Electromagnetic Induction & Faraday's Law

Unit: Magnetism & Electromagnetism

NGSS Standards/MA Curriculum Frameworks (2016): HS-PS3-5

AP® Physics 2 Learning Objectives/Essential Knowledge (2024): 12.1.A, 12.1.A.1, 12.1.A.1.i, 12.1.A.1.ii, 12.1.A.2, 12.1.A.2.i, 12.1.A.2.ii, 12.1.B.2, 12.1.B.4

Mastery Objective(s): (Students will be able to…)

- Describe and draw magnetic fields.
- Calculate magnetic flux.

Success Criteria:

- Magnetic field lines connect north and south poles of the magnet.
- Arrows on field lines point from north to south.

Language Objectives:

- Explain how a compass works.

Tier 2 Vocabulary: field, north pole, south pole

Labs, Activities & Demonstrations:

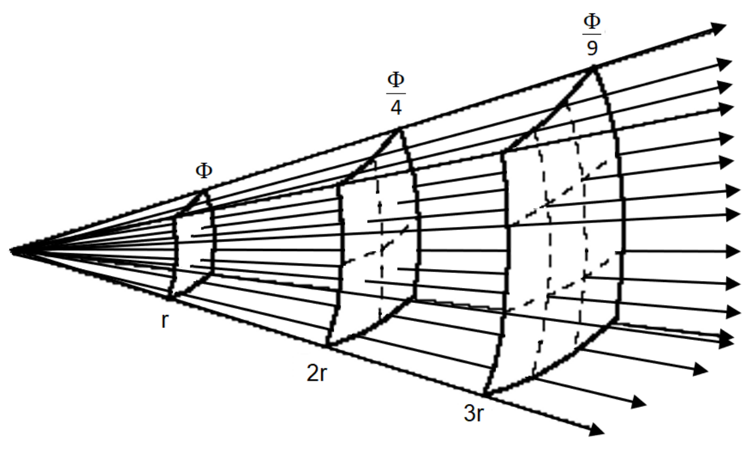
- ferrofluid
- representation of flux as dots on a balloon

Notes:

Magnetic Flux

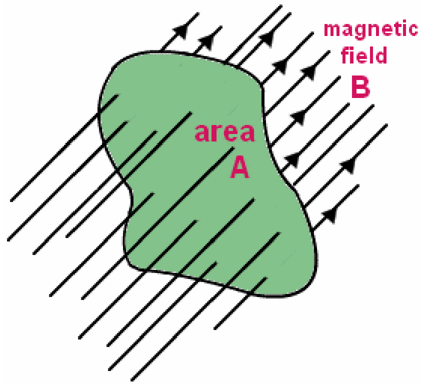
<u>flux</u>: the flow of fluid, energy or particles across a given area.

If a quantity (such as a magnetic field) originates from a point, the field spreads out and the amount of flux through a given area decreases as the square of the distance from that point.



magnetic flux (Φ): the total amount of a magnetic field that passes through a surface.

Stronger magnetic fields are generally shown with a higher density of field lines. Using this representation, you can think of the magnetic flux as the number of field lines that pass through an area.



The equation for magnetic flux is Faraday's Law, named for the English physicist Michael Faraday. The equation is usually presented as a surface integral, but in algebraic form it looks like the following:

$$\Phi_B = \vec{\boldsymbol{B}} \cdot \vec{\boldsymbol{A}} = BA\cos\theta$$

where:

Φ = magnetic flux (Wb)

$\vec{\boldsymbol{B}}$ = strength of magnetic field (T)

$\vec{\boldsymbol{A}}$ = area of the region of interest that the magnetic field passes through (m^2)

The unit for magnetic flux is the weber (Wb). One tesla is one weber per square meter.

$$1\,\text{T} \equiv 1\,\frac{\text{Wb}}{\text{m}^2}$$

Magnetic Fields and Electric Current

Like gravitational and electric fields, a magnetic field is a force field. (Recall that force fields are vector quantities, meaning that they have both magnitude and direction.) The strength of a magnetic field is measured in teslas (T), named after the Serbian-American physicist Nikola Tesla.

$$1\,\text{T} = 1\,\frac{\text{N}}{\text{A}\cdot\text{m}}$$

In the 1830s, English physicists Michael Faraday and Joseph Henry each independently discovered that an electric current could be produced by moving a magnet through a coil of wire, or by moving a wire through a magnetic field. This process is called electromagnetic induction.

If we move a conductive rod or wire that has length ℓ at a velocity *v* through a magnetic field of strength *B*, the magnetic forces send positive charges to one end of the rod and negative charges to the other. This creates a potential difference (emf) between the ends of the rod:

$$\mathcal{E} = vB\ell$$

If the rod or wire is part of a closed loop (circuit), then the induced ε produces a current around the closed loop. From Ohm's Law, $\mathcal{E} = IR$, we get:

$$I = \frac{\mathcal{E}}{R} = \frac{vB\ell}{R}$$

This production of emf is called the Hall effect, after American physicist Edwin Hall, who discovered this relationship in 1879.

EMF Produced by Changing Magnetic Flux

A changing magnetic field produces an electromotive force (emf) in a loop of wire. This emf is given by the equation:

$$\mathcal{E} = -\frac{d\Phi_B}{dt} = -\frac{\Delta\Phi_B}{\Delta t} = -\frac{\Delta(BA\cos\theta)}{\Delta t}$$

(calculus) (algebraic)

If we replace the loop of wire with a coil that has *n* turns, the equation becomes:

$$\mathcal{E} = -n\frac{d\Phi_B}{dt} = -n\frac{\Delta\Phi_B}{t}$$

(calculus) (algebraic)