



# An Introduction to Physical Science: *Electricity, Magnetism and Maxwell's Equations*

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# Electricity

- Electricity known since ancient times

AMBER



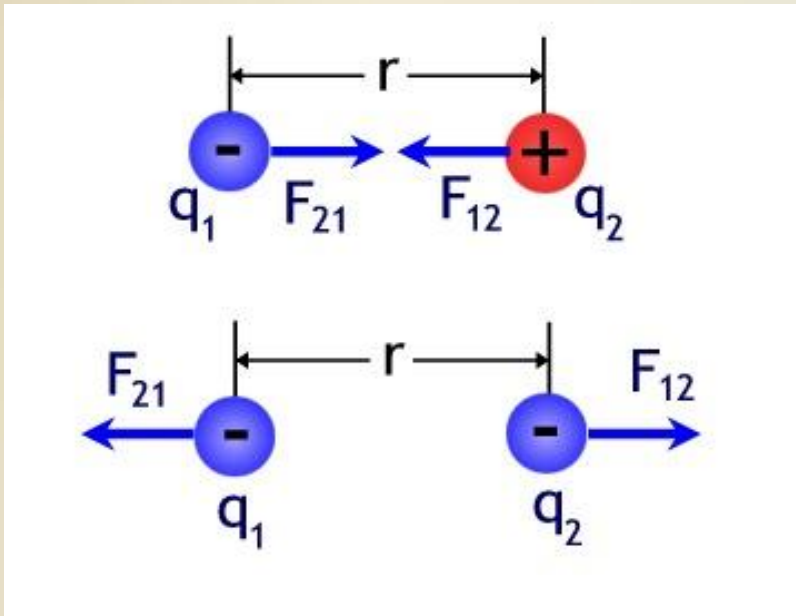
LIGHTENING





# Electricity

- Like gravity, Coulomb showed that electricity obeyed an inverse square law
- Unlike gravity, electric forces could be both attract and repulsive implying two types of charge (+ and -)

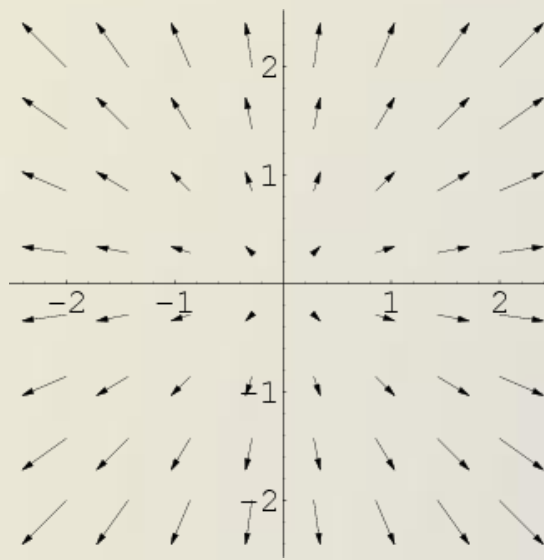
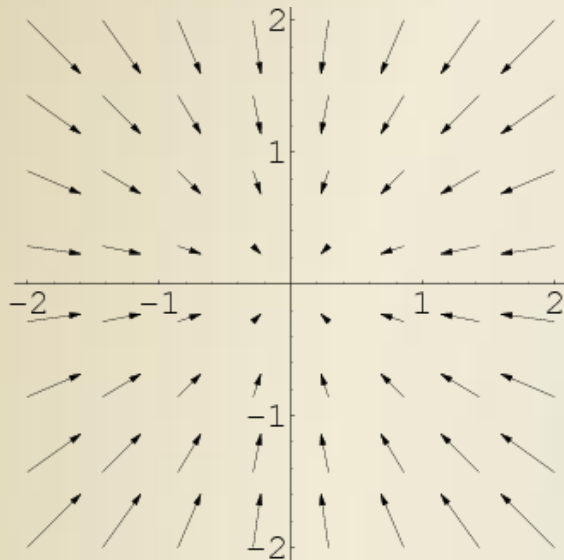


$$F = k_e \frac{q_1 q_2}{r^2}$$

# Electricity (the math)

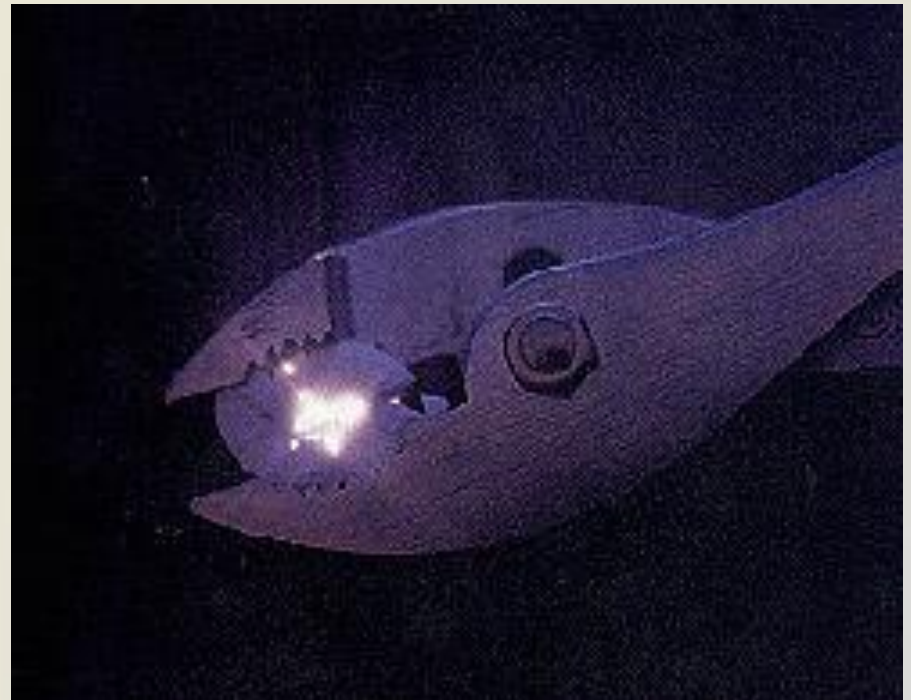
- The modern sophisticated form of Coulomb's Law is Gauss's Law.
- The advantage of Gauss's Law over Coulomb's Law is that by using electric fields one avoids "action-at-a-distance"
- Although complicated looking it says something very simple – electric charge (i.e.  $\rho$ ) creates a diverging or converging electric field.

$$\nabla \cdot \vec{E} = 4\pi k_e \rho$$



# Fun home experiments with electricity

- A small stream of water can be bent by a rubbed comb or balloon. Try it
- Wintergreen lifesavers will spark when crushed. Must be done in the dark. Only works for wintergreen (the oil of wintergreen is key) and must be real sugar lifesavers. Try it.

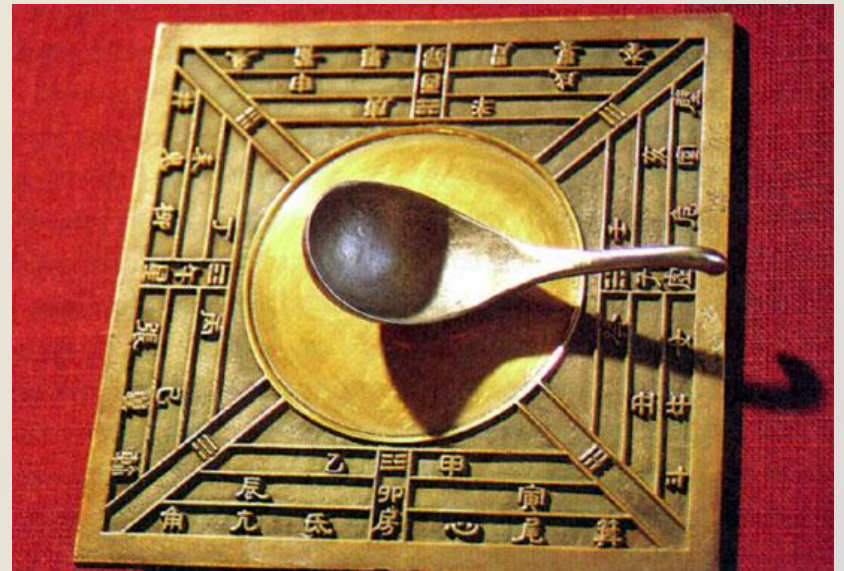


# Magnetism

- People also knew about magnetism since ancient times through lodestones (magnetite) could attract certain metals and align with North-South.
- Some similarities to electric force – both attraction and repulsion. However no apparent inverse square law and direction of magnetic force was more complex.

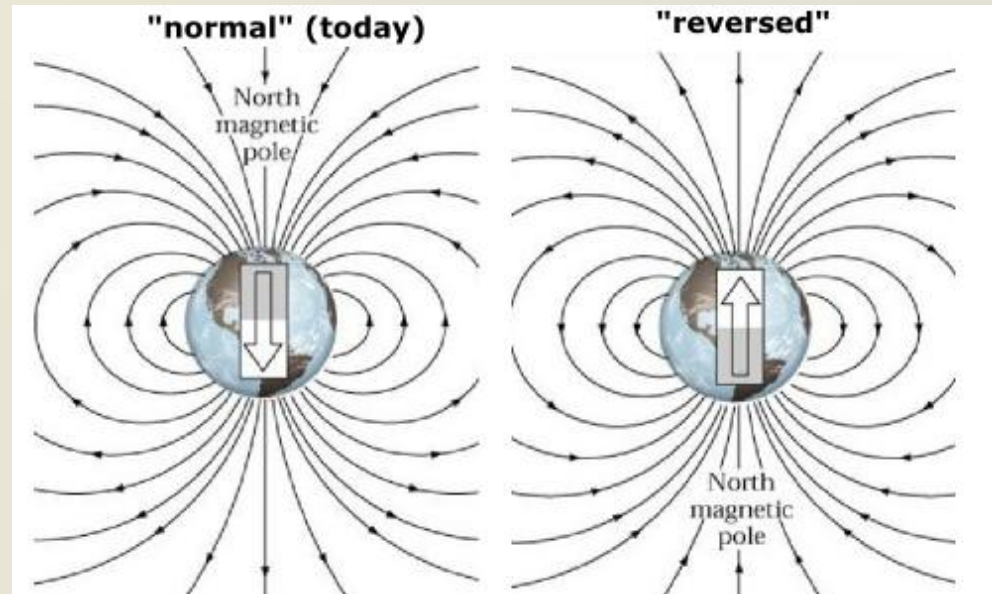


Lodestone (circa 600 BC)



# Magnetism

- The Earth (and most planets with a liquid metal core and large enough rotation rate) have magnetic fields.
- The Earth's magnetic field acts as a shield against the solar wind.
- There are periodic reverses of the Earth's magnetic field.



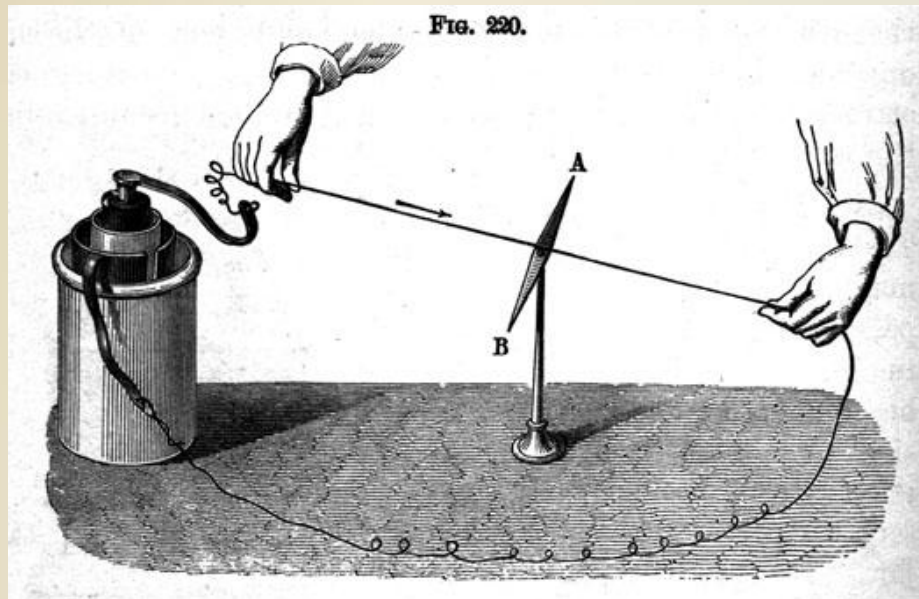
# Magnetic Money

- US money is magnetic. Amaze friends and win bets!



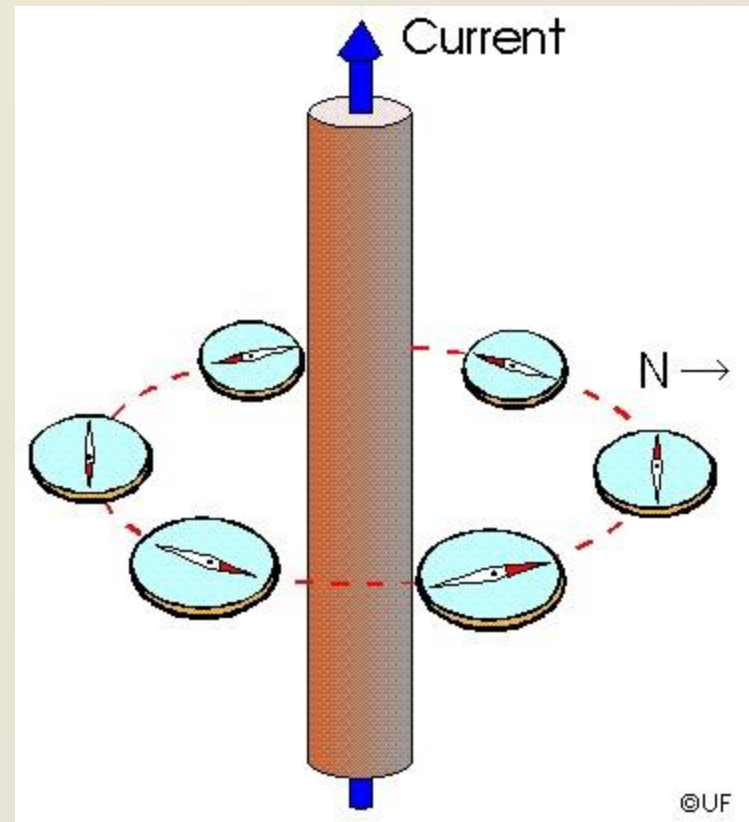
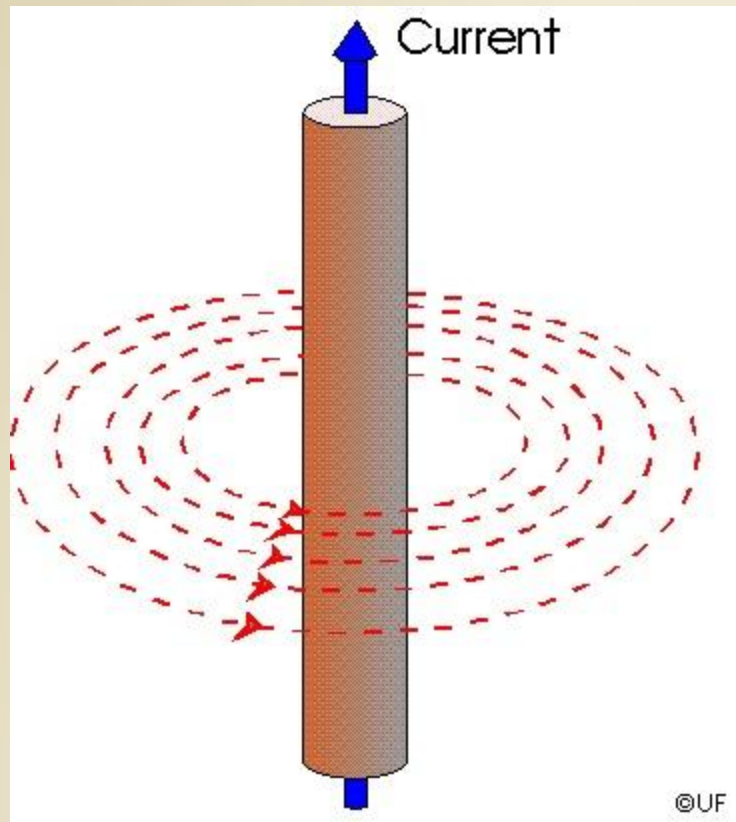
# Connection between electricity (electric current) and magnetism

- While performing a lecture demonstration on April, 21<sup>st</sup> 1820 Hans Oersted found that an electric current produced a magnetic field.
- All magnetic effects observed so far are produced by currents. Currents may be atomic currents.



# Magnetism from Electricity

- The magnetic fields produced by a current “wrap” around the current.

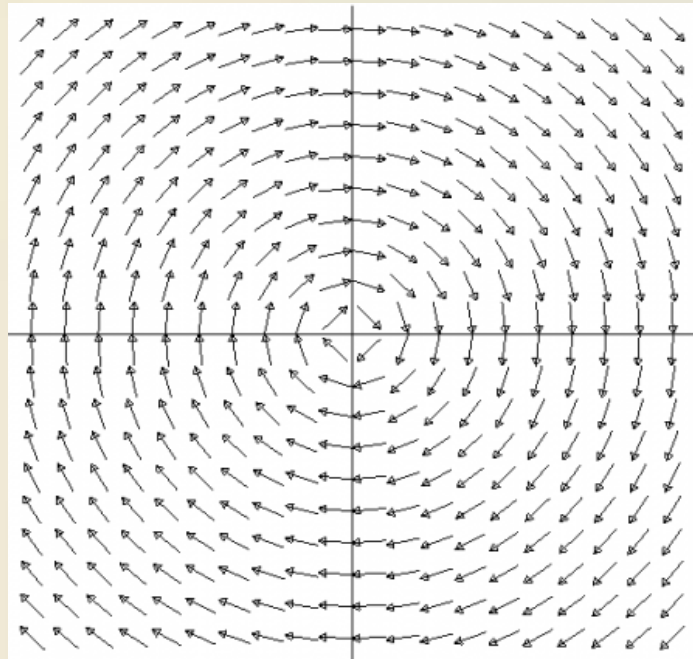


# Magnetism from Electricity (the math)

- Andre-Marie Ampere formulated a mathematical description of the connection between electric currents and magnet fields.
- The complex formula has a simple meaning – a “curling” magnetic field is created by an electric current (density).

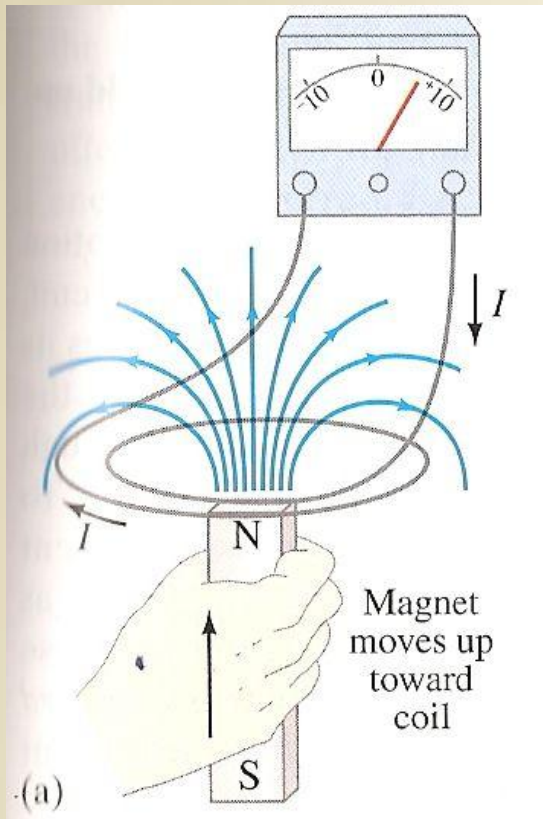
$$\nabla \times \vec{B} = \mu_0 \vec{J}$$

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



# Electric field from a (changing) magnetic effect

- Michael Faraday found that an electric field could be created by changing magnetic field in addition to being created by a charge.

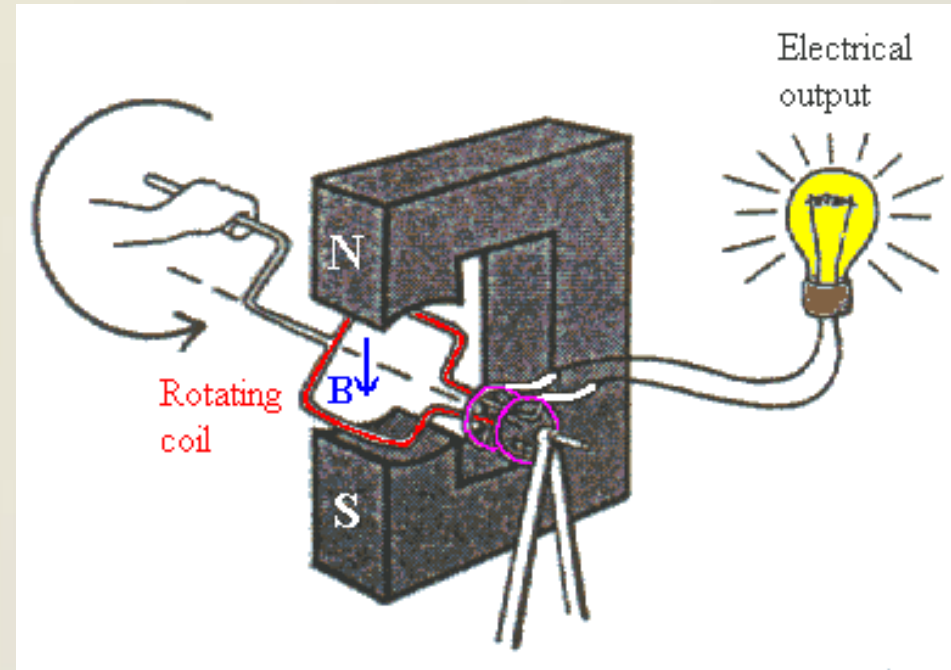
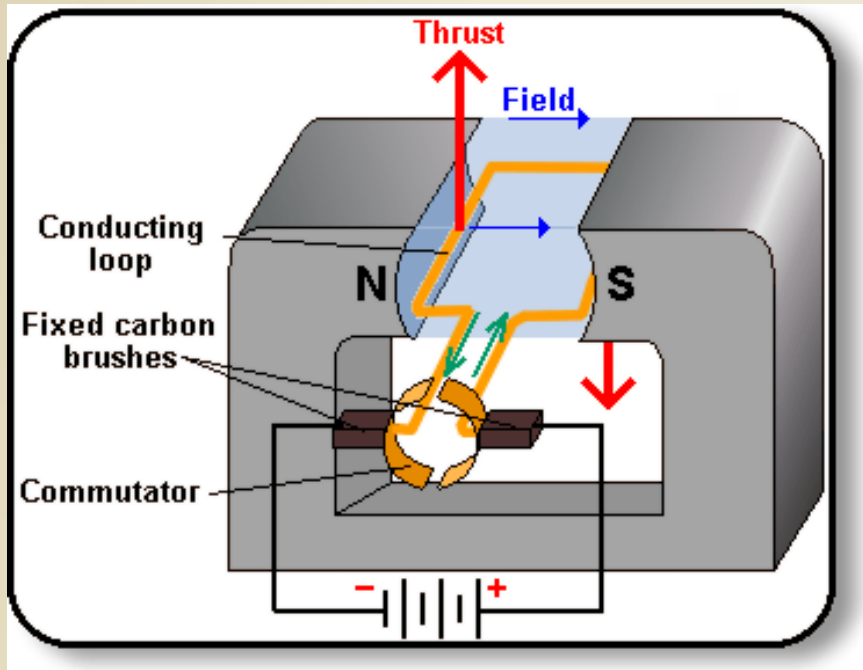


$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$



# Faraday Law of Induction (applications)

- Electric motors and generators are based on Faraday's Law of induction thus all modern society would be very different without Faraday.

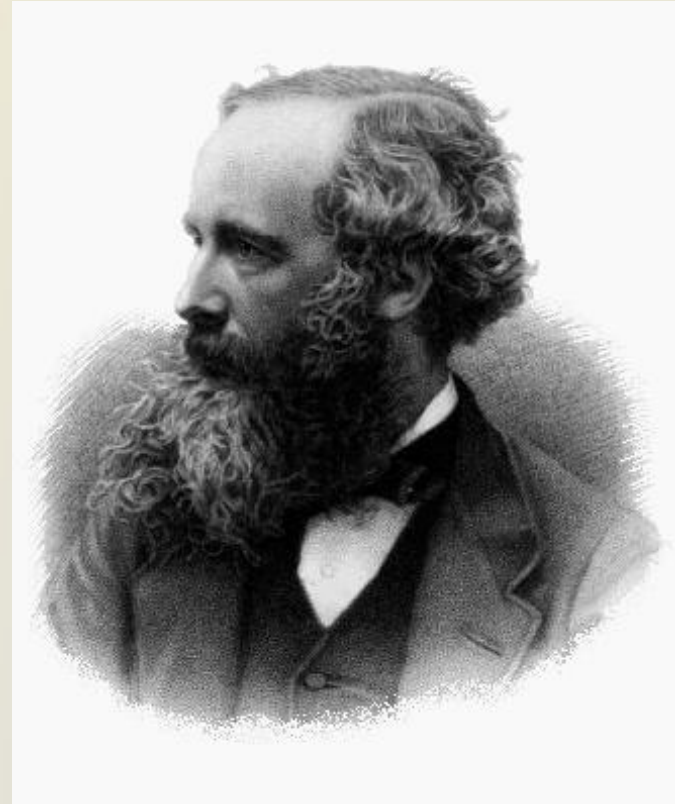


# Maxwell unifies electricity and magnetism

- Using symmetry arguments Maxwell argued that Ampere's Law should be extended to allow "curling" magnetic fields from changing electric fields

$$\nabla \times \vec{B} = \mu_0 \left( \vec{j} + \frac{1}{4\pi k_e} \frac{\partial \vec{E}}{\partial t} \right)$$

- In words – a curling magnetic field can be created by an electric current OR a changing electric field.

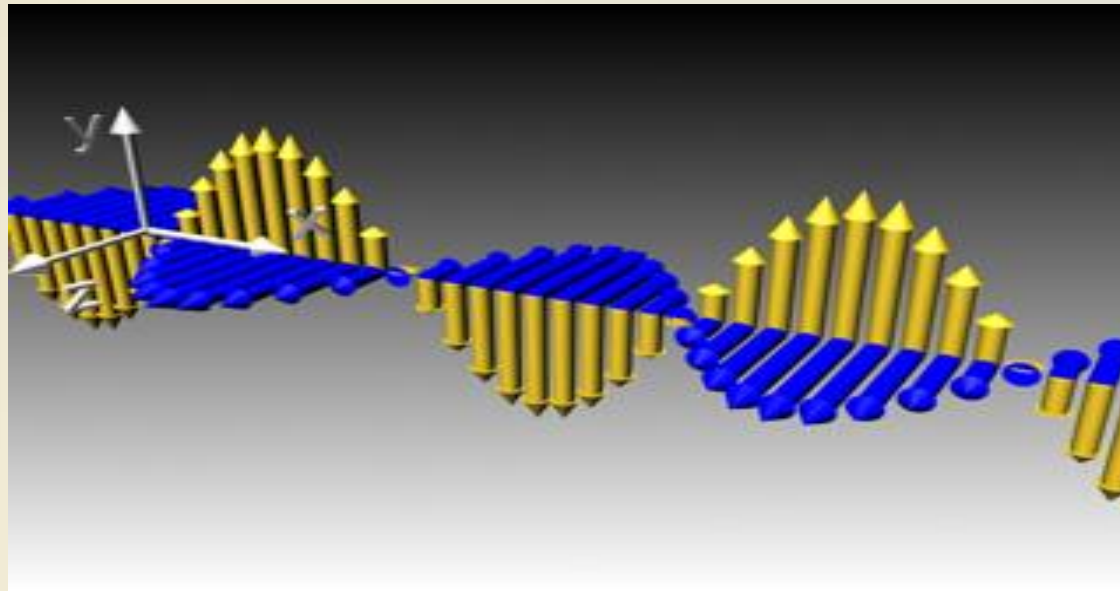


# Light is an electromagnetic wave

- Maxwell immediately showed that his unified theory of electricity and magnetism had wave solutions and the speed of these waves were

$$c = \frac{\sqrt{4\pi k_e}}{\sqrt{\mu_0}} = 2.99 \times 10^8 \text{ m/s}$$

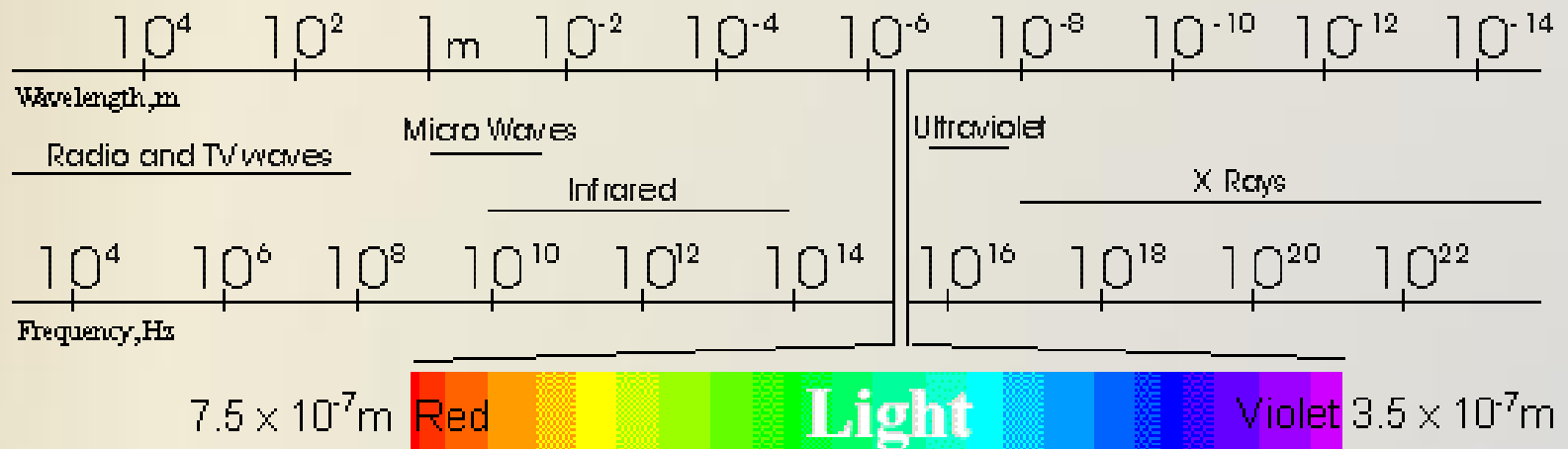
- This was the speed of light! Maxwell realized exactly what light was – an electromagnetic wave.



# Maxwell's Equation – the first unified theory

$$\nabla \cdot \vec{E} = 4\pi k_e \rho \qquad \nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \nabla \times \vec{B} = \mu_0 \left( \vec{J} + \frac{1}{4\pi k_e} \frac{\partial \vec{E}}{\partial t} \right)$$



# Electricity

- Electric charge was thought to be a fluid. In 1913 Robert Millikan showed electric charge was quantized  $q=1.6 \times 10^{-19}$  Coulombs

