1. MAGNETIC FIELDS: INTRODUCTION

1.1 What are the sources of magnetic fields?

Magnetic fields arise from moving electric charges

It is convenient to separate these into two chief sources of magnetic field:

(a) magnetic fields due to electric currents (i.e. moving charges; $i = dq/dt$) in conducting materials.

(b) fields arising from **magnetic materials**. In these, electron motion (**orbital** or **spin**) can lead to a net ‘magnetic moment’ and a resulting **magnetization**.

We will deal with magnetic materials later. The first half of this section of the course, about 7 lectures, concerns fields due to electric currents.

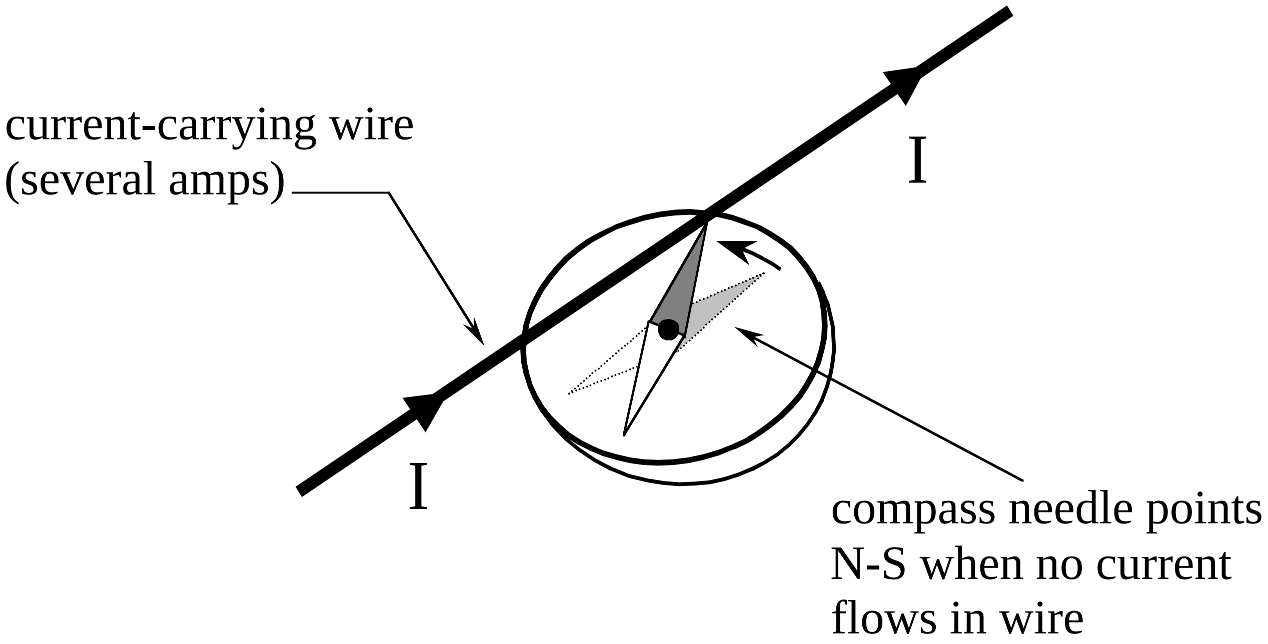
1.2 Motivation

Many useful and important technologies are underpinned by our knowledge of magnetic phenomena:

- Data Storage/read/write
- Entertainment: home theatre
- Medical: Magnetic Resonance Imaging (MRI)
- Transport: electric trains, Maglev trains….

1.3 Brief history and phenomenology

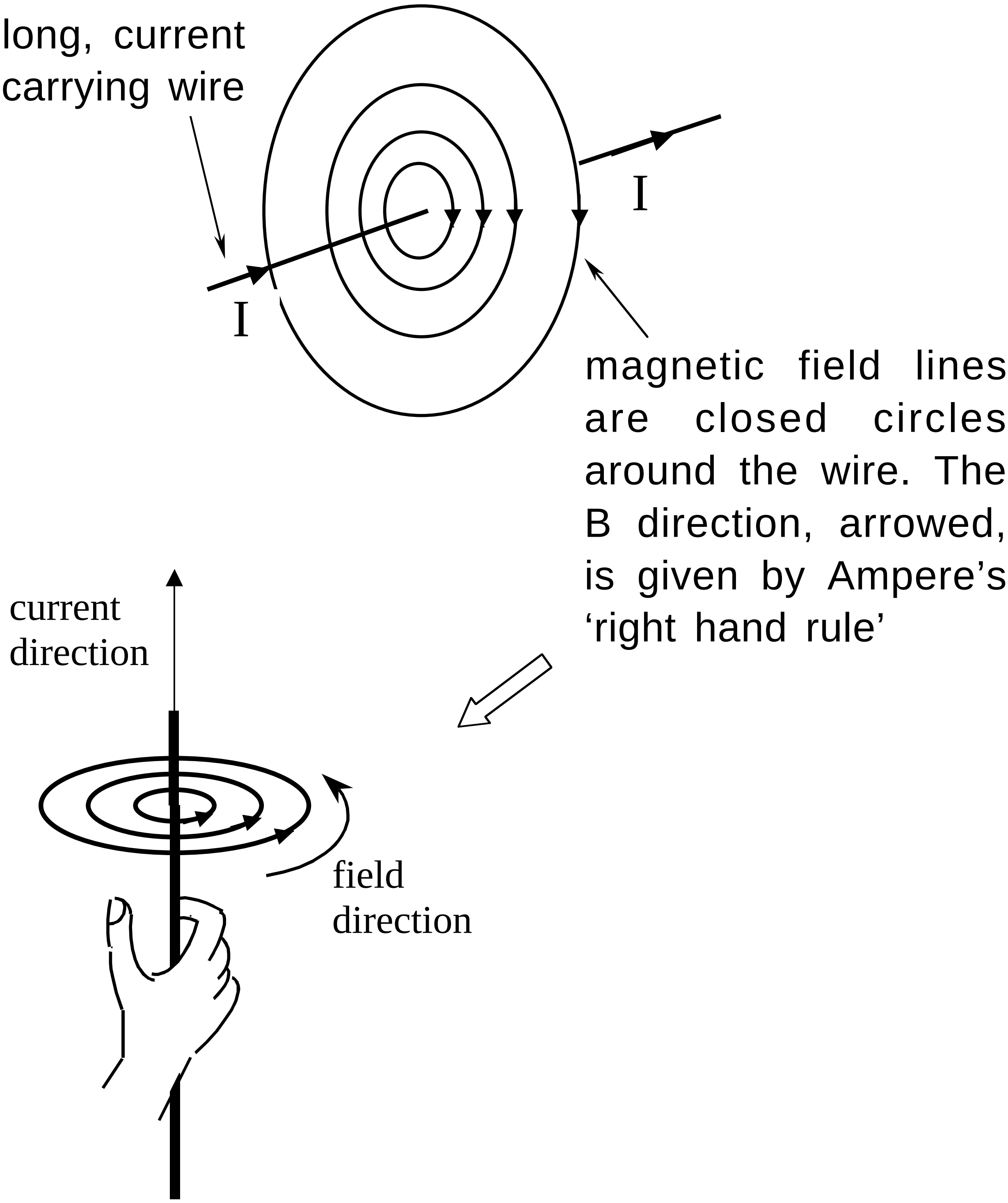
Danish physicist **Hans Oersted** found in 1819 that a current flowing in a wire deflected a compass needle:



Lecture demonstration: Oersted's experiment (compass deflected by current carrying wire)

(**Note:** the direction of deflection of the needle: towards west. The compass is shown *below* the wire, if the compass is positioned above the wire the deflection is in the opposite direction. Reversal of the current direction also causes reversal of deflection.)

Andre Ampere (1775-1836) repeated Oersted’s experiments and formulated the **right hand rule** in the early 1820s.

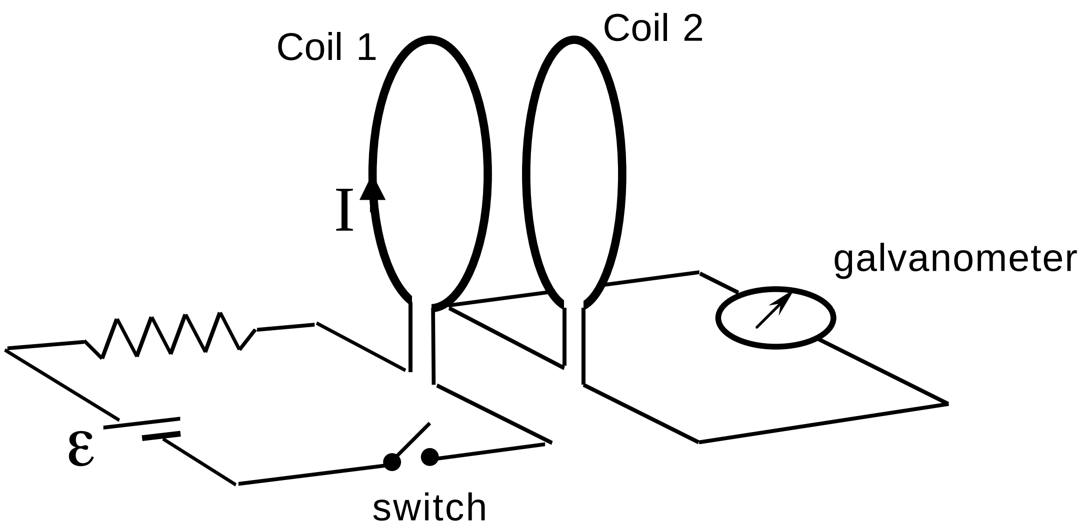


Ampere's essential contribution was to show that electricity and magnetism were *part of the same phenomenon* (prior to 1820 they had been seen as separate branches of science.)

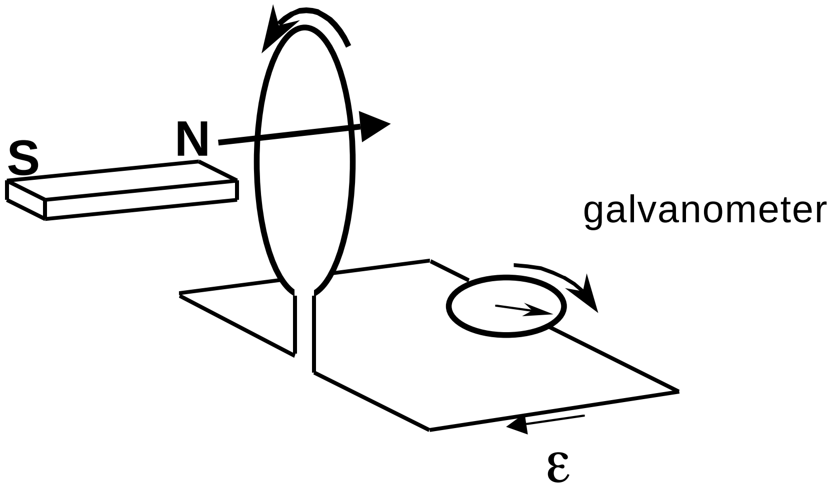
In 1831 English physicist Michael Faraday discovered electromagnetic induction,

$$\varepsilon = -\frac{d\Phi}{dt}$$

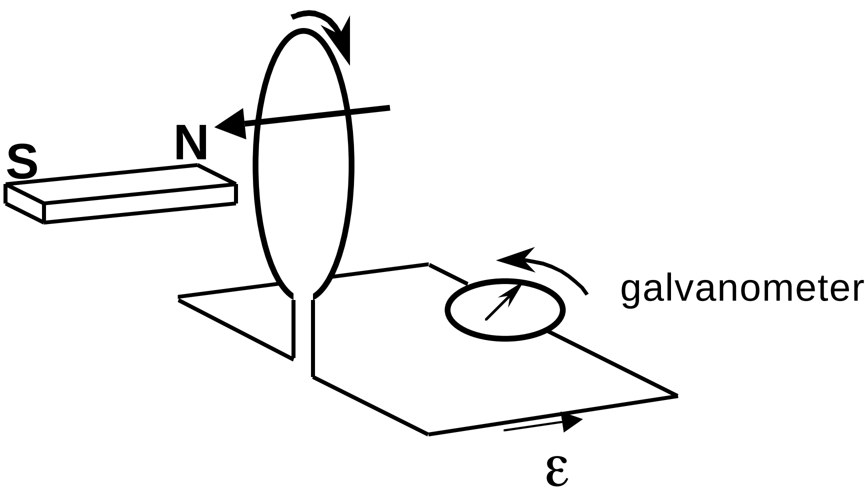
showing that an emf ε is induced in a coil by a changing magnetic flux $d\Phi/dt$.



Permanent magnet *moving into* a coil:



Permanent magnet *moving out of* a coil:



Faradays law of induction

Faraday's law quantifies the above observations:

$$\varepsilon = -\frac{d\Phi}{dt}$$

induced emf — rate of change of magnetic flux Φ

The magnetic flux Φ is the normal component of **B** integrated over surface S:

$$\Phi = \int_{S} \mathbf{B} \cdot d\mathbf{a}$$

integral over surface S — element of area da

The magnetic flux has units webers. So 1 tesla = 1 weber per metre squared ($1\mathrm{T} = 1\mathrm{Wm}^{-2}$)

1.4 Magnetic force on a moving charge

A charge Q experiences a force when it moves with velocity v in a magnetic field:

$$\mathbf{F} = Q(\mathbf{v} \times \mathbf{B})$$

↑ charge velocity

- this is an empirical fact.

The force **F** exerted by the magnetic field on the charge is perpendicular to the velocity, **v**, of the charge. So,

$$\mathbf{F}.\mathbf{v} = 0$$

↑ no power is supplied to the charge by the field

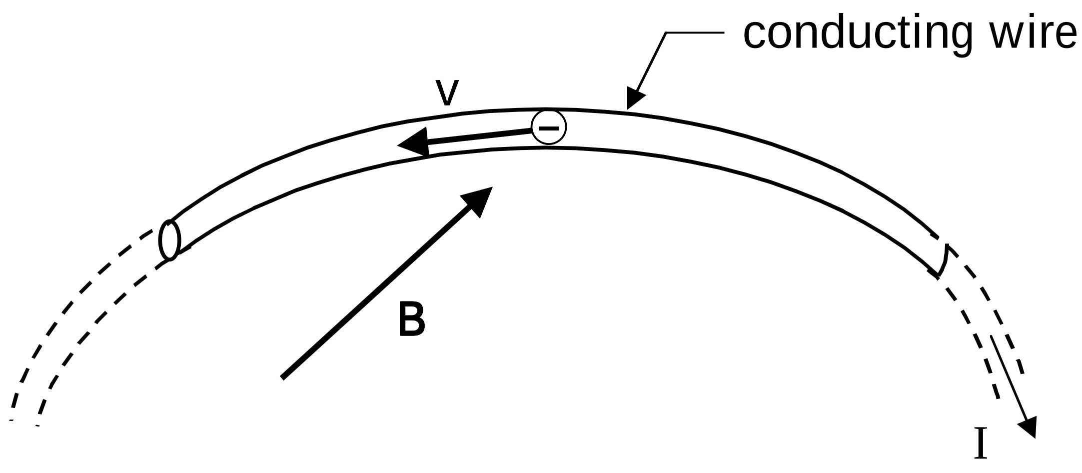
- the *direction* of the charge's velocity is changed; the magnitude of the velocity is not changed.

1.5 Electric and magnetic fields: Lorentz force

A charge in both electric and magnetic fields experiences a total force

$$\mathbf{F} = Q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad \textbf{Lorentz force}$$

1.7 Force on a current carrying wire



A conducting wire contains about $n \sim 10^{28} - 10^{29}$ conduction electrons per m^3 of metal. Each electron experiences a force

$$\mathbf{F} = Q(\mathbf{v}\mathbf{x}\mathbf{B}) = -e(\mathbf{v}\mathbf{x}\mathbf{B})$$

Length dl of wire contains nAdl conduction or ‘free’ electrons.

A is cross-sectional area of wire

So,

$$\mathbf{dF} = nAdl(-e\mathbf{v} \times \mathbf{B})$$

Now,

$$\mathbf{I} = -nAe\mathbf{v}$$

therefore,

$$\mathbf{dF} = \mathbf{I}dl \ \mathbf{x}\ \mathbf{B} = I\mathbf{dl}\ \mathbf{x}\ \mathbf{B}$$

dl is in the current direction

e.g. a straight current carrying wire of length l in a uniform magnetic field B experiences a force

$$\mathbf{F} = I\mathbf{l}\ \mathbf{x}\ \mathbf{B}$$