Electricity, Magnetism, and Electromagnetic Waves

1. Water breaking into droplets, electrochemistry in batteries, and rubbing different materials separate electrons from their atoms producing **electrical charges**.

The water dropper separated charges as the water flow broke into droplets.

The chemistry in a battery maintains a charge difference between the positive and negative terminals of the battery.

2. Electric charges produce **electric fields** between them.

We cannot see electric fields; we only see their effect on charges.

3. Electric fields in produce a **electric force** on charges.

As the charge in a drop became quite large, the droplets were pushed apart into a spray showing that like charges repelled.

As the opposite charges in the aluminum foils grew, the foils pulled together until a spark jumped between them.

The electric field from the Tesla coil lit the fluorescent light I held near it even before a spark jumped to the light.

4. Charges can be stored on pair of nearby pieces of metal, an arrangement called a **capacitor**. Capacitors can store electrical energy.

The two sides of the water dropper demonstration formed a capacitor which held the growing charge from the dripping water.

When I added 200 V to each of 45 capacitors connected in series, the result was 9000 V between the ends which formed an 8 mm spark when discharged. That arrangement can hold its charge for many days if not discharged.

5. In metal wires, some electrons are free to move in response to electric fields. This flow is an **electric curren**t.

6. Electric currents cause **heating** in wires and **magnetic fields** around wires. Electromagnets store magnetic energy.

Our electromagnets became warm after a minute or so.

The electric currents in the wire of our electromagnets produced a magnetic field that aligned the magnetic domains in the iron nail making the magnetic effect stronger.

7. Electrons and many other fundamental particles are magnets and are surround by magnetic fields.

Permanent magnets like refrigerator magnets ultimately owe their magnetism to aligned electrons in their atoms.

8. All magnets have **north and south poles**. Like poles repel, unlike poles attract.

This is easily seen when playing with magnets.

The north end of a compass needle is pulled toward the south magnetic pole of the earth (at its north geographic pole), and the south end of a compass needle is pulled toward the north magnetic pole of the earth (at its south geographic pole). The result is a twisting force on the compass needle.

9. Very large numbers of electrons in iron align their magnetic fields within **microscopic magnetic domains**.

The iron core of our electromagnets made the magnetic effect stronger.

Paper clips, magnetic sand, etc., near a magnet have their magnetic domains temporarily aligned and acquires a north and south pole of their own so that they temporarily become attracted to the magnet.

The domains mostly become random again when the magnet is removed from near the paper clip.

10. A **changing magnetic field** is surrounded by electric field loops that can cause electric currents in surrounding metal loops.

Moving a bar magnet in and out of a wire coil connected to a galvanometer (current measuring instrument) caused electric currents to flow.

The levitation of an aluminum ring was produced by the changing magnet field of the coil below it causing an electric field in the ring which in turn caused electric currents to flow producing a magnetic field in the aluminum ring. That field opposed the original field and lifted the ring. (It is a bit more complicated than this since the effect is different for very low frequencies than for higher frequencies.)

A changing magnetic field produced when an electromagnet is energized or de-energized causes an electric field around it which can cause electric currents to flow in nearby metals.

We saw that we could “stir” electrons by moving a powerful magnet above an aluminum disk. The current of “stirred” electrons produced a magnetic field that opposed our motion of the powerful magnet.

When dropping a powerful magnet into an aluminum tube, the changing magnetic field from the falling magnet caused electric field loops within the aluminum tube wall which then caused electrons to flow in loops. That electron current produced a magnetic field the opposed the falling motion of the powerful magnet making it fall more slowly.

11. A **charge moving in a magnetic field** experiences a sideways force.

When we held a magnet near the front of an oscilloscope electron beam, the beam moved away from or toward the magnet depending on which way its north pole was oriented.

12. Changing electric or magnetic fields produce **electromagnetic waves**.

The 592 kHz changing magnetic and electric fields in the tower of the Tesla coil produced radio signals picked up by the radio tuned to that frequency.

If a computer pin in a Raspberry Pi computer is energized with a 100 MHz voltage, radio signals are transmitted at that frequency. If the frequency is varied in accordance with a musical sound, the music is transmitted to a FM radio receiver tuned to that frequency.

Vibrating electric fields in atoms of a radiant heater produced electromagnetic waves over a wide range of frequencies centered on about 10^{14} Hz. This produces infra-red (heat) black-body radiation.

Visible Light is produced when atoms vibrate while changing from one energy state to another. The difference in energy of the energy states is the energy of the light photon.

Gamma rays are produced when atomic nuclei change energy states.

13. **Electromagnetic waves travel in a vacuum at the speed of light** but travel slower in a transparent material like water or glass. The ratio of these speeds is the **index of refraction** of the material. They seem to follow a path that requires the shortest (or sometimes longest) amount of time (Fermat's Principle).

The path of light rays reflected off of a mirror is a path of least travel time.

The refraction of light rays passing from air to water follows a path of least travel time.

Light passing through a transparent sphere (like a marble) can travel directly through its center (maximum time) and also around a ring near the outer edge of the sphere (minimum time).

14. Electromagnetic waves actually come in chunks called **photons**, each chunk has an **energy proportional to the frequency** of the wave. The electromagnetic wave of a photon is actually a probability wave for the possible transfer of the entire photon energy.

For very high energy electromagnetic waves, the chunkiness is obvious and we can easily detect one photon at a time.

Under very special conditions, fluctuations in the flow of photons of visible light waves can be detected by our eyes.

15. In electromagnetic waves the electric and magnetic fields are perpendicular to each other and both are perpendicular to the direction of travel for the wave. The direction of the electric field defines its **polarization direction**.

Stretched plastic lets only one polarization of light pass, and light reflected off of water is primarily horizontally polarized. Polarized sunglasses let vertical polarization pass so that the horizontally-polarized sunlight reflected from water and the surface of roads is reduced.

Light scattered off of the sky away from the sun direction is primarily horizontally polarized.

Bees use this polarized skylight for navigation.

16. Since light is a wave, it has a **wavelength** and can be diffracted by narrow openings. Generally, we talk of waves when the photon nature is not obvious and rays when it is.

Radio waves have wavelengths of meters
Microwaves have wavelengths of mm or cm.
Infra-red waves have wavelengths of microns (μm).
Light waves have wavelengths between 450 and 750 nm.
Ultra-violet rays have wavelengths of a 100-400 nm.
X-rays have wavelengths of the size of atoms, 0.01-10 nm.
Gamma rays have wavelengths that are even shorter.

We explain mirrors and lenses using the concept of straight-line rays, but when a laser beam passes through a small hole or slit, it spreads out as would be expected for waves.

The image of a bacterium in a light microscope is blurred by the fact that a bacterium has a size comparable to that of microscope light.

A telescope above the atmosphere has an angular resolution limited by the wavelength of light compared with the size of the telescope's main lens.

The colors in butterfly wings, beetle shells, small amounts of oil on water, soap bubbles, and other phenomena are the result of light of different colors having different wavelengths that interfere differently.

Maxwell's Equations - Merging Electricity, Magnetism and Light

Electrical forces involve a constant called the vacuum permittivity $\epsilon_0 = 8.85 \times 10^{-12} \frac{\mathrm{C}^2}{\mathrm{N \cdot m^2}}$.

Magnetic forces involve a constant called the vacuum permeability $\mu_0 = 4\pi \times 10^{-7} \frac{\mathrm{T \cdot m}}{\mathrm{A}}$

In 1864, theoretical physicist James Clerk Maxwell guessed that there might be a new term to the equations describing electricity and magnetism and suggested that all of electricity, magnetism and light could be described by the following four vector partial differential equations:

Electric fields are caused by charges and changing magnetic fields:

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0} \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Magnetic fields are caused by charge currents and changing electric fields:

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

The new term added by Maxwell was the $\mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$ term in the last equation.

In the vacuum of space where there are no charges or currents, these equations describe waves of electric and magnetic fields moving at a speed given by

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = \frac{1}{\sqrt{(4\pi \times 10^{-7} \frac{\mathrm{T \cdot m}}{\mathrm{A}})(8.854 \times 10^{-12} \frac{\mathrm{C}^2}{\mathrm{N \cdot m^2}})}} = 2.998 \times 10^8 \frac{\mathrm{m}}{\mathrm{s}}$$

Note: $\frac{\mathrm{T \cdot m \cdot C^2}}{\mathrm{A \cdot N \cdot m^2}} = \frac{\mathrm{T \cdot m \cdot C^2}}{\frac{\mathrm{C}}{\mathrm{s}} \cdot \mathrm{C} \cdot \frac{\mathrm{m}}{\mathrm{s}} \cdot \mathrm{T \cdot m^2}} = \frac{\mathrm{s^2}}{\mathrm{m^2}}$ where we used $F = qvB$ and $I = \frac{\Delta Q}{\Delta t}$ to aid the unit conversion.

Radio waves, infra-red radiation, visible light, ultra-violet light, x-rays, and gamma-rays are all electromagnetic waves with electric and magnetic fields that pump each other through the vacuum of space at the speed of light.