Magnetic Circuits

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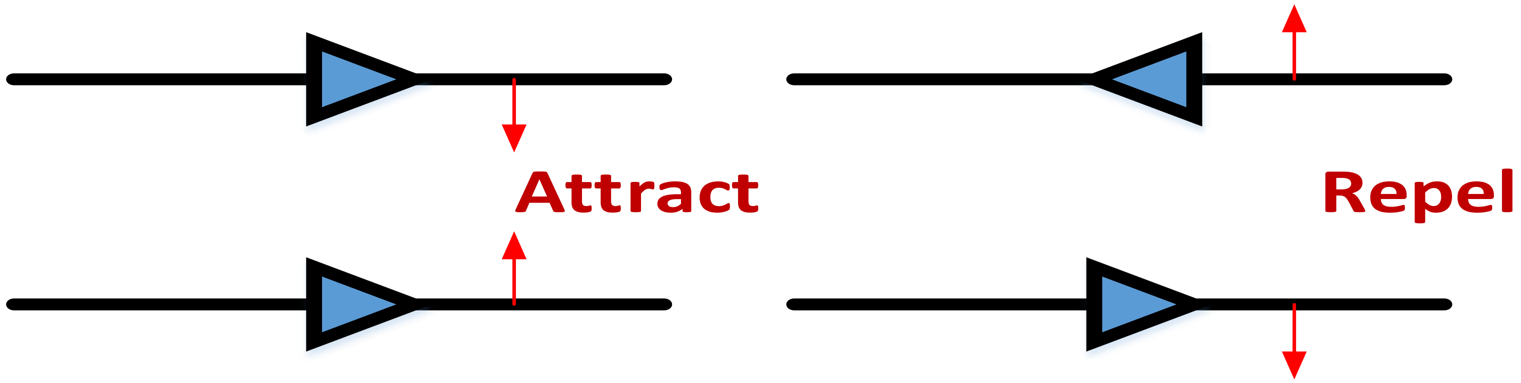
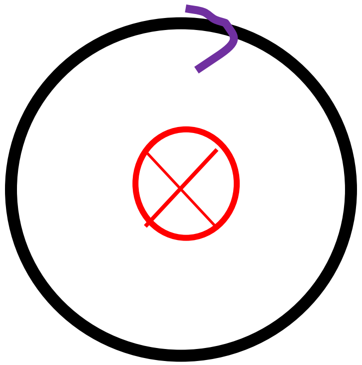
Basic Magnetic Laws and Circuits

- In 1820, the Danish physicist Hans Christian Oersted discovered that the electric current produce a magnetic field.
- André-Marie Ampère (1775-1836) demonstrated that parallel wires carrying currents attract or repelled each other





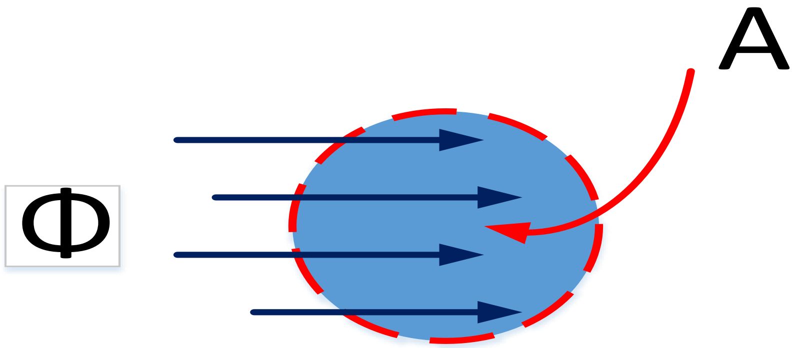
Flux Density

- Magnetic flux is measured in Webers and usually the symbol Φ used to denote it.
- Flux per unit area is called the flux density and given a unit Tesla

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

B→tesla, Φ→ weber, A→ m^2(Area)

Therefore, 1 T=1 wb/m^2



Example

If the flux density is 1.2 T and the area is 0.25 m2, determine the flux through the core.

Permeability

Permeability of a material is the core with which the magnetic flux can be established in the material.

The permeability of free space is $\mu_0 = 4\pi \times 10^{-7} wb/Am$

Permeability of all the non-magnetic materials are very close to the permeability of air or free space.

Permeability (contd..)

Materials with very high permeability are known as ferromagnetic.

The ratio of the permeability of a material to that of free space is called the relative permeability (μ_r) is shown below:

$$\mu_r = \frac{\mu}{\mu_0}$$

In general for ferromagnetic materials, the μ_r>100, and for non-magnetic materials the $\mu_r \approx$1

Reluctance

The resistance of a material to electric current is given by,

$$\boldsymbol{R = \rho \frac{l}{A}}$$

where *R* is the resistance of the material, *ρ* is the resistivity, *l* is the length, and *A* is the cross-section.

Similarly, the reluctance of a material to the setting up of magnetic flux in the material is given by,

$$\boldsymbol{\mathcal{R} = \frac{l}{\mu A}}$$

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

There is no widely accepted unit for reluctance, although the rel and the At/Wb are usually applied.

Magnetomotive force (mmf)

Magnetomotive force (mmf) is responsible for producing magnetic flux in a magnetic material, and is given by,

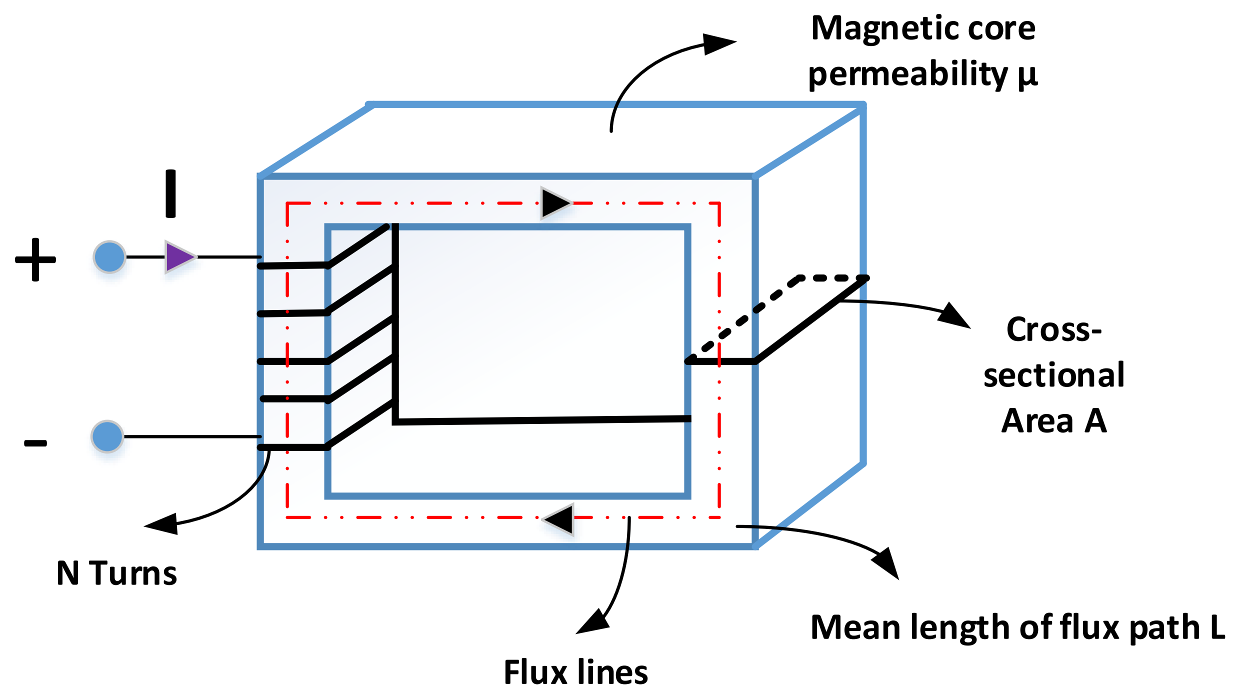
$$\digamma = \Phi\mathcal{R} = NI = HL$$

Where N is the number of turns of the coil that is producing the mmf, $\mathcal{R}$ is reluctance offered by the magnetic material to the flux path, H is the average magnitude of magnetizing force or magnetic flux intensity, L is the average length of the flux path.

The unit of H is At/m

Example:

For the magnetic circuit shown in figure, if Ni=40 At, and l is 0.2 m, find the magnetic field intensity H



Relationship between B and H

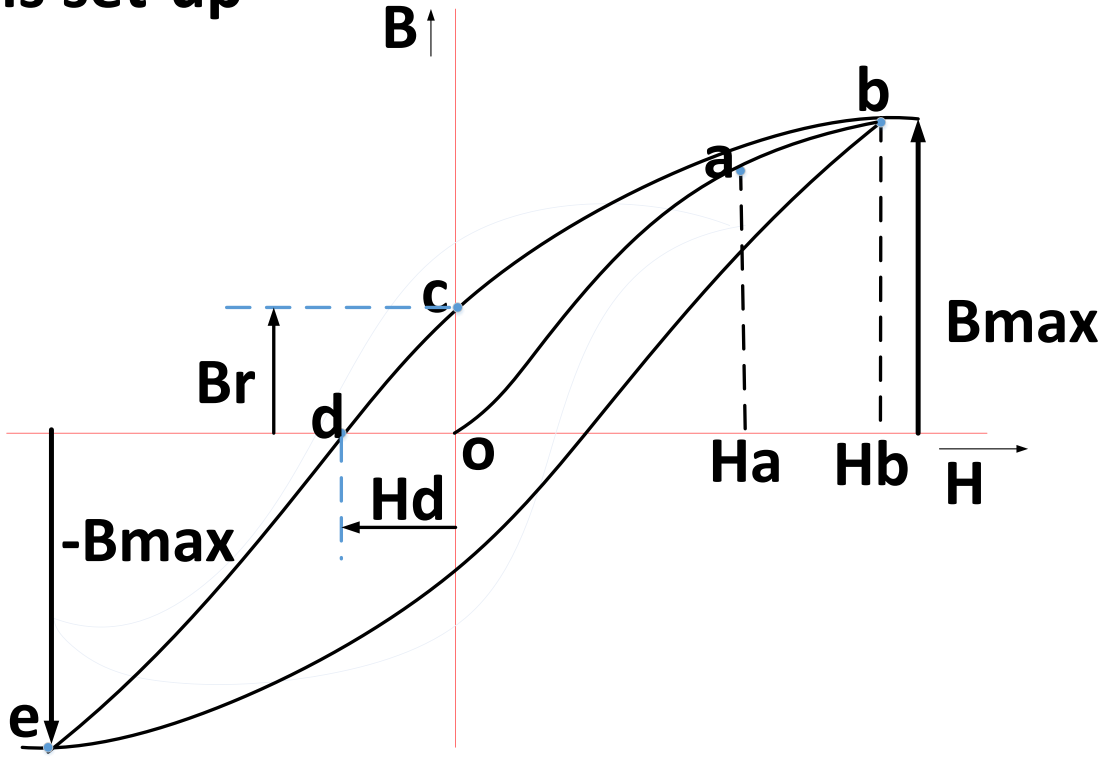
The relationship between B and H is a property of material in which it exists. It is represented as

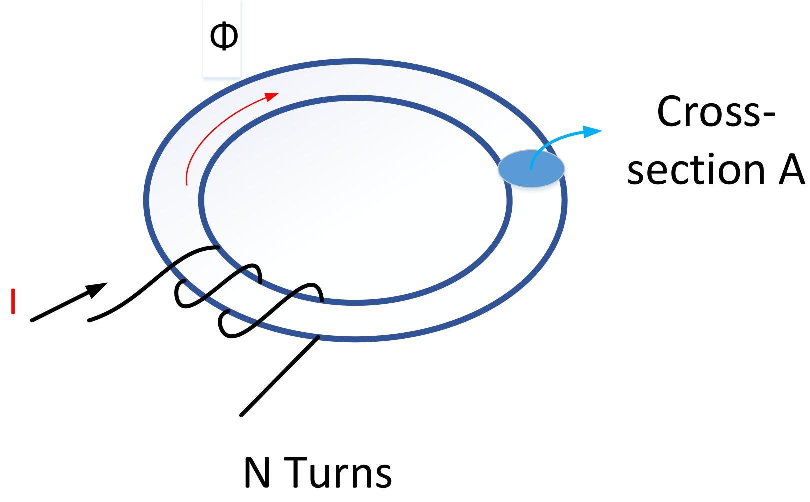
$$\boldsymbol{B} = \boldsymbol{\mu} H$$

The above relationship is not always linear, as μ changes with *H*

Hysteresis

A B-H curve of the material may be constructed using this set-up





- **Br is called residual flux and Hd called coercive force**

Hysteresis Loss

If a alternating voltage is connected to a magnetizing coil, the alternating mmf causes the magnetic domains to be continuously re-oriented along the magnetizing axis.

This molecular activity amounts to a power loss known as hysteresis loss, expressed as,

$$P_h = K_h f B_{max}^n$$

Where $P_h = $ **Hysteresis** loss **(Watt)**

f = Frequency of the flux wave

B_{max}**= Maximum value of flux density wave**

K_h**=Constant**

n= Steinmetz exponent

The value of K_h **depends on the magnetic characteristics of the material. Some typical values are: cast steel : 0.025, silicon sheet steel: 0.001, permalloy:0.0001. The value of n is also depends on the magnetic materials, and usually in the range [1.5, 2.5]**

Ampere's Circuital Laws

Magnetic	Electric
F, Magnetomotive Force	V, voltage or electromotive force
Φ, Flux	I, Current
$\mathcal{R}$, Reluctance	R, Resistance

In a magnetic circuit, the sum of the mmf's in a closed loop is zero, i.e.,

$$\sum_{loop} F = 0$$

The above equation is known as 'Ampere's Circuital Laws', which essentially says that the sum of mmf 'rises' is equal to the sum of the mmf 'drops' around a closed magnetic circuit loop.

Ampere's Circuital Laws (contd…)

The rise in mmf is given by the current multiplied by the number of turns, and mmf drops is given by the cyclic integral of H along with the complete loop. Hence,

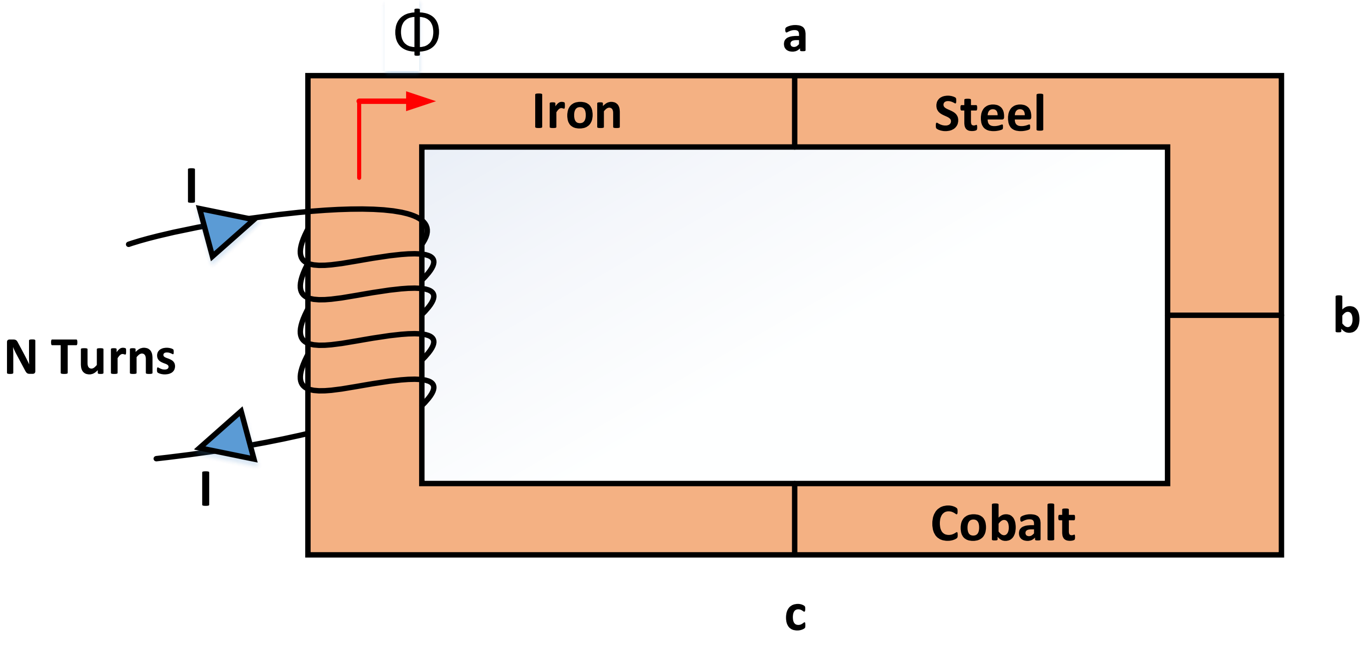
$$\oint \vec{H}.\overrightarrow{dl} = NI$$

$$\text{Or } H\, l = NI$$

Where H is the magnitude of $\vec{H}$ *and* l is the average length of the magnetic path.

Example 1

Consider magnetic circuit shown in figure. Apply ampere's circuital law.

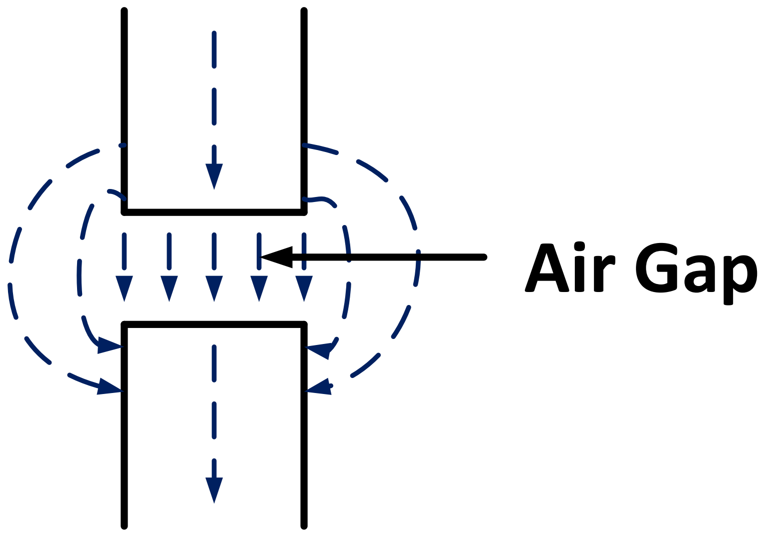


Magnetic Circuit with Air-gap

In rotating electric machines, the magnetic circuits are completed including air-gaps. Magnetic circuits with air-gaps are exists in practice.

The cross-section of magnetic flux path and the air-gap do not remains the same.

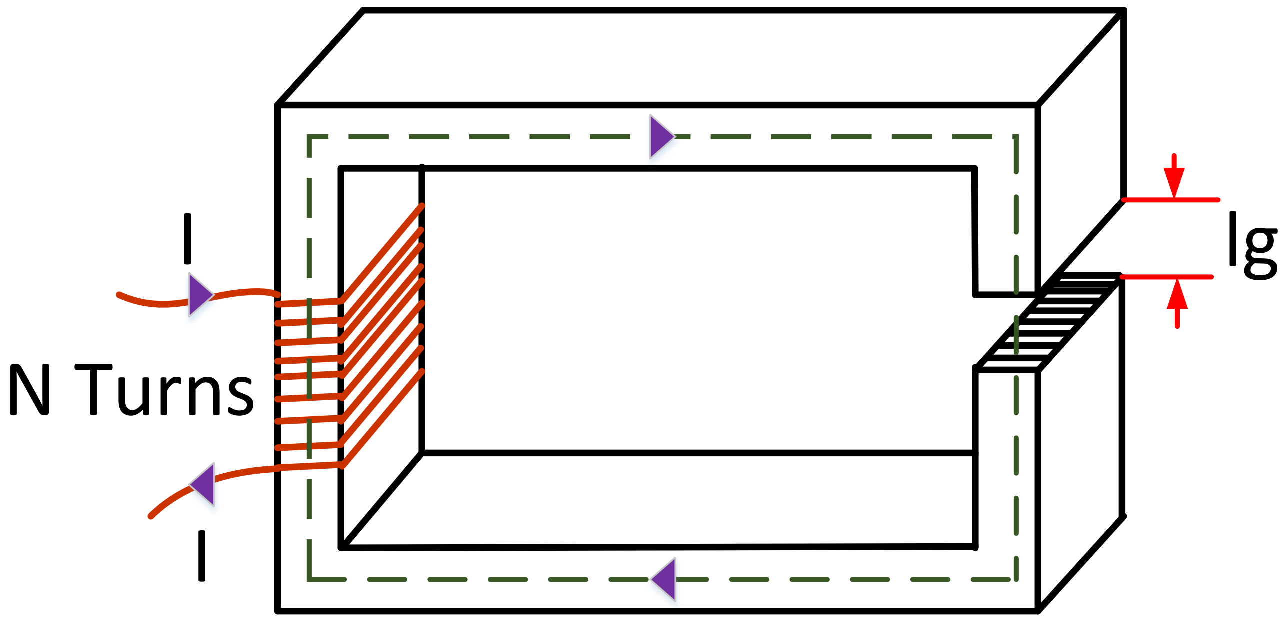
This is due to the spreading of the flux lines, known as fringing effect, as shown in figure.



Magnetic Circuit with Air-gap (contd..)

Figure shows a magnetic circuit with an air-gap.
l and lg are the mean length of the magnetic flux path in the core and air-gap respectively.
Ac and Ag are the cross-sectional area of the magnetic flux path in the core and air-gap respectively.
Let, Φ is the magnetic flux.

Flux density in the core, $B_C = \frac{\emptyset}{A_C}$



Magnetic Circuit with Air-gap (contd..)

Flux density in the air-gap, $B_g = \frac{\emptyset}{A_g}$

Applying ampere's circuital law, $F = NI = H_C l_C + H_g l_g$

Where H_C **and** H_g **are the mean values of H in the core and air-gap respectively. Using the relation between the flux density B and H, can be written as,**

$$F = \frac{B_C}{\mu} l_C + \frac{B_g}{\mu_0} l_g$$

Where the permeability of the core, μ, can be found from the B-H curve of the material, permeability of the air can be taken to be closely equal to the permeability of the free space, μ_0

Using the above equations, the following can be obtained, $F = \frac{\Phi l_C}{\mu A_C} + \frac{\Phi l_g}{\mu A_g} = \Phi\left(\frac{l_C}{\mu A_C} + \frac{l_g}{\mu A_g}\right)$

$$= \Phi\left(R_e + R_g\right)$$

Example 1

Find the value if I required to produce a magnetic flux of $\Phi = 0.75\times10^{-4}\,wb$ in the magnetic circuit made of cast steel, as shown in Figure.

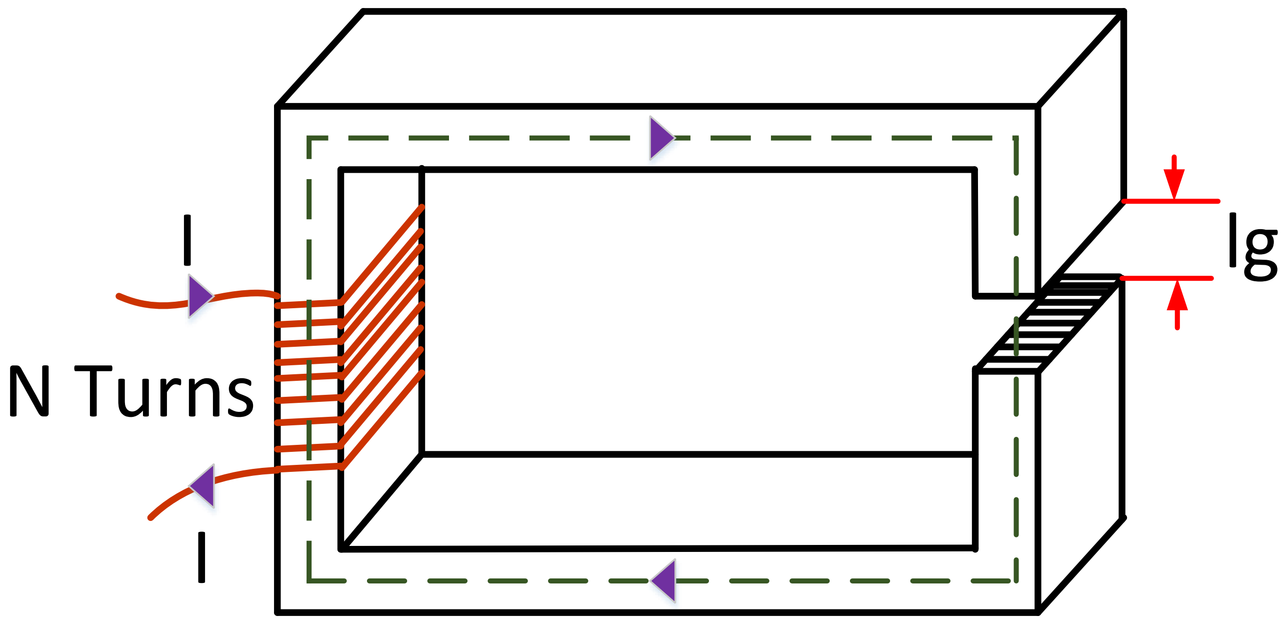
$N = 200$ Turns

$A_C = A_g = 1.15\times10^{-4}$ m^2

$l_C = 100\times10^{-3}$ m

$l_g = 2\times10^{-3}$ m

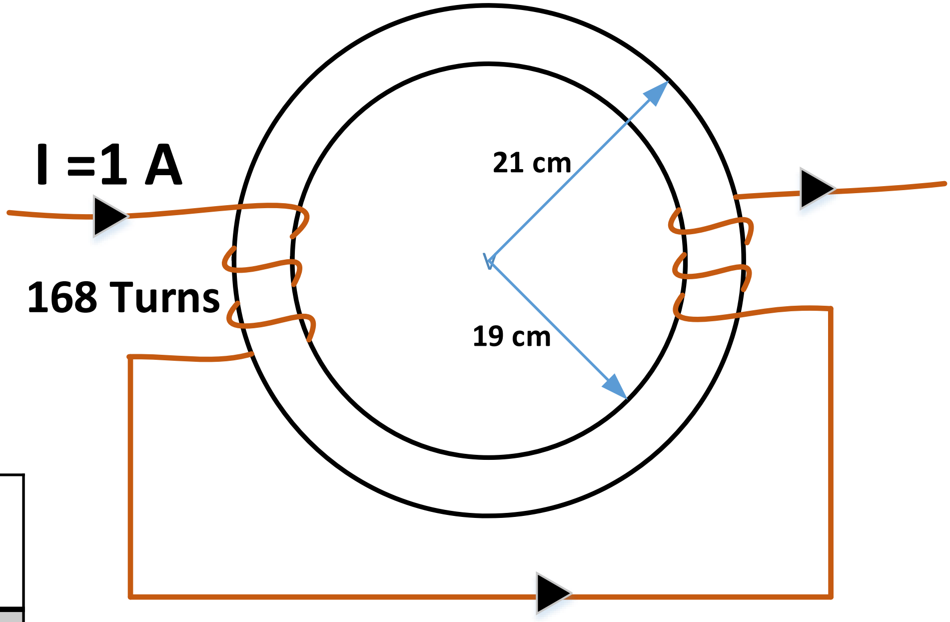
$\mu_C = 17.857\times10^{-4}$



Example 2

Two coils are wound on a toroidal core as shown in the Figure. The core is made of silicon steel for which the B-H data is given below.

The cross-section of the core is square. The coil current is 1 A.



H (At/m)	100	150	200	300	400	450	700
B (T)	0.7	0.9	1.00	1.12	1.20	1.25	1.30

Example (Contd..)

(a) Determine the flux density at the mean radius of the core.

(b) Flux in the core.

(c) The relative permeability μ_r of the core