Electromagnetic waves

Chapter 7

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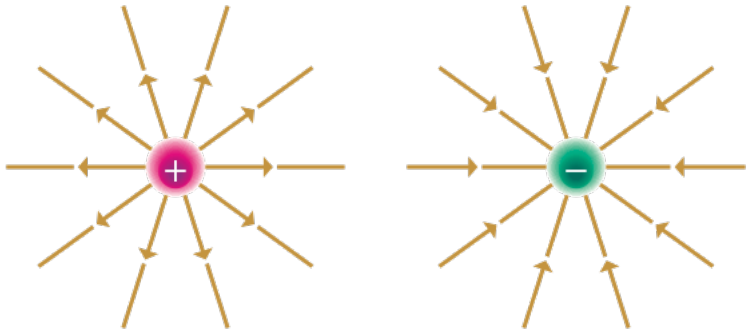
Maxwell's equations

Maxwell's equations are a beautiful theoretical summary of electromagnetism, based on the concept of electromagnetic fields.

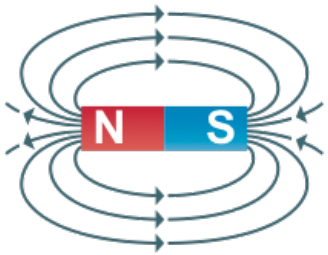
The electric field flux $\Phi(\vec{E})$ through any closed surface is proportional to the total electric charge q enclosed within the surface:

$$\Phi(\vec{E}) = \frac{q}{\varepsilon_0}$$



The magnetic field flux $\Phi(\vec{B})$ through any closed surface is zero: this means that the field lines are closed and not open as in the case of an electric field:

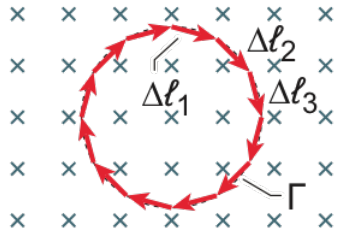
$$\Phi(\vec{B}) = 0$$



Maxwell's equations

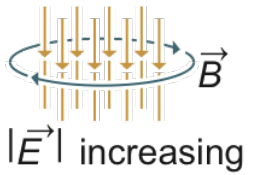
$$C(\vec{E}) = -\frac{\Delta\Phi(\vec{B})}{\Delta t}$$

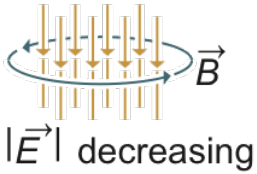
This equation represents an alternative way of writing the Faraday-Neumann law. The EMF is substituted by the circulation of the electric field, which is defined as:



$$C(\vec{E}) = \sum_{i=1}^{n} \vec{E} \cdot \Delta\vec{\ell}\, i$$

The circulation of the electric field $C(\vec{E})$ around a closed path Γ within a variable magnetic field is equal to the electromotive force. A variable magnetic field generates an electric field.





The circulation of the magnetic field $C(\vec{B})$ along a closed path is equal to the current connected with the path and to the time variation of the electric field:

$$C(\vec{B}) = \mu_0 \left[I + \varepsilon_0 \frac{\Delta\Phi(\vec{E})}{\Delta t} \right]$$

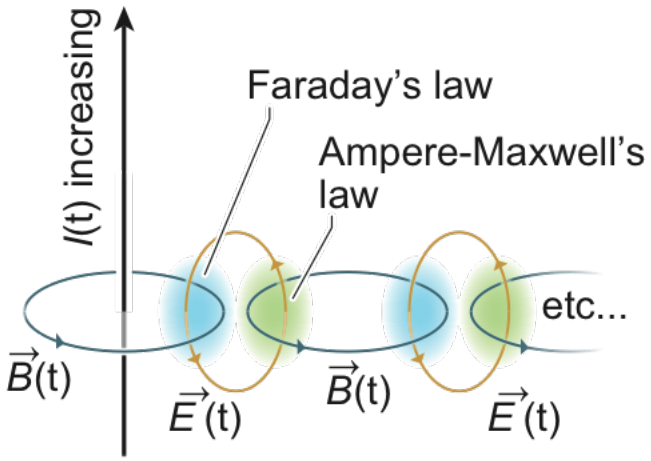
An electric current and a time variable electric field generate a magnetic field.

This equation is know as the Maxwell-Ampère equation.

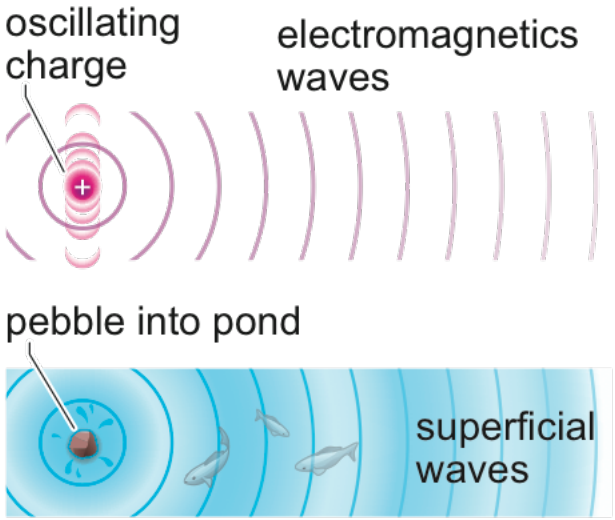
electromagnetic waves

Oscillating charges, i.e. a variation in the electric field, will produce electromagnetic waves.
They travel through space, transporting energy.

A variable current induces
a variable magnetic field
which generates
a variable alectric field, etc.

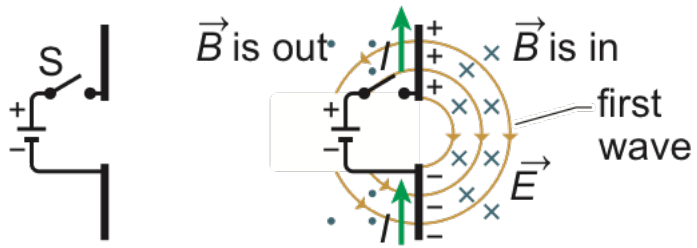


Electromagnetic field perturbations
due to the oscillation of a charge
propagate in space like the superficial
waves generated when a pebble
is thrown into a pond.

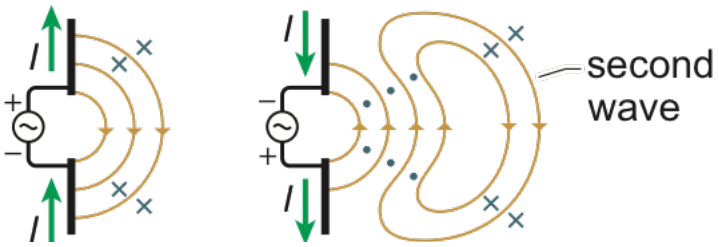


production of electromagnetic waves

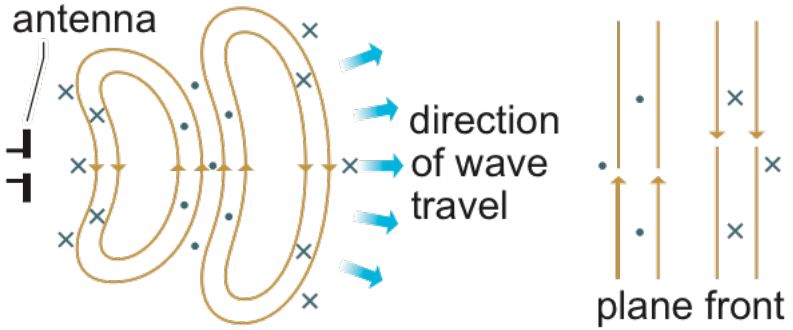
When the switch of a circuit is closed
there is a variation in the electric field
(i.e. the current starts to flow)
and a magnetic field is generated
around the wire.



Using an alternating current generator,
a magnetic field with opposite
orientation has been created,
whilst the first one
is propagating through space.



This circuit is an **antenna**
that emits electromagnetic waves
in all directions.
Very far away from the antenna
the wave fronts (field lines)
are practically flat and are
referred to as *plane* waves.



velocity of electromagnetic waves

Maxwell foresaw the existence of electromagnetic waves.
He calculated the propagation speed in vacuum v_{em} of electromagnetic waves using the relationship:

$$v_{em} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

Substituting the numerical values of ε_0 and μ_0 gives:

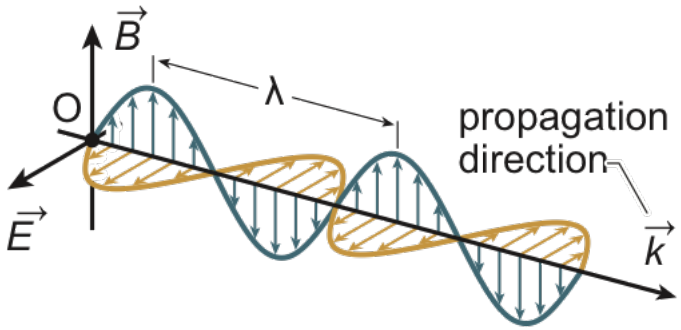
$$v_{em} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = \frac{1}{\sqrt{\left(8.854 \times 10^{-12} \frac{C^2}{N \cdot m^2}\right) \times \left(4\pi \times 10^{-7} \frac{N}{A^2}\right)}} = 2.988 \times 10^8 \text{ m/s}$$

The value obtained by Maxwell corresponded
to the speed of light in a vacuum
as measured by both Fizeau and Foucault with thir experiments.
Maxwell inferred therefore that light is an electromagnetic wave
and that it propagates in vacuum at velocity:

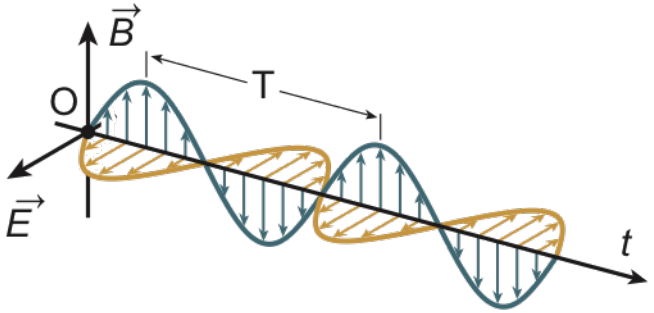
$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

the profile of electromagnetic waves

Elecromagnetic waves
are transverse waves for which
the oscillating electric
and magnetic fields
are both perpendicular
to the propagation direction.



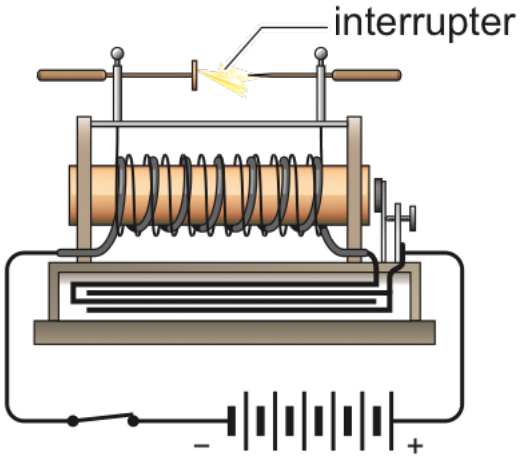
For each point in space, the amplitude
of an electromagnetic wave oscillates
as a function of time at the same
frequency *f* as the source.
The period *T* and the wavelength λ
in vacuum can be calculated
from the propagation speed *c*.

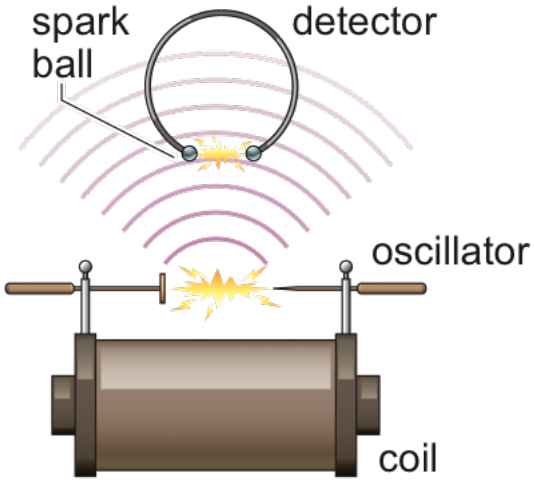


$$T = \frac{\lambda}{c} \quad \rightarrow \quad \lambda = cT = \frac{c}{f}$$

experimental proof of electromagnetic waves

Heinrich Hertz was the first to send and receive radio waves. He demonstrated experimentally for the first time the existence of electromagnetic waves.

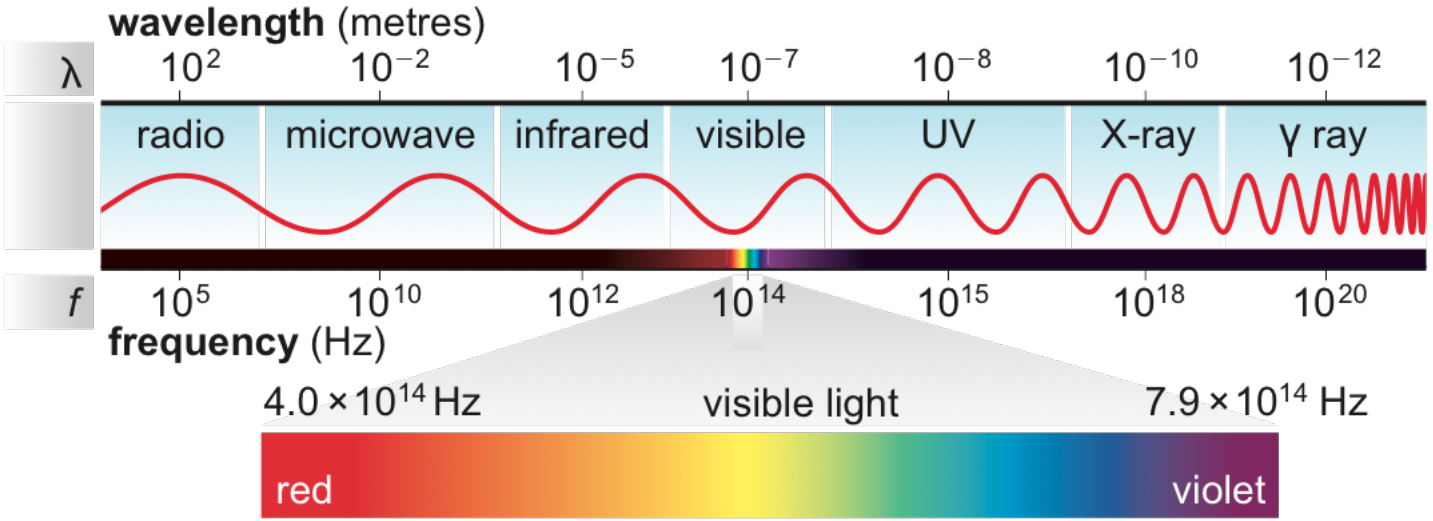




Hertz generated electromagnetic waves by means of a Ruhmkorff coil capable of producing high voltage pulses. Electromagnetic waves were detected by means of a ring with spark balls attached: the presence of an oscillating charge in the ring caused sparks to jump across the gap between the balls.

the electromagnetic spectrum

The electromagnetic spectrum is made up of all the possible frequencies or wavelengths of electromagnetic waves



Electromagnetic waves interact with objects encountered along their propagation path in different ways according to their frequencies and wavelengths.
Light, for example, can be absorbed by, reflected from, or refracted by the surface of an object, or be transmitted through it.

properties of the electromagnetic spectrum

	type of wave	typical source	typical users	danger of over exposure
low frequency long wavelength	radio	electronic circuits, cool objects	communications, radio TV	safe (unless very concentrated)
	microwaves	electronic circuits, cool objects	communication satellites, telephony, heating water and food	burning, if concentrated
	infra-red (ir)	electronic devices, warm objects, sun	security lighting, remote control	burning, if concentrated
	visible ligth	electronic devices, (LED), hot objects, sun	seeing, photography	burning, blindness, if concentrated
	ultra-violet (UV)	gas discharge, very hot objects, amps, sun	suntan lamps	sunburn, skin cancer
high frequency short wavelenght	X-rays	very fast electrons hitting a metal target	imaging defects in bones, hidden devices	cell destruction, cell mutation, cancer
	gamma rays (γ)	radioactive nuclei decaying	medical tracers, killing cancerous cells, sterilisation	cell destruction, cell mutation, cancer

learning the basics

1. The existence of electromagnetic waves was predicted by Maxwell's studies on electromagnetism. T F

2. An electromagnetic wave travels through space carrying the oscillating charge that generated it. T F

3. The experimental evidence of the existence of electromagnetic waves was provided by Maxwell. T F

applying the concepts

1. Complete the table with the missing information:

	type of wave	typical source	typical users	danger of over exposure
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applying the concepts

2. Draw the electric and magnetic fields for the electromagnetic waves in the two representations: