Magnetic Circuit

Magnetic Flux

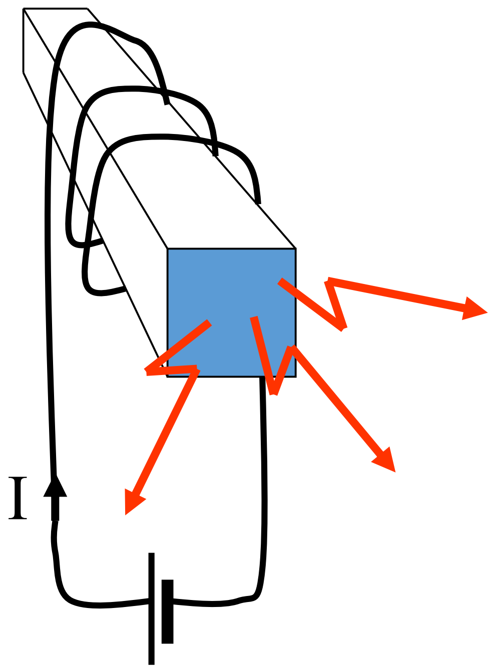
Magnetic Effects of Electric Current

Magnetic Circuit

B-H Curves

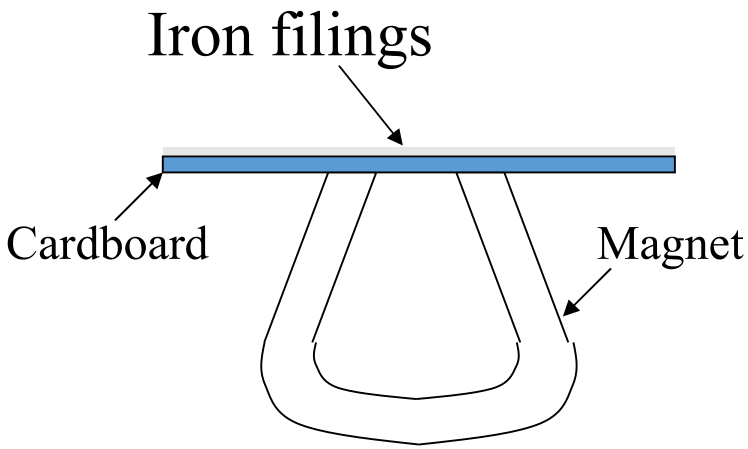
Calculations

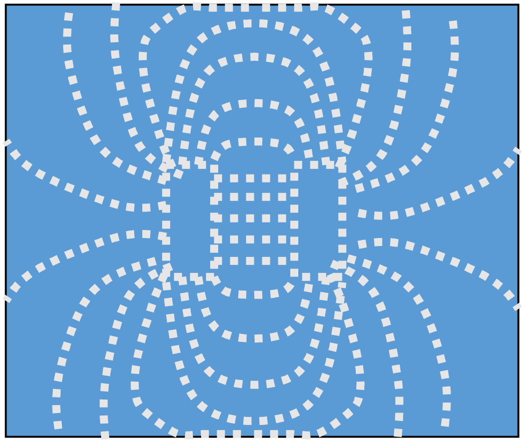
What is a Magnet?



- A coil of wire carrying an electric current can be used to magnetise a piece of iron or steel
- A magnetised piece of iron or steel will attract other pieces of iron or steel
- This property of iron or steel to attract other items of iron or steel is called magnetism
    - A material that displays magnetism is called a magnet

Magnetic Field

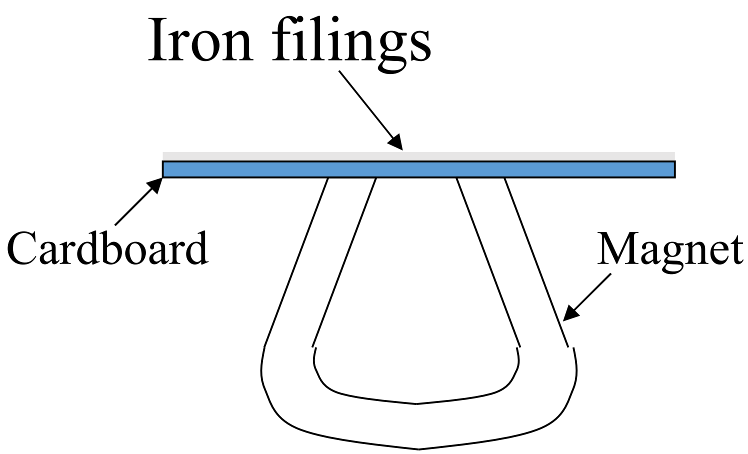


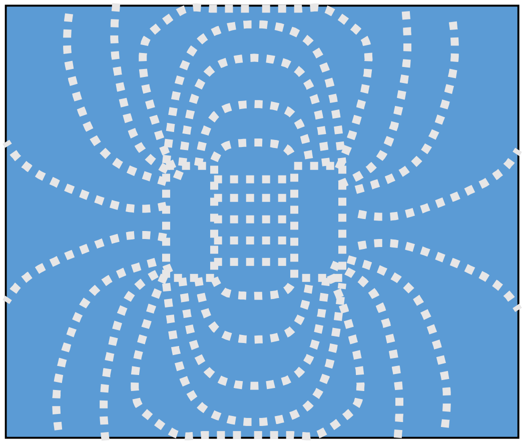


Pattern of iron filings

- Sprinkle iron filings on cardboard and then place a horseshoe magnet under the cardboard:
  - Iron filings line up in a peculiar pattern
    - The shape of the pattern will depend on how the magnet is placed under the cardboard
- The iron filings appear to assemble in **lines**

Magnetic Field



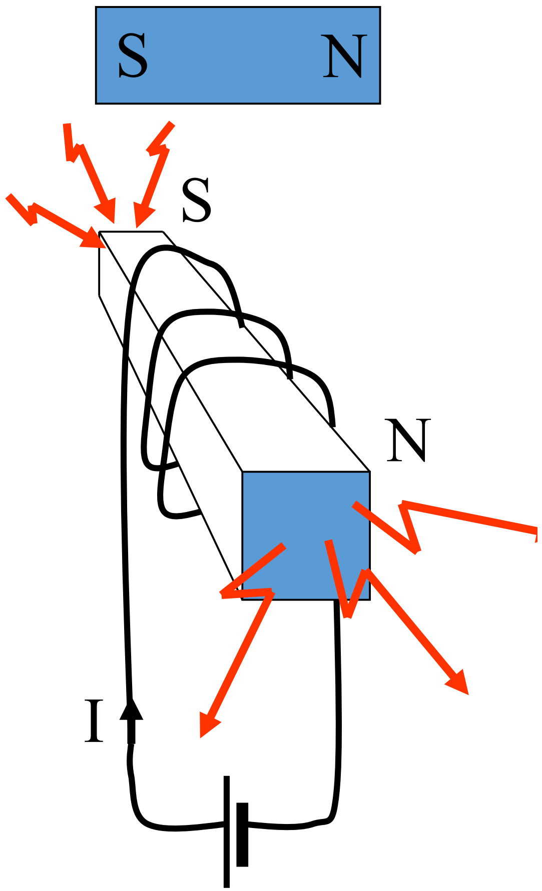


Pattern of iron filings

- The iron filings assembled in lines gives rise to the concept of **magnetic lines of force**
- The pattern of magnetic lines of force is called a **magnetic field**

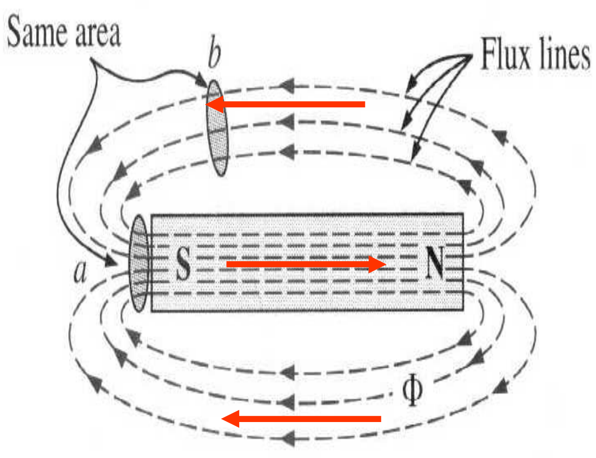
Magnetic Poles

- A bar magnet is has two **poles**
  - North pole
  - South pole
- A north pole must always have an accompanying south pole
  - This is known as a magnetic **dipole**



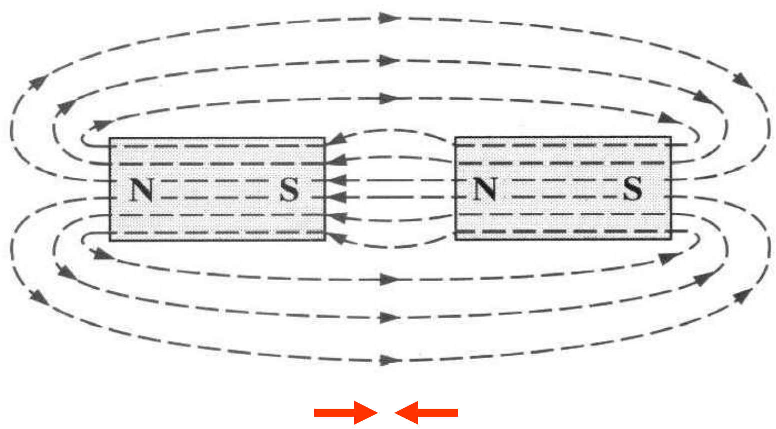
Magnetic Flux

- Magnetic lines of force are visualised as flowing through the space surrounding a magnet
  - Magnetic lines of force are also known as **magnetic flux lines**
    - Flux = flow of lines
- **Magnetic flux lines always form closed loops**
- Magnetic flux lines come out of the north pole and go into the south pole and back to the north pole
  - **North** → **South**



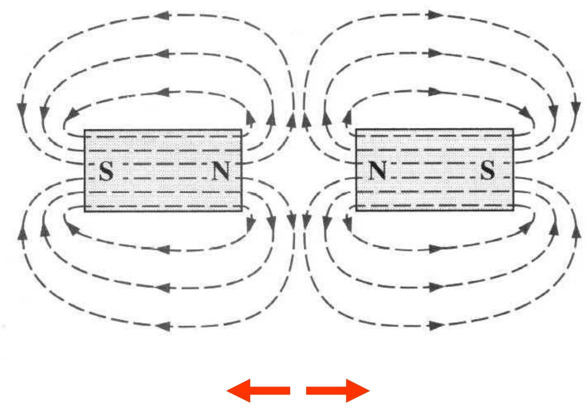
Attraction Between Unlike Poles

- When **unlike poles** of two magnets are placed close together there will be a force of **attraction** between them
- The flux lines **join** to be **continuous** between the the unlike poles of the two magnets

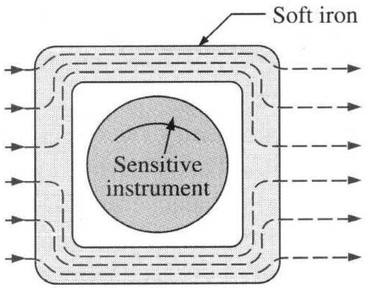


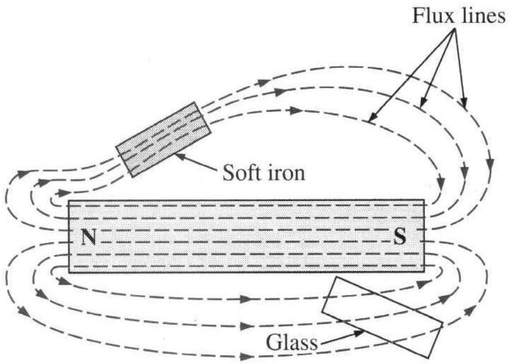
Repulsion Between Like Poles

- When **like** poles of two magnets are placed close together there will be a force of **repulsion** between them
- The flux lines will **not be continuous** between the like poles of the two magnets

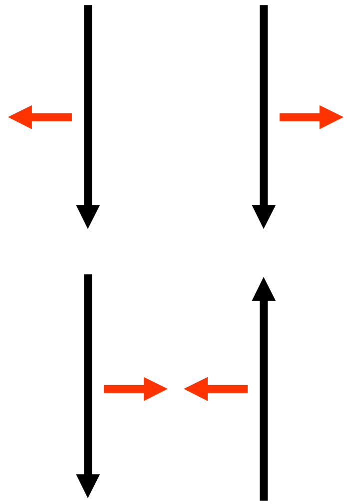


Additional Properties of Magnetic Flux Lines



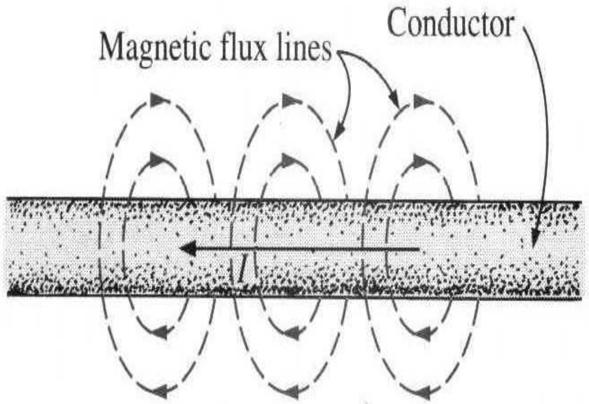


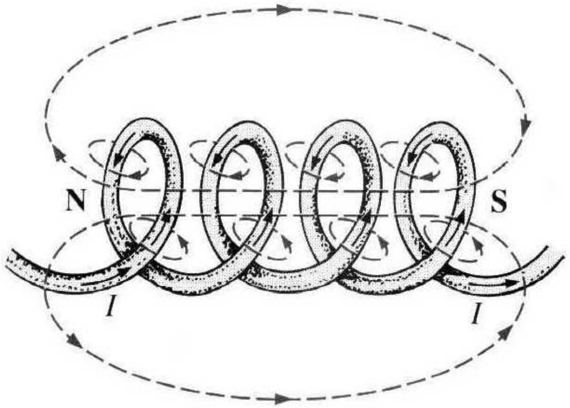
- Flux lines **never** cross
- Flux lines follow the path of **least resistance**
  - Magnetic materials will distort the magnetic field
- Flux lines in the **same** direction **repel** each other
- Flux lines in the **opposite** directions **attract** each other

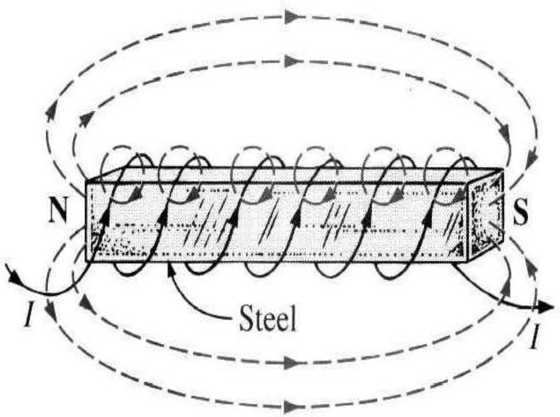


Magnetic Effects of Electric Current

- A conductor carrying an electric current will be surrounded by a magnetic field
- A conductor may be wound into a **coil** to increase the strength of the magnetic field
- An **iron core** placed inside the coil will greatly increase the strength magnetic field







Flux Density

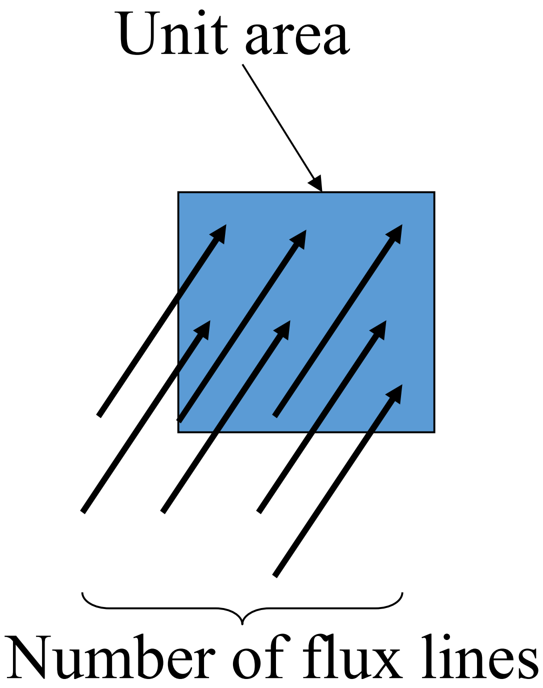
- The strength of a magnetic field is given by **flux density B**
  - Flux density **B** is the number of (imaginary) flux lines Φ passing though a unit area **A**

$$\mathbf{B = \Phi / A}$$

B = Tesla (T)

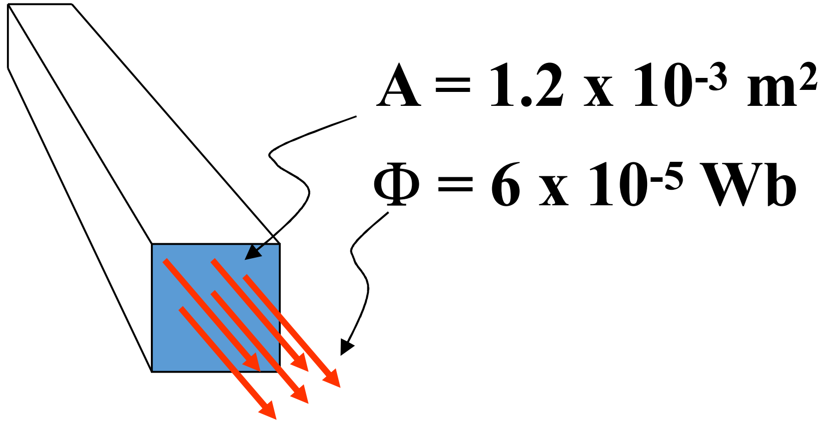
Φ = Weber (Wb)

A = square metres (m^2)



Calculation

- For the values of flux Φ and area A calculate the flux density B

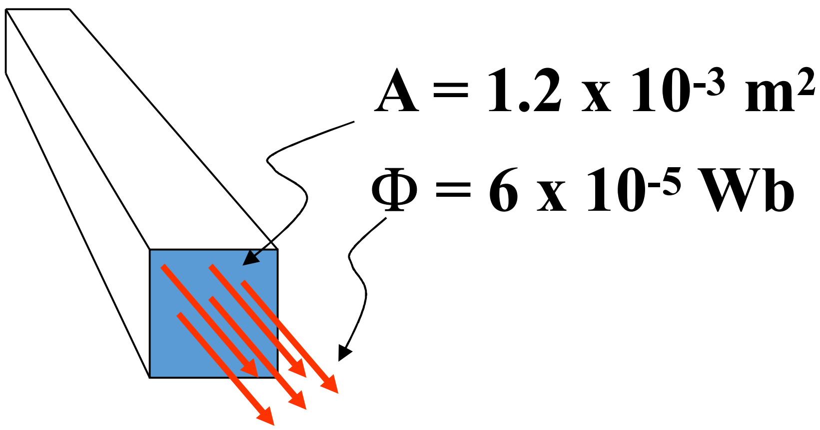


Solution

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

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

$$= 5 \times 10^{-2}\ \text{T}$$



Permeability

- To permeate means to penetrate or pass through
- The permeability of a magnetic material is a measure of how easy it is for a magnetic field to pass through it.
  - Iron has a very high permeability
    - It is easy for magnetic flux to pass through it
  - Air has a low permeability
    - It is hard for magnetic flux to pass through it

Permeability

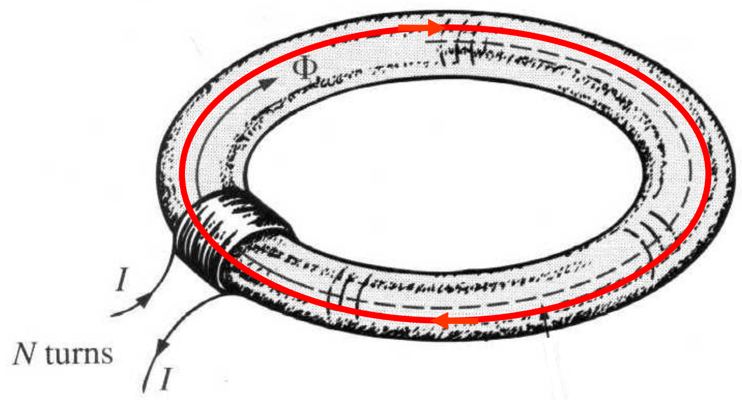
- The permeability of a material is given the Greek symbol μ
- Permeability of free space:

  $\mu_0 = 4\Pi \times 10^{-7}$ Wb/(At.m)
- Relative permeability is the permeability of the material compared to the permeability of free space:

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

Magnetic Circuit

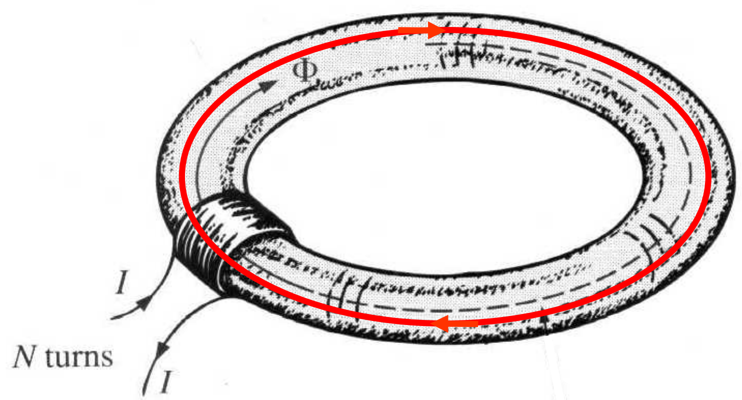
- A complete magnetic **loop** is known as a **magnetic circuit**



MagnetoMotive Force MMF

- A magnetomotive force (MMF) is required to propel magnetic flux around a loop
  - Compare this to EMF in an electric circuit
- MMF = number of current loops (turns of wire) multiplied by the current in the wire

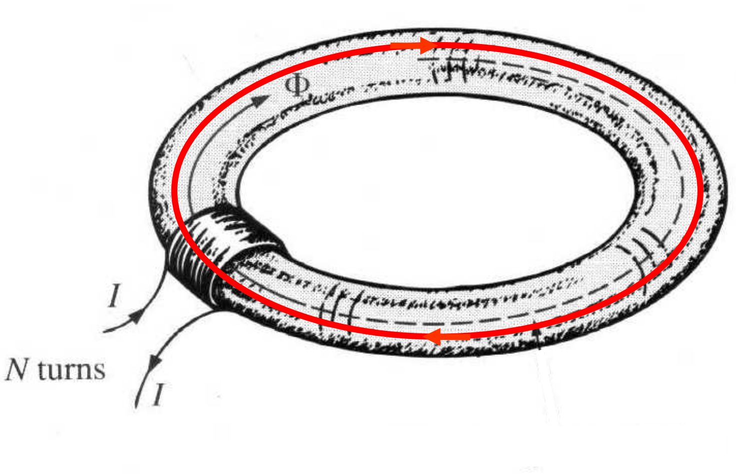
$\mathbf{MMF = NI}$ ampere turns (At)



Calculation

- Calculate the MMF for the magnetic circuit below

N = 100
I = 5A



Solution

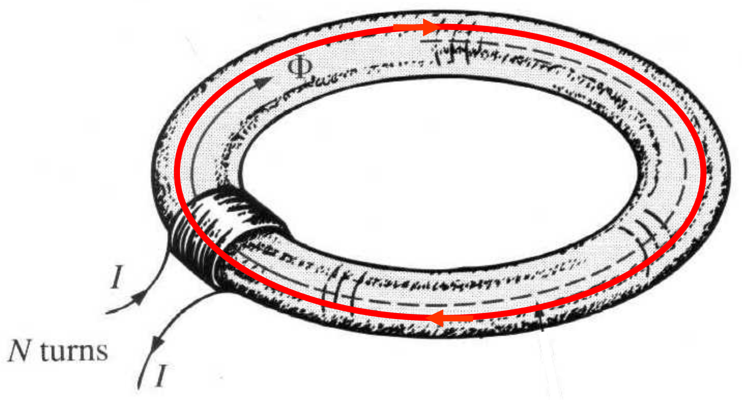
- MMF = NI (At)

  = 100t x 5A

  = 500At

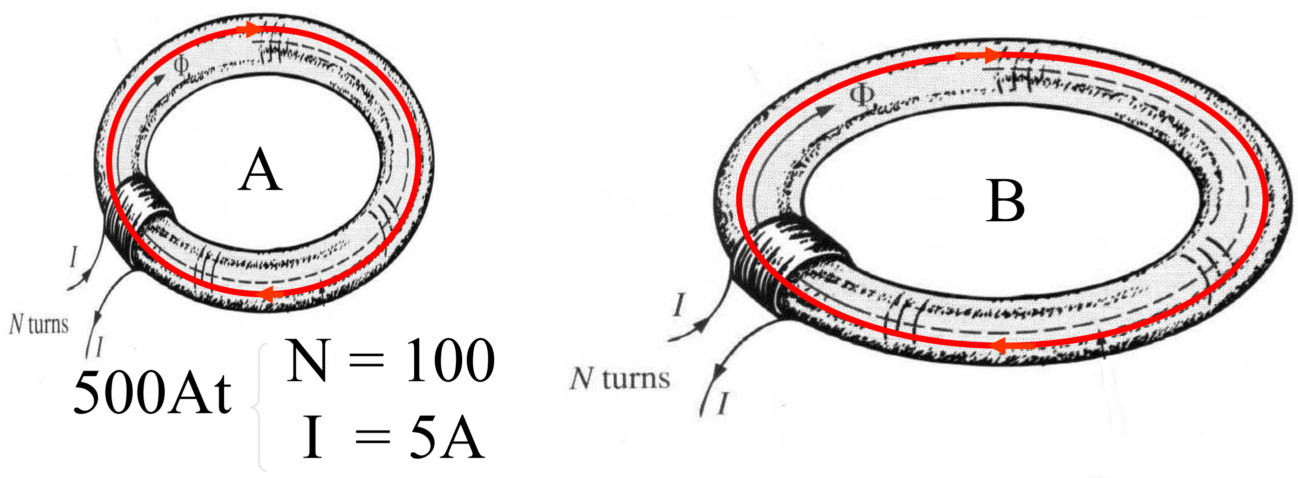
N = 100

I = 5A



Magnetising Force H

- Imagine two magnetic circuits each with the same MMF (say 500At)
  - The loop length of circuit A is shorter than the loop length of circuit B - **flux travels a shorter distance**
  - The MMF **per unit length** over the loop will be greater for A than B
  - The **field strength** will be **greater** in A than B



Magnetising Force H

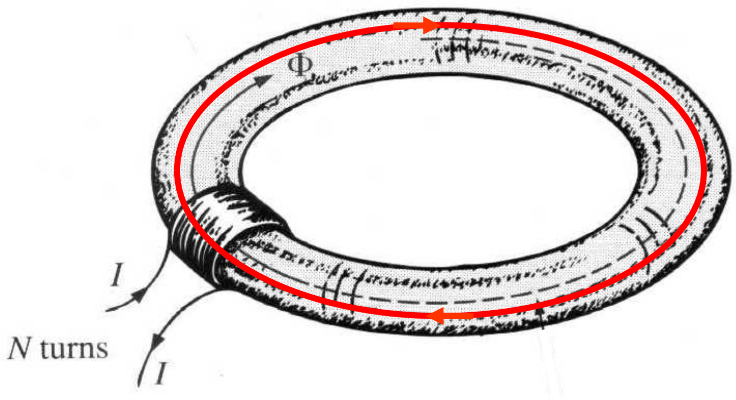
- **Magnetising force** takes into account the **loop length** l as well as the MMF
- Magnetising Force is given the symbol H **H = MMF/length**

$$\mathbf{H} = \frac{\mathbf{NI}}{l}$$

I = current (A)
N = turns (t)
l = length of magnetic circuit (m)

Calculation

- Calculate H for the magnetic circuit below:



N = 100
I = 5A
mean length = 0.2m

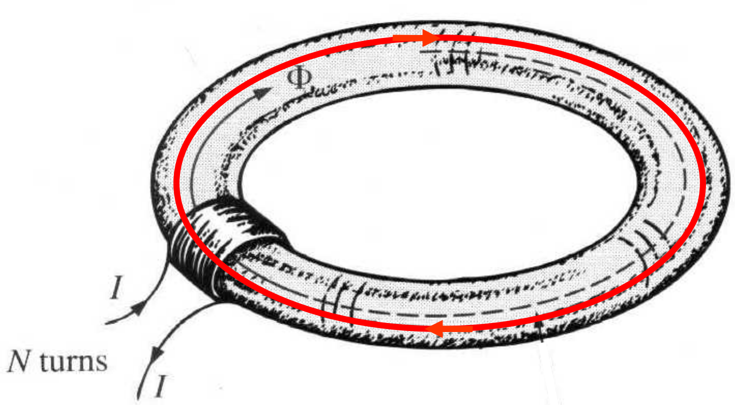
Solution

- $H = NI / l$ (At/m)

  = 100t x 5A / 0.2

  = 500 / 0.2

  = 2500 At/m



N = 100

I = 5A

mean length = 0.2m

B versus H for Non Magnetic Materials

- Magnetising force H propels the magnetic flux around the circuit
- The larger the H the stronger (denser) the flux
- For a **vacuum** and (approx) for **non magnetic** materials:

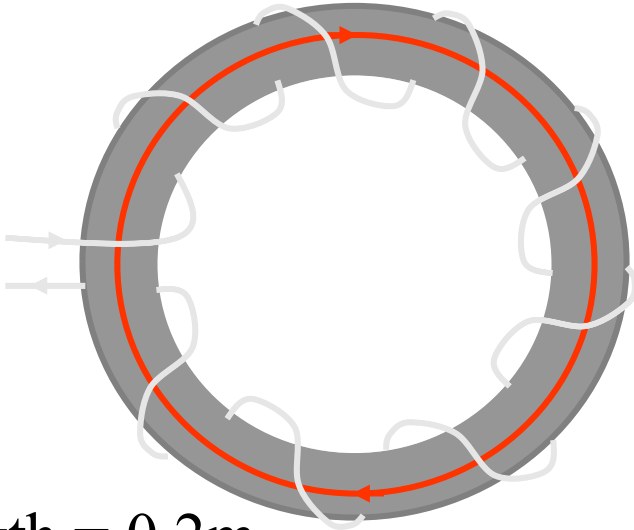
  $\mathbf{B = \mu_0 H}$

  $\mu_0 = 4\Pi \times 10^{-7}$ Wb/(At.m)

Calculation

- Calculate the flux density B and the flux Φ in the wooden ring below.

  Assume $\mu_{wood} = \mu_0 = 4\Pi \times 10^{-7}$



$N = 100$
$I = 5A$
Mean length = 0.2m
Area = 0.05m^2

Solution

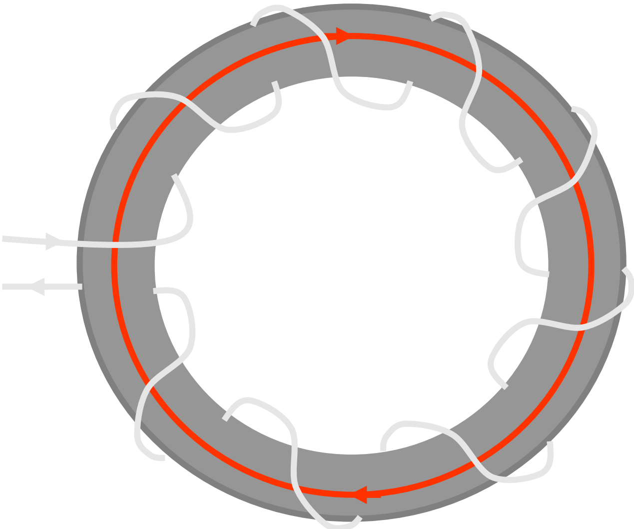
- $B = \mu_0 H$ (T)

  $= \mu_0 NI / l$

  $= 4\Pi \times 10^{-7} \times 100 \times 5 / 0.2$

  $= 0.00314$ T

  $= 3.14$mT



$B = \Phi / A$

$\Phi = BA$ (Wb)

$= 3.14 \times 10^{-3} \times 5 \times 10^{-2}$

$= 1.57 \times 10^{-4}$

$= 157\ \mu$Wb

N = 100

I = 5A

Mean length = 0.2m

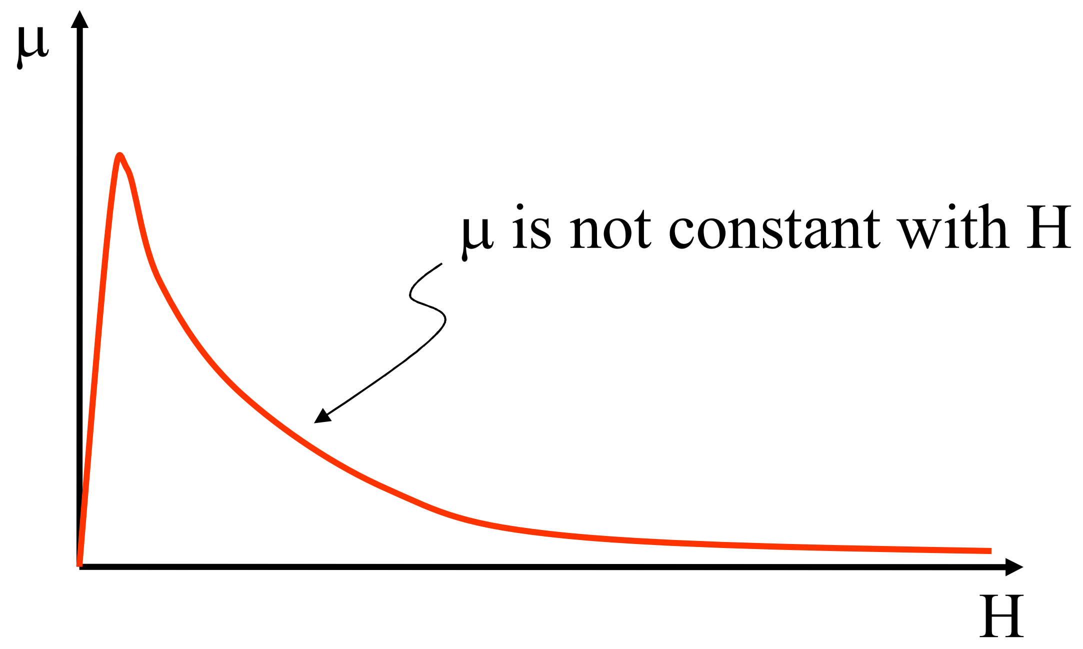
Area = 0.05m^2

B versus H

- **B = μH**

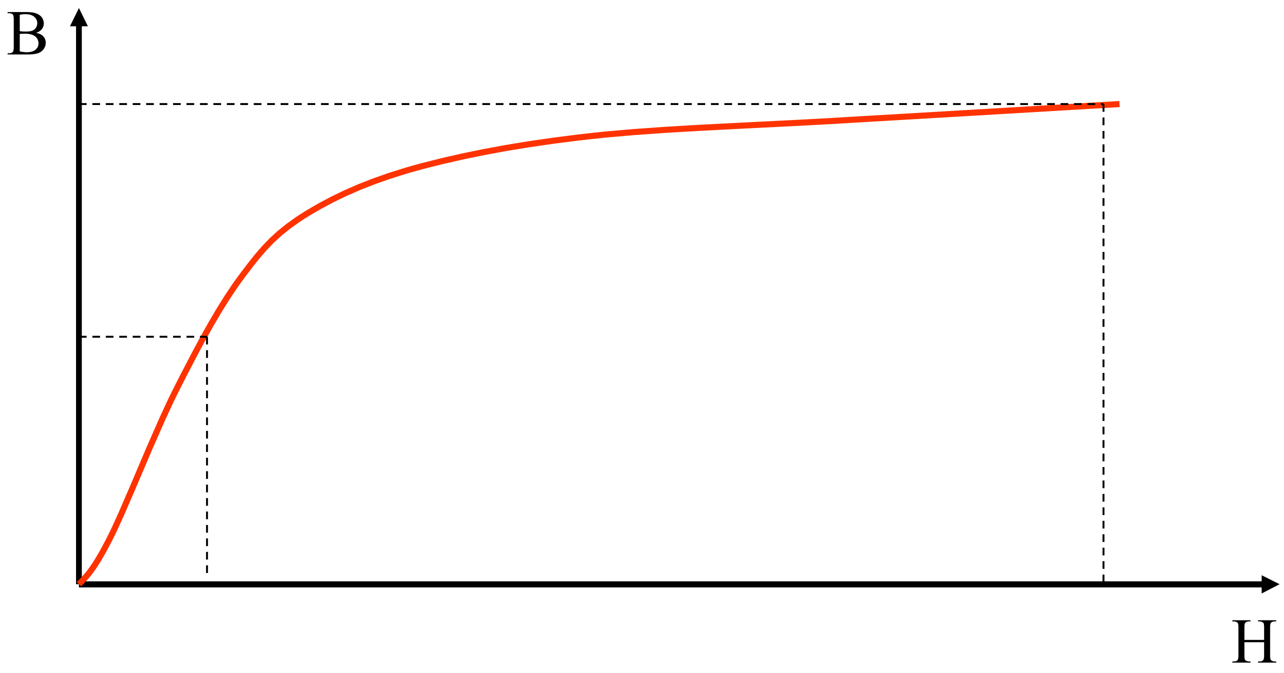
  Important: μ is not constant for magnetic materials

  - Magnetic materials exhibit a phenomenon known as **saturation**



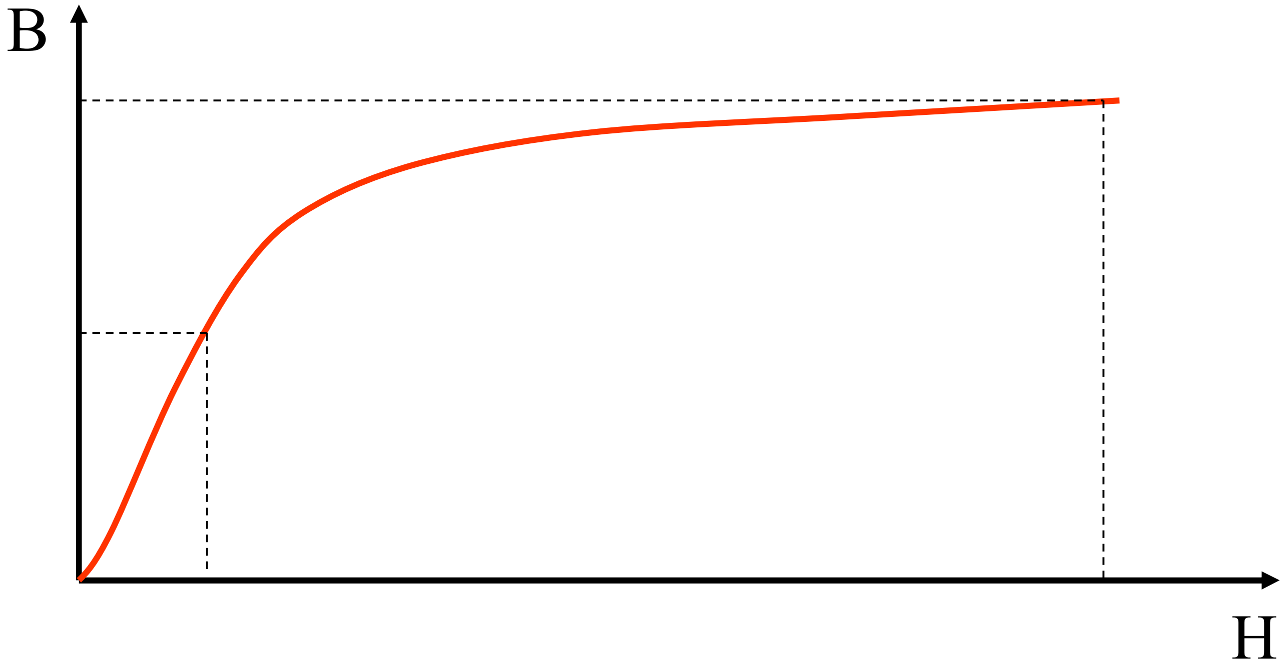
Graphical Solution Using B-H Curves

- Because μ **is not a constant for magnetic materials** the relationship $B = \mu H$ cannot be used for calculations with magnetic materials
- The solution is obtained **graphically**



Magnetising Ferro Magnetic Materials

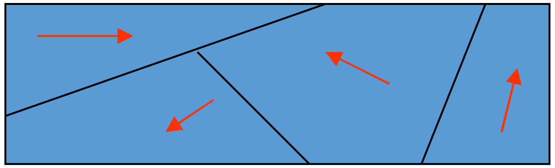
- A ferro magnetic material is an alloy of the element iron and other elements such as nickel and cobalt.
- Ferro magnetic materials exhibit a non linear magnetisation (B-H) curve



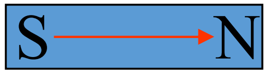
Domain Theory of Magnetisation

- An electron spinning around a nucleus produces a magnetic field
- In most elements the electron spins are randomly aligned resulting in a zero net magnetic field
- In ferro magnetic materials the magnetic fields of atoms are aligned in groups
    - These groups are called **domains**
- The domains themselves are randomly aligned resulting in a zero net magnetic field
- An external MMF can be used to align the domains
    - Aligned domains produce a strong magnetic field

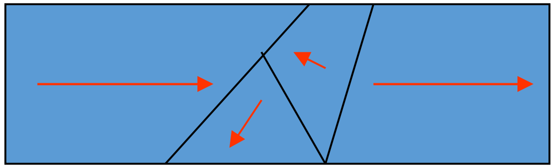
Domain Theory of Magnetisation



Non magnetised material



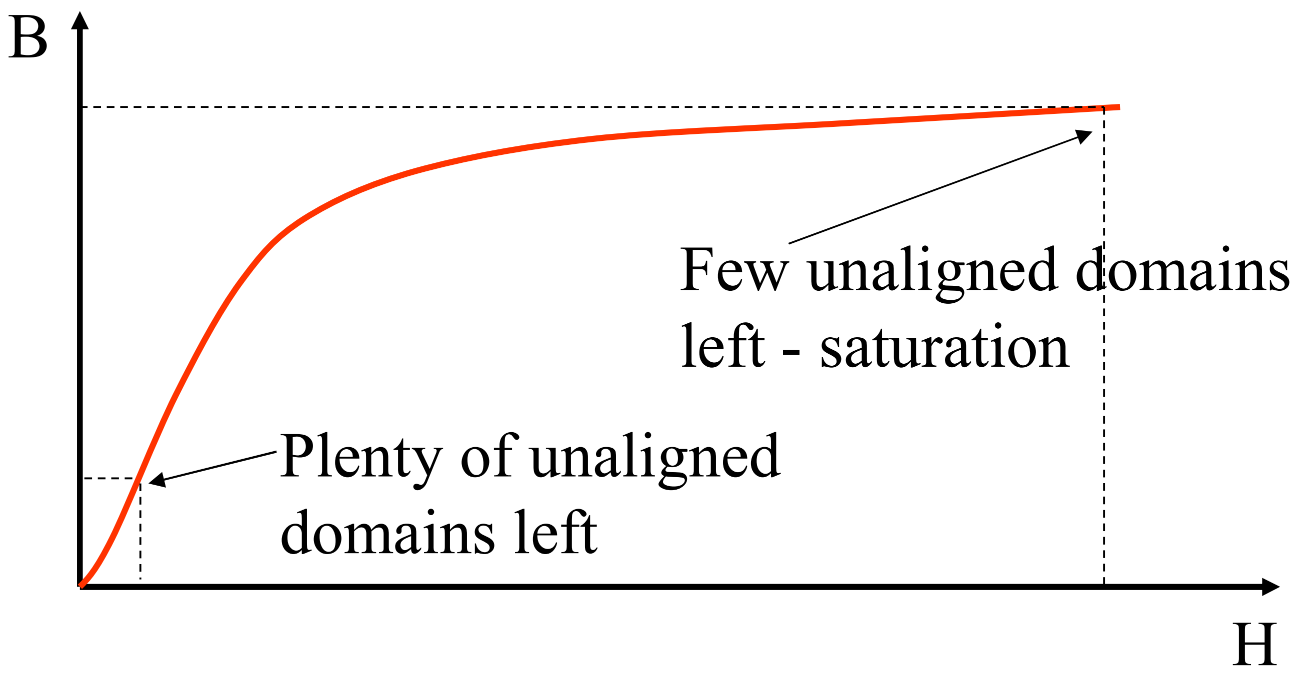
External magnet

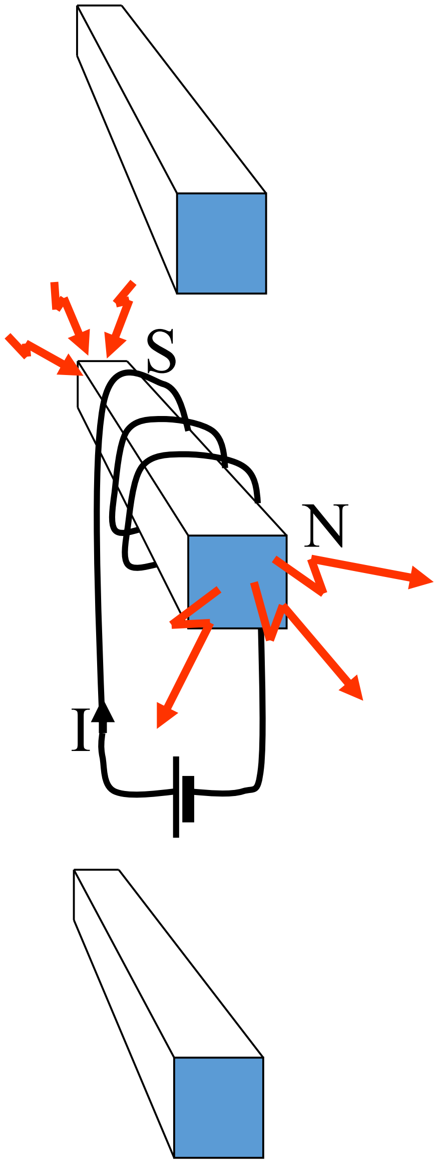


Material magnetised by external magnetic field

Domain Theory of Magnetisation

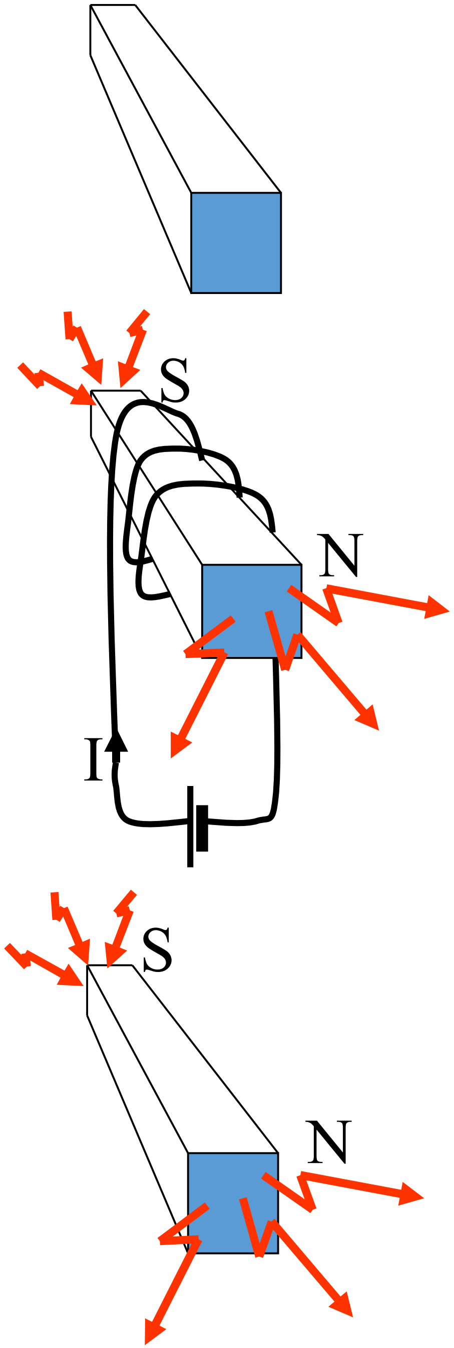
- Magnetic field strength B increases as more domains become aligned
- Once **all** the domains are aligned the can be no more increase in B no matter how much the magnetising force H increases
- The phenomenon is known as **saturation**





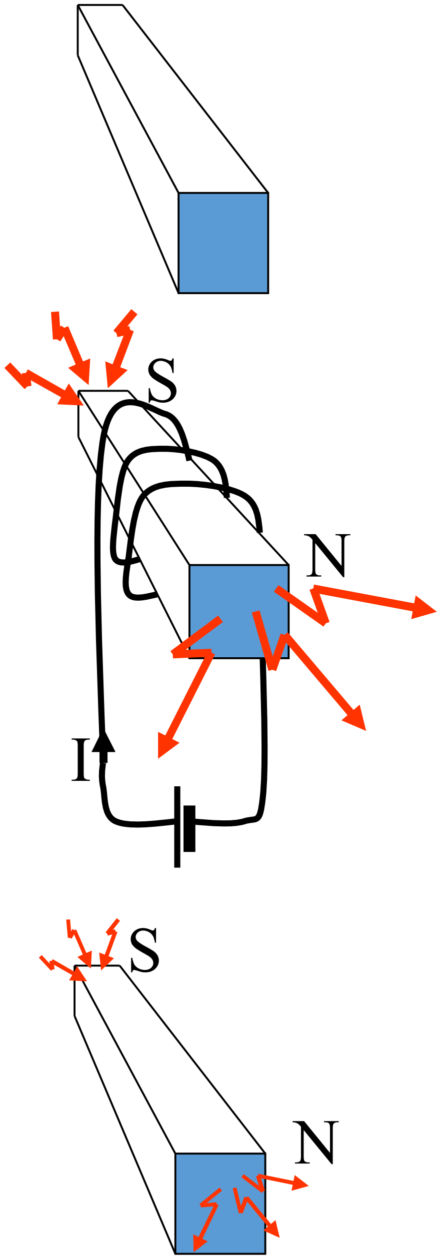
Electromagnets

- Coil of wire wound onto a core of **non magnetised** ferro magnetic material
- Current is passed through the coil
- Ferro magnetic core becomes magnetised
- When current is removed ferro magnetic core is no longer magnetised
    - **Magnetism is not retained**



Permanent Magnets

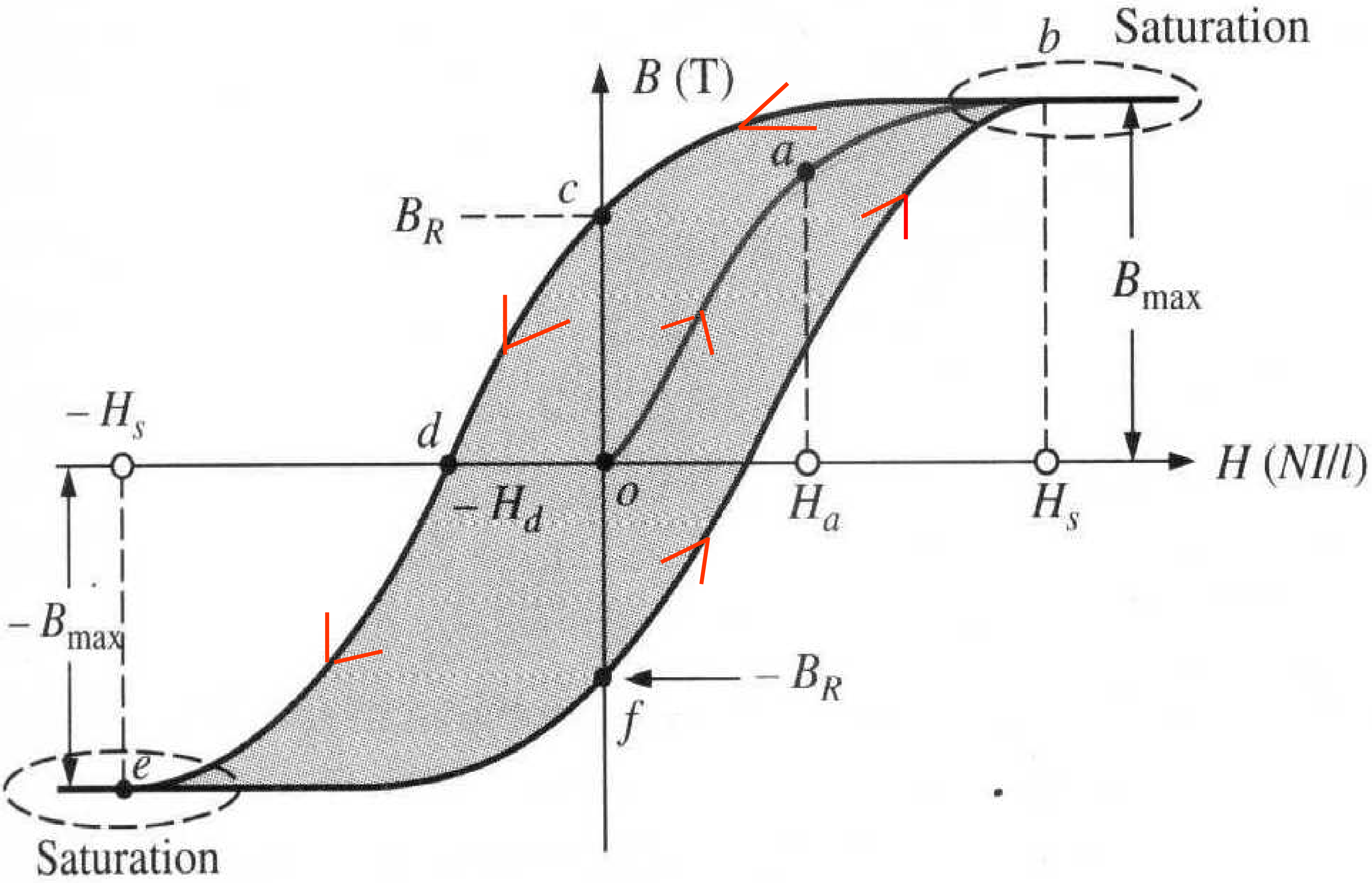
- Coil of wire wound onto a core of **non magnetised** ferro magnetic material
- Current is passed through the coil
- Ferro magnetic core becomes magnetised
- When current is removed ferro magnetic core remains magnetised
    - **A permanent magnet has been created**



Hysteresis

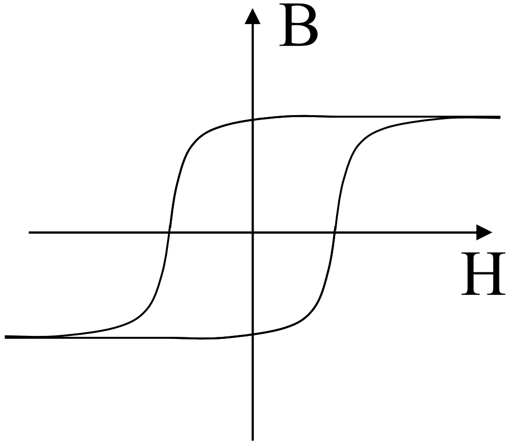
- When an non-magnetised magnetic material is placed in a magnetic field it becomes magnetised
- When the external field is removed the originally non-magnetised material retains some permanent magnetism
- **An external magnetic field has to be applied in the opposite direction to remove the residual magnetism**

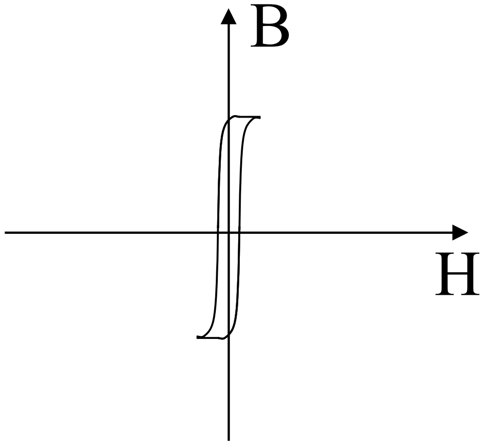
Hysteresis



Saturation
b
B (T)
a
c
B_R
B_{max}
$-H_s$
d
o
$-H_d$
H_a
H_s
H (NI/l)
$-B_{max}$
$-B_R$
f
e
Saturation

Choice of Magnetic Materials

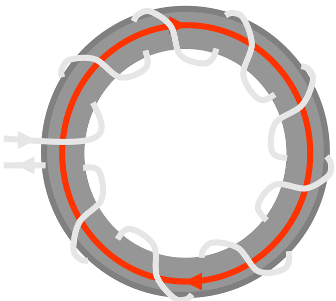




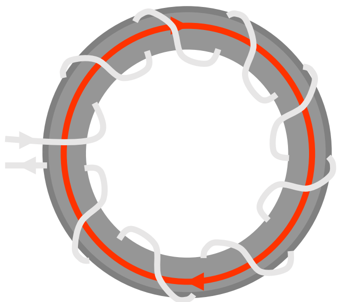
- Magnetic materials are chosen for applications based on their hysteresis curve
- Permanent magnets need materials with a very broad hysteresis curve
- Transformer cores need materials with a very narrow hysteresis curve
  - Energy losses are proportional to width of curve

Types of Calculations

- In this course you will be required to perform calculations on two types of materials:
  - Non magnetic
    Use **B** **=** μ_0**H**
  - Magnetic
    Use **B-H** graph

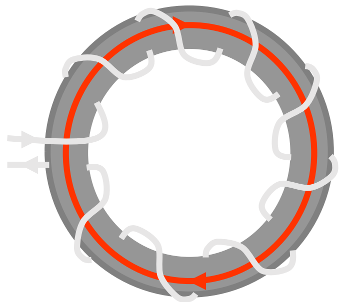


Wood

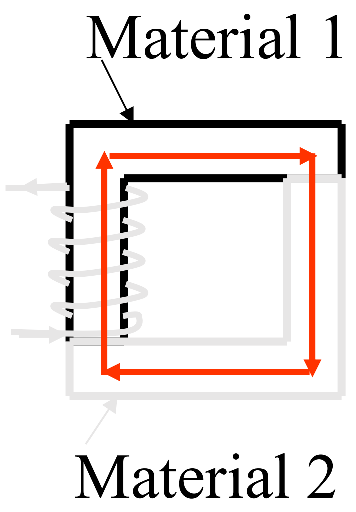


Cast iron

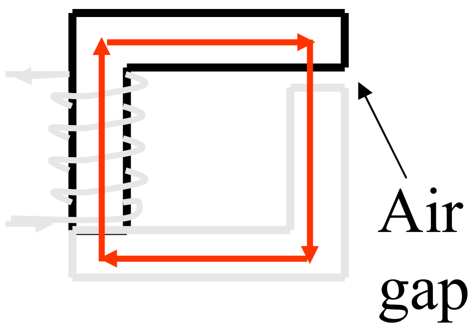
Calculations on Magnetic Materials



- In this course you will be required to perform calculations on magnetic circuits consisting of:
  - **One** type of magnetic material
  - **Two or more** types of magnetic material in the one magnetic circuit



- **Make yourself thoroughly familiar with the requirements and approaches for each type of circuit**



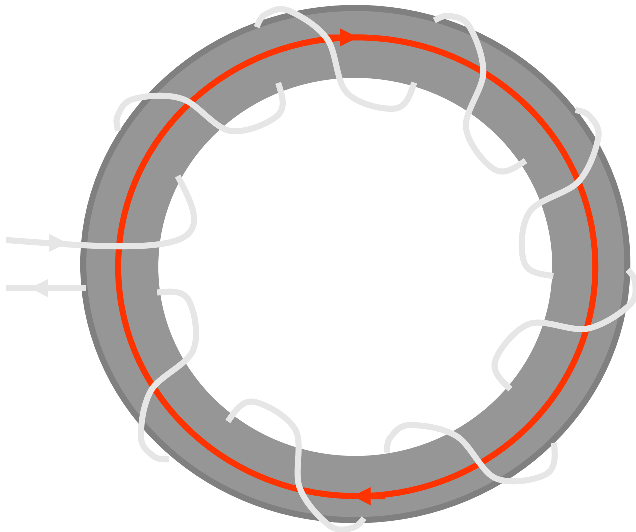
Calculation - B is Known
B to H

- Using B-H graphs calculate the value of current to establish a flux density of 0.3T if the ring is made of:
  - Cast iron
  - Cast steel
  - Sheet steel

$N = 100$

$I?$

Mean length = 0.2m

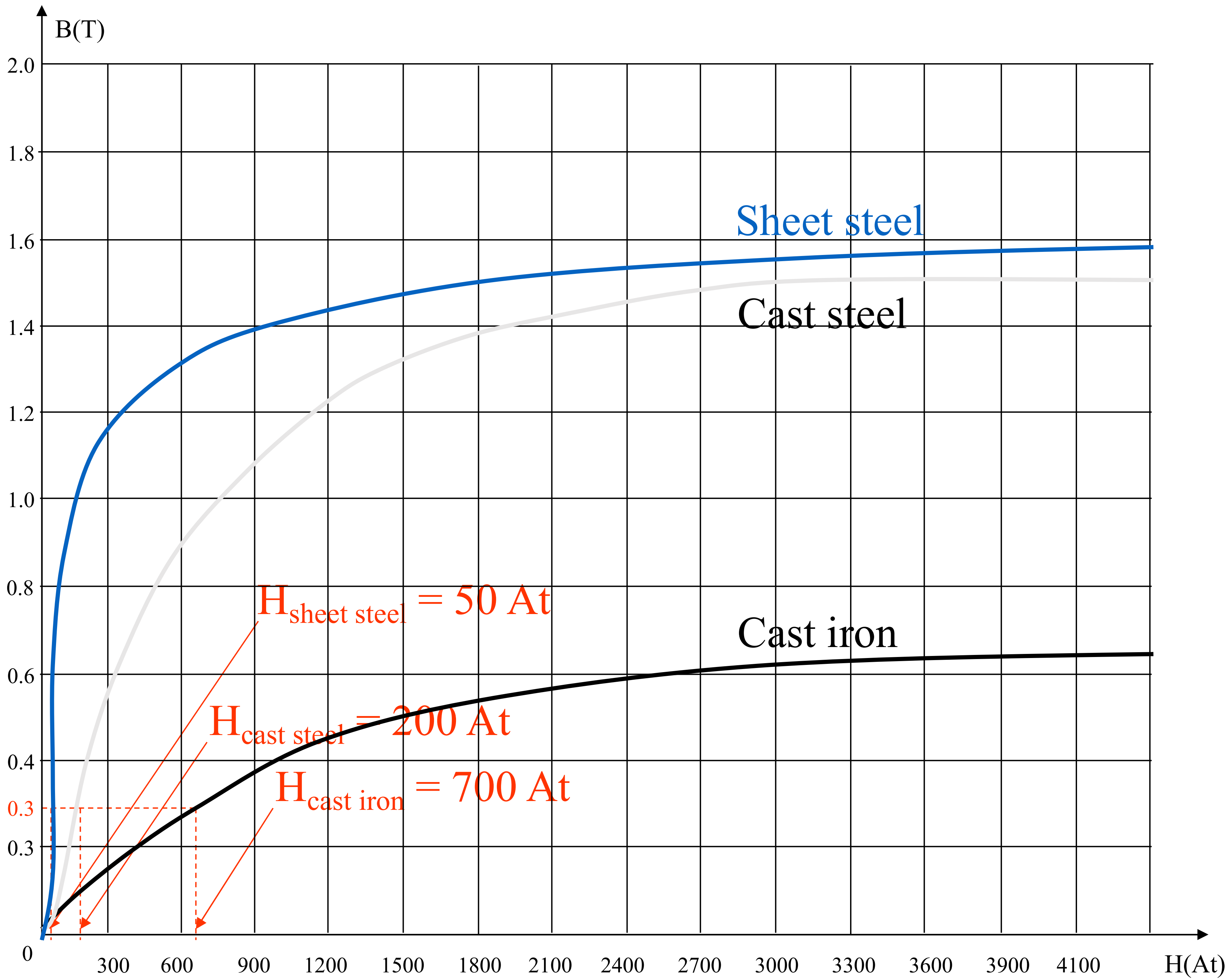


Solution

- On the B-H curve draw a horizontal line at B = 0.3T. Drop vertical projections where the B = 0.3T crosses each of the sheet steel, cast steel and cast iron graphs

- Transposing $H = NI / l$ solve for I

  $I = Hl / N$


B(T)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.3
0.3
0
300
600
900
1200
1500
1800
2100
2400
2700
3000
3300
3600
3900
4100
H(At)
Sheet steel
Cast steel
Cast iron
$H_{sheet\ steel} = 50$ At
$H_{cast\ steel} = 200$ At
$H_{cast\ iron} = 700$ At

Solution

- From the graph (use expanded graph for greater accuracy):
  - $H_{\text{cast iron}}$ = 700 At
  - $H_{\text{cast steel}}$ = 200 At
  - $H_{\text{shhet steel}}$ = 50 At
- $I_{\text{cast iron}} = Hl \;/ N$

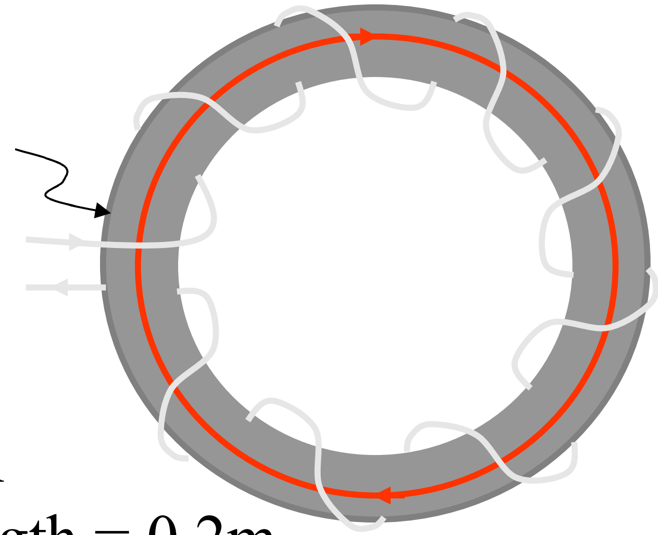
  $= 700 \times 0.2 / 100$

  $= 1.4A$

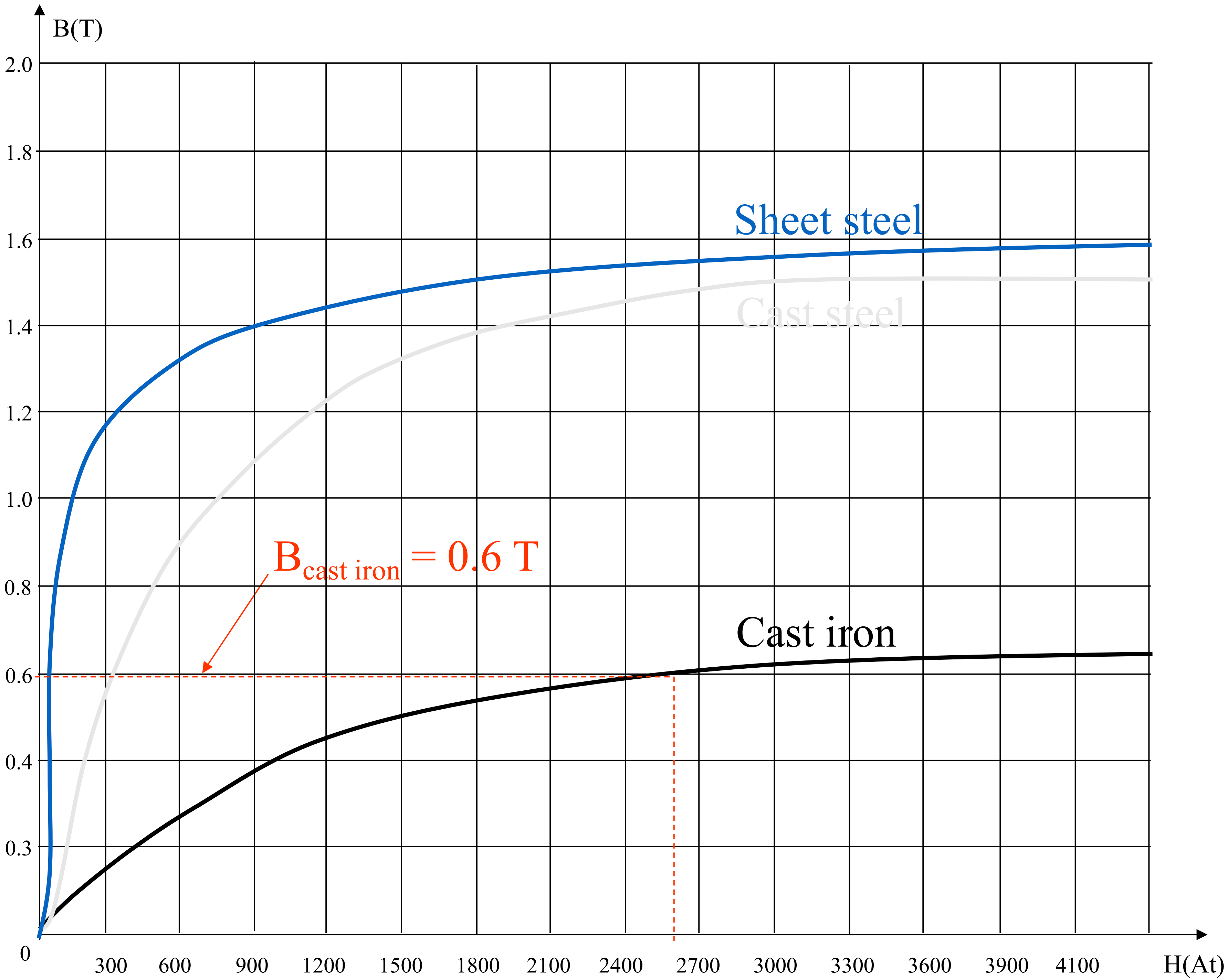
Calculation of Flux if MMF is Known - H to B

- Calculate the flux in the toroid for the values and material given

Cast iron

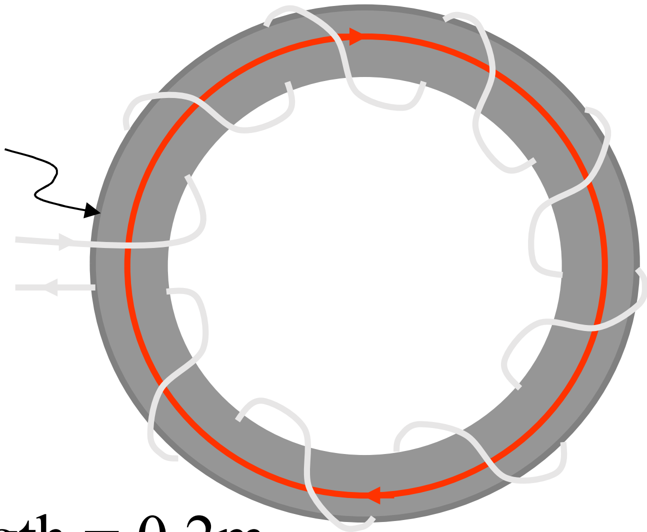


N = 100
I = 5.2A
Mean length = 0.2m
Area = 0.05m^2


B(T)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.3
0
Sheet steel
Cast steel
$B_{cast\ iron} = 0.6$ T
Cast iron
300
600
900
1200
1500
1800
2100
2400
2700
3000
3300
3600
3900
4100
H(At)

Solution

Cast iron



N = 100

I = 5A

Mean length = 0.2m

Area = $0.05m^2$

- H = NI / l (At/m)

  = 100t x 5.2A / 0.2

  = 520 / 0.2

  = 2600 At/m

- From B-H graph for cast iron and H = 2600

  B = 0.6 T

  Φ = BA (Wb)

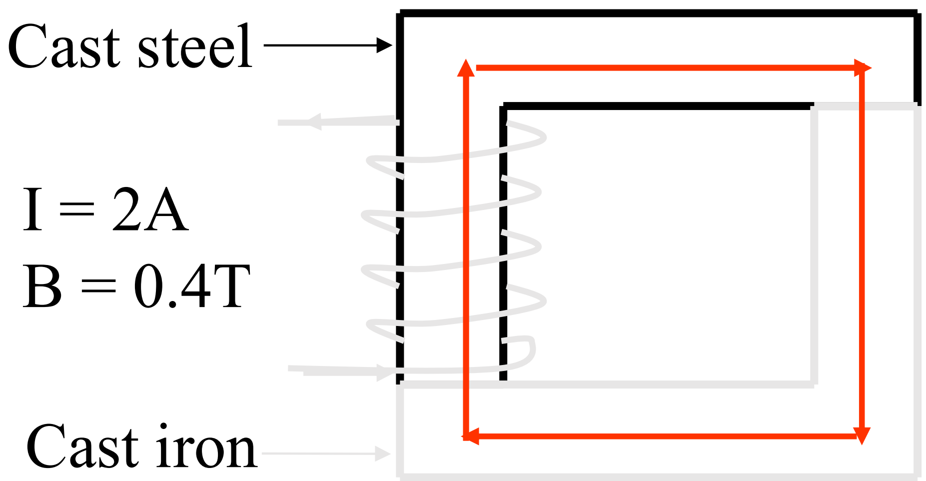
  = $6 \times 10^{-1} \times 5 \times 10^{-2}$

  = 30×10^{-3}

  = 30 mWb

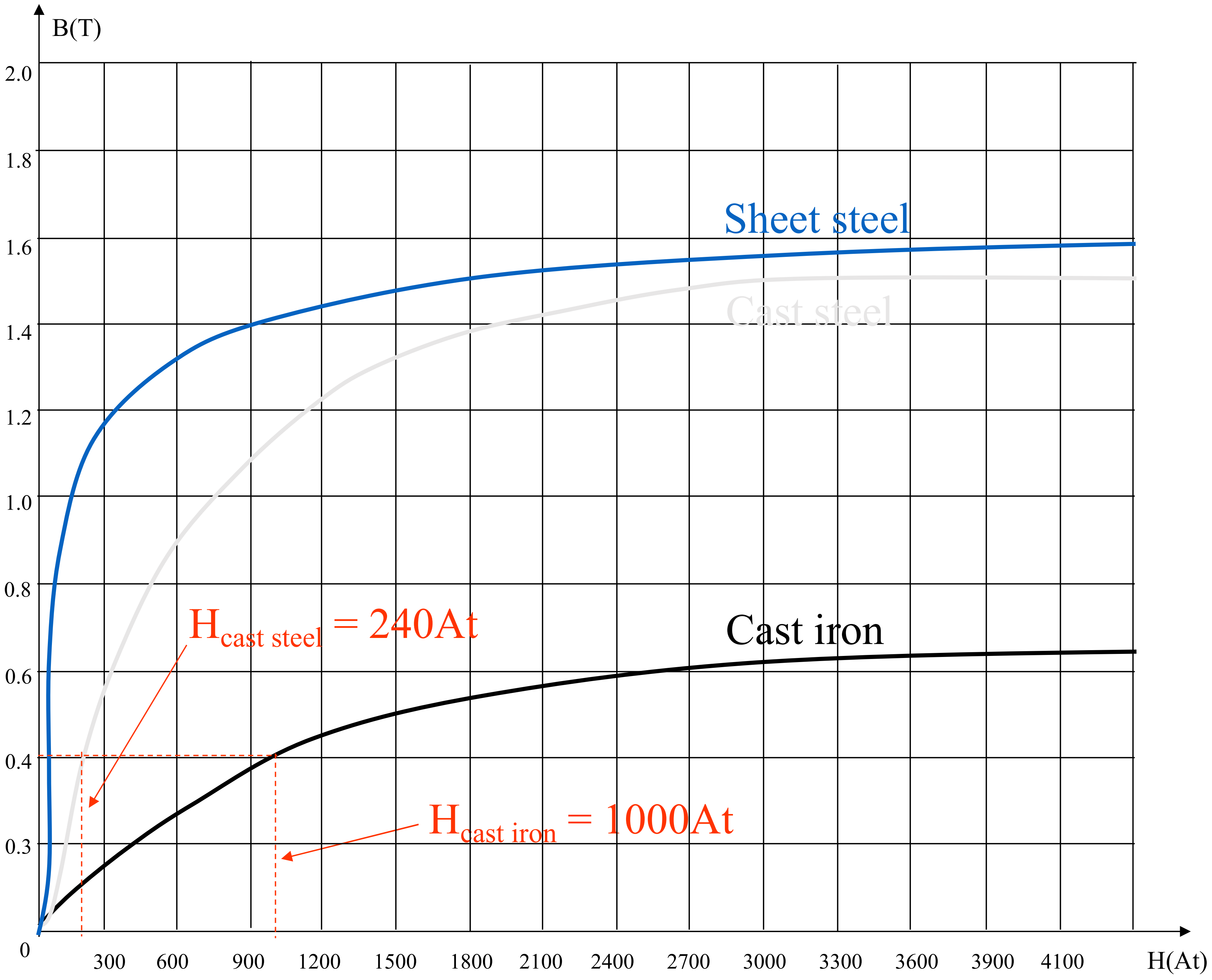
Calculation With Two Magnetic Materials

- Calculate the number of turns for the magnetic circuit below with mean dimensions as shown
  - Magnetic path: steel = iron = 10cm
  - Area: steel = iron = 4cm^2



Solution

- General approach:
  - Knowing B find $H_{cast\ steel}$ and $H_{cast\ iron}$ from B-H graph
  - From $N = Hl / I$ calculate the number of turns required for each of the steel and iron sections
  - Add the turns required for the steel and the iron to obtain the total number of turns



B(T)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.3
0
300
600
900
1200
1500
1800
2100
2400
2700
3000
3300
3600
3900
4100
H(At)
Sheet steel
Cast steel
Cast iron
$H_{cast\ steel} = 240At$
$H_{cast\ iron} = 1000At$

Solution

- Because the cross sectional area is the same for both the cast steel and the cast iron B will be the same for both
- B is given to be 0.4T

From B-H graph :

$H_{cast\ steel}$ = 240At

(use expanded graph)

$H_{cast\ iron}$ = 1000At

Solution

- $H = NI/l \quad \therefore N = Hl / I$
- $N_{cast\ steel} = 240 \times 0.1 / 2$

  $= 12t$
- $N_{cast\ iron} = 1000 \times 0.1 / 2$

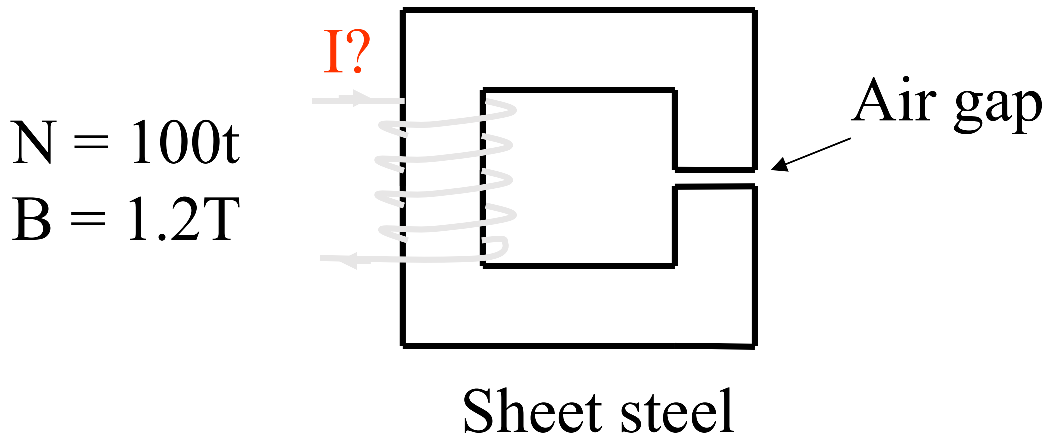
  $= 50t$
- Total turns = $turns_{steel} + turns_{iron}$

  $= 12 + 50$

  $= 62$

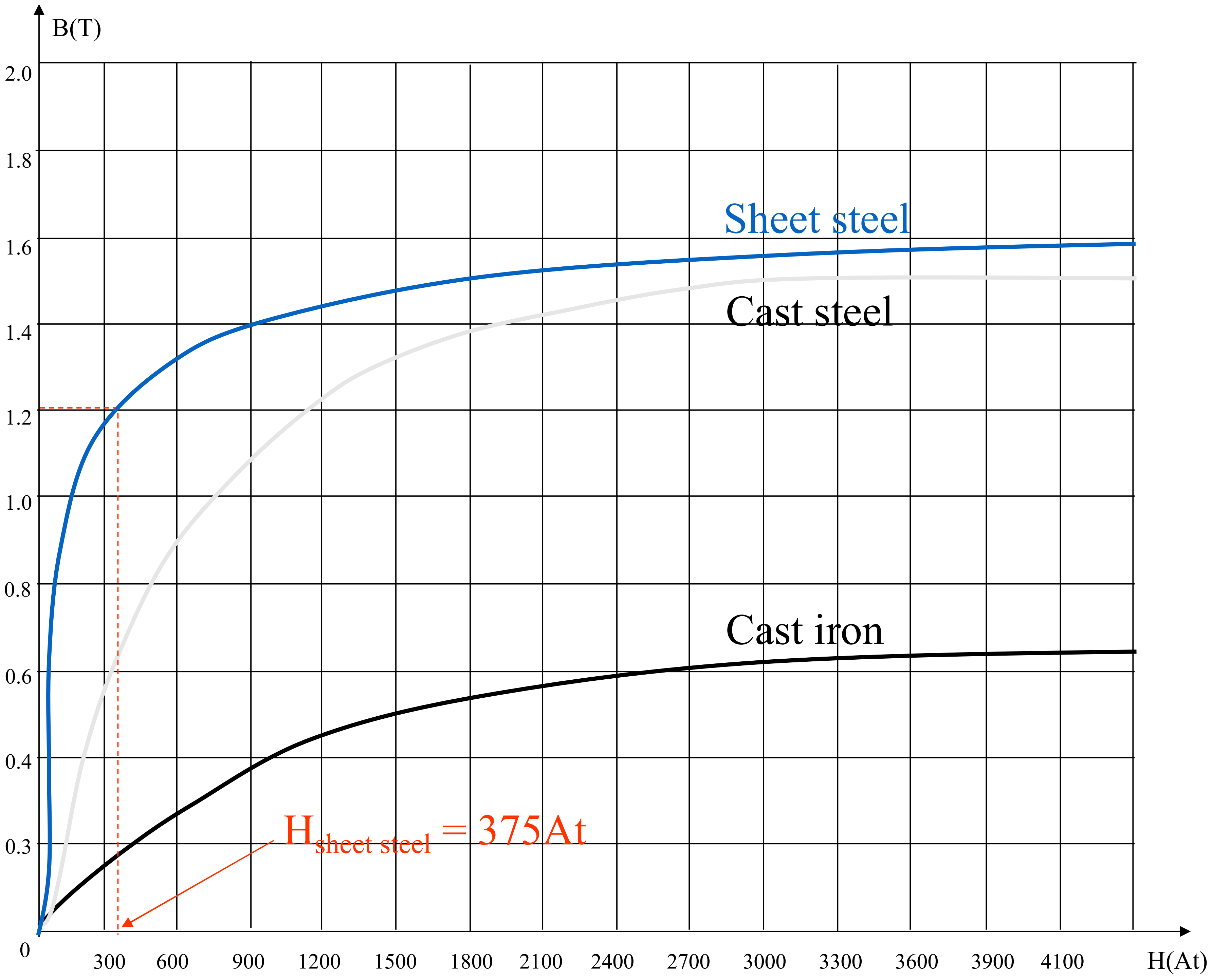
Calculation With an Air Gap

- Sheet steel is of uniform cross section
- Assume no fringing in air gap
- The mean path length for sheet steel = 100mm
- Air gap = 3mm
- Calculate the current required



Solution

- General approach:
  - Knowing B find $H_{sheetsteel}$ from B-H graph
  - From $B = \mu_0 H$ calculate H in air gap
  - From $I = Hl / N$ calculate the current required for each of the steel and air sections
  - Add the current contributions required for the steel and the air to obtain the total current



B(T)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.3
0
300
600
900
1200
1500
1800
2100
2400
2700
3000
3300
3600
3900
4100
H(At)
Sheet steel
Cast steel
Cast iron
$H_{sheet\ steel} = 375At$

Solution

- From (expanded) B-H graph

  $H_{sheet\ steel} = 375$ At

- $B_{air\ gap} = \mu_0 H \qquad \therefore\ H = B_{air\ gap} / \mu_0$

  $H_{air\ gap} = 1.2 / 4\Pi \times 10^{-7}$

  $= 9.55 \times 10^{5}$ At

  Important: what do you notice about $H_{sheet\ steel}$ and $H_{air\ gap}$

  Why?

Solution

- Calculate current requirement for each section
- $H = NI / l \quad \therefore I = Hl / N$
- $I_{air} = 9.55 \times 10^{5} \times 3 \times 10^{-3} / 100$

  $= 28.65$ A
- $I_{air} = 375 \times 0.1 / 100$

  $= 0.375$ A
- $I = 28.65 + 0.375$

  $= 29.03$ A

Formulae and Constants

- $B = \Phi / A$
- $MMF = NI$
- $H = MMF / l = NI / l$
- $B = \mu_0 H$
- $\mu_0 = 4\Pi \times 10^{-7}$
- $\mu_r = \mu / \mu_0$