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Maxwell’s equations are the basic equations of electromagnetism. They involve calculus; here is a summary:

1. Gauss’s law relates electric field to charge

2. A law stating there are no magnetic “charges”

3. A changing electric field produces a magnetic field

4. A magnetic field is produced by an electric current, and also by a changing electric field
22-2 Production of Electromagnetic Waves

Since a changing electric field produces a magnetic field, and a changing magnetic field produces an electric field, once sinusoidal fields are created they can propagate on their own.

These propagating fields are called electromagnetic waves.
22-2 Production of Electromagnetic Waves

Oscillating charges will produce electromagnetic waves:

(a) 
(b)
22-2 Production of Electromagnetic Waves

Far from the source, the waves are plane waves:
22-2 Production of Electromagnetic Waves

The electric and magnetic waves are perpendicular to each other, and to the direction of propagation.
When Maxwell calculated the speed of propagation of electromagnetic waves, he found:

\[ c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}. \]  

(22-3)

Using the known values of \( \varepsilon_0 \) and \( \mu_0 \) gives \( c = 3.00 \times 10^8 \) m/s.

This is the speed of light in a vacuum.
22-3 Light as an Electromagnetic Wave and the Electromagnetic Spectrum

Light was known to be a wave. The production and measurement of electromagnetic waves of other frequencies confirmed that light was an electromagnetic wave as well.

The frequency of an electromagnetic wave is related to its wavelength:

$$\text{Frequency} \times \text{Wavelength} = \text{Speed}$$

$$(22-4)$$
Electromagnetic waves can have any wavelength; we have given different names to different parts of the electromagnetic spectrum.
22-4 Measuring the Speed of Light

Over the years, measurements have become more and more precise; now the speed of light is defined to be:

\[ c = 2.99792458 \times 10^8 \text{ m/s} \]

This is then used to define the meter.
Example

• Calculate the wavelength of a
   a. 60-Hz EM wave
      \[ f = c\lambda \]  
      (Distance from NY to LA: 4500 KM)
   b. 93.3 MHz FM radio wave
22-5 Energy in EM Waves

Energy is stored in both electric and magnetic fields, giving the total energy density of an electromagnetic wave:

\[ u = u_E + u_B = \frac{1}{2} \varepsilon_0 E^2 + \frac{1}{2} \frac{B^2}{\mu_0}. \]  \hspace{1cm} (22-5)

Each field contributes half the total energy density.

\[ u = \frac{1}{2} \varepsilon_0 E^2 + \frac{1}{2} \frac{\varepsilon_0 \mu_0 E^2}{\mu_0} = \varepsilon_0 E^2. \]  \hspace{1cm} (22-6a)
This energy is transported by the wave.
22-5 Energy in EM Waves

The energy transported through a unit area per unit time is called the intensity:

\[ I = \epsilon_0 c E^2 = \frac{c}{\mu_0} B^2 = \frac{EB}{\mu_0}. \]  \hspace{1cm} (22-7)

Its average value is given by:

\[ \bar{I} = \frac{1}{2} \epsilon_0 c E_0^2 = \frac{1}{2} \frac{c}{\mu_0} B_0^2 = \frac{E_0 B_0}{2\mu_0}. \]  \hspace{1cm} (22-8)
In addition to carrying energy, electromagnetic waves also carry momentum. This means that a force will be exerted by the wave.

**Force per unit area exerted by the waves: Radiation Pressure**

The radiation pressure is related to the average intensity. It is a minimum if the wave is fully absorbed:

$$P = \frac{\bar{I}}{c}. \quad (22-10a)$$

and a maximum if it is fully reflected:

$$P = \frac{2\bar{I}}{c}. \quad (22-10b)$$
Radiation from the Sun that reaches the Earth’s surface transport energy at a rate of about 1000 W/m². Estimate the pressure and force exerted by the Sun on your outstretched hand.

\[ P = \frac{I}{c}, \quad P = \frac{F}{A} \quad (A = 0.02 \text{m}^2) \]
Summary of Chapter 22

• Maxwell’s equations are the basic equations of electromagnetism

• Electromagnetic waves are produced by accelerating charges; the propagation speed is given by:

\[ c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}. \]

• The fields are perpendicular to each other and to the direction of propagation.
Summary of Chapter 22

- The wavelength and frequency of EM waves are related:
  \[ c = \lambda f, \]
- The electromagnetic spectrum includes all wavelengths, from radio waves through visible light to gamma rays.