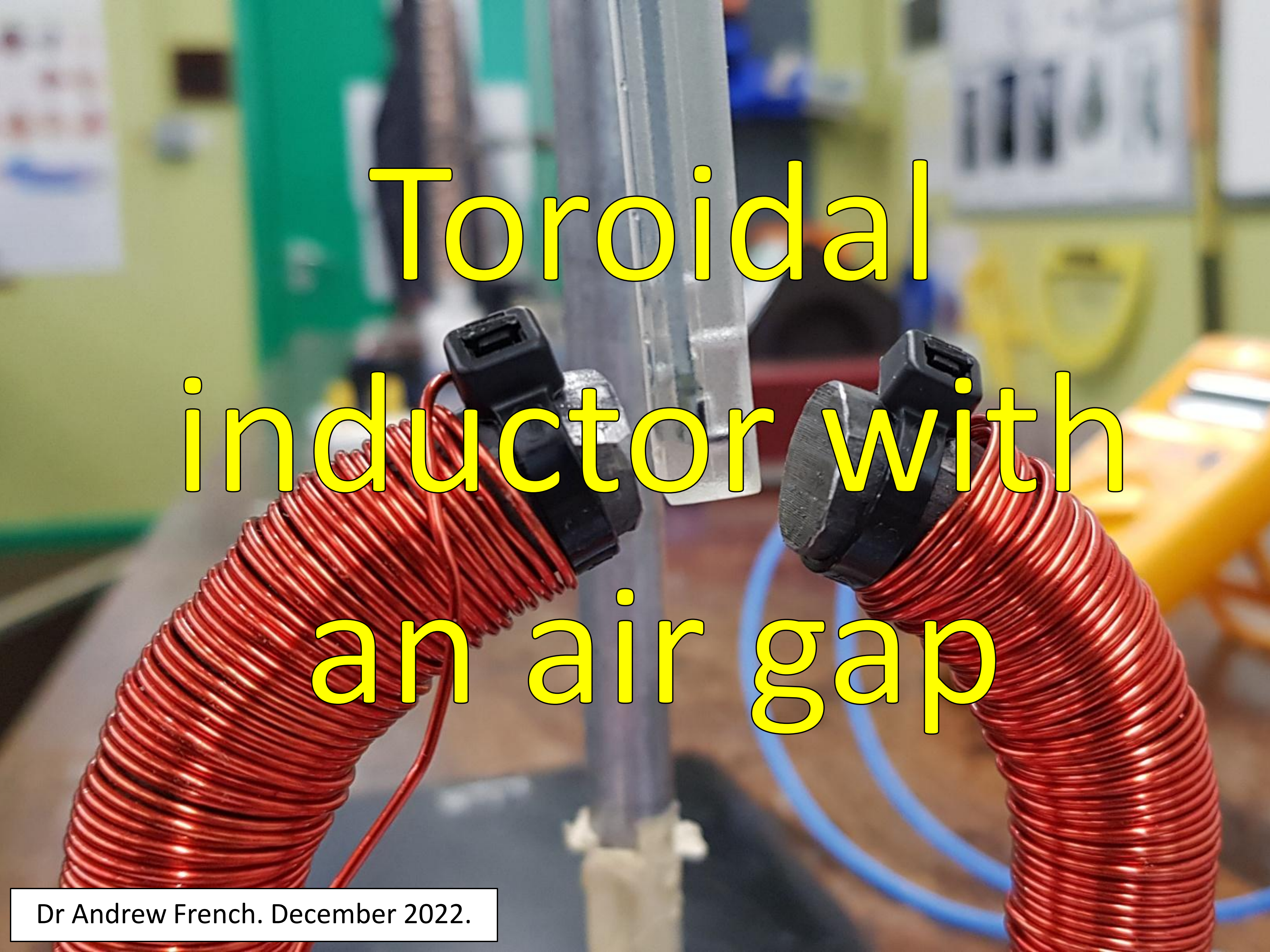
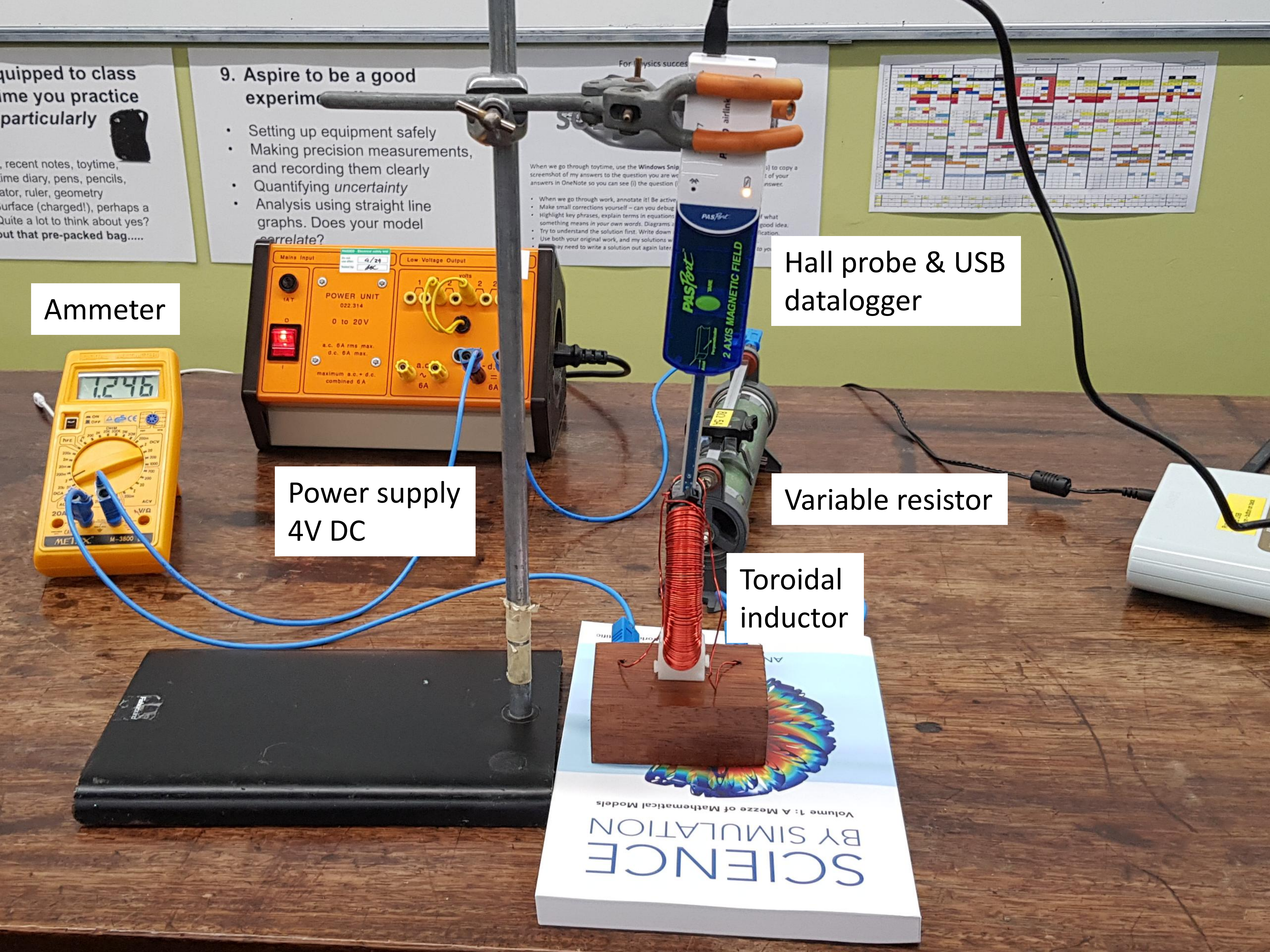
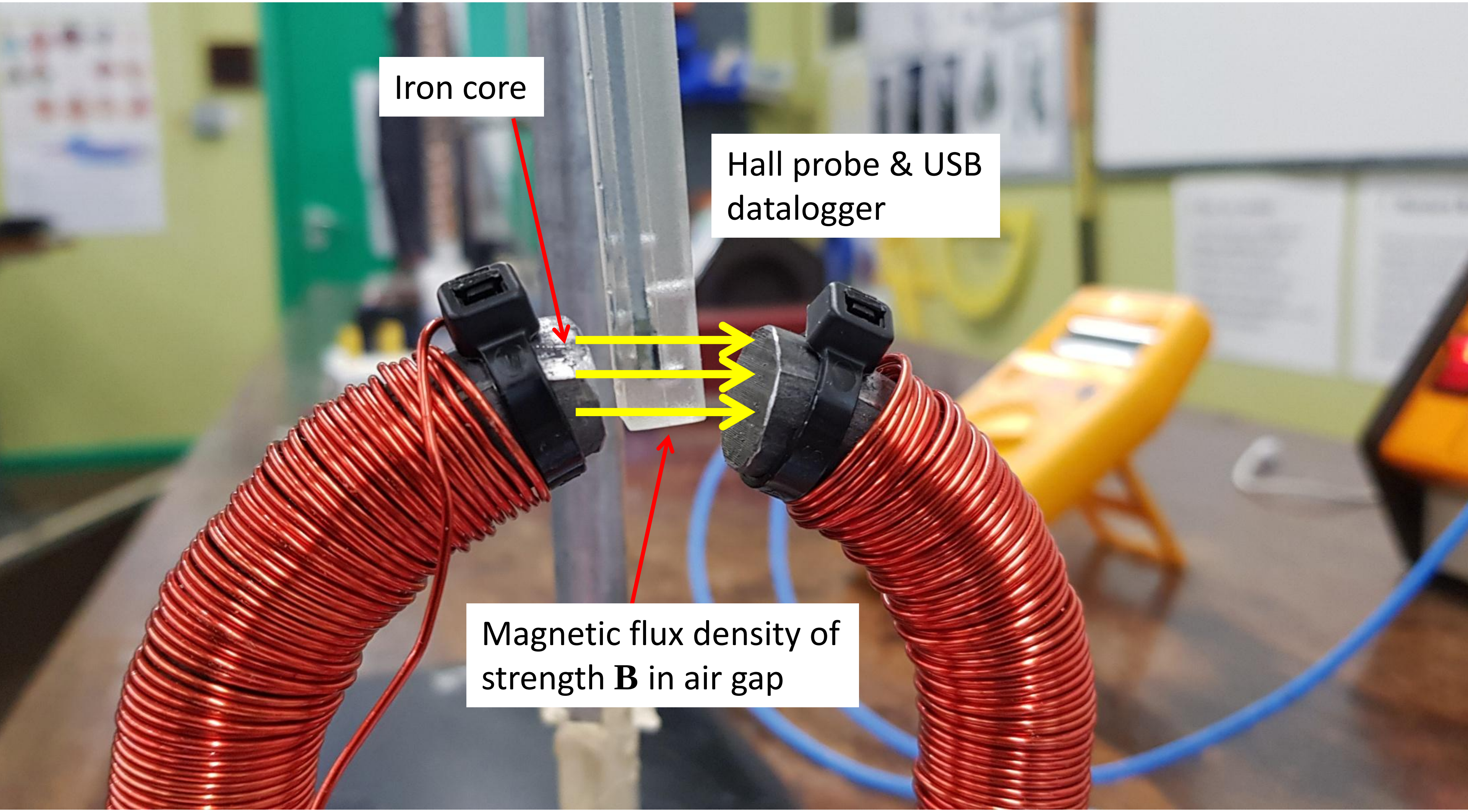
Toroidal inductor with an air gap

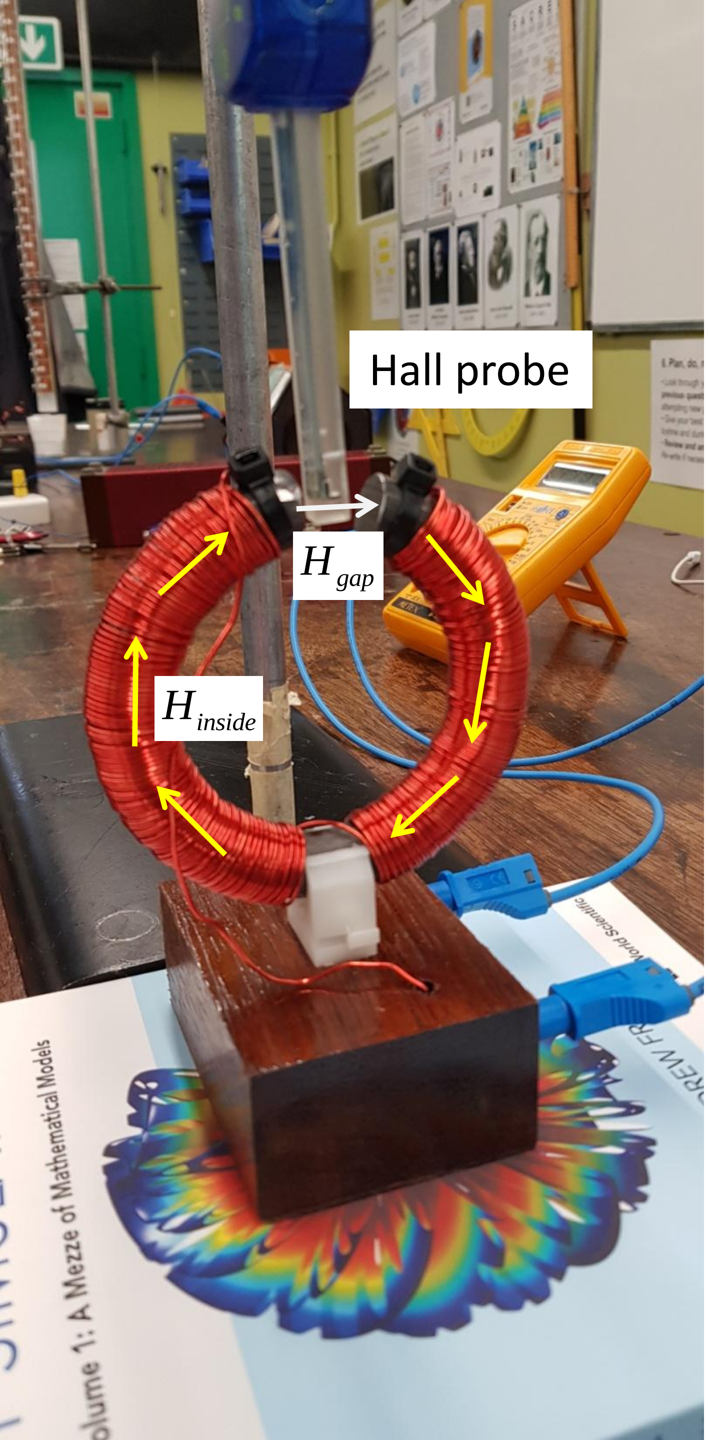


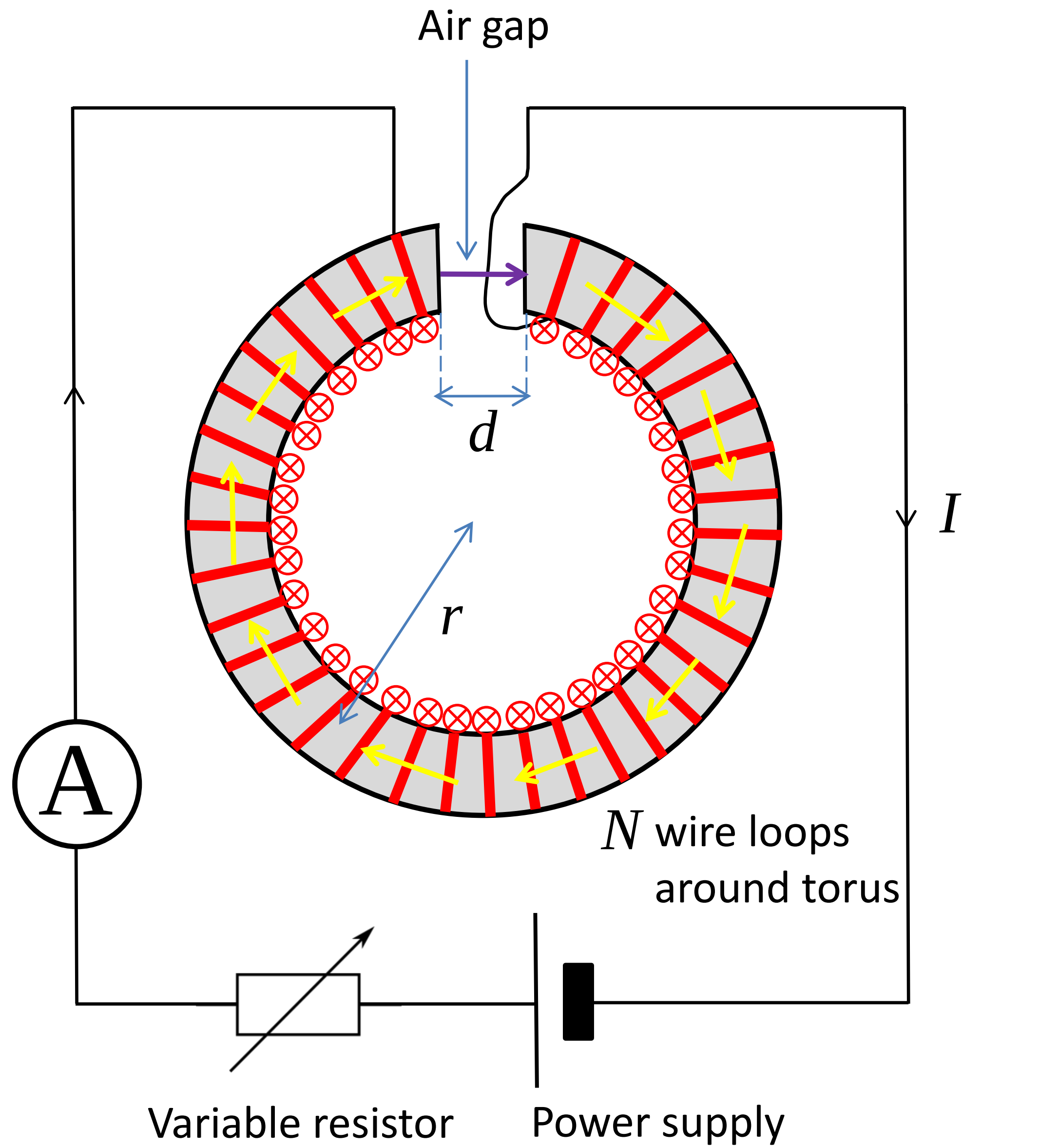
Dr Andrew French. December 2022.


Ammeter
Power supply
4V DC
Hall probe & USB
datalogger
Variable resistor
Toroidal
inductor
9. Aspire to be a good
Setting up equipment safely
Making precision measurements,
and recording them clearly
Quantifying uncertainty
Analysis using straight line
graphs. Does your model
POWER UNIT
0 to 20V
Low Voltage Output
Mains Input
2 AXIS MAGNETIC FIELD
PASPORT
SCIENCE
BY SIMULATION
Volume 1: A Mezze of Mathematical Models



1. Vary current (range 0.4A to about 2.0A) in toroidal inductor by changing resistance of variable resistor.
2. Use Hall Probe and datalogger to measure magnetic flux density B in air gap.
3. Plot magnetic flux density (in T) vs current (in A). Use the graph to calculate the relative permeability μ of the iron core.


Hall probe
H_{gap}
H_{inside}


Air gap
d
r
I
A
N wire loops around torus
Variable resistor
Power supply

Application of the Lorentz force – the Hall Efffect

A semiconductor of width w and height h is placed in a magnetic field B. Current I passes through the semiconductor as shown.The Lorentz force on charges will cause a charge separation, which in turn will result in an electric field E perpendicular to both the magnetic field and the current direction.

Equilibrium is reached when the electric force and Lorentz magnetic forces balance.

Example calculation:

$$n = 7 \times 10^{21}\,\mathrm{m}^{-3}$$

$$q = e = 1.6 \times 10^{-19}\,\mathrm{C}$$

$$h = 0.1\mathrm{mm}$$

$$\therefore qnh = \boxed{0.112}$$

$\therefore \dfrac{V_H}{I}$ can be a ratio of near-unity quantities, which are readily measureable i.e. B fields not too many orders of magnitude less than 1.0T can be easily measured.

$$qE = qvB$$

$$\therefore E = vB$$

$$E = \frac{V_H}{w}$$

The electric potential resulting from the separated charges is called the **Hall Voltage**

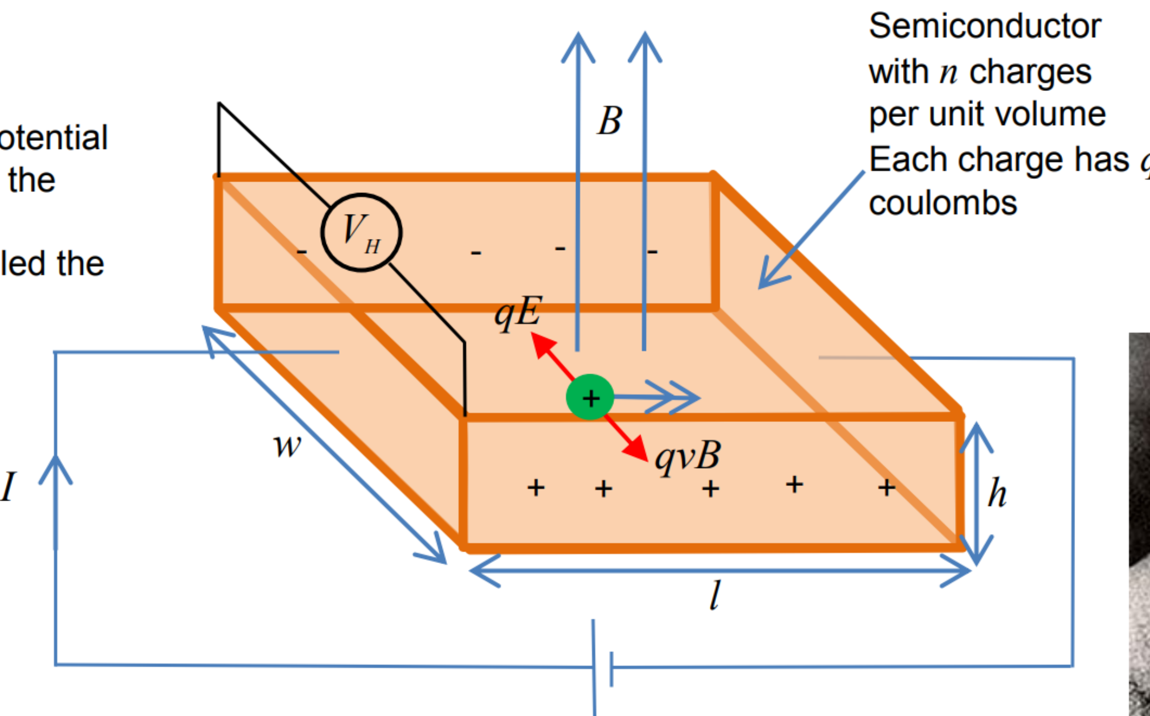
$$I = qnwhv$$

$$\therefore v = \frac{I}{qnwh}$$

$$\therefore \frac{V_H}{w} = \frac{IB}{qnwh}$$

$$V_H = \frac{IB}{qnh}$$

$$\boxed{B = \frac{qnhV_H}{I}}$$



It is possible to measure the Hall effect in a small semiconductor, so the effect can be used to determine the how a non uniform magnetic field varies in time and space.

Edwin Hall
1855-1938

Ampère's Theorem:

$$\oint_{loop} \mathbf{H}\cdot d\mathbf{l} = NI$$

Magnetic field strength inside torus is tangential to circular loop

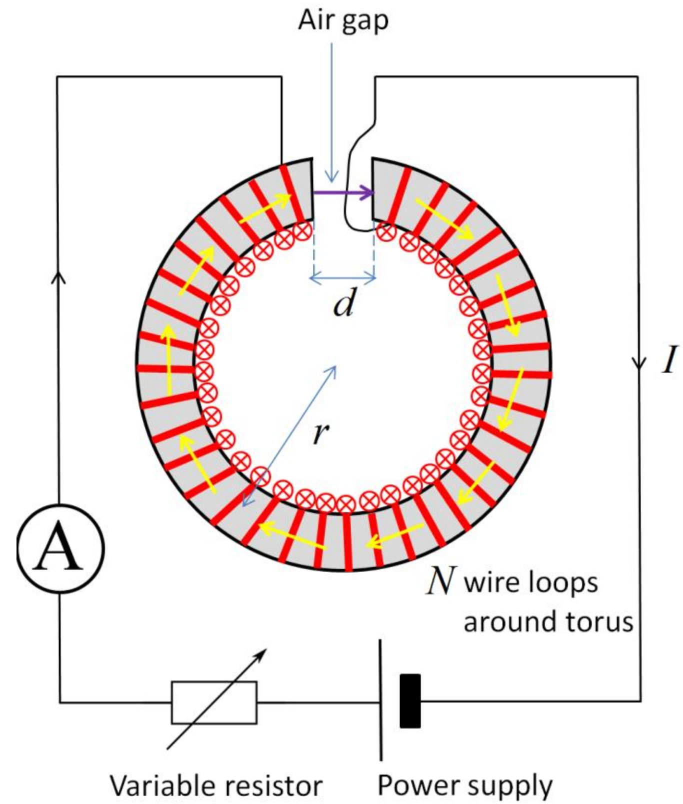
$$\therefore H_{inside}\left(2\pi r - d\right) + H_{gap} d = NI$$

if gap is small $d \ll 2\pi r$

$$B_{gap} = \mu_0 H_{gap}$$

$$B_{inside} = \mu\mu_0 H_{inside}$$

Permeability of free space $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{Hm}^{-1}$



Magnetic flux density **B** is continuous perpendicular to the iron, air boundary. (*Maxwell Equation* result).

Hence:

$$B_{gap} = B_{inside} = B$$

$$\therefore H_{gap} = \mu H_{inside}$$

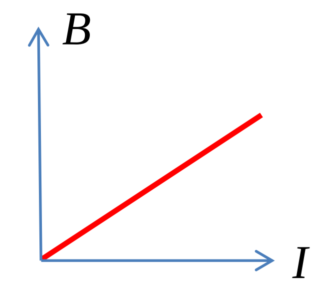
$$\therefore H_{inside} = \frac{B}{\mu\mu_0}$$

$$\therefore H_{inside}\left(2\pi r - d\right) + \mu H_{inside} d = NI$$

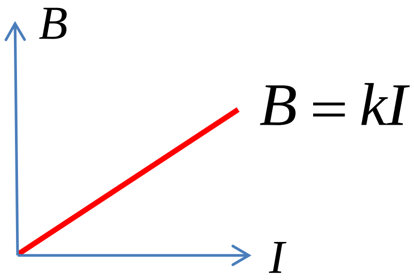
$$\therefore H_{inside}\left(2\pi r - d + \mu d\right) = NI$$

$$\therefore \frac{B}{\mu\mu_0}\left(2\pi r - d + \mu d\right) = NI$$

$$\therefore B = \frac{N\mu\mu_0}{2\pi r - d + \mu d} I$$



André-Marie Ampère (1775-1836)



$$B = kI$$

$$k = \frac{N\mu\mu_0}{2\pi r - d + \mu d}$$

$$k\left(2\pi r - d + \mu d\right) = N\mu\mu_0$$

$$k\left(2\pi r - d\right) = \mu\left(N\mu_0 - kd\right)$$

$$\therefore \mu = \frac{k\left(2\pi r - d\right)}{N\mu_0 - kd}$$

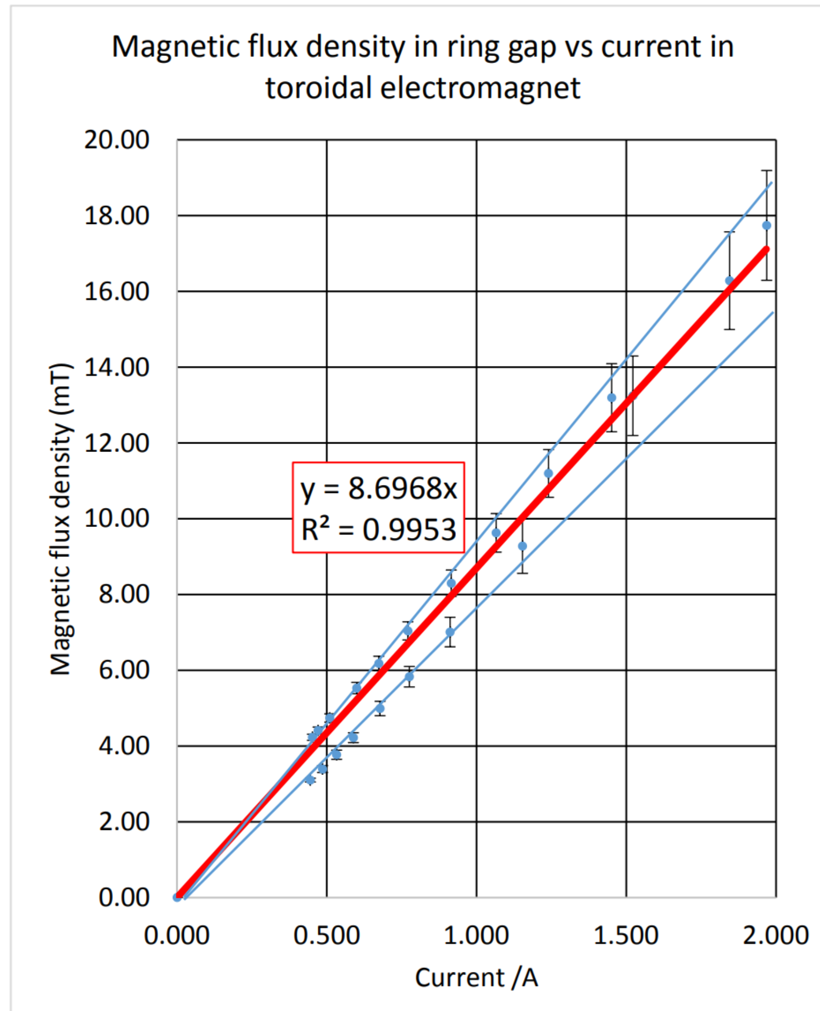
TOROIDAL ELECTROMAGNET EXPERIMENT

21/11/2022

Radius of ring /m	**0.08**
Gap in m	**0.018**
Number of coils N	**220**
μ0	**1.25664E-06**
k = dB/dI	**0.00870**
k max	**0.00950**
k min	**0.00775**
μ mean	**35.15**
μ max	**43.66**
μ min	**27.42**

Magnetic flux density B in air gap (mT)

B (mT)	**B error /mT**	**I (A)**
0.00	0.01	0.000
3.10	0.05	0.445
3.39	0.09	0.486
3.77	0.12	0.533
4.22	0.13	0.589
4.99	0.19	0.678
5.83	0.27	0.776
7.01	0.39	0.912
9.28	0.72	1.154
13.25	1.05	1.523
16.29	1.29	1.846
17.75	1.45	1.970
13.20	0.90	1.452
11.20	0.63	1.241
9.63	0.51	1.066
8.30	0.35	0.916
7.04	0.24	0.771
6.18	0.19	0.674
5.53	0.15	0.600
4.74	0.11	0.510
4.41	0.09	0.471
4.23	0.08	0.452



In many literature sources μ is quoted as being about 1,000.

So the ring metal is probably not pure iron!

Current raised then lowered to investigate *hysteresis* - only very marginal in this experiment.