This is a review of the topics will be covered in Exam 3.

Chapter 23

Snell's Law

When electromagnetic radiation travels through a vacuum, it all travels at the same speed, regardless of the wavelength, of

$$c = 3 \times 10^8 m/s$$

As light travels through a medium, the speed at which the light travels depends on the **index of refraction** for that material, which is found by

$$n = \frac{c}{v}$$

where v is the speed. When light passes from one medium to another with a different index of refraction, the light can change its direction based on the relative indices of refraction. If θ_1 is the **angle of incidence**, the angle at which the light hits the surface from incident, and θ_2 is the **angle of refraction**, the angle at which the light leaves the surface from incident, then the relative angles can be found by

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where n_1 is the index of refraction of the medium in which the light was initially traveling, and θ_2 is the medium into which the light enters. This relationship is **Snell's Law**.

If n_2 is less than n_1, then θ_2 will be greater than θ_1. If θ_1 is so large that $\theta_2 = 90°$ or higher, the light will not be able to pass through the boundary into the new material, and it will have **total internal reflection**. The **critical angle** θ_c is the angle at which light will show total internal reflection (as well as any greater angles), and is found by

$$\sin \theta_c = \frac{n_2}{n_1}$$

Chapter 24

Wave Nature of Light

Light is a wave with wavelength λ that has **wave-interference**. If two waves are in-phase, going to maximum and minimum at the same time, they will have **constructive interference** which result in a larger wave. If two waves are out-of-phase by $\lambda/2$, then the waves will cancel out in **destructive interference** which will result in no wave. This pattern of constructive and destructive interference can be demonstrated by monochromatic light passing through a double-slit. The two beams coming from the two slits will interfere and show bright and dark fringes on a screen. The angle θ at which the light will interfere constructively, resulting in bright fringes, is found by

$$d \sin \theta = m\lambda$$

where d is the separation between the slits, λ is the wavelength of the monochromatic light, and $m = 0,1,2 \ldots$ is the **order** of the fringe. The angle at which light will interfere destructive, resulting in dark fringes, is found by

$$d \sin \theta = \left(m + \frac{1}{2}\right)\lambda$$

The physical separation between the slits depends on the distance between the double slit and the screen onto which the fringes are being displayed. The separation can be found by

$$x = L \sin \theta$$

where x is the fringe separation and L is the distance from the double-slit to the screen. Because these angles are so small, $\sin\theta \approx \theta$ so this equation can be approximated by

$$x = L\theta$$

where θ is in *radians*.

If a **diffraction grating** is used, consisting of many slits, the bright fringes will be sharper and narrower while the dark fringes become very broad. The angle for bright fringes will still be found by

$$d\sin\theta = m\lambda$$

while there is no longer a specific angle for the dark fringes. This results in the diffraction pattern showing narrow, bright peaks at the constructive interference angles, and no light at all other angles.

Polarization

Light can be **polarized** such all of the photons in the beam have the electric fields pointing in the same direction. A **polarizer** selectively lets light through if it has a specific direction. If light is polarized in the same direction as a polarizer, it will pass through. If it is polarized at 90° from the polarizer, the light will not pass through. If the light is polarized at some other angle θ from the polarizer, the amount of light that will pass through the polarizer is found by

$$I = I_o \cos^2\theta$$

where I_o is the amount of light incident on the polarizer. When the light passes through the polarizer, the emerging light will then be polarized in the same direction of the polarizer.

If unpolarized light passes through a polarizer, the amount of light that will pass through is found by

$$I = \frac{I_o}{2}$$

regardless of the angle at which the polarizer is positioned.

Chapter 25

Cameras

A camera has various parameters that will change whether an image is exposed correctly or in focus. If a picture is too bright, it is **overexposed** due to receiving too much light, while a dark picture is **underexposed** due to not receiving enough light.

Two adjustments that can be made to change the exposer are the **shutter speed** and the **aperture size.** The shutter speed is how long the light is allowed to pass through the lens onto the film or CCD. The aperture size is the diameter of the opening of the "stop" or diaphragm, similar to the iris in an eye. Increasing the size of the aperture will let more light in. The aperture being used is specified by the ***f*-number**, also called the ***f*-stop**, found by

$$f - stop = \frac{f}{D}$$

where *f* is the focal length of the lens. Increasing the *f*-stop is equivalent to decreasing the aperture size. This means that if the *f*-stop is decreased, the exposure time can be decreased because the larger aperture is allowing more light in.

The *f*-number will also change the **field depth**, or the range of distances for objects that will be in focus in the image. A higher *f*-stop will result in a greater depth of field, so objects at a greater variety of distances will be in focus.

Corrective Lenses

Light traveling into the eye will be focused onto the retina at the back of the eye by the lens. A **near-point** is the closest distance at which objects can be placed and the eye still be able to view in focus, while the **far-point** is the farthest distance. For average eyes, objects between the **normal near-point** of $N = 25cm$ and objects infinitely far away can be in focus. If someone is **far-sighted**, they cannot see objects in focus if they are as close as the normal near-point. If someone is **near-sighted**, they cannot see objects in focus if they are at infinity. To correct for near- or far-sightedness, corrective lenses such as contacts or glasses can be used. For the corrections made, the lens equation can be used:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

To correct near-sightedness, corrective lenses will take an object at infinity ($d_o = \infty$) and create an image at person's far-point. This will enable the near-sighted person to see the images of those objects. The lens equation can then be used to find the person's new near-point when they wear the corrective lenses. For these types of corrections, a diverging lens with negative focal length is used.

To correct far-sightedness, the corrective lenses will take an object at the normal near-point ($d_o = N = 25cm$) and make an image at the person's near-point. For these types of corrections, a converging lens with a positive focal length is used.

Note: If the person is wearing glasses with a given distance from the eye, typically $2cm$, the near- and far-points are still relative to the eye, but the object and images distances used in the lens equation need to be relative to the position of the glasses.

Magnifying Glasses

A magnifying glass consists of a single converging lens. If an object is placed at the focal point of the lens, the image will be infinitely large and infinitely far away. To quantify the magnification of this object, the equation

$$M = \frac{N}{f}$$

is used, where $N = 25cm$ is the normal near-point and f is the focal length of the lens.

Telescopes

A refracting telescope consists of two converging lenses. The light from a distant object first enters the telescope through the **objective lens**, then through the **eyepiece** before an observer can see the object. A telescope is properly adjusted if the final image is viewed with a relaxed eye. At this telescope position, the focal points of the objective and eyepiece are at the same point. This means the length of the telescope will be

$$L = f_o + f_e$$

and the magnification of the viewed object can be found by

$$M = \frac{f_o}{f_e}$$

Reflecting telescopes are also used, where the main objective is a concave mirror. Using a mirror has the advantage that smaller telescopes can be used while increasing the diameter of the objective. Increasing the diameter of the objective is important to increase the light-collecting power and to increase the resolution of the objects being viewed. The resolution is the ability to distinguish between two objects, which is limited by the light diffraction width. The minimum angle at which two objects can be distinguished is found by

$$\theta = \frac{1.22\lambda}{D}$$

where θ is in radians, λ is the wavelength of the light being viewed, and D is the diameter of the objective lens or mirror.

Chapter 26

Special Relativity

All objects in an **inertial reference frame** are moving at the same velocity together through space, and view each other as being stationary. It was found that the speed of light is constant, regardless of the reference frame in which the speed is measured, or the speed of the observer relative to the emitting object. This is only possible if other constructs, such as time, are not actually constant as we have always considered them.

The two postulates of special relativity say that 1) the laws of physics have the same form in all inertial reference frames and 2) light propagates empty space with a definite speed c independent of the speed of the source or observer. From these postulates, there arises consequences that are not predicted by classical physics. The first is that two events that were simultaneous in one reference frame may not be simultaneous in another reference frame. Special relativity states that all reference frames are equivalent, and that no frame is a better frame, so both frames are correct. This means that simultaneity is not a "absolute" concept.

Time Dilation

Further, time is not an absolute concept either. The rate at which time is measured in one frame may be different from the rate at which time is measured in another. The amount of time measured by a clock in an inertial reference frame, called **proper time**, is signified by Δt_o. If a clock in a different inertial frame, moving relative to the first, measures a time Δt, the relationship between those times is found by

$$\Delta t = \gamma \Delta t_o$$

where

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

is a factor that depends on the relative velocity of the two reference frames. Again, Δt_o is time measured in an inertial reference frame, and Δt is time measured by someone in a second inertial reference frame that views the first reference frame as moving. Because γ is always ≥ 1, an observer will always see clocks in a moving reference frame as going slower through time than those at rest, an effect called **time dilation**. Further, if two reference frames are moving relative to each other, observers in both frames will observe the other as moving slower in time.

Length Contraction

The measurement of the length of an object also depends on the reference frame in which the measurement was made. The **proper length** of an object, L_o, is made by someone in that objects inertial reference frame. If someone sees that object as moving, they will measure a different length, L. The relationship between those lengths is found by

$$L = \frac{L_o}{\gamma}$$

Because $\gamma \geq 1$, the length L measured by the person who sees the object as moving will always measure the object as shorter than its proper length. This is called **length contraction**.

Mass and Energy

The mass of an object also depends on the reference frame in which is it measured. If a mass is seen as moving, its mass will be measured as

$$m = \gamma m_o$$

where m_o is the mass as measured at rest. When the mass has a velocity v, the relativistic momentum of the particle is found by

$$p = \gamma m_o v$$

The energy that a mass has in a rest frame due to its mass is found by

$$E = m_o c^2$$

If the mass is seen to have a velocity, the total energy of an object is found by

$$E = mc^2 = \gamma m_o c^2$$

This total energy is due to having both mass and kinetic energy:

$$E = \gamma m_o c^2 = KE + m_o c^2$$

Thus, the kinetic energy can be found by

$$KE = (\gamma - 1)m_o c^2$$

Chapter 27

Quantum Theory

Blackbody radiation describe the spectrum of light that all objects emit. As an object gets hotter, the peak of the spectrum moves to shorter wavelengths, and the total power emitted increases. Classical physics was not able to describe the blackbody spectrum, but Planck found that the spectrum could be described if atoms and molecules could only have energies of specific values, where the energy E was related to the frequency f of light being emitted by

$$E = hf$$

where $h = 6.626\times10^{-34}\ J \cdot s$ is **Planck's constant.**

Einstein suggested that not is the energy of atoms and molecules quantized, but electromagnetic radiation also came in packets of energy called **photons**, each with an energy $E = hf$. This concept, that light was not just a wave but also a particle, was demonstrated by the **photoelectric effect**. This experiment illuminates a surface with light, and if the light ejects an electron from an atom, the electron will be removed from the surface by a voltage and detected. This allowed Einstein to test when electrons are ejected from atoms, and to measure the kinetic energy of the electrons.

If light was just a wave, increasing the amplitude should change how many electrons are released and their kinetic energy, while the frequency of the light should not be a factor. If light is a particle with energy $E = hf$, there are several predictions that can be made.

1. If the light has a high enough energy to eject electrons, then
    a. increasing the amplitude will increase the number of electrons that are emitted.
    b. increasing the frequency will increase the kinetic energy of the electrons emitted.
2. If the light doesn't have enough energy to eject electrons, then
    a. increasing the amplitude will not release electrons either.
    b. no electrons will be released until the frequency of light is raised to the minimum cutoff frequency, which gives the light enough energy to release electrons.

Einstein's experiment showed that light really was a particle, as the photoelectric effect shows these predictions that were made.

Although light acts like a particle, it still doesn't not have mass. However, it does have energy which resides in its momentum, where

$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

Light acts like both a particle and a wave, giving it a **wave-particle duality** nature. However, it's not just light that has this property: all matter displays this wave-particle duality. The **de Broglie wavelength** of all matter can be found by

$$\lambda = \frac{h}{p}$$

where p is the momentum of the mass found by $p = mv$.

Electrons in an Atom

Electrons in an atom can only have specific **energy levels**, also called orbitals. In order for an electron to move from a lower to a higher energy level, it has to absorb a photon with the same energy as the difference in energy between those energy levels. If it goes from a higher to a lower energy level, it releases a photon with the same energy as the change in energy between those energy levels. This results in the light being emitted and absorbed by atoms only having specific wavelengths of light.

The wavelength of light that is emitted or absorbed as an electron transitions between orbitals can be found by

$$\frac{1}{\lambda} = R\left(\frac{1}{n_{low}^2} - \frac{1}{n_{high}^2}\right)$$

where $R = 1.0974\times10^7\ m^{-1}$ is the **Rydberg constant**, n_{low} is the **quantum number** of the lower orbital and n_{high} is the quantum number of the higher orbital. By using the wavelength of the light that is emitted or absorbed, the difference in energy between orbitals can also be found by

$$E = \frac{hc}{\lambda}$$

The wavelength of light that would be eject an electron can be found by setting $n_{high} = \infty$. If light has a shorter wavelength, and thus a higher energy, any energy beyond what is needed to eject the electron will go into the kinetic energy of the electron.