Electromagnetism

Ampère's Law

- how electricity creates magnetism

Faraday's Law

- how magnetism creates electricity

Electromagnetic Induction

Faraday's Law

Lenz's Law

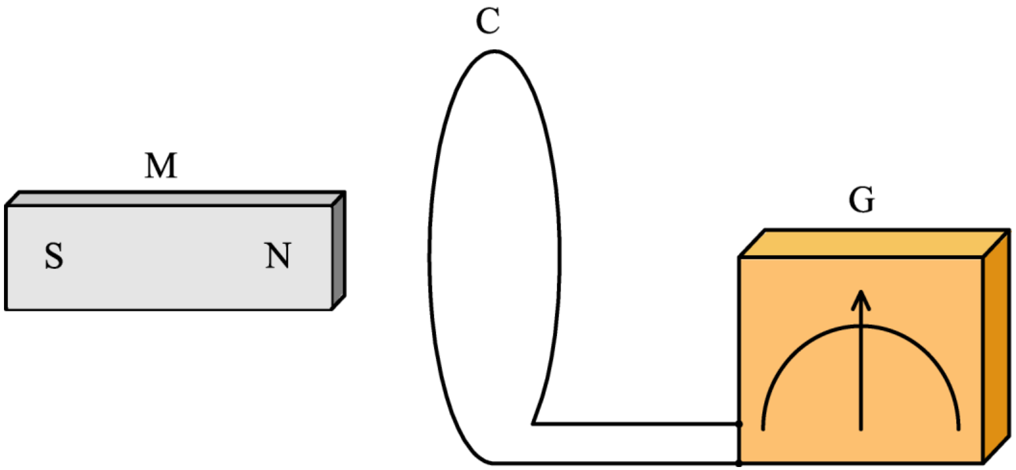
How do we create electricity from magnetism?

Electromagnetic Induction

… discovered in 1831 by Michael Faraday and Joseph Henry

(England) (America)

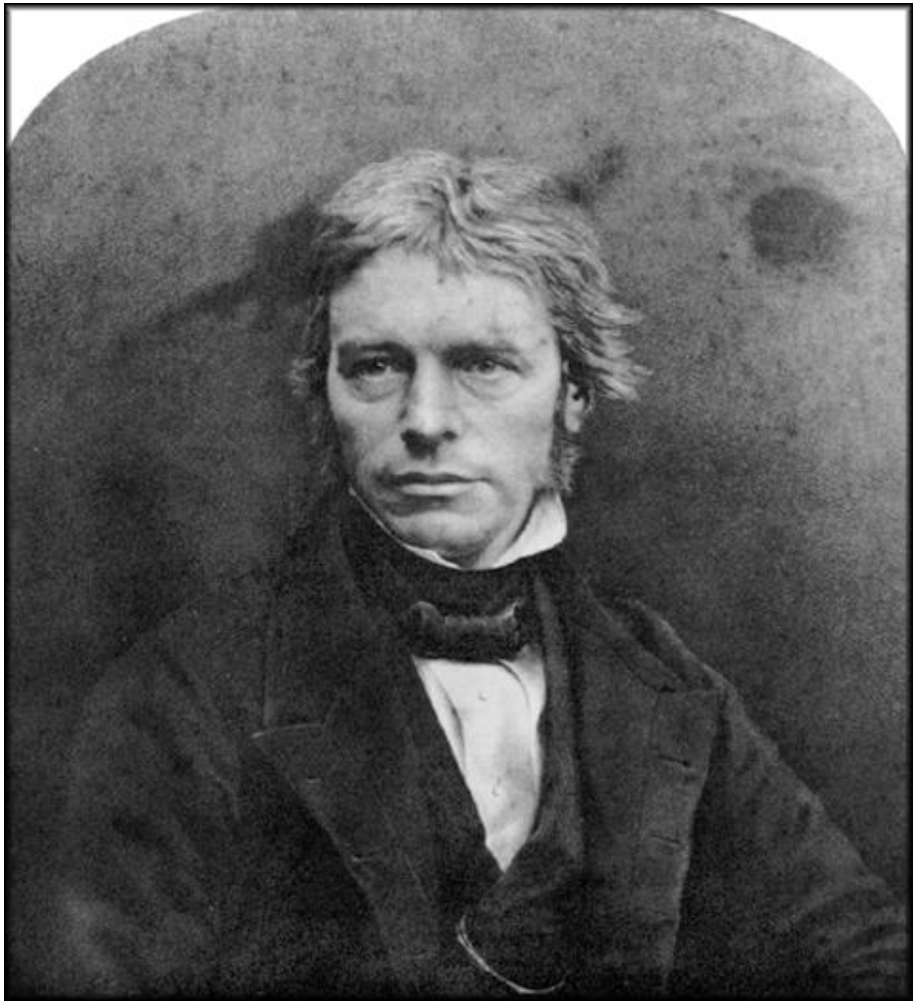
Simplest demonstration



When M moves, a current flows around C and produces a deflection of the galvanometer needle.

Demo: Electromagnetic induction

Michael Faraday



Faraday's experiments

He used *several methods* to generate a current by a magnetic effect.

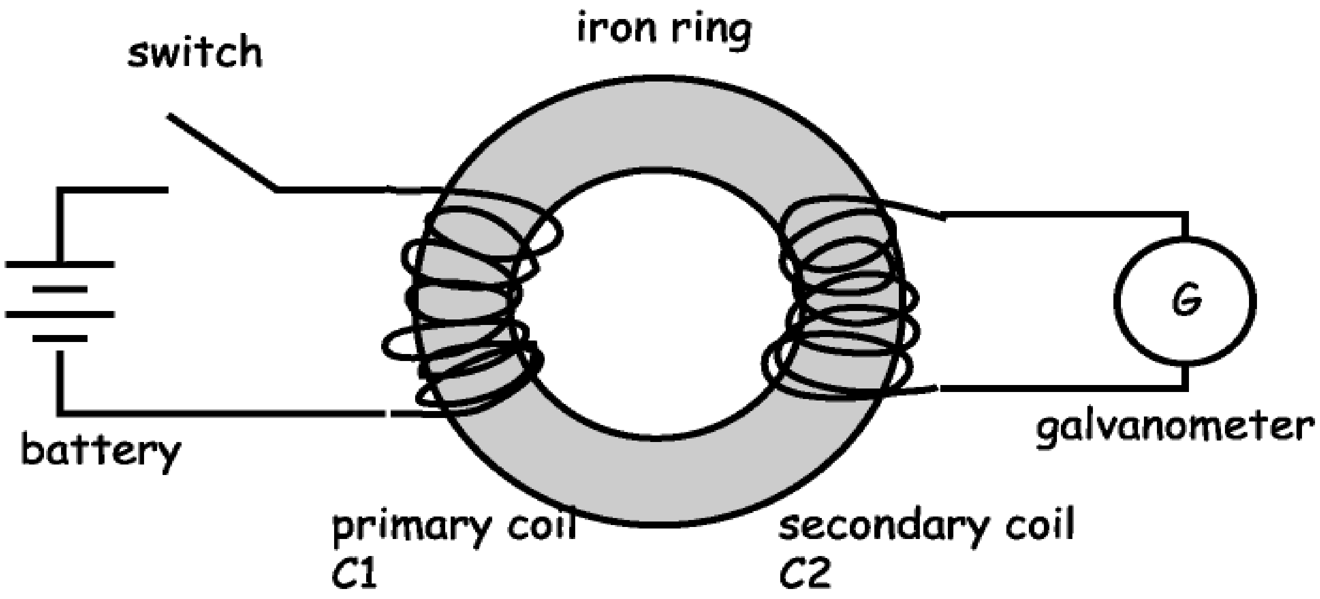
► Common feature: A changing magnetic field produces an electric current in a conductor.

► But the current is really a *secondary effect* – caused by an induced electric field.

Electromagnetic induction: a changing magnetic field produces an electric field.

Faraday's experiments

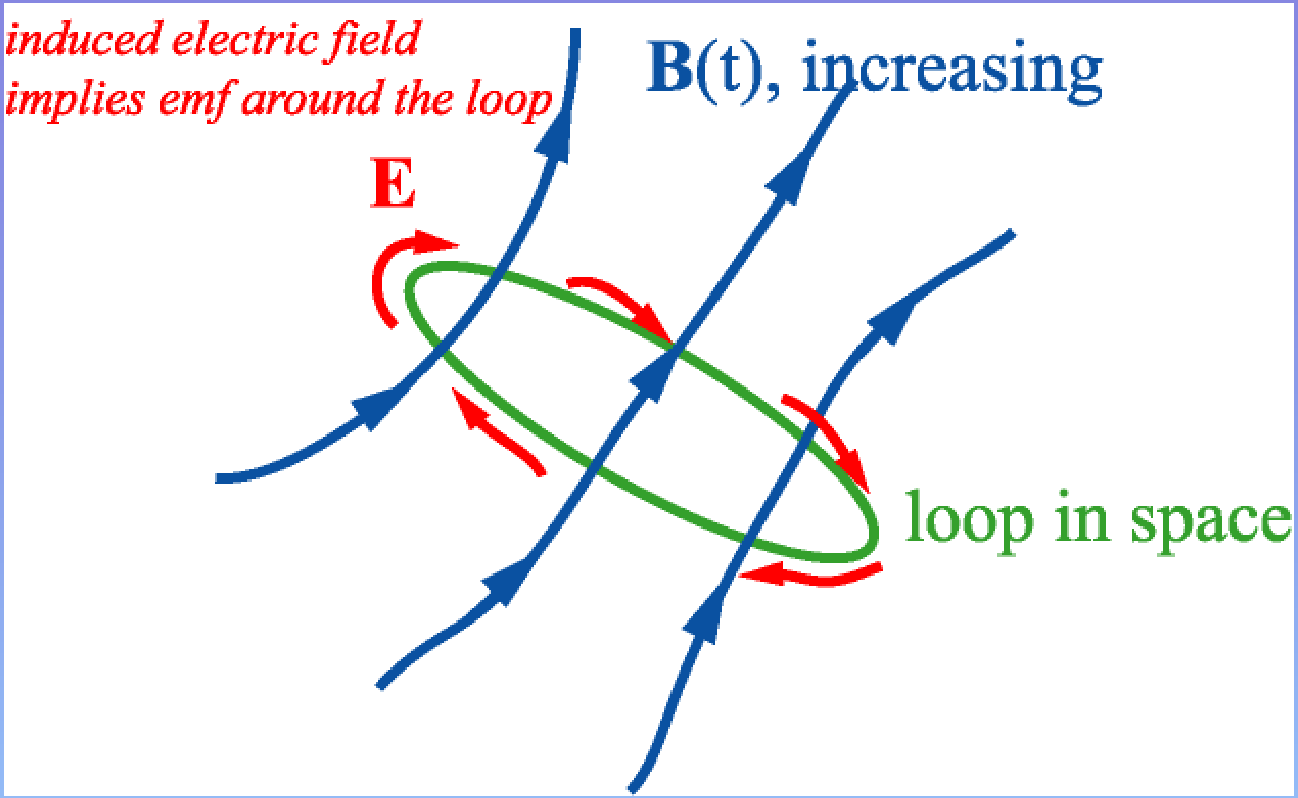
Example. When current is turned on or off in the primary coil, a current is observed in the secondary coil.



Explanation:

- Current C1 creates a magnetic field B(t) in the iron, amplified by the iron core.
- The changing magnetic field creates an electric field around C2. (induction)
- The electric field creates a current C2.

Faraday's law of electromagnetic induction



Electromagnetic induction is a phenomenon of the fields; it happens even if no conductor is present.

Faraday's law

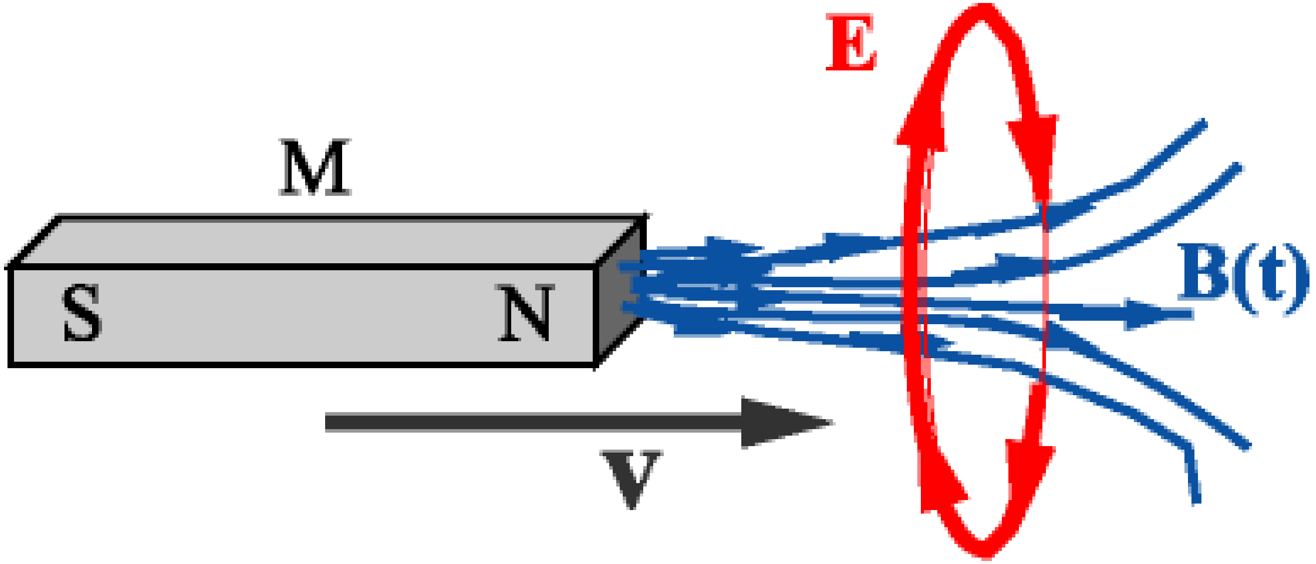
$$emf = -\frac{\Delta\Phi}{\Delta t}$$

Define *magnetic flux*

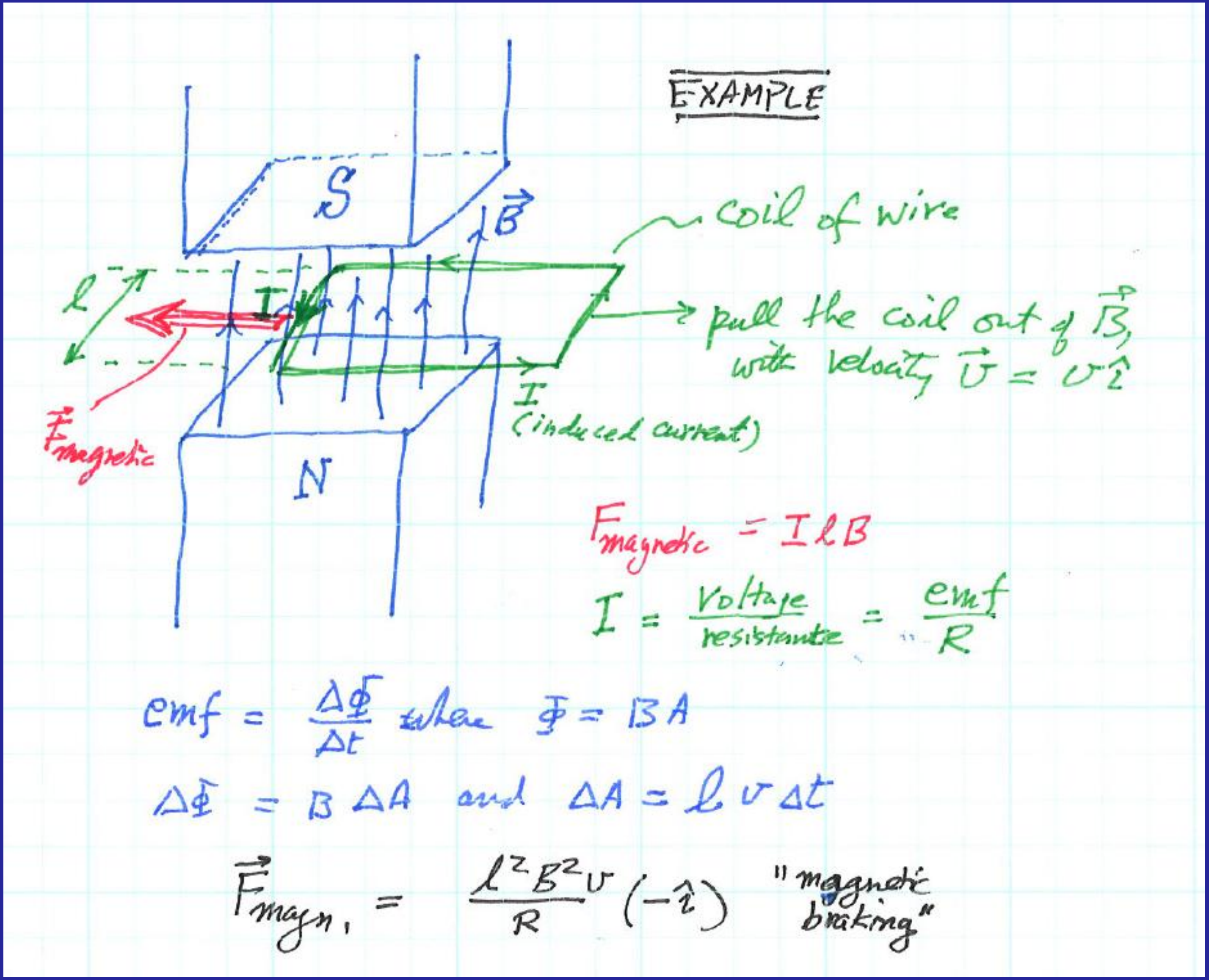
$$\Phi = BA$$

Faraday’s Law of Electromagnetic Induction …
… another use of the right-hand rule

If the magnetic field B changes, there is an induced electric field E; the direction of E is curling around the *change* of the magnetic field, opposite to the right hand rule.



Lenz’s law: If a conductor is present, the induced electric field opposes the change of the magnetic field.



EXAMPLE

$F_{magnetic} = I l B$

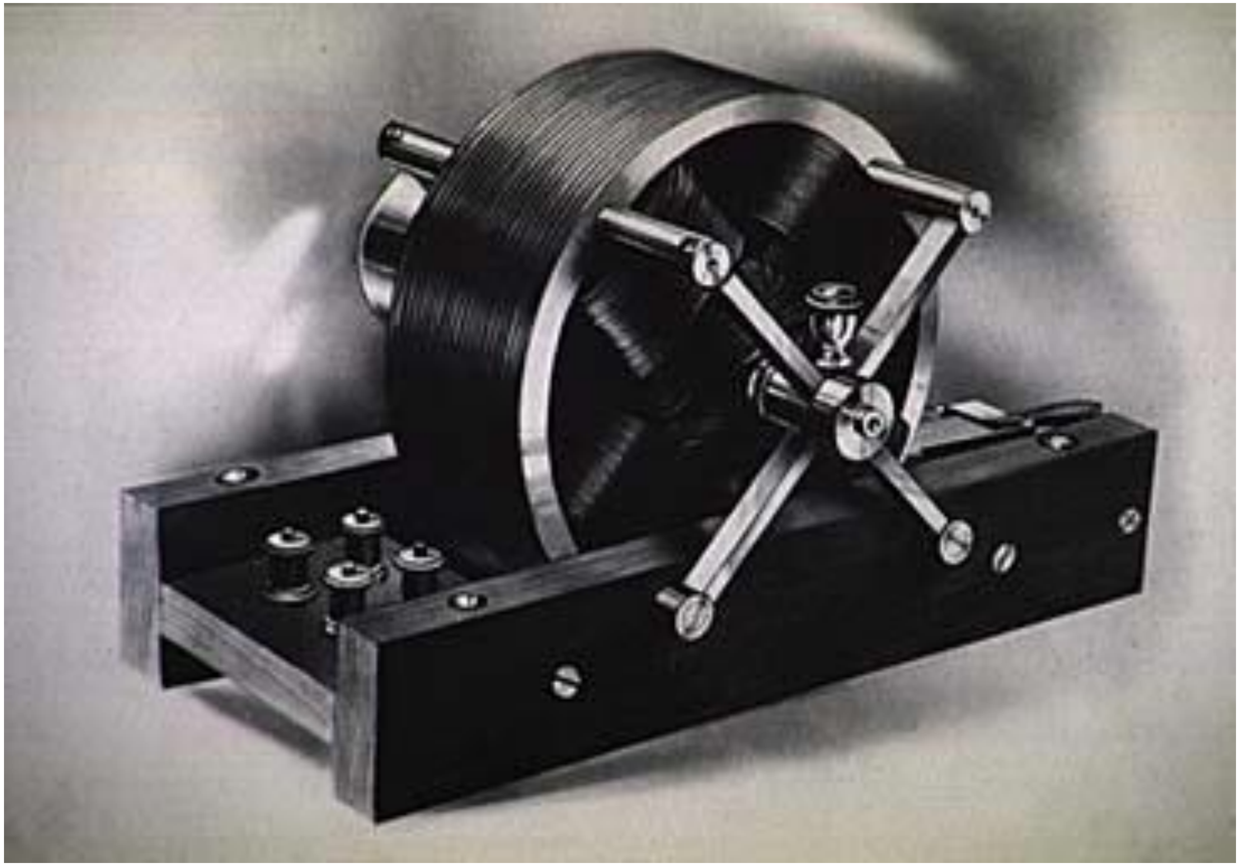
$I = \frac{\text{Voltage}}{\text{resistance}} = \frac{emf}{R}$

$emf = \frac{\Delta\Phi}{\Delta t}$ where $\Phi = BA$

$\Delta\Phi = B\,\Delta A$ and $\Delta A = l\,v\,\Delta t$

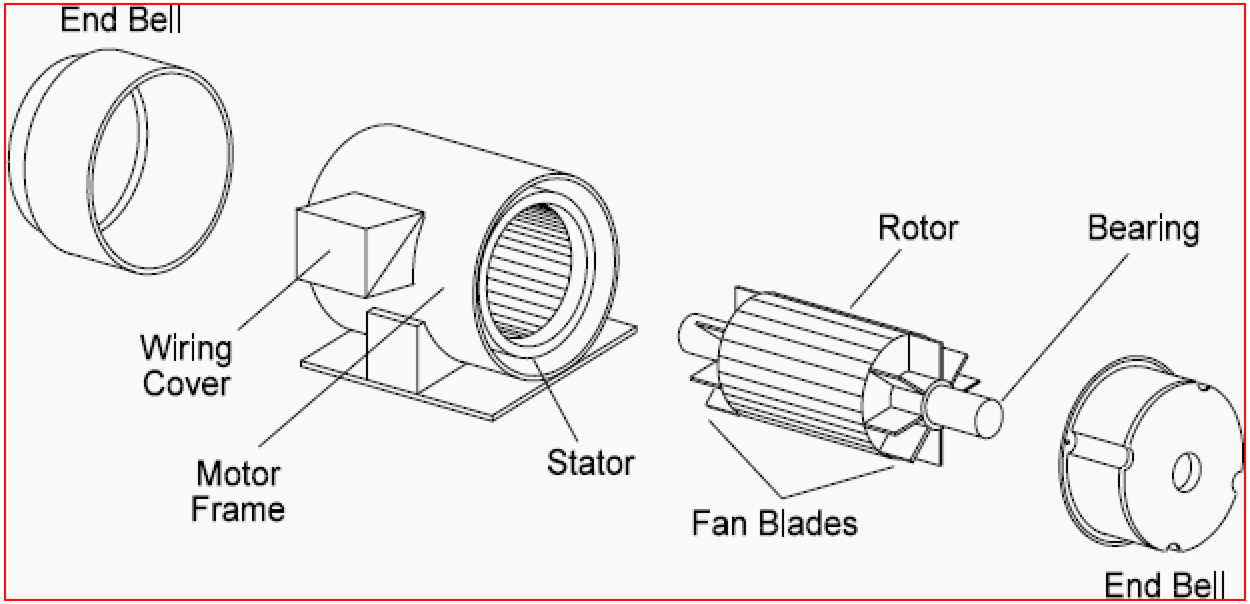
$\vec{F}_{magn.} = \frac{l^2 B^2 v}{R}(-\hat{i})$ "magnetic braking"

An example of electromagnetic induction in everyday life – the AC induction motor (Nikola Tesla)



Parts:

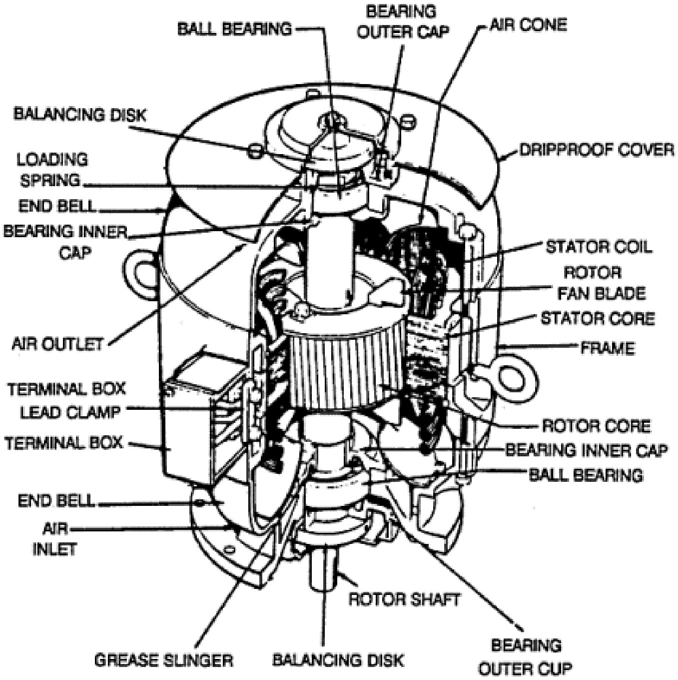
- terminals for AC current;
- stationary coil;
- rotating coils;
- iron cores



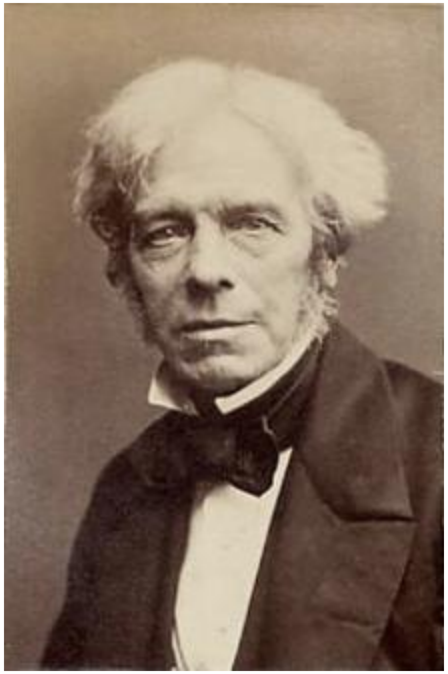
Electromagnetic induction motors:

The electric current in the rotor is driven by electromagnetic induction. The magnetic field produced by I(t) (Ampère's Law) varies in time, and so creates an electric field (Faraday's Law) which drives the current in the rotor. No wire is required to bring current to the rotor.

Demonstration: coca cola motor;
Demo: induction motor how it works



History of the Science of Electromagnetic Waves



Faraday:
- e.m. induction (1831);
- lines of force (1838 – 1852)

Maxwell:
- the electromagnetic field theory (1860-1865);
- wave solutions (1865)

Heinrich Hertz:
- produced e.m. waves in the laboratory; what we now call *radio* waves. (1886)

Maxwell's electromagnetic field theory

written in the mathematical language of vector calculus…

$$\nabla \cdot \mathbf{E} = \rho / \varepsilon_0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

(1) Gauss's law; implies $\vec{\mathbf{E}} = \frac{q\,\hat{\mathbf{r}}}{4\pi\varepsilon_0 r^2}$

(2) Gauss's law for $\mathbf{B}$

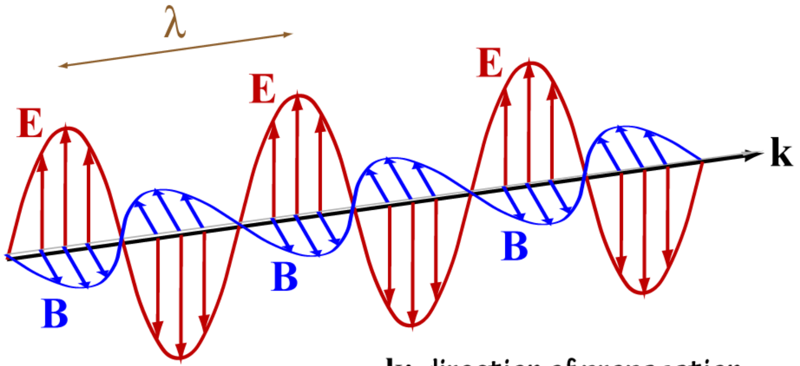
(3) Faraday's law; implies $emf = -\frac{\Delta\Phi}{\Delta t}$

(4) Ampère's law; implies $\vec{\mathbf{B}} = \frac{\mu_0 I\,\hat{\varphi}}{2\pi R}$

(4b) Maxwell's "displacement current"; Maxwell had to postulate this part of curl $\mathbf{B}$ in order for the equations to be self-consistent.

Electromagnetic Waves

Snapshot of the electric and magnetic field vectors along a line in the direction of propagation of a harmonic polarized electromagnetic wave



k: direction of propagation

Properties required by Maxwell's equations:

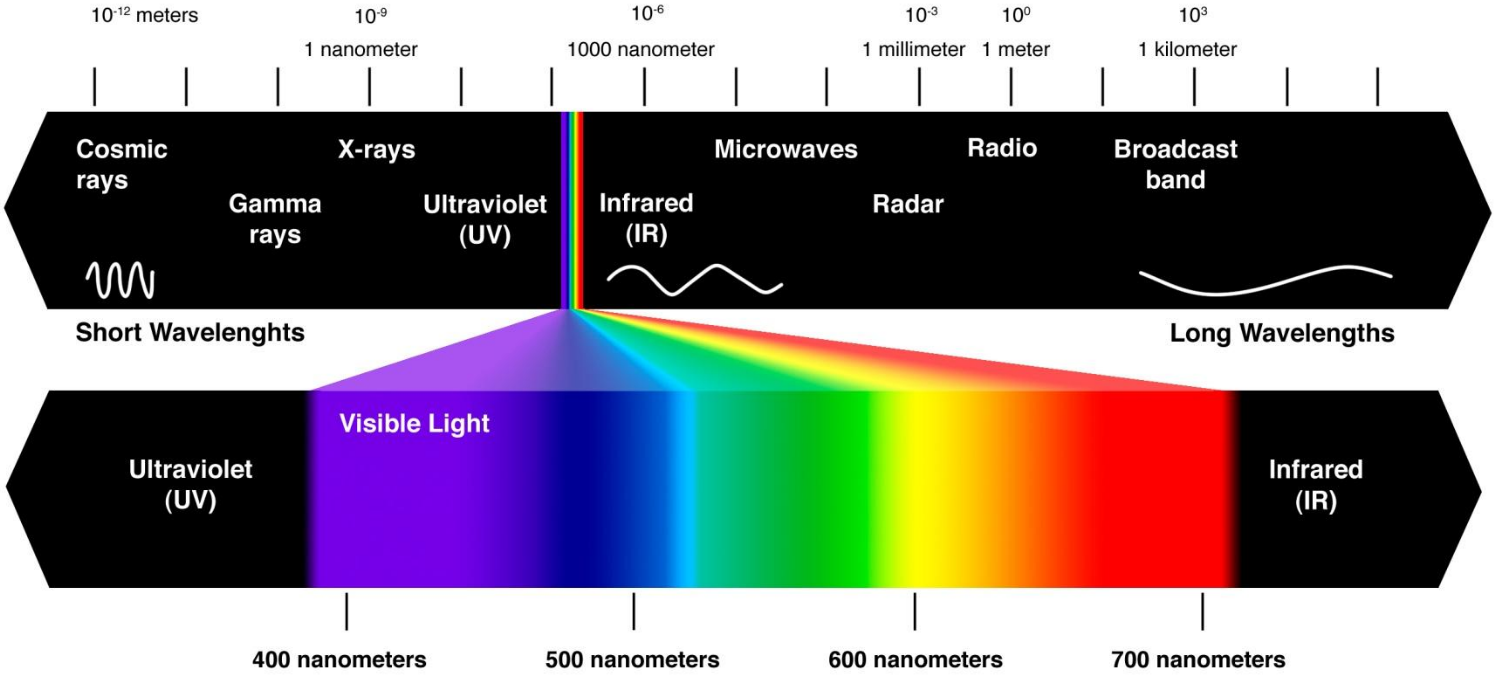
1. Wavelength λ, frequency f, wave velocity *c*: $\lambda f = c$
2. Polarization: **E**, **B** and **k** are mutually orthogonal .
3. The wave velocity is $c = (\mu_0 \varepsilon_0)^{-1/2}$
4. $|\mathbf{B}| = |\mathbf{E}|/c$

Maxwell, knowing the values of μ_o and ε_o from measurements of electric and magnetic forces, calculated *c*. He found the result $c = 3.00 \times 10^8$ m/s, which is equal to the speed of light. So he concluded that *light is an electromagnetic wave.*

Electromagnetic Waves

Maxwell's field theory predicted the existence of an infinite spectrum of electromagnetic waves, of which visible light is just the range 400 < λ < 700 nm, or, 0.75 > f > 0.46 PHz.

nm = nanometer = 10^{-9} m
PHz = petahertz = 10^{15} cycles/sec



Electromagnetic Waves

Nature is simple.

That's why we can understand it.

When we understand a phenomenon we can develop technologies based on it.

Each part of the E. M. spectrum has applications in technology.

END