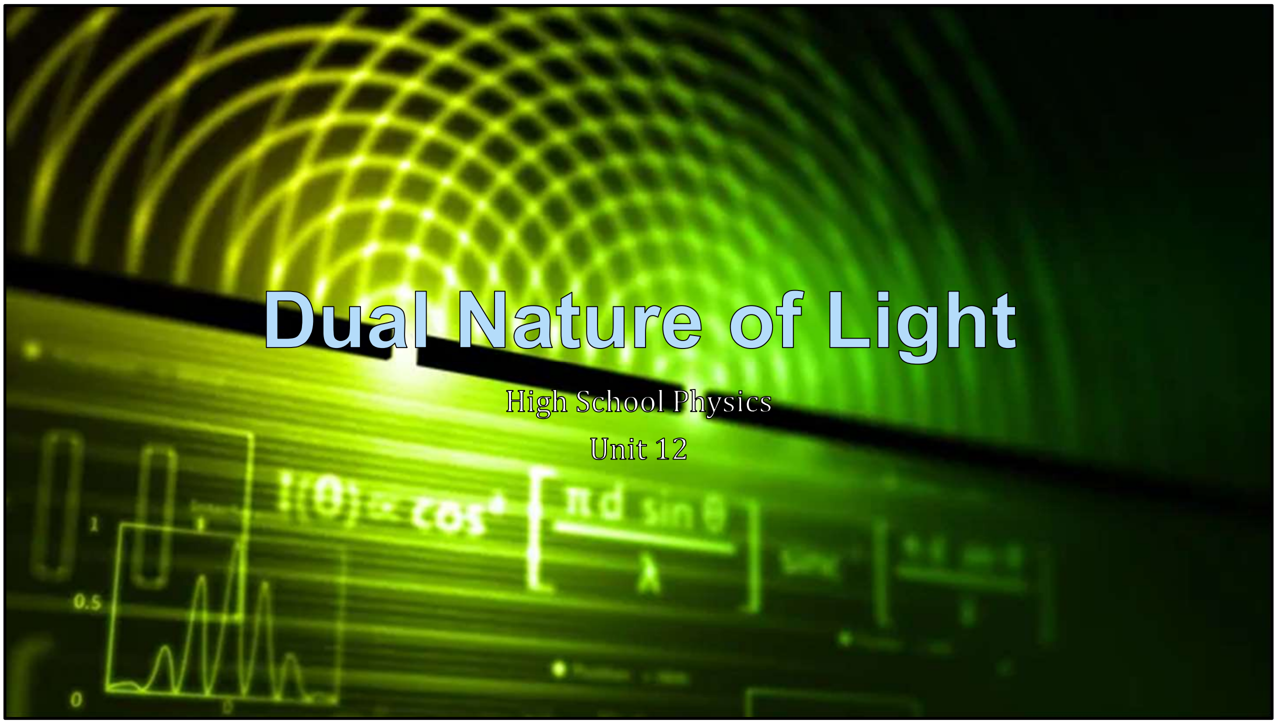

NAD 2023 Standard ER1 (Electromagnetic Radiation)

Credits

- This Slideshow was developed to accompany the textbook
  - *OpenStax High School Physics*
    - *Available for free at https://openstax.org/details/books/physics*
    - *By Paul Peter Urone and Roger Hinrichs*
    - *2020 edition*
- Some examples and diagrams are taken from the *OpenStax College Physics, Physics,* and *Cutnell & Johnson Physics* 6th ed.

Slides created by
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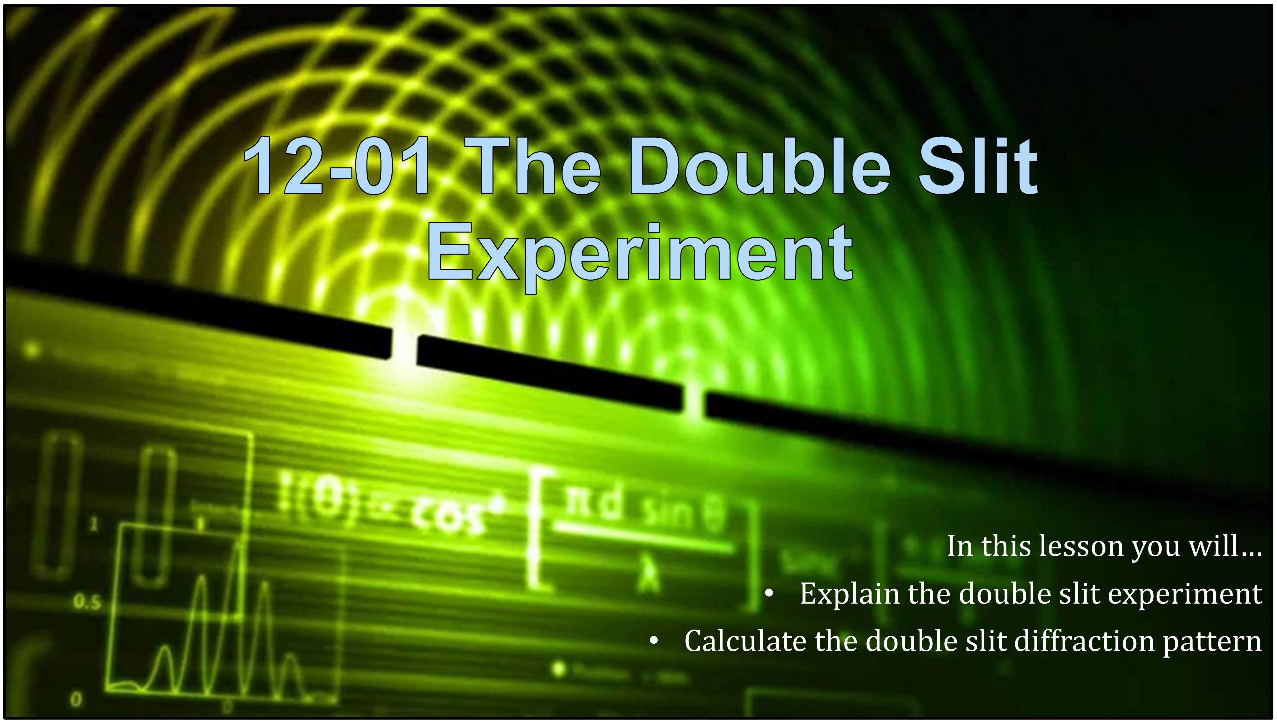


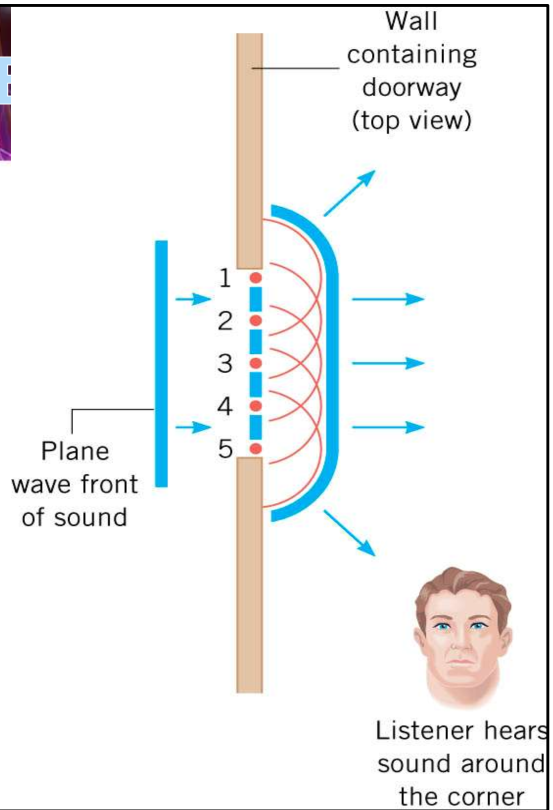
OpenStax High School Physics 17.1-2
OpenStax College Physics 2e 27.1-27.3

12-01 The Double Slit Experiment

- Wave Character of Light
  - When interacts with object several times it’s wavelength, it acts like a ray
  - When interacts with smaller objects, it acts like a wave

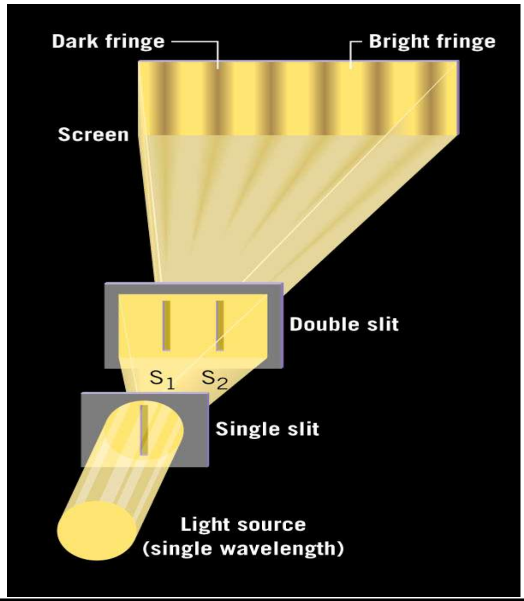
12-01 The Double Slit E

- Huygens' Principle
  - Every point on a wave front acts as a source of tiny wavelets that move forward with the same speed as the wave; the wave front at a later instant is the surface that is tangent to the wavelets.



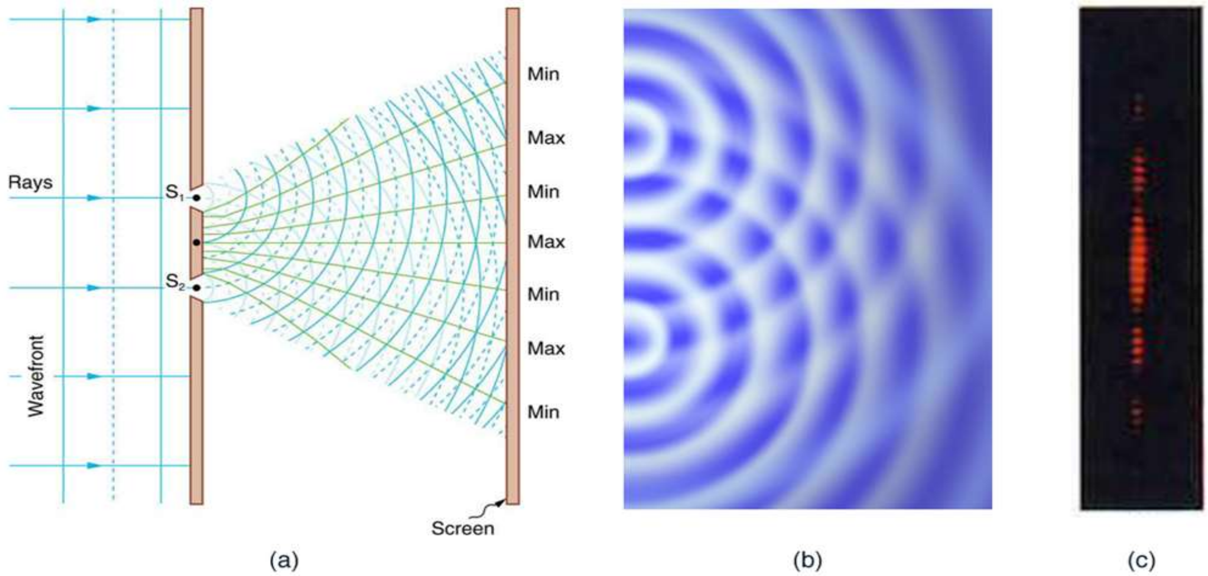
12-01 The Double Slit Experiment

- In 1801, Thomas Young showed that two overlapping light waves interfered and was able to calculate wavelength.

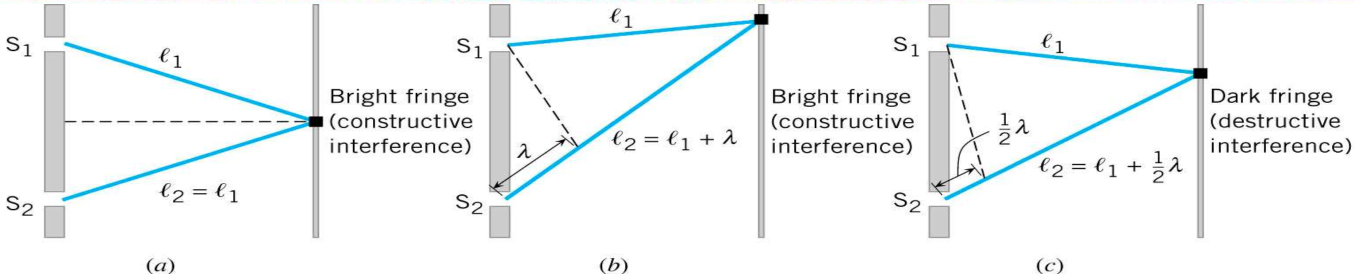


Have laser and double slit for demo (optics bench?)

12-01 The Double Slit Experiment



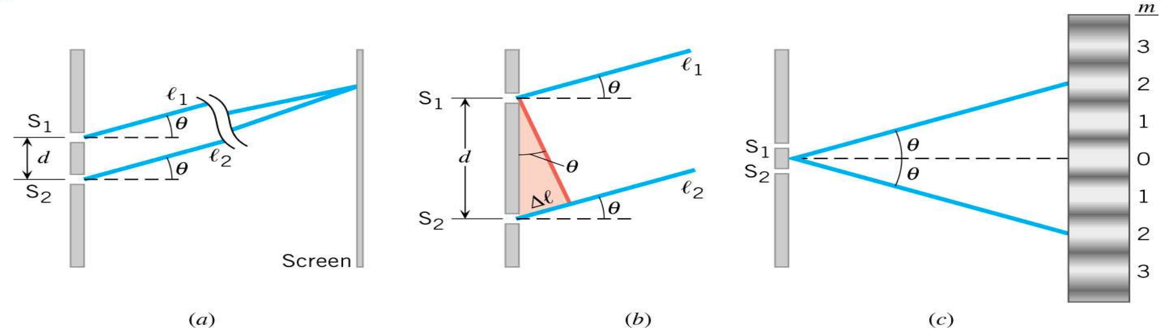
12-01 The Double Slit Experiment



- Bright fringe where $\ell_1 - \ell_2 = m\lambda$
- Dark fringe where $\ell_1 - \ell_2 = (m + \frac{1}{2})\lambda$

- Brightness of fringes varies
  - Center fringe the brightest and decreases on either side

12-01 The Double Slit Experiment



- A) Rays from slits S_1 and S_2, which make approximately the same angle θ with the horizontal, strike a distant screen at the same spot.
- B) The difference in the path lengths of the two rays is $\Delta\ell = d \sin\theta$.
- C) The angle θ is the angle at which a bright fringe (m = 2, here) occurs on either side of the central bright fringe (m = 0)

12-01 The Double Slit Experiment

- $\Delta\ell = d \sin\theta$
- Bright fringe $\Delta\ell = m\lambda$
  - $d \sin\theta = m\lambda$

$$\sin\theta = m\frac{\lambda}{d}$$

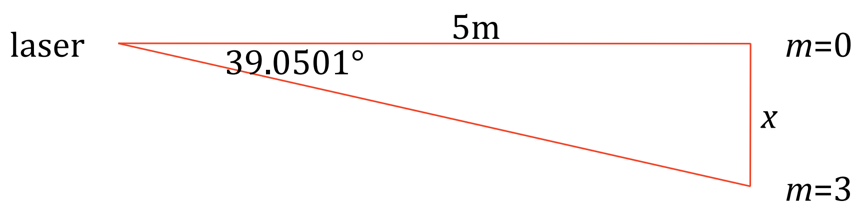
- Dark fringe $\Delta\ell = (m + \frac{1}{2})\lambda$
  - $d \sin\theta = (m + \frac{1}{2})\lambda$

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

θ = angle between fringe and center
m = integer
λ = wavelength
d = distance between slits

12-01 The Double Slit Experiment

- A laser beam (λ = 630 nm) goes through a double slit with separation of 3 μm. If the interference pattern is projected on a screen 5 m away, what is the distance between the third order bright fringe and the central bright fringe?
- 4.06 m



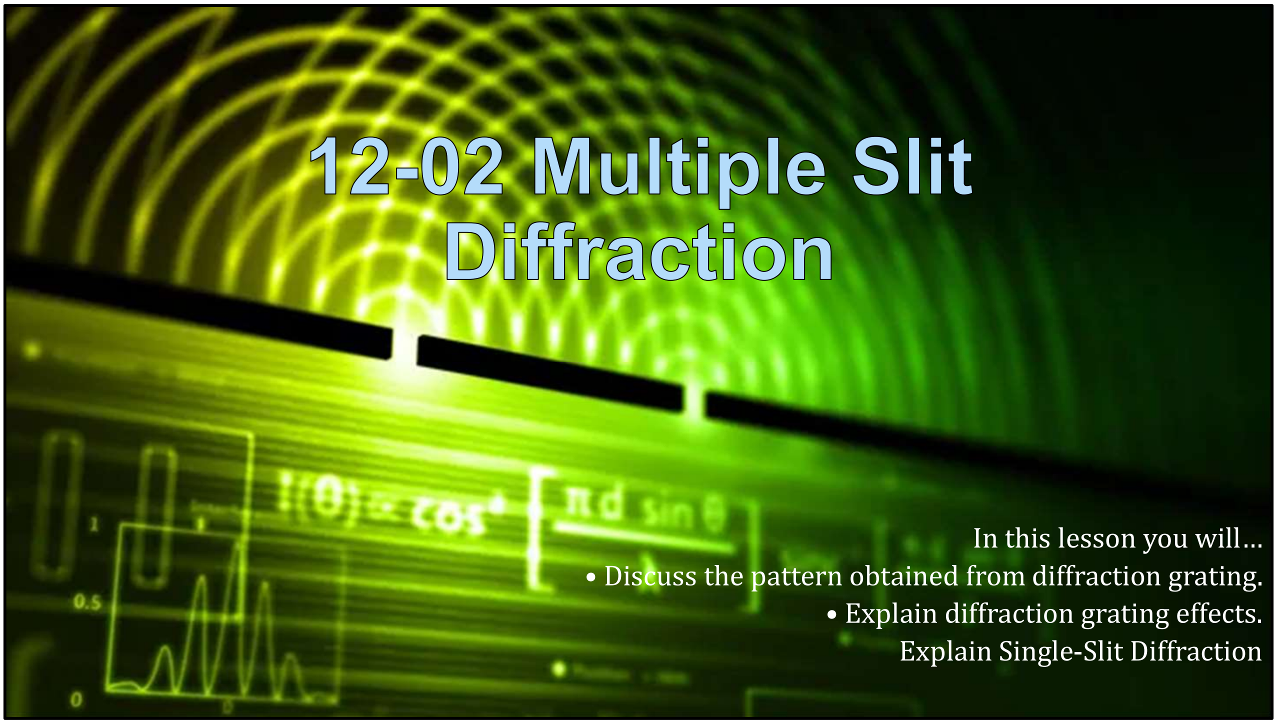
$$\sin\theta = m\frac{\lambda}{d} \rightarrow \sin\theta = 3\,\frac{630\times10^{-9}\,m}{3\times10^{-6}\,m} \rightarrow \sin\theta = 0.63 \rightarrow \theta = 39.0501°$$

$$\tan 39.0501° = \frac{x}{5\,m} \rightarrow 5\,m\,(\tan 39.0501°) = x = 4.06\,m$$

12-01 Practice Work

- Don’t let your other work interfere with these problems.

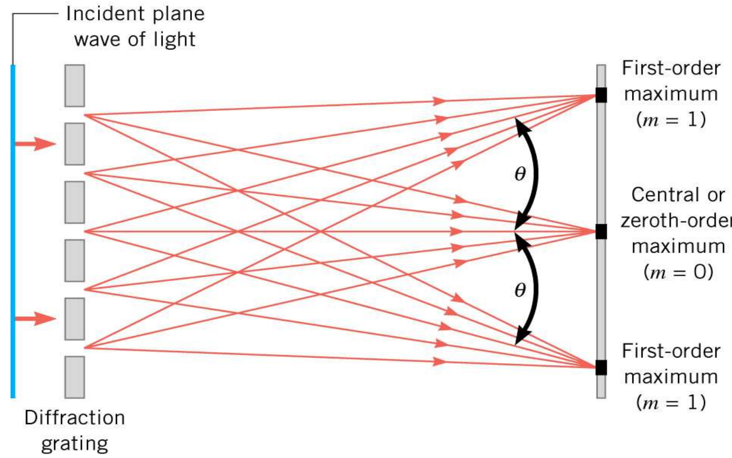
- Read
  - OpenStax College Physics 2e 27.4
  - OR
  - OpenStax High School Physics 17.1-2



OpenStax High School Physics 17.1-2
OpenStax College Physics 2e 27.4

12-02 Multiple Slit Diffraction

- Arrangement of many closely spaced slits
- As many as 40,000 slits per cm
- Produces interference patterns

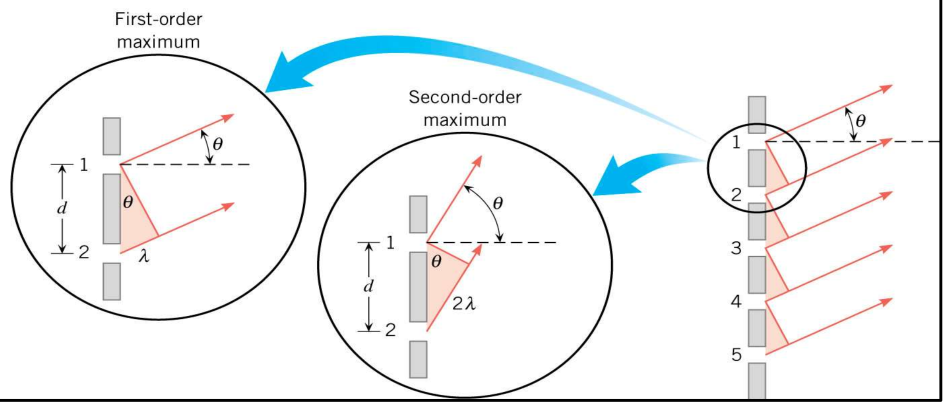


Have a couple diffraction gratings to play with

12-02 Multiple Slit Diffraction

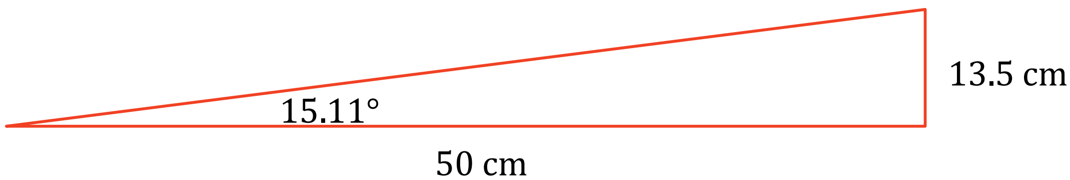
- The light rays are essentially parallel.
- The principal maxima occur when light from one slit travels $m\lambda$ more to meet light from a 2^{nd} slit producing constructive interference.
- Principal maxima

$$\sin\theta = m\frac{\lambda}{d}$$



12-02 Multiple Slit Diffraction

- A laser which produces 650 nm light shines through a diffraction grating. An interference pattern is produced on a screen 50 cm away. The distance on the screen between the second order maxima and the center is 13.5 cm. What is the slit separation in the grating?
  - 4.99×10^{-6} m

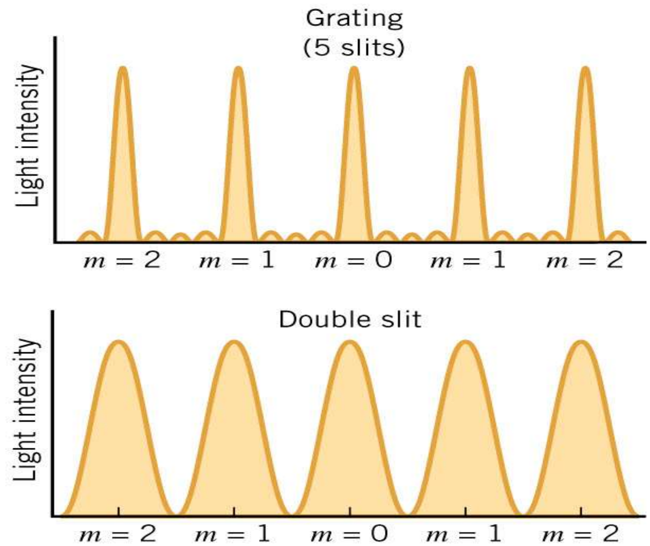


$$\tan\theta = \frac{13.5\ cm}{50\ cm} \rightarrow \theta = \tan^{-1}\frac{13.5}{50} = 15.11°$$

$$\sin\theta = m\frac{\lambda}{d} \rightarrow \sin 15.11° = 2\frac{650 \times 10^{-9}\ m}{d} \rightarrow d = 2\frac{650 \times 10^{-9}\ m}{\sin 15.11°}$$
$$= 4.99 \times 10^{-6}\ m$$

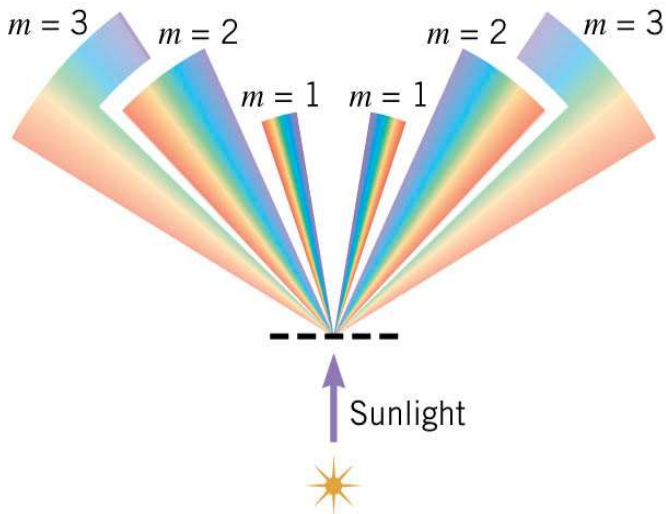
12-02 Multiple Slit Diffraction

- Diffraction gratings produce narrower, more defined maxima, but have small secondary maxima in between.



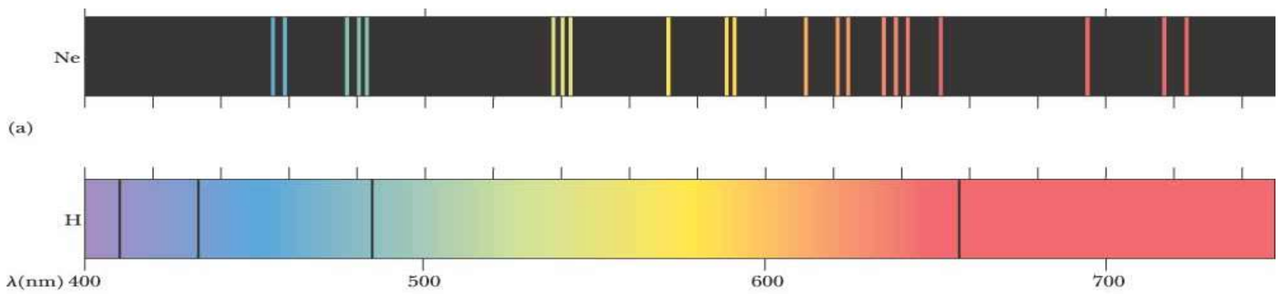
12-02 Multiple Slit Diffraction

- Splitting colors
  - Each color of light is a different wavelength, so each color bends a different angle.
  - Which color bends the most?
    - Red
  - Which color bends the least?
    - Violet



12-02 Multiple Slit Diffraction

- Application - Determining Elements in Stars
  - Each element in a hot gas emits or absorbs certain wavelengths of light.
  - By using a diffraction grating the light can be split and the wavelengths measured.

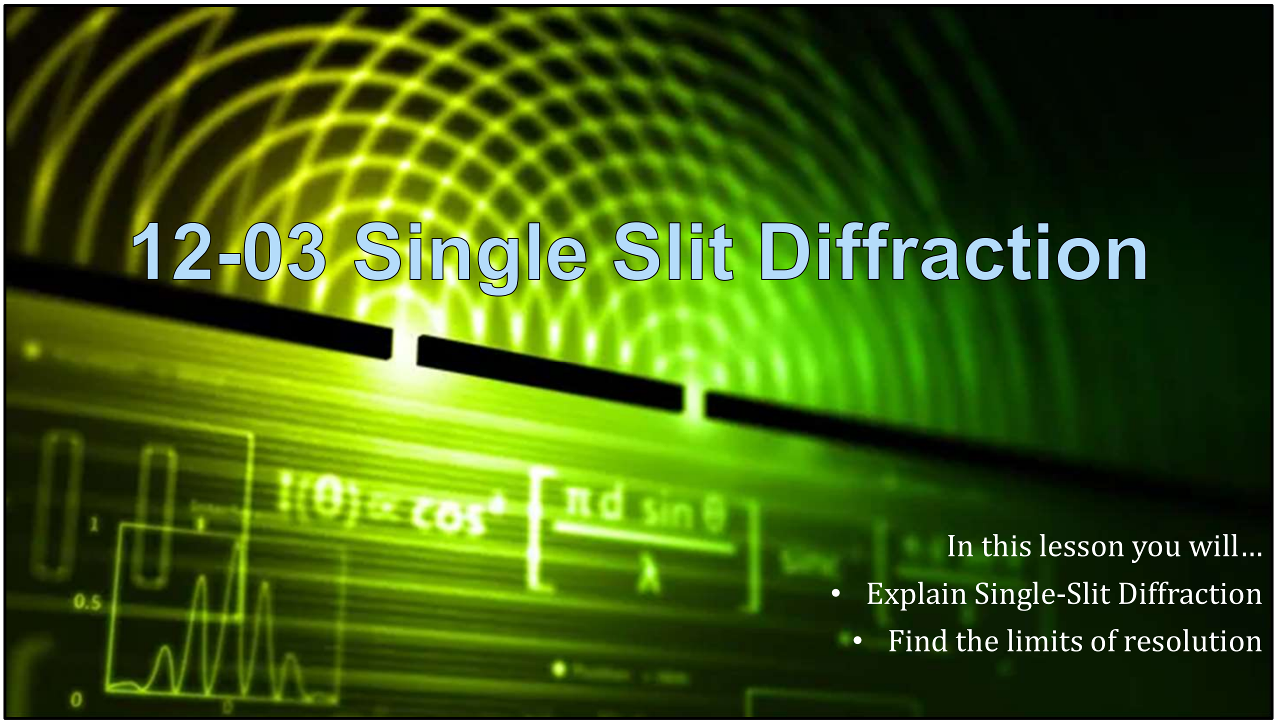


Top is an emission spectra of Neon
Bottom is an absorption spectra of Hydrogen

12-02 Practice Work

- I hope you don't find these problems grating.

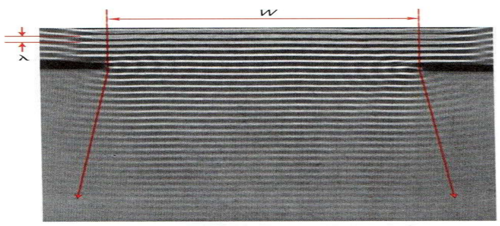
- Read
  - OpenStax College Physics 2e 27.5-27.6
  - OR
  - OpenStax High School Physics 17.1-2



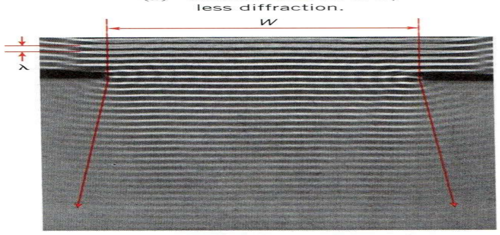
OpenStax High School Physics 17.1-2
OpenStax College Physics 2e 27.5-27.6

12-03 Single Slit Diffraction

Large opening → small bend

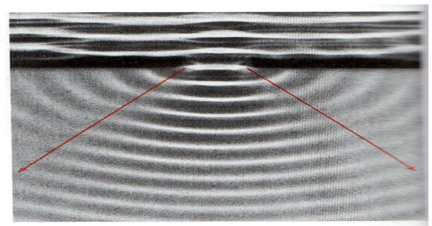


(a) Smaller value for λ/W, less diffraction.

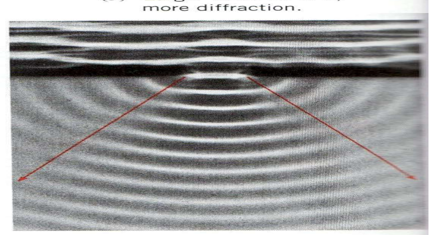


(a) Smaller value for λ/W, less diffraction.

Small opening → large bend



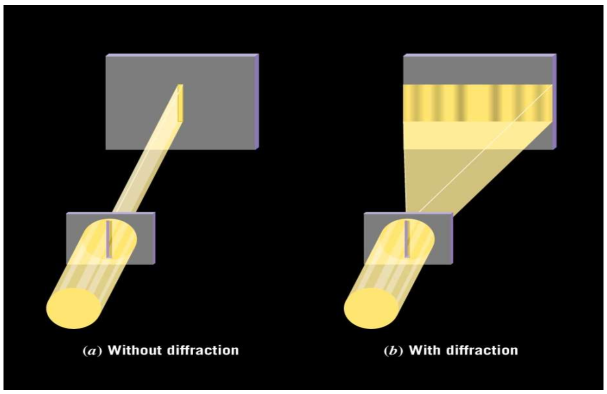
(b) Larger value for λ/W, more diffraction.



(b) Larger value for λ/W, more diffraction.

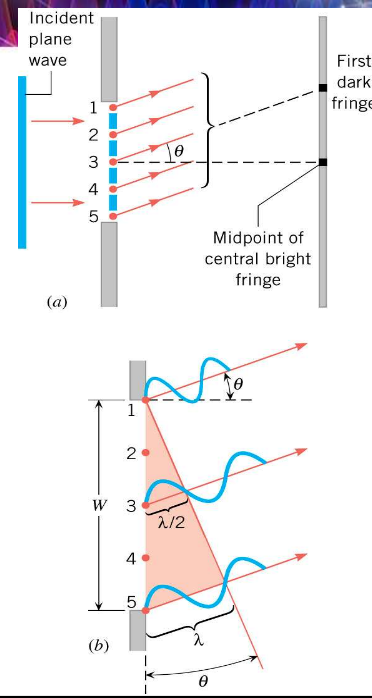
12-03 Single Slit Diffraction

- Single slit produces a diffraction pattern
- The Huygens wavelets interfere with each other
- The center bright band is twice width of the other bands.



12-03 Single Slit Diffraction

- First order dark band occurs when left edge and right edge path lengths differ by 1 wavelength.
- The center wave path length differs by ½ wavelength leading to the destructive interference.
- The wavelet slightly below #1 will cancel with wavelet slightly below #3 and so on.



The screen is far from the single slit so that wavelets are parallel. We are looking at the part of the wavelets that are traveling at an angle to the normal.

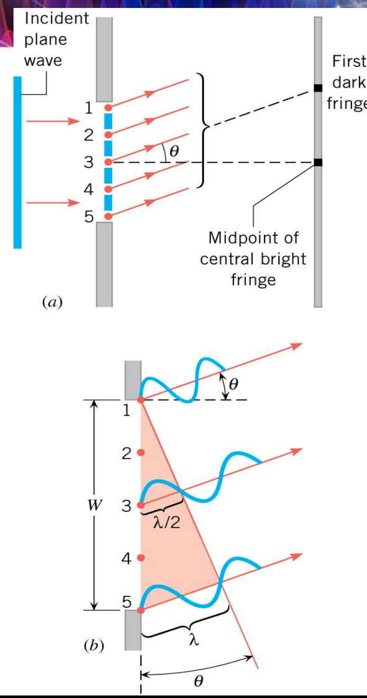
12-03 Single Slit Diffraction

$$\sin\theta = \frac{\lambda}{W}$$

- For multiple dark fringes

$$\sin\theta = m\frac{\lambda}{W}$$

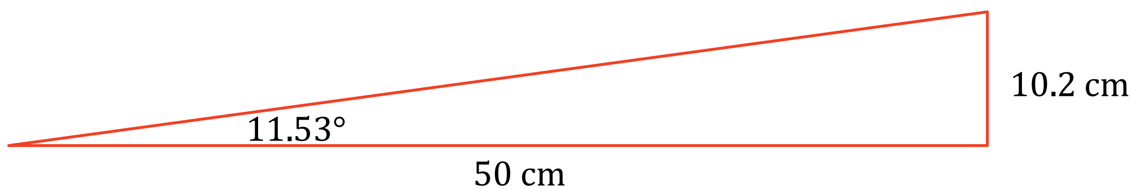
- Where
  - θ = angle between wave and normal to slit
  - m = dark band order
  - λ = wavelength
  - W = width of slit



The screen is far from the single slit so that wavelets are parallel. We are looking at the part of the wavelets that are traveling at an angle to the normal.

12-03 Single Slit Diffraction

- A laser shines through a single slit of width 3.25×10^{-6} m. The first order dark fringe is 10.2 cm from the center and the slit is 50 cm from the screen. What is the wavelength of the laser?
  - 650 nm



$$\tan\theta = \frac{10.2\ cm}{50\ cm} \rightarrow \theta = \tan\left(\frac{10.2}{50}\right) = 11.53°$$

$$\sin\theta = m\frac{\lambda}{W} \rightarrow \sin 11.53° = 1\frac{\lambda}{3.25 \times 10^{-6}\ m} \rightarrow 6.496 \times 10^{-7}\ m = \lambda$$

12-03 Single Slit Diffraction

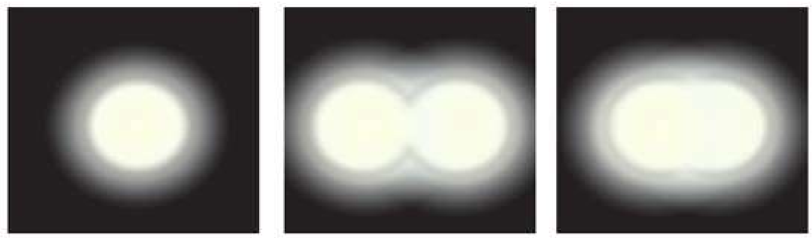
- Application – Microchip Production
  - Very small electrical components are used.
  - Make masks similar to photographic slides.
  - Light shines through the mask onto silicon wafers coated with photosensitive material.
  - The exposed portions are chemically removed later.
  - If too much diffraction occurs, the lines will overlap.
  - Currently UV rays which have smaller wavelengths than visible light is used to minimize λ/W ratio.
  - To improve could use X-rays or Gamma Rays with even smaller wavelengths.

12-03 Single Slit Diffraction

- Light going through a circular aperture has diffraction
  - Also true for light from lens and mirrors
- 1st minimum at

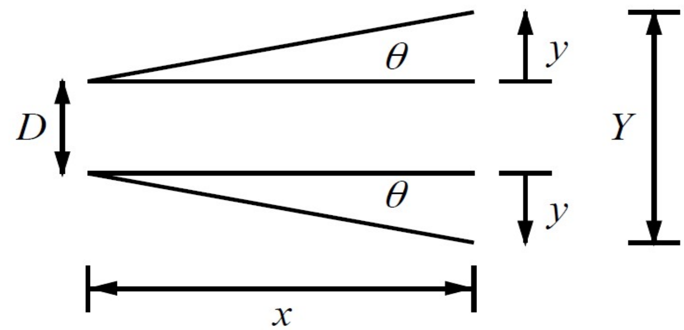
$$\theta = 1.22\frac{\lambda}{D}$$

  - Where
  - θ is in radians
  - λ is the wavelength
  - D is the diameter of aperture, lens, mirror, etc.
- The diffraction limits the amount of detail or resolution
- Two images are just resolvable when the center of the diffraction pattern of one is directly over the first minimum of the other.



12-03 Single Slit Diffraction

- (a) What is the minimum angular spread of a 633-nm wavelength He-Ne laser beam that is originally 1.00 mm in diameter? (b) If this laser is aimed at a mountain cliff 15.0 km away, how big will the illuminated spot be?
- 23.2 m



$$(a)\,\theta = 1.22\frac{\lambda}{D} = 1.22\frac{633\times10^{-9}\ m}{1\times10^{-3}\ m} = 7.72\times10^{-4}\ radians$$

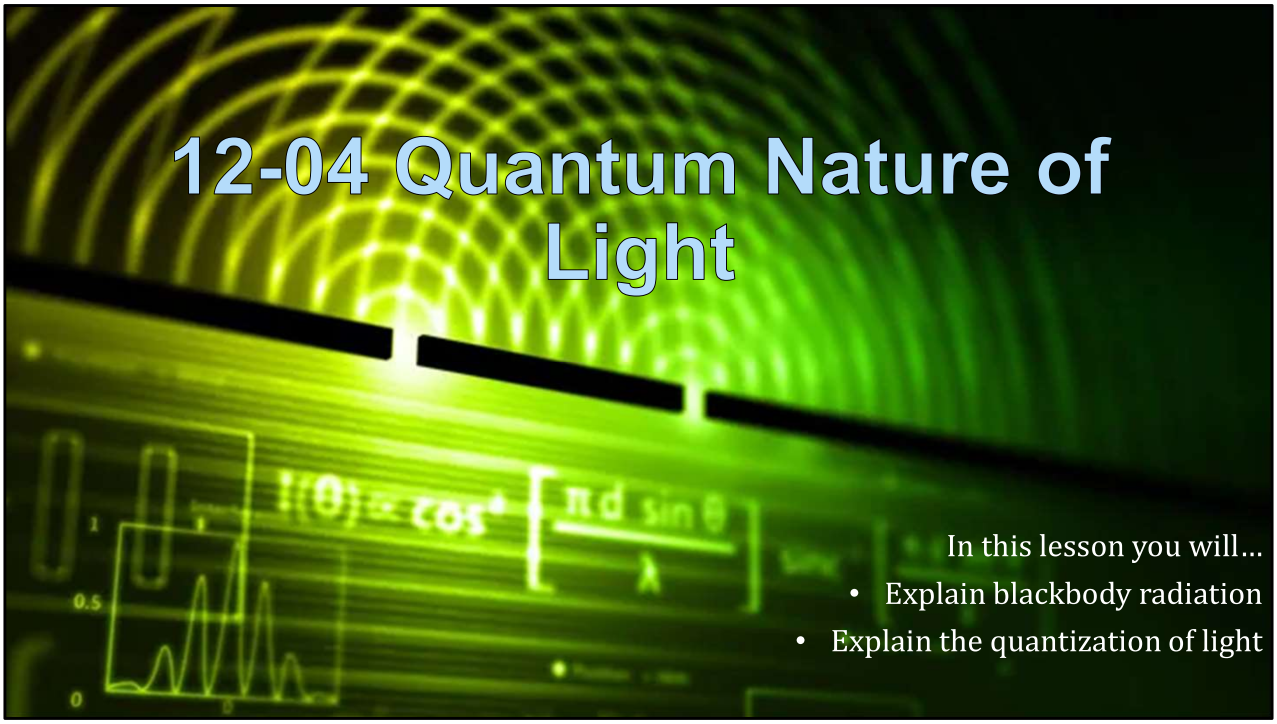
$$(b)\tan\theta = \frac{y}{x} \rightarrow \tan 7.72\times10^{-4}\ rad = \frac{y}{15000\ m} \rightarrow y = (15000\ m)\tan 7.72\times10^{-4}\ rad = 11.58\ m$$

$$Y = 2y + D = 2(11.58\ m) + 1\times10^{-3}\ m = 23.2\ m$$

12-03 Practice Work

- Don’t let frivolities interfere with your learning.

- Read
  - OpenStax College Physics 2e 29.1
  - OR
  - OpenStax High School Physics 21.1



12-04 Quantum Nature of Light

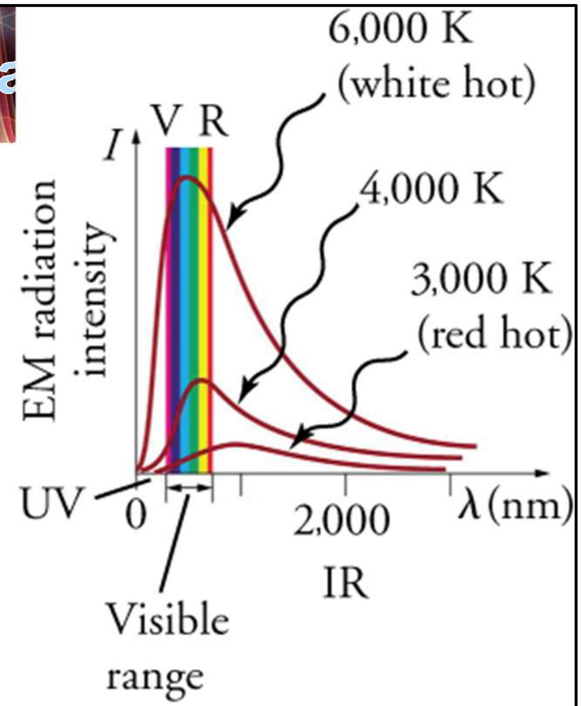
In this lesson you will…

- Explain blackbody radiation
- Explain the quantization of light

OpenStax High School Physics 21.1
OpenStax College Physics 2e 29.1

12-04 Quantum Na

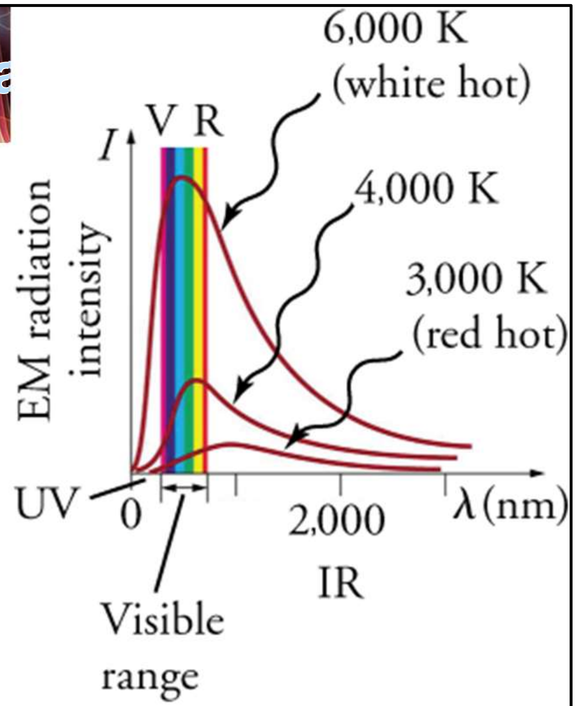
- It is hotter to wear black clothes in the sun than to wear white
- Black absorbs all light
    - It also re-emits that light
- Blackbody
    - Absorbs all light
    - Re-emits all that light
- The color that a hot object (blackbody) emits depends on its temperature.



The peak shows what the most common wavelength that is emitted for a given temperature.

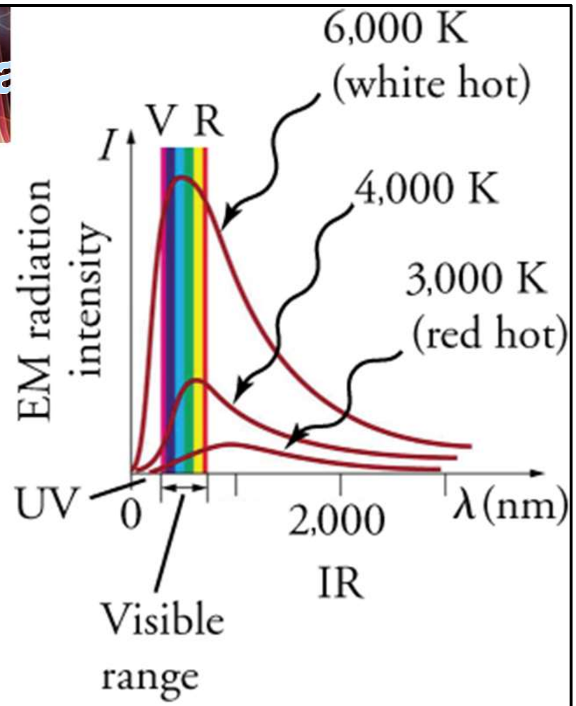
12-04 Quantum Na

- As the temperature increases, the total amount of energy increases
- While all the wavelengths are emitted, there is one peak wavelength
- As the temperature increases, the peak wavelength gets shorter
  - The increased temperature atoms move faster and the frequency of the light increases.
  - By $v = f\lambda$, the wavelength decreases



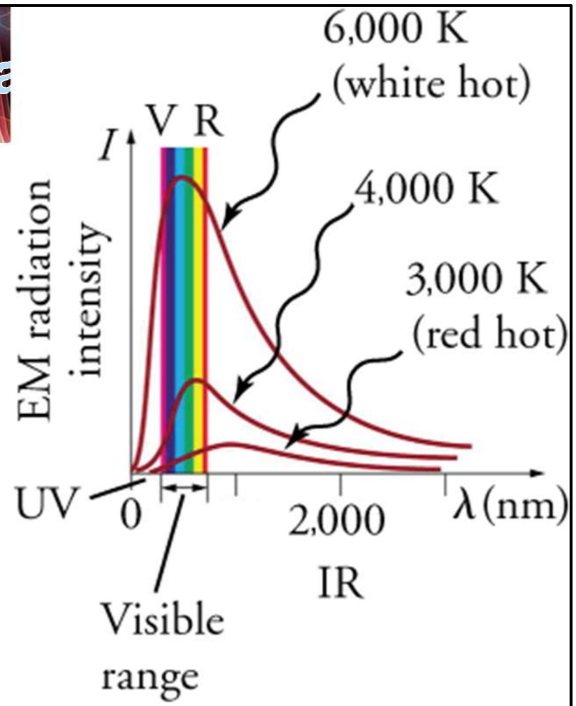
12-04 Quantum Na

- This graph does not match classical physics which is based on continuous energy
- Planck invented the idea that the frequencies emitted are based on probabilities
- Energy is quantum
  - Only exists in certain amounts
  - Like the number of electrons in something must be a whole number
  - $E = nhf$



12-04 Quantum Na

- Energy is quantum
  - $E = nhf = n\frac{hc}{\lambda}$
    - n = 0, 1, 2, 3, … (# of photons)
    - $h = 6.626\times10^{-34}$ J·s
    - f = frequency of light
  - Low frequency (long λ) light is low energy
  - High frequency (short λ) light is high energy
- Low temperature has low energy so more low frequency light
- High temperature has higher energy so more higher frequency light



h is Planck's constant

12-04 Quantum Nature of Light

- The idea of quantized energy earned Planck the Nobel Prize in physics
- Other things that are quantized
  - Atoms and molecules
  - Charge
  - Electrons

12-04 Quantum Nature of Light

- How many photons per second does a typical 10W LED lightbulb produce if 80% of the electrical energy is turned into useable light with an average wavelength of 520 nm?

$$E = nhf$$

$$c = f\lambda \rightarrow f = \frac{c}{\lambda}$$

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

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

$$\frac{E}{n} = \frac{(6.626 \times 10^{-34}\ J \cdot s)\left(3.00 \times 10^{8}\,\frac{m}{s}\right)}{520 \times 10^{-9}\ m} = 3.82 \times 10^{-1}\quad \frac{J}{photon}$$

$$1\ W = \frac{1\ J}{s}$$

$$80\%(10\ W) = 8\frac{J}{s}$$

$$\frac{J}{s} \div \frac{J}{photon} = \frac{J}{s} \cdot \frac{photon}{J} = \frac{photon}{s}$$

$$\left(8\frac{J}{s}\right) \div \left(3.82 \times 10^{-19}\,\frac{J}{photon}\right) = 2.09 \times 10^{19}\ photons/s$$

12-04 Quantum Nature of Light

- Compare the energy of one photon of UV light (λ = 250 nm) with IR light (λ = 890 nm).

$$c = f\lambda \rightarrow f = \frac{c}{\lambda}$$

$$E = nhf \rightarrow \frac{E}{n} = \frac{hc}{\lambda}$$

UV

$$\frac{E}{n} = \frac{(6.626 \times 10^{-34}\, J \cdot s)\left(3.00 \times 10^{8}\, \frac{m}{s}\right)}{250 \times 10^{-9}\, m} = 7.95 \times 10^{-19}\, \frac{J}{photon}$$

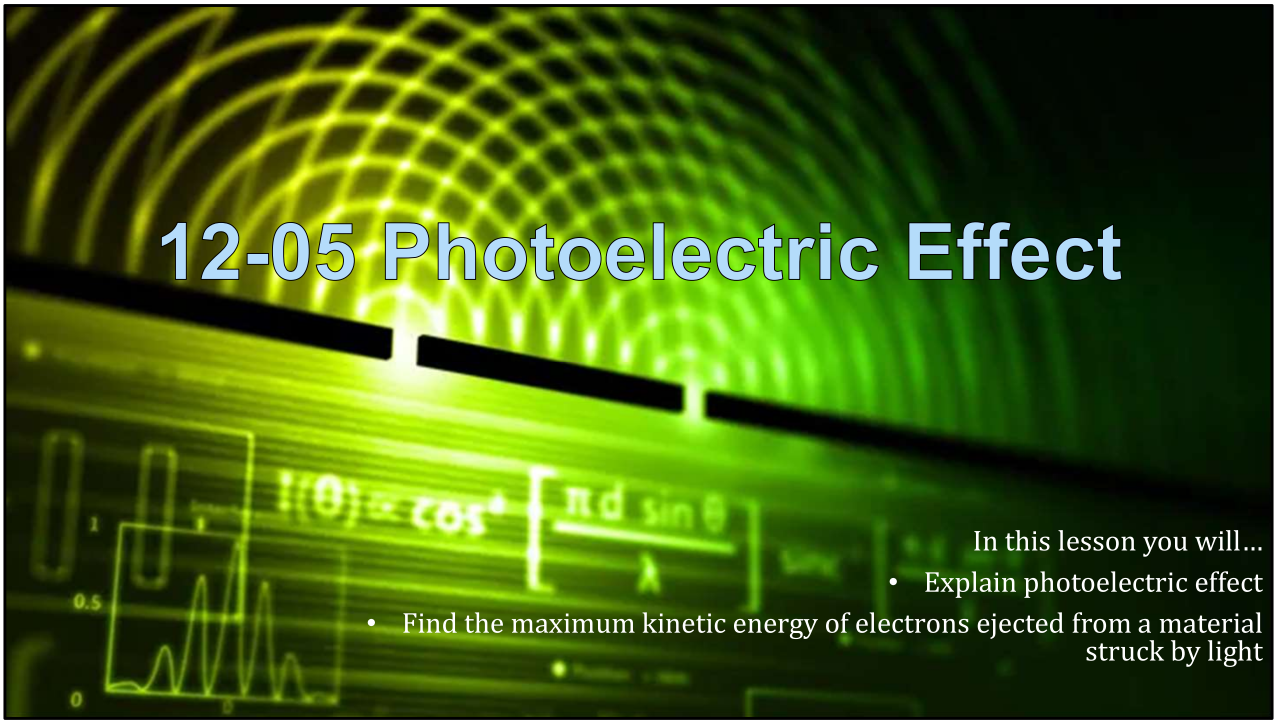
IR

$$\frac{E}{n} = \frac{(6.626 \times 10^{-34}\, J \cdot s)\left(3.00 \times 10^{8}\, \frac{m}{s}\right)}{890 \times 10^{-9}\, m} = 2.23 \times 10^{-1}\ \ \frac{J}{photon}$$

12-04 Practice Work

- Radiate the love of Jesus to the world.

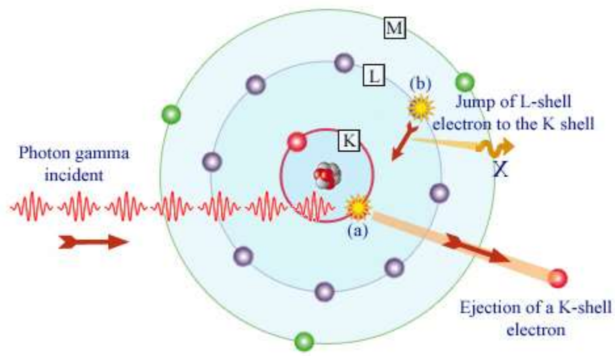
- Read
  - OpenStax College Physics 2e 29.2-29.3
  - OR
  - OpenStax High School Physics 21.2



OpenStax High School Physics 21.2
OpenStax College Physics 2e 29.2-29.3

12-05 Photoelectric Effect

- When a photon of light hits an electron, the electron absorbs the energy and jumps to a higher orbital
- If the photon has enough energy, the electron can completely leave the atom
- If there is a wire for the electrons to move through, then there will be a current
- This the is photoelectric effect



It is easier to eject electrons from the electron sea in a metal surface

12-05 Photoelectric Effect

- Einstein discovered
  - Light waves are not continuous streams
  - They are made up of discrete quantum particles of energy called photons
- Energy of photon from photoelectric effect is $E = hf = \frac{hc}{\lambda}$

12-05 Photoelectric Effect

1. For a given material, there is a threshold frequency f_0 for the EM radiation below which no electrons are ejected, regardless of intensity. Using the photon model, the explanation for this is clear. Individual photons interact with individual electrons. Thus if the energy of an individual photon is too low to break an electron away, no electrons will be ejected. However, if EM radiation were a simple wave, sufficient energy could be obtained simply by increasing the intensity.
2. Once EM radiation falls on a material, electrons are ejected without delay. As soon as an individual photon of sufficiently high frequency is absorbed by an individual electron, the electron is ejected. If the EM radiation were a simple wave, several minutes would be required for sufficient energy to be deposited at the metal surface in order to eject an electron.

12-05 Photoelectric Effect

3. The number of electrons ejected per unit time is proportional to the intensity of the EM radiation and to no other characteristic. High-intensity EM radiation consists of large numbers of photons per unit area, with all photons having the same characteristic energy, *hf*. The increased number of photons per unit area results in an increased number of electrons per unit area ejected.
4. The maximum kinetic energy of ejected electrons is independent of the intensity of the EM radiation. Instead, as noted in point 3 above, increased intensity results in more electrons of the same energy being ejected. If EM radiation were a simple wave, a higher intensity could transfer more energy, and higher-energy electrons would be ejected.

12-05 Photoelectric Effect

5. The kinetic energy KE of an ejected electron equals the photon energy minus the binding energy BE of the electron in the specific material. An individual photon can give all of its energy to an electron. The photon's energy is partly used to break the electron away from the material. The remainder goes into the ejected electron's kinetic energy. In equation form, this is given by $KE_e = hf - BE$ where KE_e is the maximum kinetic energy of the ejected electron, hf is the photon's energy, and BE is the binding energy of the electron to the particular material.

12-05 Photoelectric Effect

- What is the energy in joules and electron volts of a photon of 250 nm ultraviolet light?
- What is the maximum kinetic energy of electrons ejected from cesium by 250 nm UV light, given that the binding energy of electrons from silver is 3.894 eV?

$$E = hf$$

$$c = f\lambda \rightarrow f = \frac{c}{\lambda}$$

$$f = \frac{3.00 \times 10^{8}\,\frac{m}{s}}{250 \times 10^{-9}\,m} = 1.2 \times 10^{15}\ /s$$

$$E = (6.626 \times 10^{-3}\ \ J \cdot s)\left(1.2 \times 10^{15}\,\frac{}{s}\right) = 7.95 \times 10^{-19}\,J$$

Convert to eV

$$7.95 \times 10^{-1}\ \ J\left(\frac{1\ eV}{1.60 \times 10^{-19}\,J}\right) = 4.97\ eV$$

$$KE_e = hf - BE$$

$$KE_e = 4.97\ eV - 3.894\ eV = 1.08\ eV$$

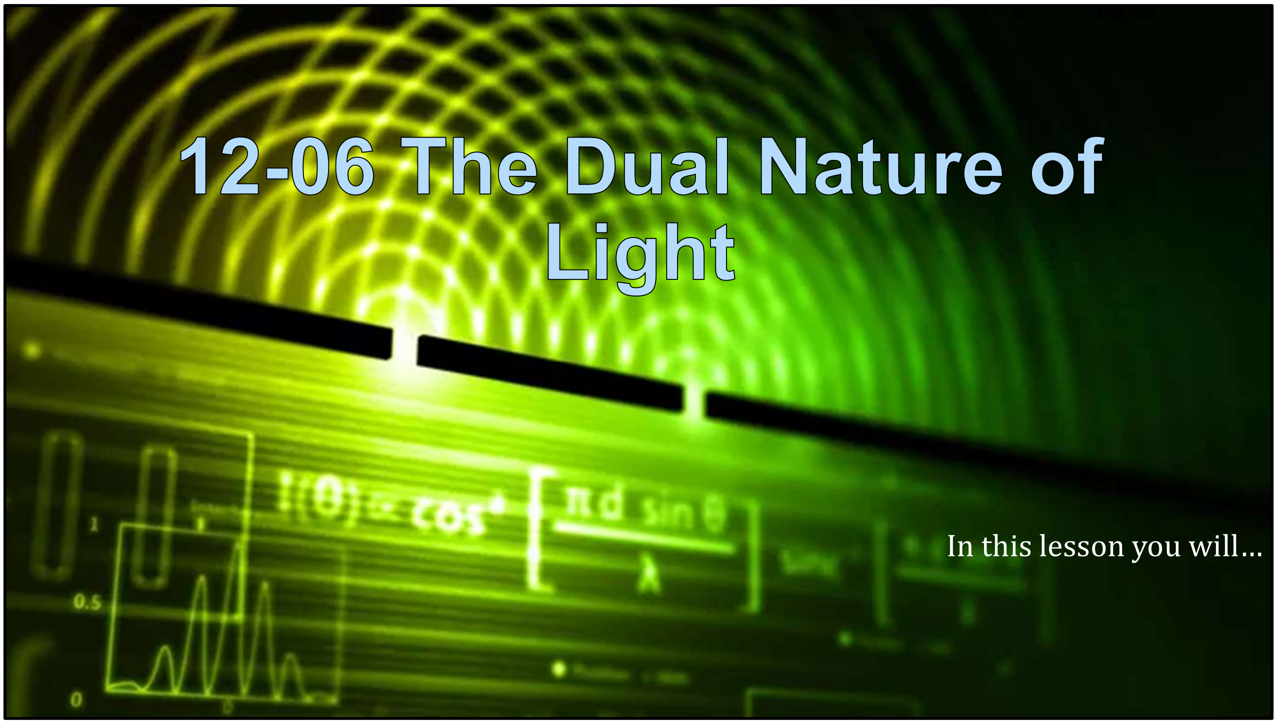
12-05 Photoelectric Effect

- Uses of the photoelectric effect
  - Photovoltaic solar cells
    - Light knocks electrons off metal which are then stored in a battery
  - Electric eye
    - Lights turn on in the dark
      - When it is day, the light knocks electrons off a piece of metal which is then filled with a new electron from a circuit. This make current. When the current goes away, the light turns on.
    - Automatic faucets, paper towels, toilets, etc.

12-05 Practice Work

- Light can change matter. Be a light to the world and change it.

- Read
  - OpenStax College Physics 2e 29.4-29.6
  - OR
  - OpenStax High School Physics 21.3



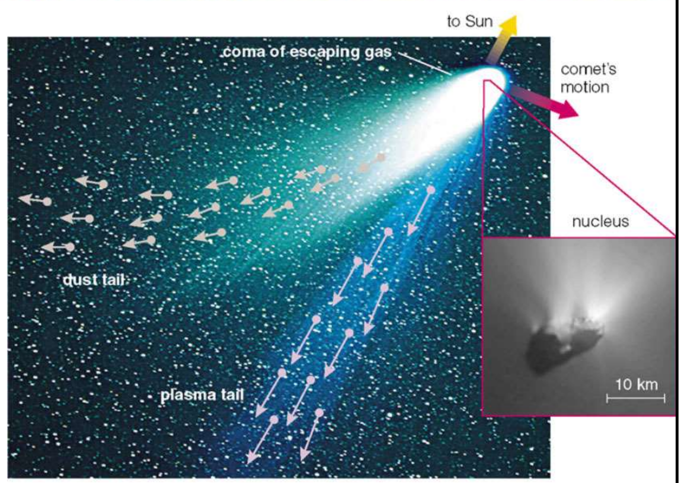
OpenStax High School Physics 21.3
OpenStax College Physics 2e 29.4-29.6

12-06 The Dual Nature of Light

- Light behaves as a wave
  - Diffracts
  - Reflects
  - Interference
- Light behaves as a particle
  - Discrete energy
    - Blackbody radiation
  - Photoelectric effect
  - Momentum

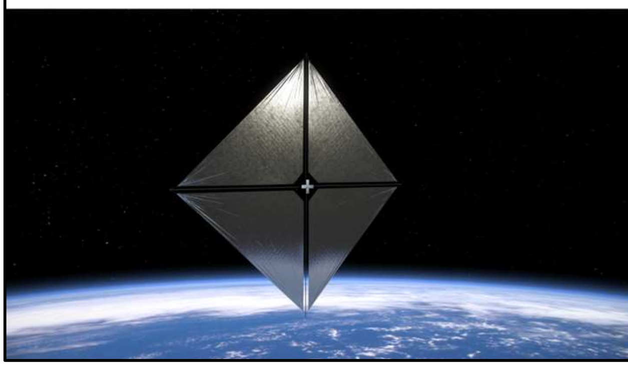
12-06 The Dual Nature of Light

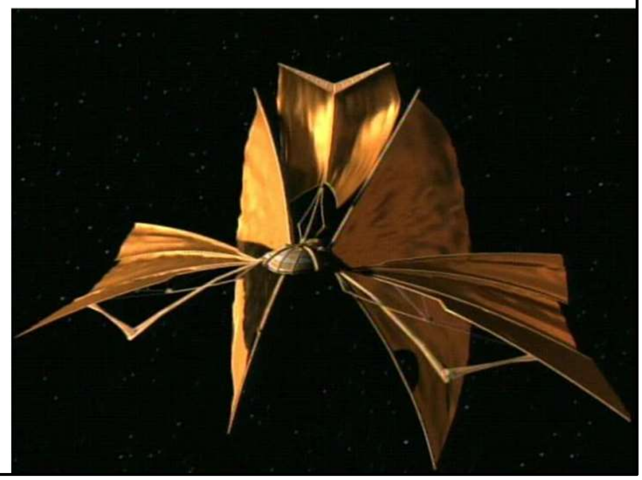
- Momentum of light
  - Light from the sun pushes a comet's tail away



12-06 The Dual Nature of Light

- Momentum of light
  - NASA is developing a sail spaceship that is pushed away from the sun using a sail that is hit by the sunlight

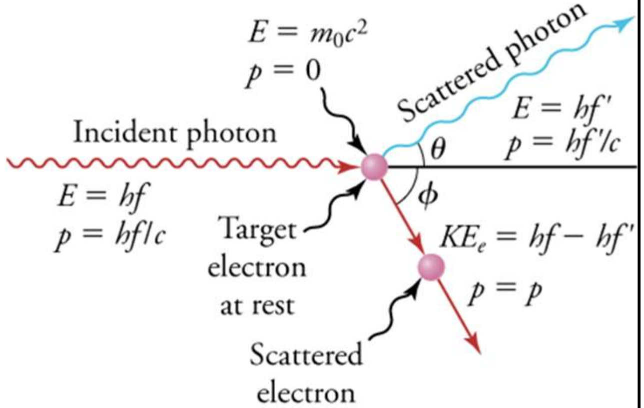




Left: NASA sail ship
Right: Bajoran lightship from Star Trek: Deep Space 9

12-06 The Dual Nature of Light

- Momentum of light
  - When X-rays are shot through atoms, then they scatter from hitting electrons
    - The scattered electrons have less energy than before because they gave some to the electron like a momentum collision
  - $p = \frac{h}{\lambda} = \frac{hf}{c}$



12-06 The Dual Nature of Light

- Calculate the momentum of a visible photon that has a wavelength of red light 680 nm.
- Find the velocity of an electron with the same momentum.

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

$$p = \frac{6.626 \times 10^{-34}\ J \cdot s}{680 \times 10^{-9}\ m} = 9.74 \times 10^{-28}\ \mathrm{kg}\frac{\mathrm{m}}{\mathrm{s}}$$

$$p = mv$$

$$9.74 \times 10^{-2}\quad kg\frac{m}{s} = (9.11 \times 10^{-31}\ kg)v$$

$$v = 1070\frac{m}{s}$$

This is nonrelativistic

12-06 The Dual Nature of Light

- What is the energy of the electron, and how does it compare with the energy of the photon?

Electron

$$KE = \frac{1}{2}mv^2$$

$$KE = \frac{1}{2}(9.11 \times 10^{-31}\ kg)\left(1070\frac{m}{s}\right)^2 = 5.21 \times 10^{-2}\ \ J$$

$$5.21 \times 10^{-25}\ J\left(\frac{1\ eV}{1.60 \times 10^{-19}\ J}\right) = 3.26 \times 10^{-6}\ eV$$

Very small

Photon

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

$$E = \frac{(6.626 \times 10^{-34}\ J \cdot s)\left(3.00 \times 10^{8}\frac{m}{s}\right)}{680 \times 10^{-9}\ m} = 2.92 \times 10^{-19}\ J$$

$$2.92 \times 10^{-19}\ J\left(\frac{1\ eV}{1.60 \times 10^{-19}\ J}\right) = 1.83\ eV$$

About a million times more energy than the electron

12-06 The Dual Nature of Light

- Particle-Wave Duality
  - Light waves can act as particles
  - Particles can act as waves
    - Electrons can interfere with each other
    - Electron currents can cancel out
  - All matter is both waves and particles

12-06 Practice Work

- We are called to a duality: Be in the world, but not of the world.