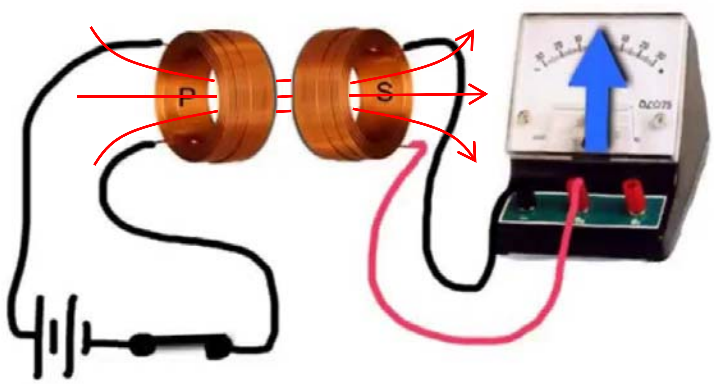
PHYS:1200 LECTURE 28 — ELECTRICITY AND MAGNETISM (6)

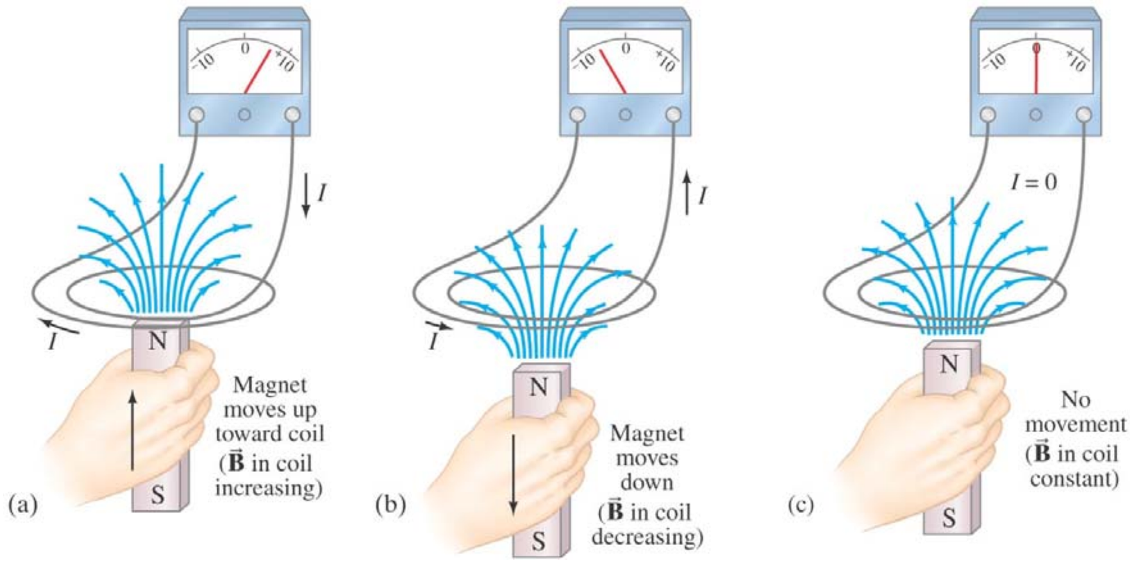
This final lecture on Electricity and Magnetism presents the discoveries of electromagnetic induction by Michael Faraday in 1831, and electromagnetic waves by James Clerk Maxwell in 1864 and Heinrich Hertz in 1879. These are among the most important discoveries ever made in Physics. Along with the laws governing the interactions of electric charges and currents and magnetic fields, these discoveries provide a complete set of principles of all electromagnetic phenomena (the basic principles of magnetism are summarized on **slide 2**).

28-1. Faraday's Law of Electromagnetic Induction.—Faraday was aware of the work of Oersted on the production of magnetic fields by currents. He surmised that if currents produced magnetic fields that magnetic fields might produce currents. Faraday set up a circuit to study whether a magnetic field could regulate the flow of a current in an adjacent wire, but he found no such relationship. He used an apparatus similar to the one

Michael Faraday
(1791-1867)

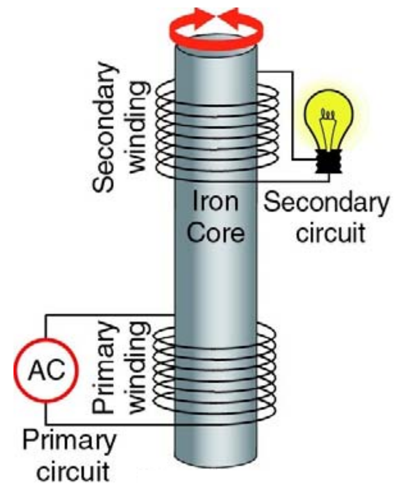


shown below. Two coils of wire, labeled P (primary) and S (secondary) are next to each other. The primary coil is connected to a battery to produce a current in it which can be turned on or off with a switch. The secondary coil is connected to an instrument that records the presence of current in the secondary coil. The meter deflects to the right or left depending on which direction the current flows. When current flows in the primary coil, a magnetic field is generated, and the magnetic field lines are indicated in red. There is no direct connection between the primary and secondary coils, but some of the magnetic field lines from the primary are linked (pass through) to the secondary. Faraday's observation was that when the current in the primary coil was constant in time, there was no indication of any effect in the secondary coil. However, when the switch was closed or opened, a brief (transient) current did appear in the secondary. In other words, a current in the secondary coil was induced when the current in the primary, and consequently the magnetic field of the primary that was linked to the secondary, was changing in time. We say that when the magnetic field of the primary was changing, a current was induced in the secondary – this phenomenon is called electromagnetic induction.

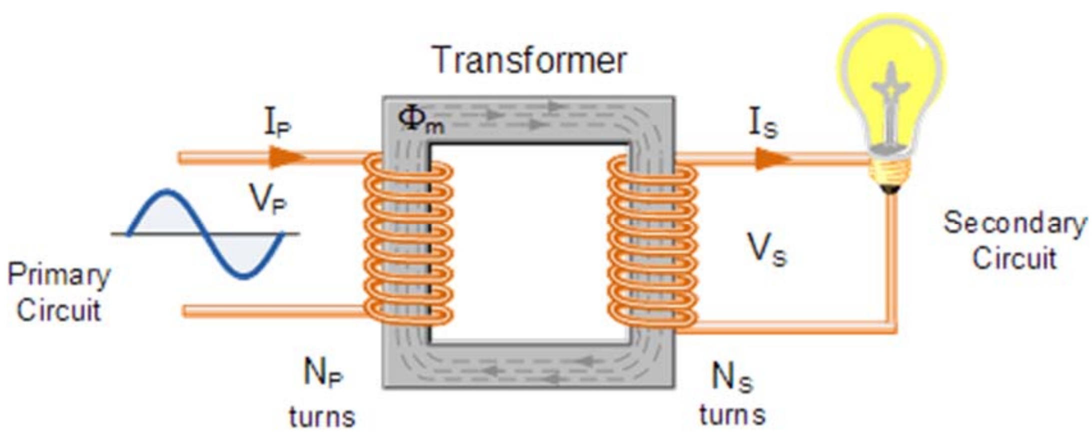


If the magnetic field passing through a coil changes for any reason, a current is induced in the coil. This is illustrated in the diagrams below. In this demonstration a two-turn loop of wire is connected to an instrument that detects the presence of current in the loop. A bar magnet is held under the loop. An essential point to keep in mind is that the magnetic field of a bar magnet is strongest in the region nearest the poles and its strength decreases as one moves away from the poles. When the magnet is thrust upward as in part (a) the magnetic field over the plane of the loop increases, and this change in magnetic field induces a current in the loop, according to Faraday's law. In part (b) the magnet is pulled away from the loop causing the magnetic field over the plane of the loop to decrease. This change in magnetic field also induces a current in the loop but in the opposite direction. In part (c) the magnet is held fixed and no current is induced in the loop. A current appears in the loop only when the magnet is moved toward or away from the loop. In fact, only the relative motion of the loop and coil is necessary. If the magnet is held fixed and the coil is moved toward the coil, the same result as in (a) is observed. If the magnet is held fixed and the coil is moved away from the magnet, the same result as in (b) is observed.

Induced currents can also be generated without any relative motion of two coils if the primary coil is **powered by alternating current** (AC). If the current in the coil changes direction periodically, as with AC, the magnetic field produced by the coil also changes direction periodically. If a secondary coil is nearby, some of the magnetic field lines from the primary coil will pass through it, and an induced current will be generated in the secondary coil as illustrated on the right. A light bulb is added to the secondary circuit to show the presence of the induced current. Both coils are wrapped around an iron core. The iron core helps to concentrate the magnetic field lines from the primary coil, so that more of them pass through the secondary coil, thus improving the efficiency of the configuration.

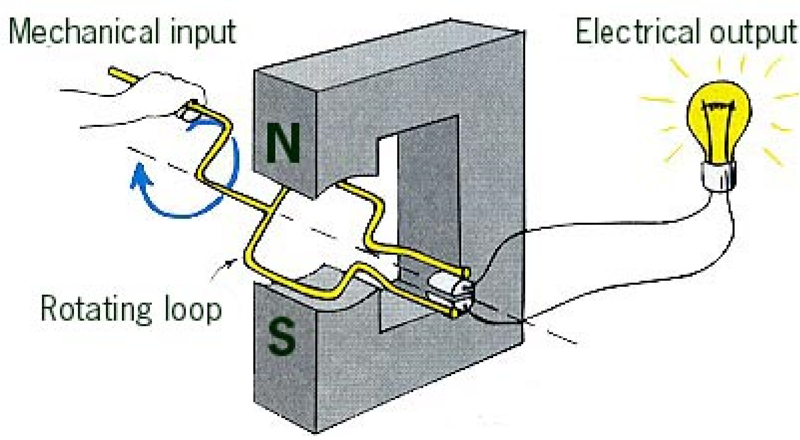


a. The transformer.—One of the advantages we discussed with AC power is that AC voltages can be changed up or down using transformers. **Transformers are electrical devices that are based on Faraday's law of electromagnetic induction**. Actually, the figure above is an example of a transformer which has a primary and secondary circuit. A more typical example of a

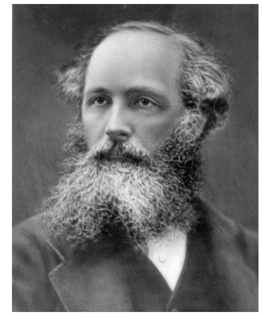


transformer is shown above. The primary circuit is powered with an AC voltage source. Both the primary and secondary circuits are wound on iron cores which increases the coupling of the magnetic field from the primary to the secondary. The voltage on the secondary circuit depends on the number of turns in the secondary coil. Each turn of the secondary coil sees the changing magnetic field produced by the primary current. The more turns there are on the secondary, the more voltage that is induced. If the secondary contains more turns than the primary, the secondary voltage is increased above the primary voltage – this is called a **step-up transformer**. If the secondary contains less turns than the primary, the secondary voltage is decreased below the primary voltage – this is called a **step-down transformer**. Transformers are used in the electrical power distribution system (grid) first to step-up the voltage at the generation point for transmission over long distances, then to step down the voltage before distribution to businesses and homes. A typical transformer found on a utility pole is shown on the right. This is the last in a series of step-down transformers between the power plant and your home, used to reduce the voltage down to 120 V and 240 V. Cell phone batteries are either 3.7 V or 4.2 V. The charging unit must step down the AC line voltage from 120 down to these voltages. The stepped down voltages are still alternating, so a rectifying circuit is used to produce a single-polarity voltage for charging.

b. Electric generators.—The generation of electrical power is also based on induced currents as illustrated in the diagram on the right. A coil that is rotated in the magnetic field of a permanent magnet sees a magnetic field that changes with time and thus a current is induced in it according to Faraday's law. Some mechanical means must be applied to rotate the coil. This can be a gasoline engine, a steam turbine, wind turbine, or water turbine.



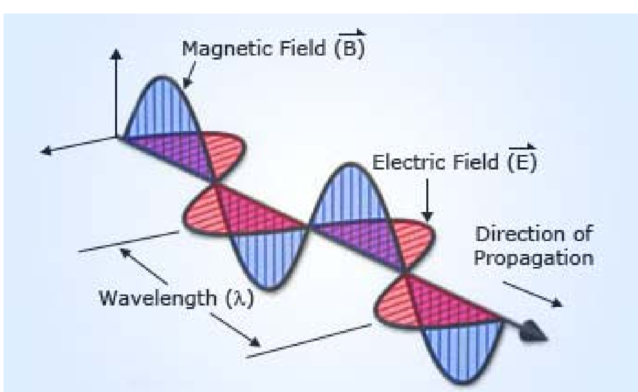
28-2. Electromagnetic Waves

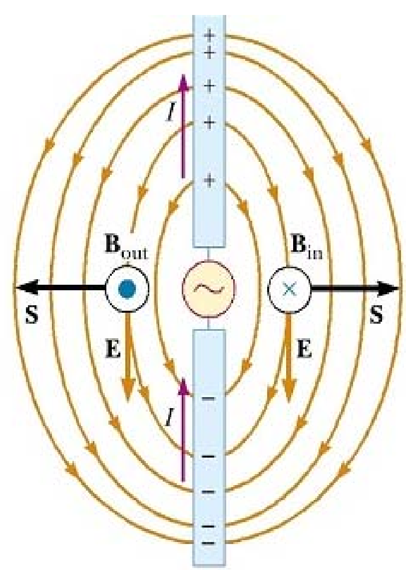


a. Theoretical prediction—A comprehensive statement of the laws of electricity and magnetism were put into mathematical form by James Clerk Maxwell in 1862. These laws were formulated in terms of electric and magnetic fields. Electric charges produce electric fields and electric currents produce magnetic fields. Faraday showed that electric currents could be produced by changing magnetic fields. Since electric fields cause charges to move, Faraday's law of electromagnetic induction could also be stated that changing magnetic fields produce electric fields. (By changing, we mean varying in time.) Maxwell's contribution was to predict that a changing electric field would produce a magnetic field. So Faraday's and Maxwell's contributions can be summarized as:

- A changing magnetic field produces a changing electric field (Faraday)
- A changing electric field produces a changing magnetic field (Maxwell)

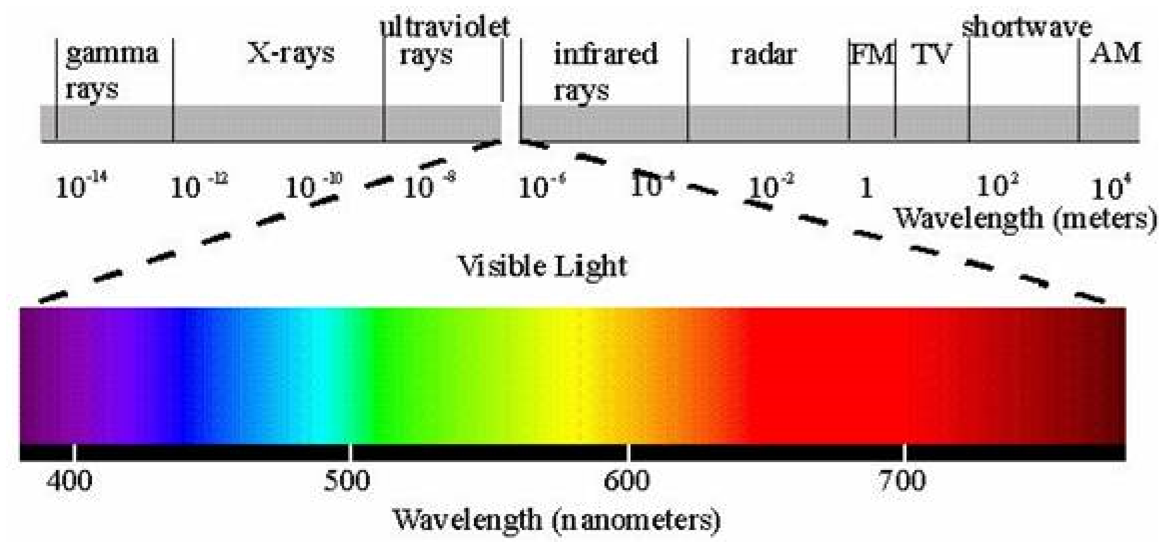
Maxwell realized then that changing electric and magnetic fields could reproduce each other, thus giving rise to an **electromagnetic wave**. An electromagnetic wave can be produced by causing the electrons in a conductor to oscillate rapidly as in the diagram on the right below. The oscillating electrons produce a time-varying electric field. The time-varying electric field then generated a time-varying magnetic field which then generates a time-varying electric field, and so forth. The fields are self-reproducing and propagate away from the antenna at a speed of $3x10^8$ m/s --- the speed of light. This sequence of events requires no medium, the fields





exist even in a vacuum. **An electromagnetic wave contains both an electric and magnetic component that are perpendicular to each other**, and the direction of propagation is perpendicular to both the electric and magnetic field**--- an electromagnetic wave is a transverse wave.** Maxwell's prediction of the existence of electromagnetic waves was verified experimentally in 1979 by **Heinrich Hertz.**

Electromagnetic waves span all wavelengths and frequencies which are related by the



periodic wave relation $\lambda f = c$, where **c is the speed of light** = $3\text{x}10^8$ m/s. The frequencies or wavelengths are illustrated schematically in the electromagnetic spectrum. The visible spectrum is that part of the electromagnetic spectrum that our eyes are sensitive to, and covers the wavelength range of roughly 400 nm to 700 nm (1 nm = 10^{-9} m). Other commonly used parts of the spectrum are also shown in the diagram above.

Example 28-1: What is the frequency of an FM radio wave having a wavelength of 3 m?

Solution-

$$c = \lambda f \rightarrow f = \frac{c}{\lambda} = \frac{3\times 10^8\ m/s}{3\ m} = 1\times 10^8\ Hz = 100\ MHz.$$

1 MHz = 1 million Hz.

b. Experimental observation of electromagnetic waves.—Between 1886 and 1889 Heinrich Hertz conducted a series of experiments that would prove the effects he was observing were results of Maxwell's predicted electromagnetic waves. Hertz used the apparatus shown above to generate radio waves having a frequency of 100 MHz (= 10^8 Hz). These waves have a wavelength given by:

$$\lambda = \frac{c}{f} = \frac{3\times10^8\ m/s}{10^8\, s^{-1}} = 3\ m.$$

The waves were detected by a circular loop antenna (receiver). Hertz is honored for his work by having the unit of frequency named for him.