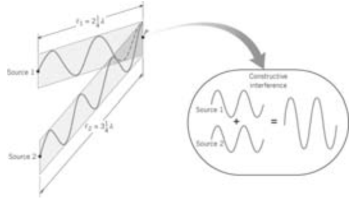
Chapter 27 & 29

Wave Properties, Waves and Particles

27.1 The Principle of Linear Superposition-Constructive Interference

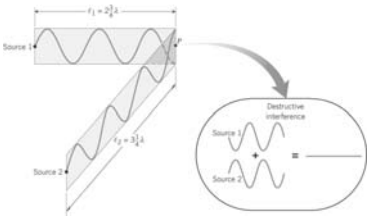
When two or more light waves pass through a given point, their electric fields combine according to the principle of superposition.



The waves emitted by the sources start out in phase and arrive at point P in phase, leading to ***constructive interference.***

$$\ell_2 - \ell_1 = m\lambda \qquad m = 0,1,2,3,\ldots$$

27.1 The Principle of Linear Superposition – Destructive Interference



The waves emitted by the sources start out in phase and arrive at point P out of phase, leading to ***destructive interference.***

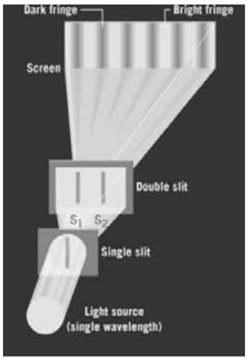
$$\ell_2 - \ell_1 = \left(m + \tfrac{1}{2}\right)\lambda \qquad m = 0,1,2,3,\ldots$$

27.1 The Principle of Linear Superposition

If constructive or destructive interference is to continue occurring at a point, the sources of the waves must be ***coherent sources***.

Two sources are coherent if the waves they emit maintain a constant phase relation.

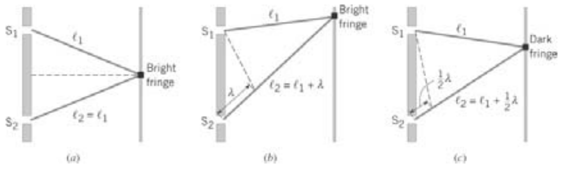
27.2 Young's Double Slit Experiment



In Young's experiment, two slits acts as coherent sources of light.

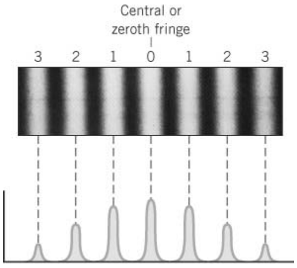
Light waves from these slits interfere constructively and destructively on the screen.

27.2 Young's Double Slit Experiment

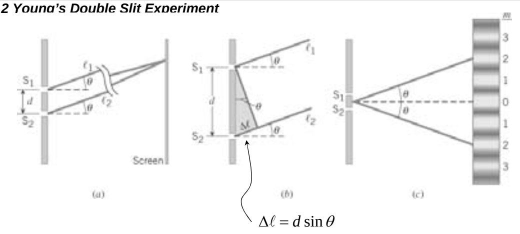


The waves coming from the slits interfere constructively or destructively, depending on the difference in distances between the slits and the screen.

27.2 Young's Double Slit Experiment



27.2 Young's Double Slit Experiment



$$\Delta \ell = d \sin\theta$$

Bright fringes of a double-slit

$$\sin\theta = m\frac{\lambda}{d} \qquad m = 0,1,2,3,\ldots$$

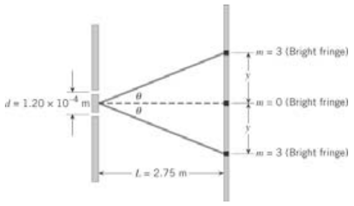
Dark fringes of a double-slit

$$\sin\theta = \left(m + \tfrac{1}{2}\right)\frac{\lambda}{d} \qquad m = 0,1,2,3,\ldots$$

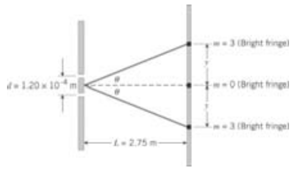
27.2 Young's Double Slit Experiment

Example 1 **Young's Double-Slit Experiment**

Red light (664 nm) is used in Young's experiment with slits separated by 0.000120 m. The screen is located a distance 2.75 m from the slits. Find the distance on the screen between the central bright fringe and the third-order bright fringe.



27.2 Young's Double Slit Experiment



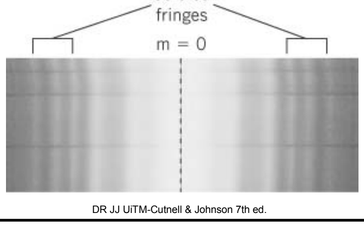
$$\theta = \sin^{-1}\left(m\frac{\lambda}{d}\right) = \sin^{-1}\left(3\frac{664\times10^{-9}\,\text{m}}{1.20\times10^{-4}\,\text{m}}\right) = 0.951^\circ$$

$$y = L\tan\theta = (2.75\,\text{m})\tan(0.951^\circ) = 0.0456\,\text{m}$$

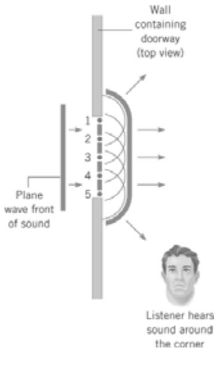
27.2 Young's Double Slit Experiment

Conceptual Example 2 **White Light and Young's Experiment**

The figure shows a photograph that illustrates the kind of interference fringes that can result when white light is used in Young's experiment. Why does Young's experiment separate white light into its constituent colors? In any group of colored fringes, such as the two singled out, why is red farther out from the central fringe than green is? Why is the central fringe white?



27.5 Diffraction

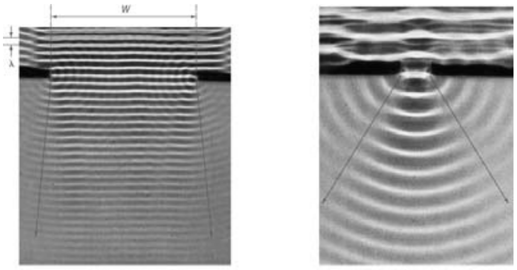


Diffraction is the bending of waves around obstacles or the edges of an opening.

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 latter instant is the surface that is tangent to the wavelets.

27.5 Diffraction

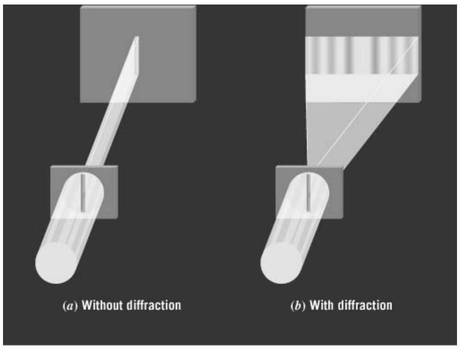


(a) Smaller value for λ/W, less diffraction.

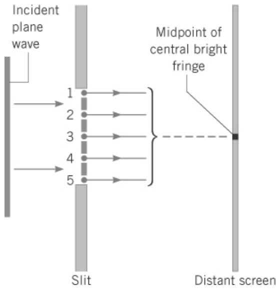
(b) Larger value for λ/W, more diffraction.

The extent of the diffraction increases as the ratio of the wavelength to the width of the opening increases.

27.5 Diffraction

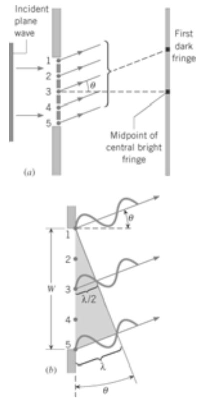


27.5 Diffraction



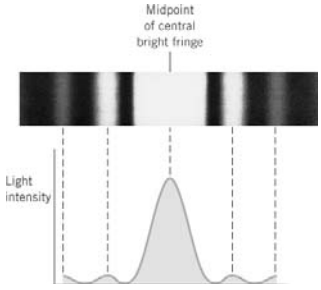
This top view shows five sources of Huygens' wavelets.

27.5 Diffraction



These drawings show how destructive interference leads to the first dark fringe on either side of the central bright fringe.

27.5 Diffraction



Dark fringes for single slit diffraction

$$\sin\theta = m\frac{\lambda}{W} \qquad m = 1, 2, 3, \ldots$$

27.6 Resolving Power

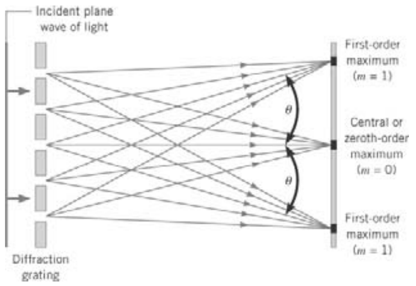
Conceptual Example 8 **What You See is Not What You Get**

The French postimpressionist artist Georges Seurat developed a technique of painting in which dots of color are placed close together on the canvas. From sufficiently far away the individual dots are not distinguishable, and the images in the picture take on a more normal appearance.

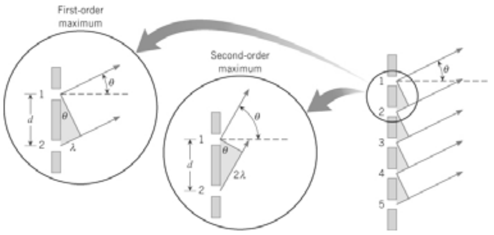
Why does the camera resolve the dots, while his eyes do not?

27.7 The Diffraction Grating

An arrangement consisting of a large number of closely spaced, parallel slits is called a ***diffraction grating.***

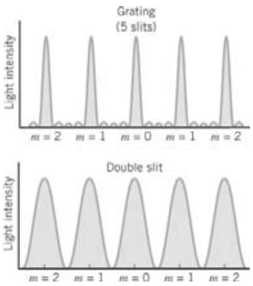


27.7 The Diffraction Grating



The conditions shown here lead to the first- and second-order intensity maxima in the diffraction pattern.

27.7 The Diffraction Grating



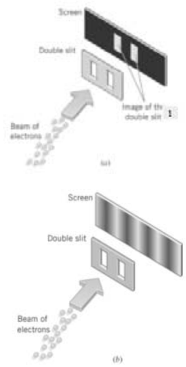
The bright fringes produced by a diffraction grating are much narrower than those produced by a double slit.

Principal maxima of a diffraction grating

$$\sin\theta = m\frac{\lambda}{d} \qquad m = 0,1,2,3,\ldots$$

distance between slits

29.1 Wave Particle Duality



Can a beam of electrons passing through a double slit produce dark and bright fringes too?

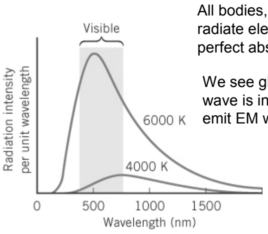
If electrons only exhibit particle-like characteristics, only shape of the slits would be seen on the screen

Can particles exhibit wave-like characteristics?
Can waves exhibit particle-like characteristics??

When a beam of electrons is used in a Young's double slit experiment, a fringe pattern occurs, indicating interference effects.

Wave-particle duality:
Waves can exhibit particle-like characteristics, and particles can exhibit wave-like characteristics.

29.2 Blackbody Radiation and Planck's Constant



All bodies, no matter how hot or cold, continuously radiate electromagnetic waves. A black body is a perfect absorber & emitter

We see glow of hot objects because the emitted EM wave is in the visible region. Human body (T=310K) emit EM wave.

The energy of EM wave is continuous but this cannot explain the radiation produced by a black body

Max Planck calculated the blackbody radiation curves. Assumed that each energy of each atomic oscillator can only have discrete values. Electromagnetic energy is quantized. It has values in multiples of ***hf: E=hf, 2hf, 3hf, …***

frequency

$$E = nhf = nh\frac{c}{\lambda} \qquad n = 0,1,2,3,\ldots$$

Planck's constant $h = 6.626\times10^{-34}\,\mathrm{J\cdot s}$

Energy lost by oscillators is energy carried by electromagnetic wave

29.3 Photons and the Photoelectric Effect

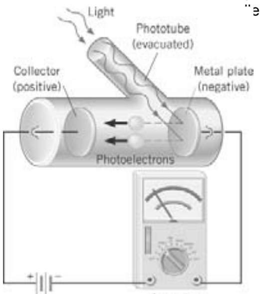
Waves have characteristics of material matter

Particles have energy *E (KE+PE)* which is continuous and have momentum *p = mv*

Electromagnetic waves are composed of particle-like entities or energy packets called ***photons.***

$$E = hf \qquad p = h/\lambda$$

29.3 Photons and the Photoelectric Effect



Experimental evidence shows that light consists of photons comes from a phenomenon ed the ***photoelectric effect.***

When light shines on a metal, a photon can give up its energy to an electron in that metal. The minimum energy required to remove the least strongly held electrons is called the ***work function.***

$$\underbrace{hf}_{\text{Photon energy}} = \underbrace{KE_{max}}_{\text{Maximum kinetic energy of ejected electron}} + \underbrace{W_o}_{\text{Minimum work needed to eject electron}}$$

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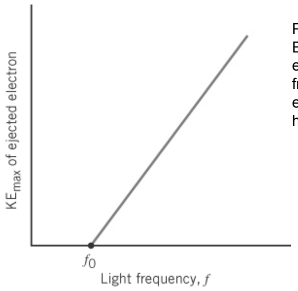
29.3 Photons and the Photoelectric Effect



Photoelectric theory:
Einstein explained the photoelectric effect by asserting that light of frequency f, is made up of packets of energy called photons. Each photon has energy $E = hf$

Increase in intensity only increase the number of photons and hence the number of photoelectrons ejected if the frequency of incident light exceeds the threshold frequency.

$$\underbrace{\mathrm{KE}_{\mathrm{max}}}_{\text{Maximum kinetic energy of ejected electron}} = \underbrace{hf}_{\text{Photon energy}} - \underbrace{W_o}_{\text{Minimum work needed to eject electron}}$$

29.3 Photons and the Photoelectric Effect

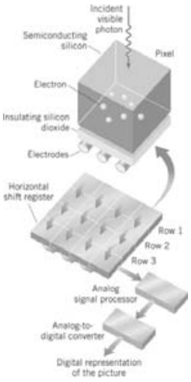
Example 2 **The Photoelectric Effect for a Silver Surface**

The work function for a silver surface is 4.73 eV. Find the minimum frequency that light must have to eject electrons from the surface.

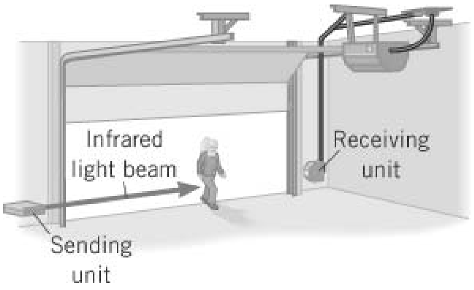
$$hf_o = \underbrace{\mathrm{KE}_{\mathrm{max}}}_{=0\,\mathrm{J}} + W_o$$

$$f_o = \frac{W_o}{h} = \frac{(4.73\,\mathrm{eV})(1.60\times10^{-19}\,\mathrm{J/eV})}{6.626\times10^{-34}\,\mathrm{J\cdot s}} = 1.14\times10^{15}\,\mathrm{Hz}$$

29.3 Photons and the Photoelectric Effect

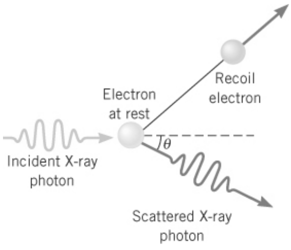


29.3 Photons and the Photoelectric Effect



29.4 The Momentum of a Photon and the Compton Effect

Photon has momentum – proven by the Compton Effect

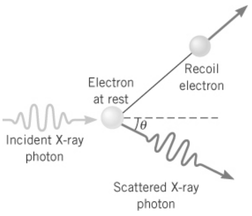


The scattered photon and the recoil electron depart the collision in different directions.

Due to conservation of energy, the scattered photon must have a smaller frequency.

This is called the ***Compton effect.***

29.4 The Momentum of a Photon and the Compton Effect



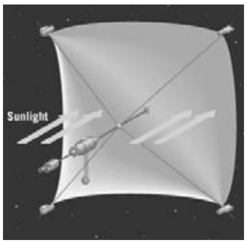
Momentum and energy are conserved in the collision.

$$\lambda' - \lambda = \frac{h}{mc}(1-\cos\theta)$$

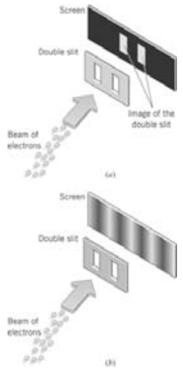
29.4 The Momentum of a Photon and the Compton Effect

***Conceptual Example 4* Solar Sails and the Propulsion of Spaceships**

One propulsion method that is currently being studied for interstellar travel uses a large sail. The intent is that sunlight striking the sail creates a force that pushes the ship away from the sun, much as wind propels a sailboat. Does such a design have any hope of working and, if so, should the surface facing the sun be shiny like a mirror or black, in order to produce the greatest force?



29.5 The de Broglie Wavelength and the Wave Nature of Matter



All matter exhibits wave characteristics, interference & diffraction (Davisson & Germer). Hence can associate wavelength to material matter.

The wavelength of a particle is given by the same relation that applies to a photon:

$$\lambda = h/p$$

de Broglie wavelength

Only particles of mass equivalent to an electron or proton will have λ that are observable

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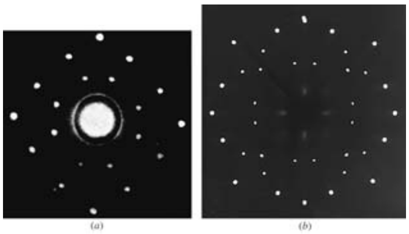
29.5 The de Broglie Wavelength and the Wave Nature of Matter



Neutron diffraction is a manifestation of the wave-like properties of particles.

29.5 The de Broglie Wavelength and the Wave Nature of Matter

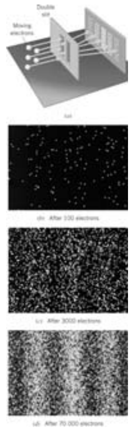
***Example 5* The de Broglie Wavelength of an Electron and a Baseball**

Determine the de Broglie wavelength of (a) an electron moving at a speed of 6.0×10^{6} m/s and (b) a baseball (mass = 0.15 kg) moving at a speed of 13 m/s.

$$\lambda = h/p = \frac{(6.63\times10^{-34}\ \mathrm{J/s})}{(9.1\times10^{-31}\mathrm{kg})(6.0\times10^{6}\ \mathrm{m/s})} = 1.2\times10^{-10}\mathrm{m}$$

$$\lambda = h/p = \frac{(6.63\times10^{-34}\ \mathrm{J/s})}{(0.15\,\mathrm{kg})(13\,\mathrm{m/s})} = 3.3\times10^{-34}\mathrm{m}$$

29.5 The de Broglie Wavelength and the Wave Nature of Matter



***Electrons' version of the Young's double-slit experiment*.**

***Particles are waves of probability*.**

Concepts	Particle	Photon
Energy	*E = KE+PE* *continuous*	*E = hf* *quantized*
Momentum	*p = mv*	*p = h/λ*
Wavelength	*λ = h/p*	*λ= c/f* *λ = h/p*

Characteristic interference fringes only observable after a large number of electrons have struck the screen

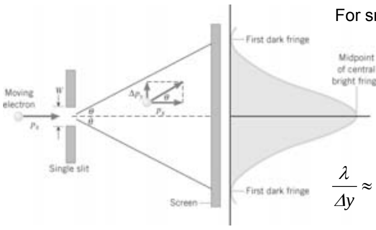
29.6 The Heisenberg Uncertainty Principle

Wave nature of electrons

Diffraction pattern of dark and bright fringes after sufficient number of electrons pass through a single slit

Δp_y *is the uncertainty in the y-component of the electron's momentum*

Location of first dark fringe $\sin\theta = \frac{\lambda}{W}$ But $\tan\theta = \frac{\Delta p_y}{p_x}$ $p_x = \frac{h}{\lambda}$



For small θ, sin θ ≈ tan θ

then $\frac{\lambda}{W} \approx \frac{\Delta p_y}{p_x}$

But electrons at the slit can pass thru anywhere within slit width W. Then

$\frac{\lambda}{\Delta y} \approx \frac{\Delta p_y}{h/\lambda}$ And $\Delta p_y \Delta y \approx h$

29.6 The Heisenberg Uncertainty Principle-Complete Analysis

THE HEISENBERG UNCERTAINTY PRINCIPLE

Limits (imposed by nature) on specifying simultaneously the accuracy in position and momentum of a particle

Momentum and position

$$(\Delta p_y)(\Delta y) \geq \frac{h}{4\pi}$$

Uncertainty in *y* component of the particle's momentum

Uncertainty in particle's position along the *y* direction

29.6 The Heisenberg Uncertainty Principle

THE HEISENBERG UNCERTAINTY PRINCIPLE

Limits (imposed by nature) on specifying simultaneously the accuracy in energy of a certain state of a particle and the time interval of the particle in that state

Energy and time

$$(\Delta E)(\Delta t) \geq \frac{h}{4\pi}$$

Uncertainty in the energy of a particle when the particle is in a certain state

time interval during which the particle is in that state

29.6 The Heisenberg Uncertainty Principle

Conceptual Example 7 **What if Planck's Constant Were Large?**

A bullet leaving the barrel of a gun is analogous to an electron passing through the single slit. With this analogy in mind, what would hunting be like if Planck's constant has a relatively large value? h = 6.6 x 10^{-34} J.s