Unit 14: Waves and Optics – Physical Optics

OBJECTIVES

Big Idea 6: Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena.

Enduring Understanding 6.B: A periodic wave is one that repeats as a function of both time and position and can be described by its amplitude, frequency, wavelength, speed and energy.

Essential Knowledge 6.B.3: A simple wave can be described by an equation involving one sine or cosine function involving the wavelength, amplitude, and frequency of the wave.

Learning Objective 6.B.3.1: The student is able to construct an equation relating the wavelength and amplitude of a wave from a graphical representation of the electric or magnetic field value as a function of position at a given time instant and vice versa, or construct an equation relating the frequency or period and amplitude of a wave from a graphical representation of the electric or magnetic field value at a given position as a function of time and vice versa.

Enduring Understanding 6.C: Only waves exhibit interference and diffraction.

Essential Knowledge 6.C.2: When waves pass through an opening whose dimensions are comparable to the wavelength, a diffraction pattern can be observed.

Learning Objective 6.C.2.1: The student is able to make claims about the diffraction pattern produced when a wave passes through a small opening and to qualitatively apply the wave model to quantities that describe the generation of a diffraction pattern when a wave passes through an opening whose dimensions are comparable to the wavelength of the wave.

Essential Knowledge 6.C.3: When waves pass through a set of openings whose spacing is comparable to the wavelength, an interference pattern can be observed. Examples should include monochromatic double-slit interference.

Learning Objective 6.C.3.1: The student is able to qualitatively apply the wave model to quantities that describe the generation of interference patterns to make predictions about interference patterns that form when waves pass through a set of openings whose spacing and widths are small, but larger than the wavelength.

Essential Knowledge 6.C.4: When waves pass by an edge, they can diffract into the "shadow region" behind the edge. Examples should include hearing around corners, but not seeing around them, and water waves bending around obstacles.

Learning Objective 6.C.4.1: The student is able to predict and explain, using representations and models, the ability or inability of waves to transfer energy around corners and behind obstacles in terms of the diffraction property of waves in situations involving various kinds of wave phenomena, including sound and light.

Enduring Understanding 6.F: Electromagnetic radiation can be modeled as waves or as fundamental particles.

Essential Knowledge 6.F.1: Types of electromagnetic radiation are characterized by their wavelengths, and certain ranges of wavelength have been given specific names. These include (in order of increasing wavelength spanning a range from picometers to kilometers) gamma rays, x-rays, ultraviolet, visible light, infrared, microwaves, and radio waves.

Learning Objective 6.F.1.1: The student is able to make qualitative comparisons of the wavelengths of types of electromagnetic radiation.

Essential Knowledge 6.F.2: Electromagnetic waves can transmit energy through a medium and through a vacuum.

a. Electromagnetic waves are transverse waves composed of mutually perpendicular electric and magnetic fields that can propagate through a vacuum.

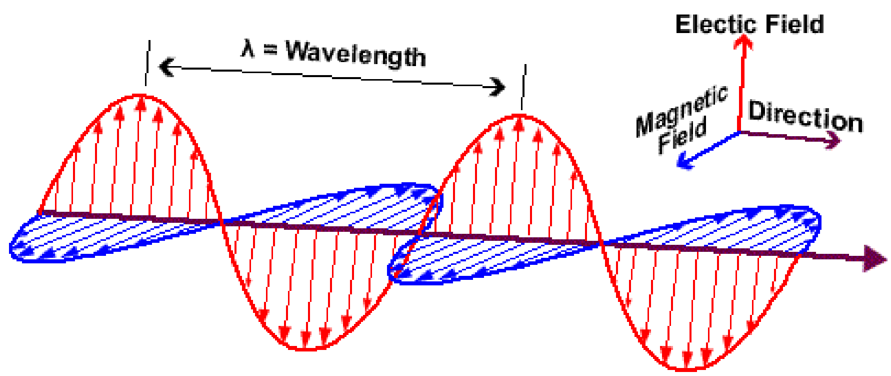
b. The planes of these transverse waves are both perpendicular to the direction of propagation.

Learning Objective 6.F.2.1: The student is able to describe representations and models of electromagnetic waves that explain the transmission of energy when no medium is present.

NOTES

I. ____

A. Electromagnetic waves: _______________waves of _____________________________________[1] oriented _______________to each other



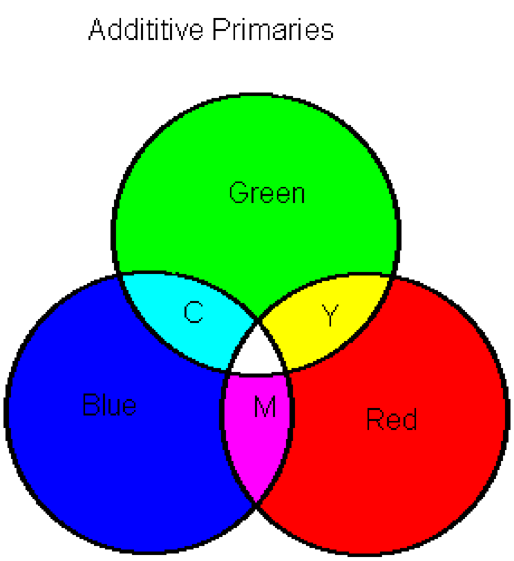
____

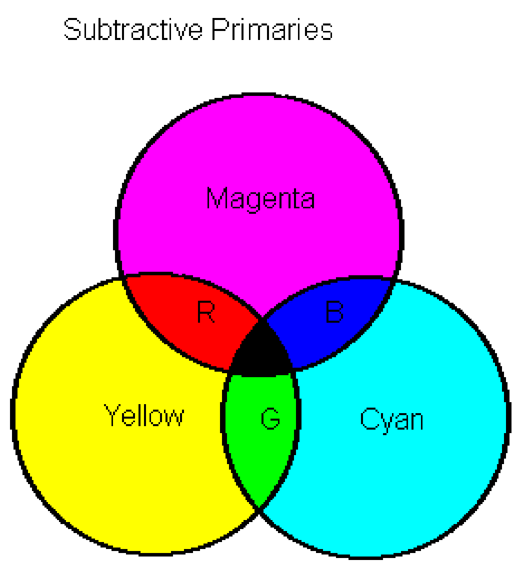
[1] Electromagnetic radiation is made up of electromagnetic waves. It ALSO behaves as a particle called a photon, as we will see in our unit on modern physics. It is the photon that carries the energy of the wave.

B. The ____ of the waves _______________ the _______________ of the radiation. The ____ creates what is called the electromagnetic spectrum, which consists of the following types, in order from short wavelength/high frequency to long wavelength/low frequency. The higher the frequency, the higher the energy of the radiation.[2]

- Gamma rays
- X-rays
- Ultraviolet light
- Visible light
    - Blue
    - Green
    - Red
- Infrared
- Radio waves

Note: White light actually consists of a blend of all of the colors of the rainbow. When these wavelengths combine together, they create white. These are “additive primaries” and are different from what you likely learned in art class, which are the “subtractive primaries” of pigments. We’ll learn about those in the next unit.



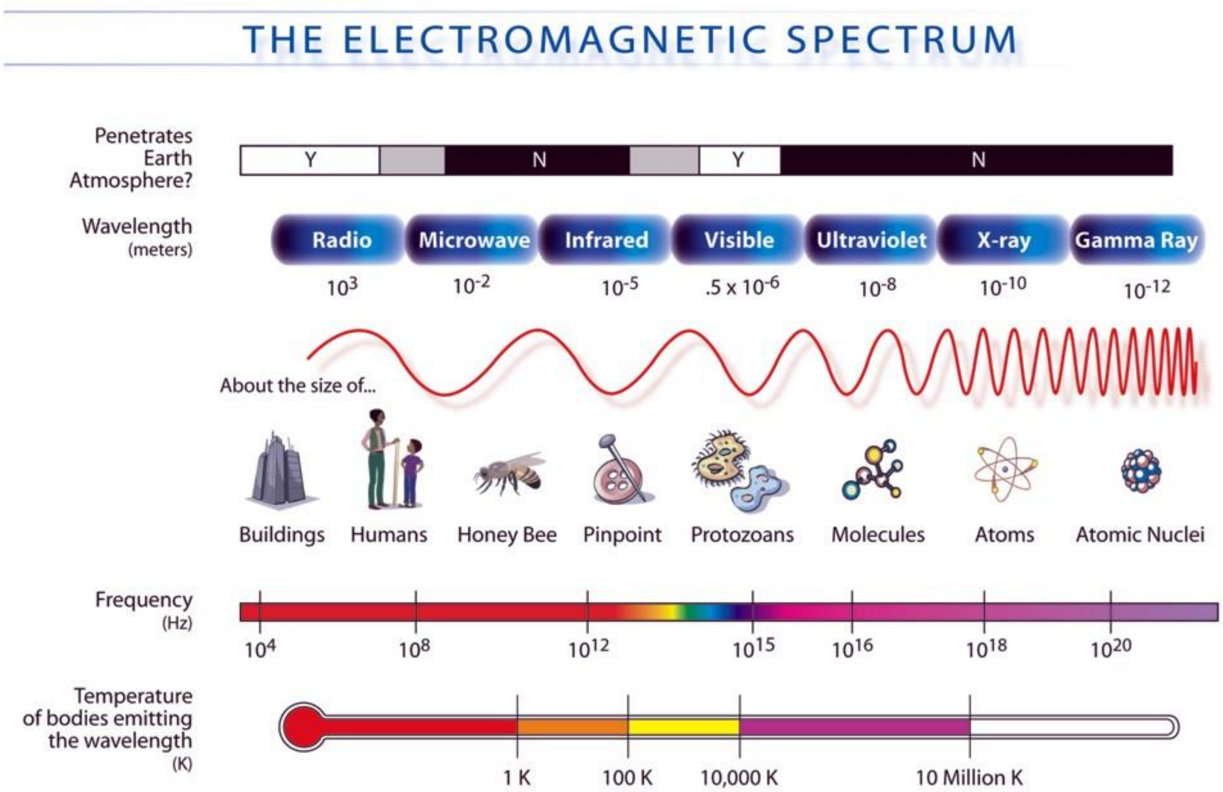


[2] We will see why in our unit on modern physics.

C. Electromagnetic waves ______________________________ AND can travel through __________.

D. The electric field or the magnetic field can be described by a _____________________________.

E. When _________________ occurs, it is usually considered to be polarization of the electric field. The magnetic field reestablishes itself on the other side of the polarization filter.



II. ___________________

A. Interference basics:

1. Constructive interference occurs at point P when waves from different sources arrive in-phase. Amplitudes add together.

2. Destructive interference occurs at point P when waves arrive from different sources out-of-phase.

3. Example:

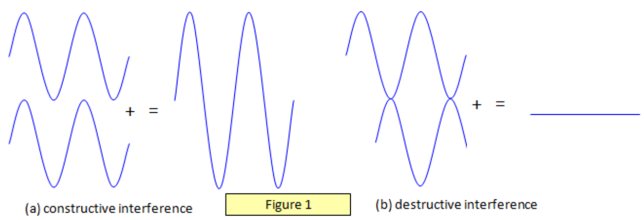


Figure 1

4. ______________________________________: When multiple sources[3] create steady constructive or destructive interference at point P, they must be coherent sources, meaning they emit waves in a ______________________________________ relationship ("___________________") so that the waves do not shift relative to each other over time.

- For example, light from lasers is coherent. (We will see how in our unit on modern physics.)

B. Waves will interfere constructively at point P if the distance traveled by one wave is the same as, or differs by an integral number of wavelengths from, the path length traveled by the second wave. For the waves to interfere destructively, the path lengths must differ by an integral number of wavelengths plus half a wavelength.

1. Condition for constructive interference: Path length difference $= m\lambda$ where m is an integer.

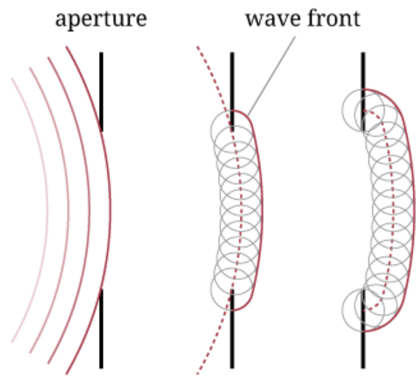
2. Condition for destructive interference: Path length difference $= (m + \frac{1}{2})\lambda$

[3] Sources (plural) means the source of each photon of light. These can be from the same emitter, as in a laser, or from separate emitters, as we will see.

III. Diffraction Patterns and the Single Slit

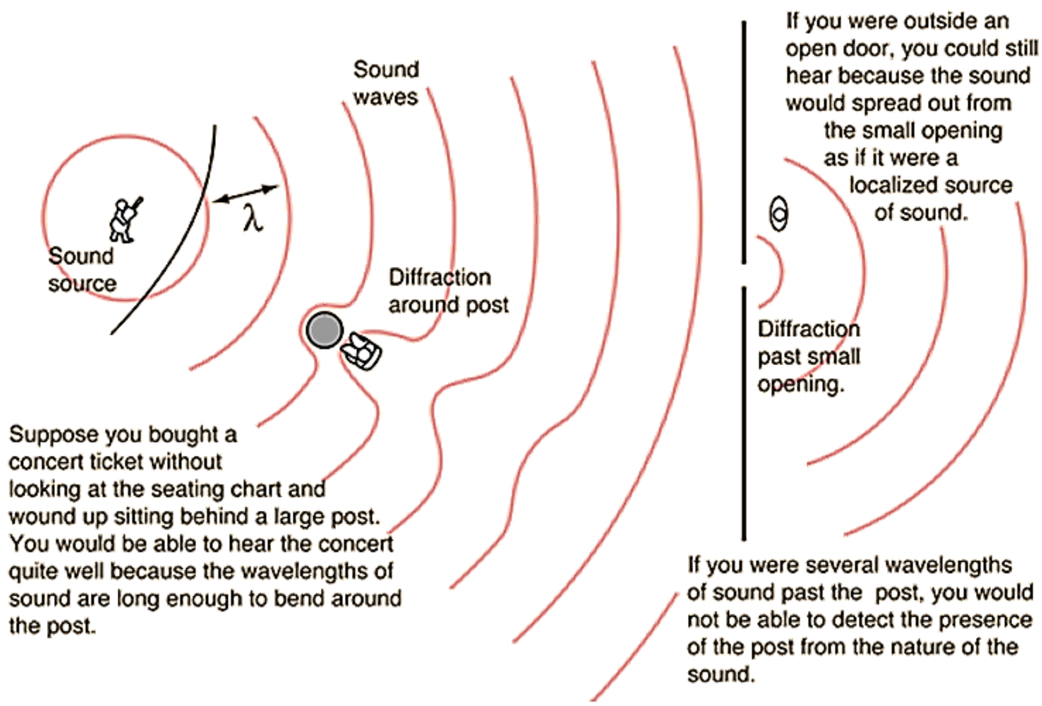
A. When light travels through small openings, such as a single slit, or around obstacles, it ______________________________. This is called _________________.

B. Diffraction occurs because the front of a wave of light consists of tiny _________________, or tiny spherical wave fronts.[4] The wave front created by the overlap of multiple wavelets is tangent to the wavelets. (This is Huygens' principle from 1670. It was the first to suggest that light behaves as waves. However, his work wasn't discovered until after Young's experiment in 1803. (Below))



C. ___________________________________

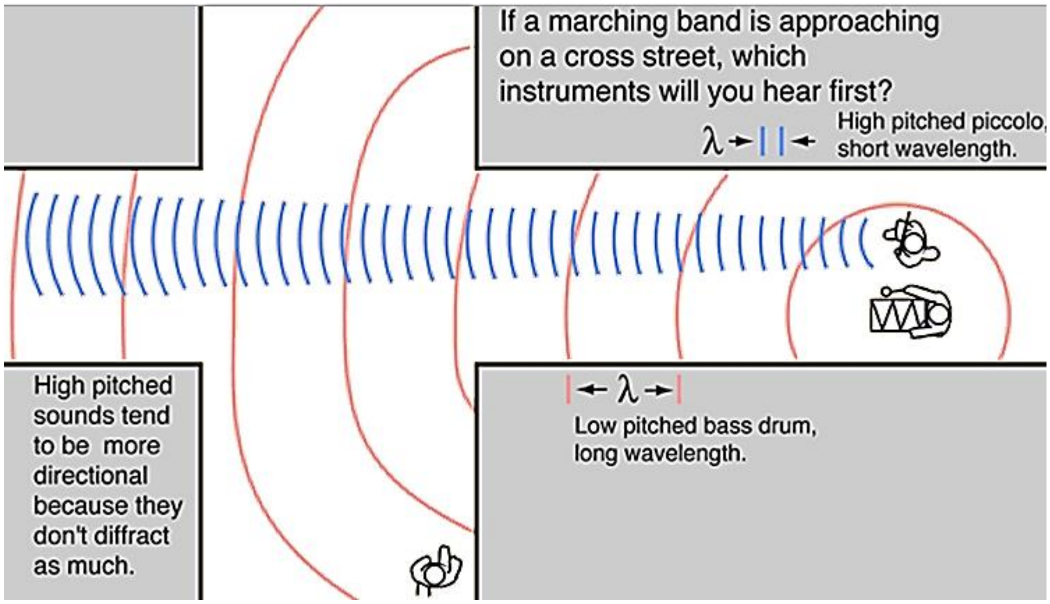
1. When waves pass by an edge, they can diffract into the "_____________________________" behind the edge.



[4] Consider wave fronts to act similar to water waves in the ocean: https://vimeo.com/82575216

2. The ___________________________________compared to the scale of the obstacle, the

___________________________________.



3. This ____.

4. This works for all kinds of waves, including water waves and electromagnetic radiation.

- For example, radio waves are used for transmission of cell phone signals because they have a long wavelength and diffract well around obstacles.

D. _________________through a __________________________________

1. A __________________________________ consists of _______________________________ ____ that occur where wavelets constructively and destructively interfere with each other when __________________________ of _________________ coherent light passes through a _________________[5] single slit or around a small object onto a screen a large distance away (so that the rays heading toward any part of the screen can be considered parallel.)

2. How diffraction patterns work:

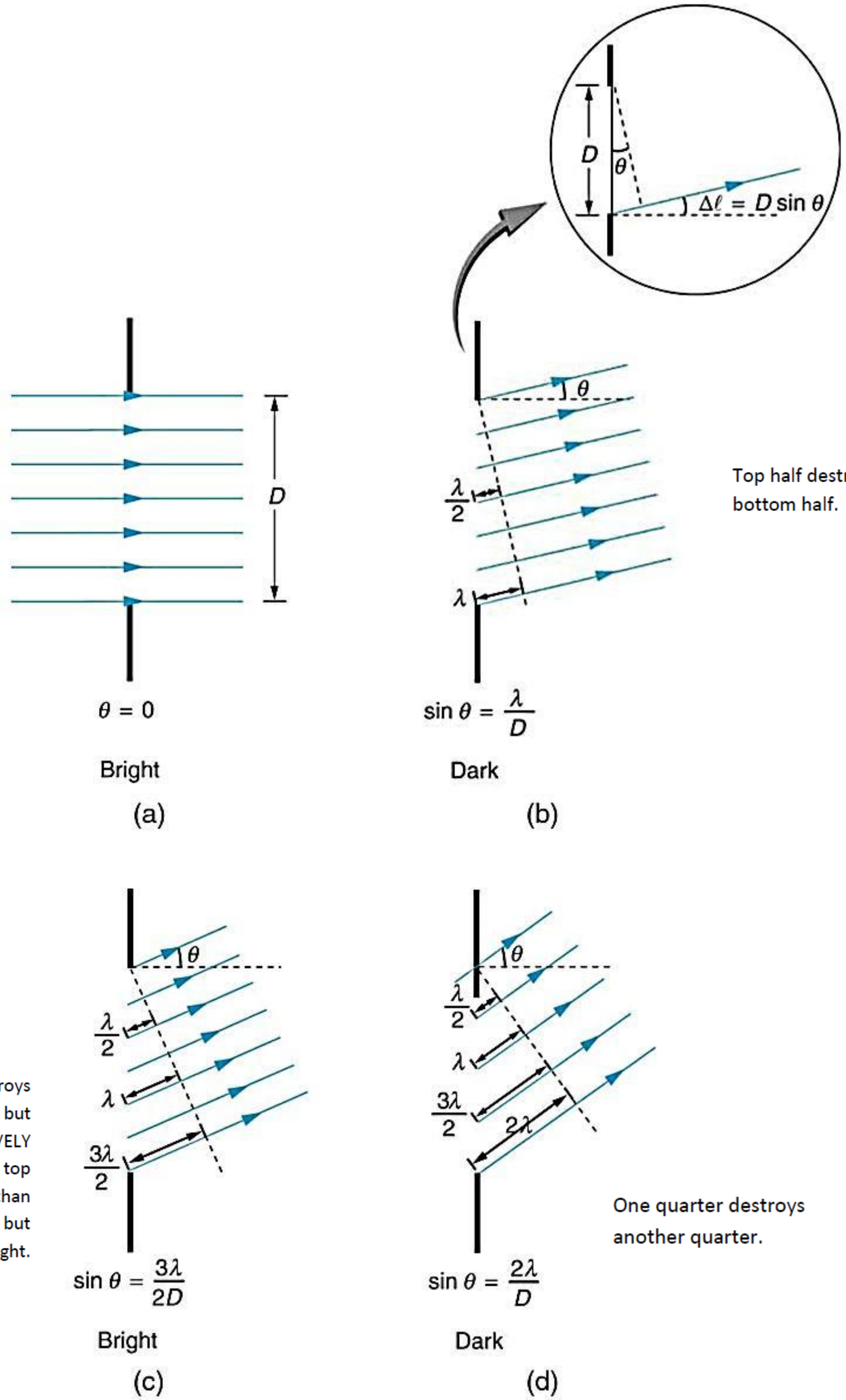
a. __________________________________of the slit ______________________________. These make the brightest spot on the diffraction pattern (first image, below.)

b. There is an angle where the rays are bent so that the rays through the bottom half of the slit are $\frac{1}{2}\lambda$ out of phase with waves from the top half. At this angle, the waves destructively interfere and make a dark spot on the screen. This angle is defined by

where d is slit width. (Image (b) below)

c. There is an angle where the rays are bent so that the rays from the bottom third of the slit are $^1/_2\,\lambda$ out of phase with waves from the middle third, creating destructive interference. However, the bottom third will *constructively* interfere with waves from the top third. This creates a bright band that's somewhat dimmer than the central band. This angle is defined by $sin\theta = \frac{3\lambda}{2d}$. (Image (c) below)

[5] Very small means the opening is on the same size scale as a wavelength of the light.



Top half destroys bottom half.

Bottom third destroys middle third but CONSTRUCTIVELY interferes with top third…dimmer than central maximum but still bright.

One quarter destroys another quarter.

d. The pattern continues as the slit width is divided by integer parts (1/4, 1/5, etc.) to create bands of brightness and darkness that obey the following where d is the slit width and m is an integer.

1.) Minima:

(This is on the formula sheet.)

2.) Maxima: midway in between the minima

(This can be derived conceptually, but it is not on the formula sheet.)

- _______________________ (0^{th} fringe): Maximum intensity occurs at the center where $\theta = 0^o$

This all keeps in mind a general formula that the difference in path length equals an integer multiple of the wavelength:

e. <u>Example 1</u>: Light of wavelength 750 nm (red) passes through a slit 1.0E-6m wide. Calculate the where the first minima will occur both in terms of (a) degrees and in terms of (b) positions on a screen 20cm away? (c) How wide, therefore, is the central maxima? (d) How could you increase the width of the maxima?

f. Example 2: When a monochromatic light source shines through a 0.2 mm wide slit onto a screen 3.5 m away, the first dark band in the pattern appears 9.1 mm from the center of the bright band. What is the wavelength of the light?

IV. ________________________________ and Young's Double Slit Experiment

A. What the bro did:

1. Young passed monochromatic (single wavelength) light through two very thin slits and projected this light onto a screen.

2. If light were made of particles, the screen should have shown two beams of light from the slits. However a wave interference pattern (fringes) appeared, proving that light behaves as a wave. (Again, Huygens' work wasn't known even though it preceded Young's work.)

B. The interference pattern of light passing through two slits resembles the pattern of diffraction fringes through a single slit.

1. The 0^{th} fringe (central maxima) is halfway between the slits opposite the slits on the screen. It's the brightest because both rays travel the least distance.

2. Maxima occur where the difference in path lengths is an integer number of wavelengths:

where d is the distance between the slits and

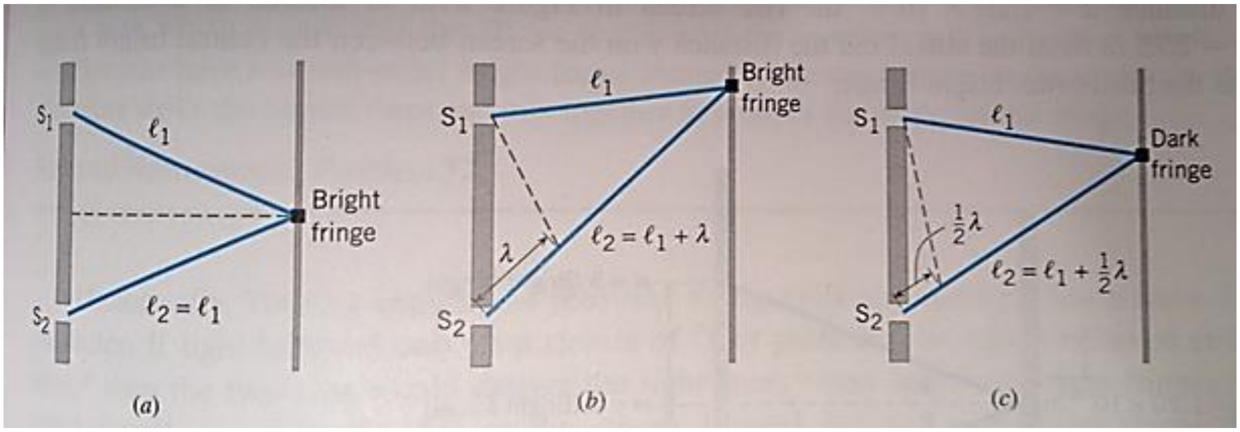
θ is the angle from the center of the slits to the fringe on the screen.

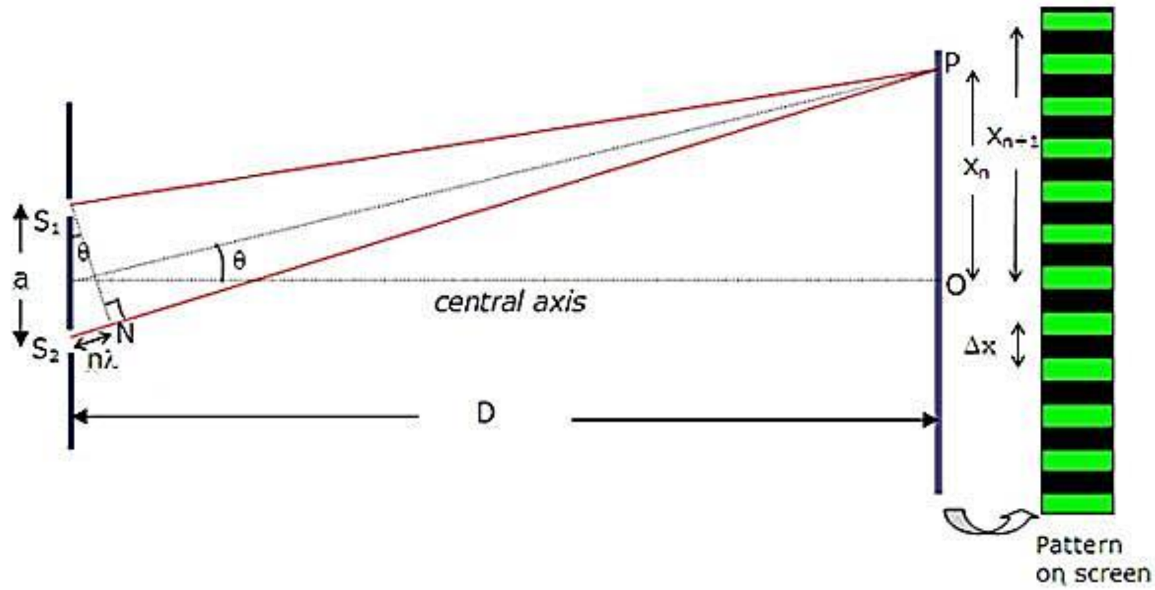
Note: This is the *same* formula for diffraction pattern *minima*. It *is* on the formula sheet.

3. Minima occur where the difference in path lengths is an odd integer of half wavelengths.

Note: This is the *same* formula for diffraction pattern *maxima*. It *is not* on the formula sheet.

- http://phet.colorado.edu/en/simulation/wave-interference





4. Example 3: A screen containing two slits 0.100 mm apart is 1.20m from the viewing screen. Light of wavelength 500 nm falls on the slits from a distant source. Approximately how far apart will the bright interference fringes be on the screen?

5. Example 4: In a double-slit experiment with slit separation of 0.08 mm, blue light (440 nm) gives a second-order bright fringe at a certain location on a flat screen. What wavelength of visible light would produce a dark fringe at the same location? Assume that the range of visible wavelengths extends from 380 nm to 750 nm.

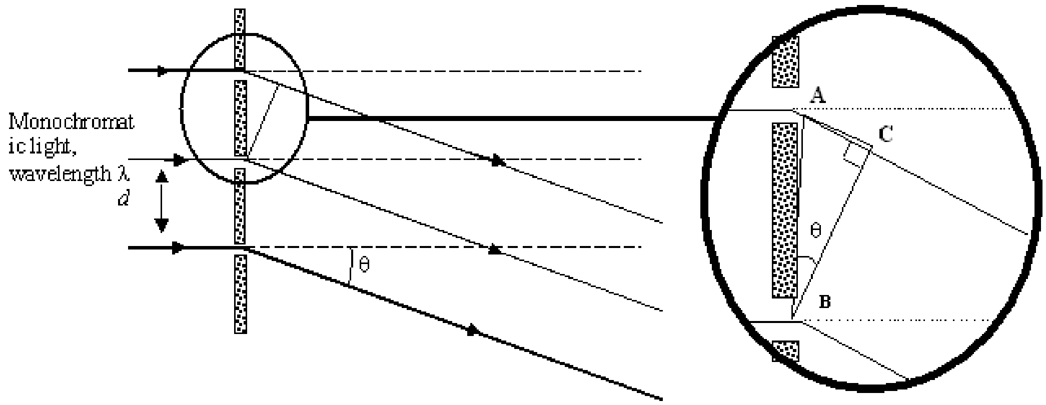
6. Example 5: Look at *Check your Understanding 2* on page 860 of your textbook. Solve and explain.

V. ________________________________

A. A diffraction grating is a filter with multiple parallel, closely-spaced slits.

B. Maxima & minima

1. The maxima occur where the distance traveled equals whole integer multiples of the wavelength so that light from slit 1 is one wavelength different from light from slit 2 and two wavelengths different from light from slit 3, and so on.



2. Minima occur where the distance traveled equals half integer multiples.

3. The same formulas apply as with two-slit interference. The principal maxima (central maxima) occur where $m = 0$ and lies on the central axis.

VI. Resolution

A. ________________ is the ________________ of a filter to distinguish two separate light sources.

1. When the two central maxima from the two sources overlap, they can't be distinguished. This is low resolution.

2. When the central maxima from one source overlaps the minima from the other, creating a break in the light. This creates higher resolution.

B. A multiple-slit grating is better than a two-slit grating for making accurate determinations of wavelength because the large number of slits increases the chance that destructive interference will occur near the maxima, making them very narrow and, hence, sharper and easier to read with precision. (See *Giancoli*, 5th ed., page 736 for a more complete explanation.)

SUMMARY OF DIFFRACTION AND INTERFERENCE

Single Slit Diffraction	**Double Slit Interference**	**Diffraction Grating**
Very wide central maximum	Wide central maximum	Narrow central maxima
Much fainter secondary maxima	Wide secondary maxima that's almost as bright as the central maxima	Many narrow additional maxima that are almost as bright as the central maxima
$dsin\theta = m\lambda$ is for MINIMA, and d is the width of the slit.	$dsin\theta = m\lambda$ is for MAXIMA, and d is the separation of the slits.	$dsin\theta = m\lambda$ is for MAXIMA, and d is the separation of the slits[6].
$dsin\theta = (m + \frac{1}{2})\lambda$ Is for MAXIMA.	$dsin\theta = (m + \frac{1}{2})\lambda$ Is for MINIMA.	

Please fill out the following chart. (Remember $sin\theta$ is directly proportional to θ.)

As…	…the pattern gets (wider/narrower).
d increases	
wavelength increases	

[6] This appears not to be in the AP Physics 1/AP Physics 2 curriculum.