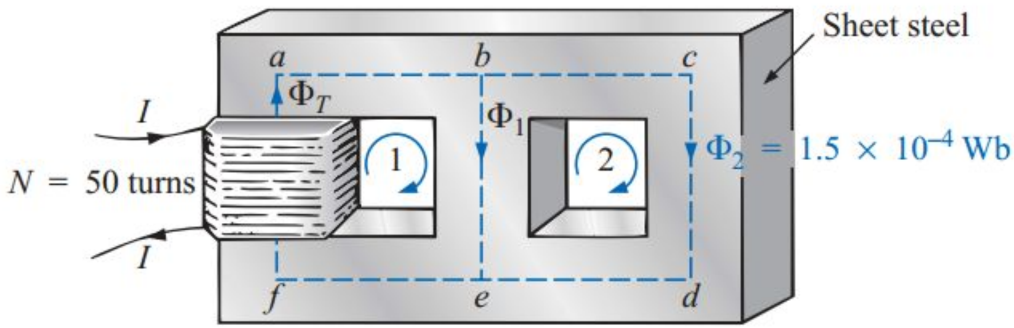
$$(200 \text{ t})I = 824 \text{ At}$$
$$I = \mathbf{4.12\ A}$$

Note from the above that the air gap requires the biggest share (by far) of the impressed *NI* due to the fact that air is nonmagnetic.

SERIES-PARALLEL MAGNETIC CIRCUITS

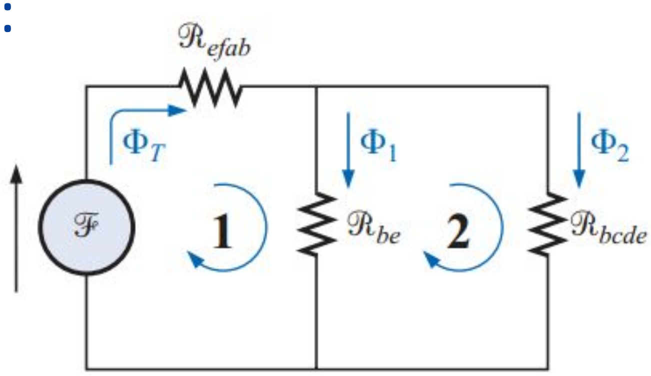
EXAMPLE.6:

Determine the current *I* required to establish a flux of $\emptyset = \mathbf{1.5} \times \mathbf{10^{-4}}$Wb in the section of the core indicated in Fig.



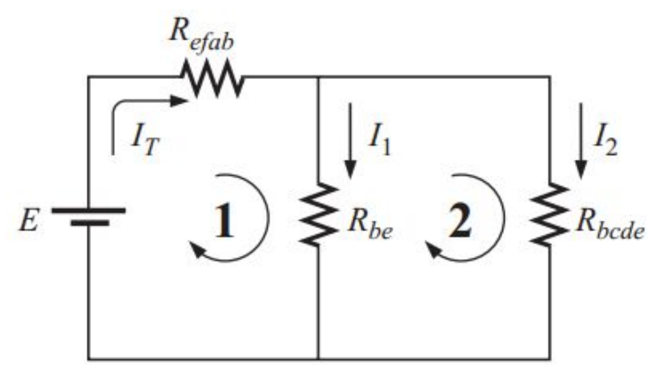
$l_{bcde} = l_{efab} = 0.2$ m
$l_{be} = 0.05$ m
Cross-sectional area $= 6 \times 10^{-4}$ m^2 throughout

Solution:



(a)

Magnetic circuit equivalent



(b)

Electric circuit analogy

$$B_2 = \frac{\Phi_2}{A} = \frac{1.5 \times 10^{-4}\ \text{Wb}}{6 \times 10^{-4}\ \text{m}^2} = 0.25\ \text{T}$$

Applying Ampère’s circuital law around loop 2

$$\Sigma_{\circlearrowright}\ \mathscr{F} = 0$$

$$H_{be}l_{be} - H_{bcde}l_{bcde} = 0$$

$$H_{be}(0.05\ \text{m}) - (40\ \text{At/m})(0.2\ \text{m}) = 0$$

$$H_{be} = \frac{8\ \text{At}}{0.05\ \text{m}} = 160\ \text{At/m}$$

From BH Curve:

$$\boxed{B_1 \cong 0.97\ \text{T}}$$

$$\boxed{\Phi_1 = B_1 A = (0.97\ \text{T})(6 \times 10^{-4}\ \text{m}^2) = 5.82 \times 10^{-4}\ \text{Wb}}$$

Table

Section	Φ (Wb)	A (m^2)	B (T)	H (At/m)	l (m)	Hl (At)
bcde	1.5×10^{-4}	6×10^{-4}	0.25	40	0.2	8
be	5.82×10^{-4}	6×10^{-4}	0.97	160	0.05	8
efab		6×10^{-4}			0.2	

The table reveals that we must now turn our attention to section ***efab***:

$$\Phi_T = \Phi_1 + \Phi_2 = 5.82 \times 10^{-4}\ \text{Wb} + 1.5 \times 10^{-4}\ \text{Wb}$$
$$= 7.32 \times 10^{-4}\ \text{Wb}$$

$$B = \frac{\Phi_T}{A} = \frac{7.32 \times 10^{-4}\ \text{Wb}}{6 \times 10^{-4}\ \text{m}^2}$$
$$= 1.22\ \text{T}$$

From B-H Graph $H_{efab} \cong 400\ \text{At}$

Applying Ampère’s circuital law,

$$+NI - H_{efab}l_{efab} - H_{be}l_{be} = 0$$
$$NI = (400\ \text{At/m})(0.2\ \text{m}) + (160\ \text{At/m})(0.05\ \text{m})$$
$$(50\ \text{t})I = 80\ \text{At} + 8\ \text{At}$$
$$I = \frac{88\ \text{At}}{50\ \text{t}} = \mathbf{1.76\ A}$$

To demonstrate **that μ is sensitive to the magnetizing force H**,

 The permeability of each section is determined as follows.

For section ***bcde,***

$$\mu = \frac{B}{H} = \frac{0.25\text{ T}}{40\text{ At/m}} = 6.25 \times 10^{-3}$$

$$\mu_r = \frac{\mu}{\mu_o} = \frac{6.25 \times 10^{-3}}{12.57 \times 10^{-7}} = \mathbf{4972.2}$$

For section ***be,***

$$\mu = \frac{B}{H} = \frac{0.97\text{ T}}{160\text{ At/m}} = 6.06 \times 10^{-3}$$

$$\mu_r = \frac{\mu}{\mu_o} = \frac{6.06 \times 10^{-3}}{12.57 \times 10^{-7}} = \mathbf{4821}$$

For section ***efab,***

$$\mu = \frac{B}{H} = \frac{1.22\text{ T}}{400\text{ At/m}} = 3.05 \times 10^{-3}$$

$$\mu_r = \frac{\mu}{\mu_o} = \frac{3.05 \times 10^{-3}}{12.57 \times 10^{-7}} = \mathbf{2426.41}$$

PROBLEMS.2&3:

Calculate the magnetic flux φ for the magnetic circuit of Fig. (a) and (b)

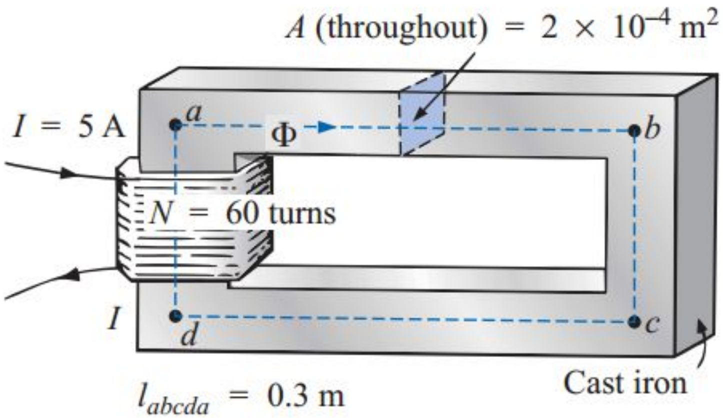


Fig.(a)

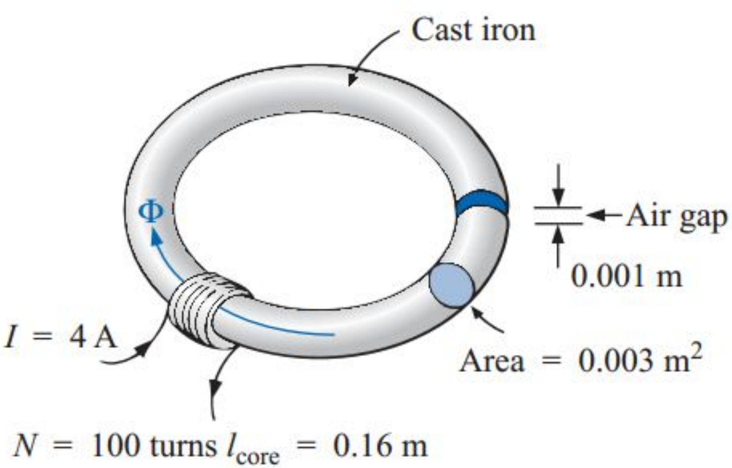


Fig.(b)

Use the B-H Curves to solve this problems