CHAPTER 26: PROPERTIES OF LIGHT ____________ 02/18/19

ELECTROMAGNETIC WAVES

- At the end of last chapter, there was a more general statement of Faraday's Law:
  - **Faraday's Law**: An electric field is created in any region of space in which a magnetic field is changing with time. The magnitude of the induced electric field is proportional to the rate at which the magnetic field changes. The direction of the induced electric field is at right angles to the changing magnetic field.
- and James Clerk Maxwell found a counterpart to Faraday's Law:
  - **Maxwell's extension of Ampere's Law**: A magnetic field is created in any region of space in which an electric field is changing with time. The magnitude of the induced magnetic field is proportional to the rate at which the electric field changes. The direction of the induced magnetic field is at right angles to the changing electric field.
- These two statements are two of the most important in all of physics. They are the basis for our understanding of light and electromagnetic waves.
- Think about shaking one end of a long rope up and down - a wave moves down the rope. If you move charges back and forth in space, an electromagnetic wave will move through space. How?
  - Remember, that moving charges (i.e. currents) produce magnetic fields.
  - Changing currents produce changing magnetic fields (electromagnetic induction).
  - A changing magnetic field can induce voltage in a wire loop. What is really happening is that the changing magnetic field induces a changing electric field, which then gives rise to voltages, currents, etc.
  - From Maxwell, the induced changing electric field will then induce a changing magnetic field, and so on and so on.
  - A vibrating, or oscillating, electric charge will produce oscillating magnetic and electric fields that regenerate each other as they move outward from the charge – this is an electromagnetic wave.
  - What is "waving" in an EM wave? – The electric and magnetic fields.
    - FIG. 26.2, ANIM: EM Wave

ELECTROMAGNETIC WAVE VELOCITY

- EM waves cannot speed up or slow down while traveling through space because of conservation of energy.
  - According to the equations describing EM waves, speeding up would mean the changing electric field would generate a stronger magnetic field, generating a stronger electric field, etc. Continually increasing energy without limit. Impossible with conservation of energy.
  - Slowing down would the changing electric field would generate a weaker magnetic field, which would generate a weaker electric field until the wave died out. No energy would be transported.

    - This is in contrast to a cruising spaceship which can be sped up or slowed down due to gravity (the craft can exchange kinetic energy for gravitational potential energy).
    - Only one speed keeps the mutual induction continuous with no gain or loss of energy. From Maxwell's equations for induction, he ***found*** the speed of light to be ~300,000 km/sec.
- Maxwell discovered what light is: Light is an energy-carrying wave of electric and magnetic fields that continually regenerate each other and travel at a single fixed speed.

ELECTROMAGNETIC SPECTRUM

- All electromagnetic (EM) waves have the same speed, but they can differ in their frequency (and wavelength). The classification of EM waves according to frequency is the **electromagnetic spectrum.**
    - TRANSPARENCY: EM spectrum
        - Radio: few kilohertz (10^3 Hz) – few hundred megahertz (10^8 Hz); AM,VHF,FM,UHF
        - Microwave: 10^9 Hz – 10^{12} Hz
        - Infrared: 10^{12} Hz – 4.3×10^{14} Hz; "heat waves"
        - Visible Light: 4.3×10^{14} Hz – 7×10^{14} Hz
        - Ultraviolet: 7×10^{14} Hz – 10^{17} Hz; sunburns
        - X-rays: 10^{16} –
        - Gamma-rays: 10^{17} –
- The frequency of an EM wave is the same as the frequency of the oscillating electric charge generating it.
    - The wavelength is found from the relationship $c = f\lambda$.
        - $\lambda = c/f$: 10,000 Hz radio wave has a wavelength of 30 km.

CHAPTER 26: PROPERTIES OF LIGHT ___________ 02/20/19

TRANSPARENT MATERIALS

- Light is an energy-carrying wave that comes from vibrating electrons. When light goes into matter, it makes the electrons in the matter vibrate: vibrations in the emitter are transmitted to vibrations in the receiver.
    - Material responds to light based on the frequency of the light and the natural vibrating frequency of the electrons in the material's atoms.
    - The electrons in the atoms have natural frequencies at which they vibrate more readily, or strongly. It is somewhat as if they were connected to the nucleus by springs.
        - FIG. 26.6
    - When the frequency of light hitting a material matches the natural frequency of the electrons in the material, the electrons vibrate very strongly (matched tuning forks, pushing someone on a swing, etc.) and hold the vibrations for a long time – this is called resonance.
- The energy of a vibrating electron can either be re-emitted as new light or passed on to neighboring atoms by collisions.
    - At resonance, the electrons can keep vibrating, holding on to their energy for a long time.
      DEMO: tuning forks
      Long enough to have many collisions with other atoms, giving up the energy as heat. In other words, the incident light energy is dumped into the material as heat.
        - Glass has resonant frequencies in the ultraviolet (UV) range. It is not transparent to UV. Energy from UV rays heats up windows instead of going through them. Glass is also not transparent to infrared light, because the resonant frequency of entire atoms or molecules matches infrared frequencies.
    - At other frequencies, the incident light causes the electrons to vibrate at those non-resonant frequencies. The electron vibrations are not as strong or long. They don't hold the energy long enough to make many collisions. The vibrating energy is re-emitted as light instead, which then goes to the next atom, which vibrates and re-emits to the next atom, and so on, until new light at the same frequency gets re-emitted out of the other side of the material.
        - FIG. 26.7
        - DEMO: line of folks and ball
            - Push the first guy, he pushes the next, so on. – energy heats the material up.
            - Throw ball to the first, he to the second, etc, last throws it out – energy re-emits and leaves. (but with light its not the same ball, new light comes out).
        - This is called transparency. Light coming in produces the same frequency light coming out. Glass is transparent to visible light.

        - There is a time delay in light getting through a transparent material. The time it takes for an electron to begin vibrating, re-emit light, and then the next one to do the same, and so on. So the *average* speed of light through transparent materials is less than the speed of light in space (a vacuum).

OPAQUE MATERIALS

- Materials that absorb light rather than re-emit it are called opaque. The light energy turns into heat energy from kinetic collisions.
    - Metals are opaque. But when the free electrons in a metal (rather than the ones tied strongly to atoms) are set to vibrate, they re-emit the light right back out instead of resonating and transferring their energy as heat. In other words, the light is reflected. That's why metals are shiny.
    - Atmosphere is opaque to most UV and infrared
    - Clouds are semitransparent to UV: you can get a sunburn on a cloudy day.
    - Glass is opaque to UV: you cannot get a sunburn through glass.
        - FIG. 26.9

SEEING LIGHT – THE EYE

- Structure of the eye
    - FIG. 26.15
    - Cornea: transparent lens-like cover does 70% of focusing work
    - Iris: colored part that regulates pupil size – how much light gets in
    - Lens: does the final focusing of light onto the back of the eye
    - Retina: back of the eye that is the sensitive light detector of the eye
        - Fovea: "sweet spot" of the retina with most distinct, detailed vision
        - Blind spot: spot on the retina where the optic nerve connects
            - DEMO: Cross and X picture (FIG. 26.16)
- Retina is composed of millions of tiny electrical antennae that resonate to incoming light (EM waves): rods and cones.
    - FIG. 26.17
    - Cones: three types that respond to either low-frequency, mid-frequency, or high-frequency visible light. Frequency ranges overlap to be able to distinguish exact colors. Denser toward the center of the eye, closer to the fovea.
    - Rods: only sensitive to light intensity (light or dark – black and white). Much more sensitive than cones to low-intensity light, i.e. the cones require more energy to pick up a signal. Predominate toward the periphery of the retina.
        - Color disappears in our peripheral vision
        - Peripheral vision is very sensitive to motion (changes in intensity)
        - In very dim light, we see little color (moonlight, stars, etc.)
        - Females have better cones (better color vision and less color-blindness), males better rods (better night vision)
    - The retina does a lot of pre-thinking for us

- Rod and cone cells are very interconnected with only a few carrying the collected, or digested info to the optic nerve, and from there to the brain.
  - The iris reflects this pre-thinking by adjusting to light intensity (and emotions: pleased – pupils expand, displeased – pupils contract)
  - DEMO: Cross and X picture
- We can see things 500 million times brighter than the dimmest things we see, but we don’t actually perceive that much difference. A cell sends a very strong (bright) signal to the brain and to other cells to tell them to back off, dim their response. This evens out the visual field and lets us see more detail in bright and dark areas. This is lateral inhibition (camera film doesn’t have it – over and underexposures).
  - DEMO: shaded blocks (FIG. 26.20)
  - Lateral inhibition exaggerates difference in brightness – edges. Our eye accentuates differences. (stepping off a ledge vs. judging others)

CHAPTER 27: COLOR   02/25/19

SELECTIVE REFLECTION/TRANSMISSION

- Most objects don't produce their own light, but rather they reflect or transmit a portion of the light that shines on them, and absorb the rest. The part that they reflect (or transmit) gives them their color.
    - If an object reflects all frequencies of visible light, then it will appear white.
    - If it reflects no frequencies of visible light it will appear black.
    - If it only reflects light in the red portion of the visible spectrum, it will appear red.
- A material absorbs light that matches its resonant frequencies, where the amplitudes and durations of electron oscillations are large. It reflects light at non-resonant frequencies.
- An object can only reflect light that is incident upon it. Many light sources aren't really "white" light containing a balance of all visible light frequencies.
    - Sunlight has white light containing all frequencies, but it is most intense in the yellow-green part of the spectrum.
        - Our eyes evolved to have maximum sensitivity in yellow-green.
            - Newer and airport fire engines, tennis balls, sodium-vapor streetlights.
    - Incandescent bulbs – more lower wavelength, red and yellow.
    - Fluorescent bulbs – more higher wavelength, more blue

MIXING COLORED LIGHT

- All colors combined make white. But also, we perceive the combination of just red, green and blue to be white.
    - This is because we have three types of cones in our eyes:
        1. Sensitive to frequencies in the lower third of the spectrum, perceives red.
        2. Sensitive to frequencies in the middle third of the spectrum, perceives green.
        3. Sensitive to frequencies in the upper third of the spectrum, perceives blue.
    - When all three cones are stimulated, we perceive white.
- When two of these three colors are added, another color is produced. Mixing various amounts of red, green and blue frequencies can produce any color in the spectrum, or white when all three are added equally.
    - RGB are the **additive primary colors**
    - TV picture tube makes a picture out of lots of tiny RGB spots that appear mixed together into different colors at a distance.
- **COMPLEMENTARY COLORS**: two colors added together to make white
    - R + B = MAGENTA, complement of G   MAGENTA + G = WHITE
    - R + G = YELLOW, complement of B   YELLOW + B = WHITE
    - B + G = CYAN, complement of R   CYAN + R = WHITE
- DEMO: RGB lamps and shadows.

MIXING COLORED PIGMENTS

- Adding colored paint is completely different from adding colored light. Pigments in materials are particles that absorb certain frequencies of light. What's left is reflected to give the material its color.
    - Something painted red absorbs cyan (everything except red) and reflects red, painted blue absorbs yellow, painted green absorbs magenta. Paint, dye, pigment is all about what is being subtracted from the light.
    - MYC are the **subtractive primary colors**. They subtract out RGB respectively.
    - Color printing with inkjets is accomplished by depositing various combinations of MYC dots to subtract out various frequencies from white light.
- DEMO: MYC gels on overhead

WHY…

- The sky is blue
    - Selective scattering: just like electrons and atoms can re-emit light that caused them to vibrate, so can molecules or larger particles. The smaller the particle, the greater amount of high frequency re-emission (like bells). Nitrogen and oxygen molecules "ring" at high frequencies and the re-emitted light goes in all directions, it is scattered. Violet is scattered most, then blue, but our eyes are more sensitive to blue, so the sky appears blue due to the blue scattered light.
        - What happens when it is dusty, or very humid? A whiter sky because there are larger particles for the lower frequency colors to scatter from.
- Sunsets are red
    - Lower frequency light is the least scattered in the atmosphere. At noon, sunlight goes through the least atmosphere, and high frequencies are only scattered a little, just enough to turn the sun a little yellow. As it gets toward sunset, sunlight passes through much more atmosphere, and higher frequencies are scattered more, leaving the transmitted light much redder.
- Clouds are white
    - Water droplets in clouds are too large to cause the scattering common from tiny particles. Instead they reflect and refract all colors about equally in all directions, resulting in white light. Big clouds appear dark because there are enough droplets to absorb a lot of the light.
- Water is cyan (greenish blue)
    - Water absorbs (resonates at) infrared and somewhat red. ¼ of the red in sunlight is absorbed by 15 meters of water. Take away red from white and what do you get? Cyan. Red lobsters or crabs look black deep underwater.

CHAPTER 28: REFLECTION AND REFRACTION ___ 02/27/19

- When light falls on an object it is either re-emitted at the same frequency or absorbed as heat.
- When it is re-emitted, if it is returned to the medium from which it came, it is ***reflected***. If it crosses from one transparent material into another, it is ***refracted***.

REFLECTION

- Whatever frequencies of light an object re-emits determine what color the object appears as.
- **PRINCIPLE OF LEAST TIME:** Out of all possible paths that light might take to get from one point to another, it takes the path that requires the shortest time.
    - Light takes the most efficient path and travels in a straight line as long as nothing is obstructing its path between two points (in this case, a straight line also takes the least time). If there is an object in between that can reflect or refract the light, then the principle of least time determines the path that the light will take.
- **LAW OF REFLECTION**
    - FIGS. 28.2, 28.3, 28.4
        - Shortest distance (and time) will be if light bounces off the mirror somewhere between A and B.
        - Construct artificial point B', which is on the opposite side of the mirror, the same distance below as B is above. Where a line from A to B' intersects the mirror is the point of reflection for the shortest path and least time from A to B.
        - FIG. 28.6
          LAW OF REFLECTION: The angle of incident light (from A to C) equals the angle of reflection (from C to B).
            - The angles are measured from the *normal*, which is a line perpendicular to the surface of the mirror.
- **PLANE MIRRORS**
    - To find where an image forms in a plane mirror, trace several rays from one point on an object in front of the mirror.
        - FIG. 28.7
            - The rays diverge from the object and the mirror, but appear to come from one point behind the mirror.
        - That point is where the image is seen by an observer.
        - The light doesn't actually come from that point, so the image is a ***virtual image***.
        - The image is as far behind the mirror as the object is in front, and the same size as the object.
        - Note: Left-right are not reversed in a plane mirror, nor are up-down: it is front-back that gets reversed in a plane mirror.
        - FIG. 28.9: Curved mirrors:
            - Convex: image is smaller and closer to mirror
            - Concave: image is larger and farther from mirror

REFRACTION

- Refraction, or bending of light when it goes at an angle from one transparent medium to another, is due to the fact that the speed of light is different in different materials.
  - Speed of light is c = 300,000 km/sec in a vacuum, slightly less in air, 0.75 c in water, 0.67 c in glass, 0.41 c in diamond.
- Why would light bend just because the materials have different speeds? Think of the principle of least time and a lifeguard reaching a drowning person.
      - FIG. 28.13: spend a little more time traveling in the region where you travel fastest to get to a point in the shortest amount of time.
      - FIG. 28.14: Just like light that travels faster in air than in water.
  - Light through glass.
    - FIG. 28.15: Pane of glass: opposite sides are parallel
      - A-B: straight line shortest distance is the same as least time – no bending or refraction.
      - A-C: straight line would spend too much time traveling slowly through the glass. Spend more time traveling fast in air and shorten the path in glass where light travels slowly.
        - The angles in and out are the same. That means the incoming and outgoing light rays are parallel, but displaced from each other. Check this by looking through thick glass.
        - If light took the shortest possible distance through the glass (straight perpendicular line) then the extra time in air would make a longer travel time than the in-between bent case.
    - FIG. 28.16: Prism: opposite sides of glass are not parallel.
      - Light passes through a thinner section of glass, but not the thinnest, since that would make the trip through air too long to save the most time.

EXAMPLES OF REFRACTION

- Sunset: we see the sun several minutes after it sets below the horizon because the atmosphere is thinner at the top and denser at the bottom – light travels faster in thinner less dense air. Sunlight will take a longer distance path through higher air to get to us. Lower edge is bent more than the upper edge, “squashing” the sun.
  - FIGS. 28.19, 28.20
- Mirage: Very hot air just above a hot road or other surface is thinner, less dense than cooler air higher up. A “sunset” effect in reverse direction. The quickest path for light is to move down through the thin air near the ground and then back up to our eyes. Not a trick of the mind – it is real light from a real object.
  - FIG. 28.21

CHAPTER 28: REFLECTION AND REFRACTION ___ 03/04/19

DISPERSION

- The speed of light in a vacuum is the same for all frequencies (colors). In materials, the speed of light is different for different frequencies. It is slower for high frequency light near the resonant ultraviolet, because light with frequency near resonance interacts with the material more, thus it travels slower.
  - Violet is about 1% slower than red in glass.
  - Since refraction is caused by a change in the speed of light from one material to another, different colors refract by different amounts.
- In a prism, the first refraction slightly separates white into different colors. The second refraction bends the light farther away from the direction of the incoming light, further separating the colors to a point at which it becomes quite noticeable.
  - FIG. 28.29
  - DEMO: light source and prism
- When light goes through a pane of glass with parallel sides, the first refraction slightly separates white into different colors. The second refraction bends the light back in the opposite direction back to a path parallel with the incoming light. This puts the colors back together into white.
  - DEMO: light source and rectangular block
- The separation of white light into colors by refraction is called ***dispersion.***

RAINBOWS

- A rainbow is the result of dispersion by water droplets. It is seen when the sun is behind us and water drops are in front of us.
- The spherical water droplets act like prisms: a refraction, a reflection, another refraction.
- Outgoing red light peaks 42° from the incoming sunlight, violet at 40°.
  - FIG. 28.30
- Each drop sends out all colors in a full circle, but you only see one color from each drop, the other colors you see are from drops in other places (e.g. above or below the first drop).
  - FIG. 28.31
  - DEMO: Raindrop and light model
    - No one else can see your rainbow because your line of sight is different than someone else's next to you.
- A rainbow always faces you squarely. You can't get to the side (or end) of a rainbow, because then the sun isn't at your back and no rainbow is produced in your direction.
- Rainbows are actually raincircles. It's just that the ground blocks the other part of the circle. Looking down from an airplane with the sun above you, you can see a complete circle rainbow.
  - FIG. 28.32
  - DEMO: water sphere raincircle.

- Secondary rainbows are produced by the light that undergoes and extra reflection and refraction in the raindrops. It is dimmer with reversed colors compared to the primary rainbow.
    - FIGS. 28.34, 28.35

TOTAL INTERNAL REFLECTION

- Normally when light hits a transparent surface, some light is reflected and some refracted.
    - For light hitting glass normally (perpendicularly): 4% reflected off, 96% refracted in.
- DEMO: laser and prism, TIR
- FIG.. 28.36, ANIM: TIR
  In a material where the speed of light is less than it is outside, as the angle of incidence increases from 0°, the amount of light refracted out diminishes, and the amount reflected back in increases. When the angle of incidence reaches a certain point, no light gets out – all of it is reflected back in.
    - That angle is called the ***critical angle*** and the effect is called ***total internal reflection***.
        - Glass to air: 43° critical angle
            - Prisms used in optics like binoculars instead of mirrors which only reflect about 90% of light.
            - FIGS. 28.38, 28.39
        - Water to air: 48° critical angle
            - TRANSPARENCY: Fig. 28.37 180° horizon to horizon view outside is seen in only 96° underwater (fisheye lens)
- DEMO: laser and water stream -> Fiber Optics

LENSES

- A properly curved prism gives many equal least time paths. For all paths from a certain point in front through the prism to a certain point on the other side, the curve always makes the glass just thin enough to compensate exactly for the extra time light takes to get to that height on the glass. This makes a ***converging lens***.
    - DEMO: light source and converging lens
    - It converges, or brings together, incoming light rays.
    - Thicker in the middle than at the edges.
    - Principal axis: line joining the centers of curvature for the two surfaces.
    - Focal point: point at which incoming rays parallel to the principal axis converge (one on each side of the converging lens).
    - Focal length: distance between the center of the lens and the focal point.
        - FIG. 28.44
    - Forming images with a converging lens
        - If the object is **outside** the focal point, an upside-down real image is formed on the opposite side of the lens from the object. The

light rays actually do come from the place the image is formed, so it is a ***real image***. This is how a slide projector or camera works.

        - FIGS. 28.42a, 28.46, 28.49
        - When the object is very far away, the light rays coming in are essentially parallel, so the image is formed at the focal point. When a camera is set to focus on distant objects, the film is put at the focal point.
        - DEMO: light bulb and converging lens
    - If an object is **inside** the focal point, a converging lens will produce an enlarged, right-side up image on the same side as the object but farther away from the lens. No light rays actually come from the image, so it is a ***virtual image***. This is how a magnifying glass works.
        - FIG. 28.48

- A lens that is thicker at the edges than in the middle is a ***diverging lens***.
    - It diverges, or fans out, light rays.
    - Image is always virtual, right-side up, and smaller than the object. It is also on the same side of the lens as the object. Camera viewfinders use a diverging lens.
    - FIG. 28.42b, 28.50
    - DEMO: light source and diverging lens