Phase Difference at P: \( \Delta \phi = \frac{2\pi}{\lambda} \Delta r \)

Constructive: \( \Delta \phi = 2m\pi, \quad \Delta r = m\lambda, \quad m = 0,1,2,3... \)

Destructive: \( \Delta \phi = (2m+1)\pi, \quad \Delta r = (m + \frac{1}{2}), \quad m = 0,1,2,3... \)
Double Slit Interference

“m” is the fringe order.

• Maxima: bright fringes

\[ d \sin \theta = m \lambda \]

\[ y_{\text{bright}} = \frac{\lambda L}{d} m \quad (m = 0, \pm 1, \pm 2 \ldots) \]

• Minima: dark fringes

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

\[ y_{\text{dark}} = \frac{\lambda L}{d} \left( m + \frac{1}{2} \right) \quad (m = 0, \pm 1, \pm 2 \ldots) \]
Intensity

The intensity of a wave, the power per unit area, is the rate at which energy is being transported by the wave through a unit area $A$ perpendicular to the direction of travel of the wave:

$$I = \frac{\phi \text{Power}}{\text{Area}} \left[ \frac{\text{W}}{\text{m}^2} \right]$$

Power Transmitted on a String:

$$\phi = \frac{1}{2} \mu \omega^2 A^2 v$$

Power Transmitted by Sound:

$$\phi = \frac{1}{2} \rho A \omega^2 s_{\text{max}}^2 v$$

Intensity $\sim (\text{Amplitude})^2$
Ignoring Intensity drop due to distance in inverse square law. We assume that the amplitude remains constant over the short distances considered. Only considering the intensity change due to interference!

\[ I = \frac{P}{4\pi r^2} \left[ \frac{W}{m^2} \right] \]
Intensity of Light Waves

\[ E = E_{\text{max}} \cos (kx - \omega t) \]
\[ B = B_{\text{max}} \cos (kx - \omega t) \]

\[
\frac{E_{\text{max}}}{B_{\text{max}}} = \frac{\omega}{k} = \frac{E}{B} = c
\]

\[ I = S_{\text{av}} = \frac{E_{\text{max}} B_{\text{max}}}{2\mu_0} = \frac{E_{\text{max}}^2}{2\mu_0 c} = \frac{c B_{\text{max}}^2}{2\mu_0} \]

\[ I \propto E_{\text{max}}^2 \]
Intensity Distribution Resultant Field

- The magnitude of the resultant electric field comes from the superposition principle
  \[ E_P = E_1 + E_2 = E_0 \sin(\omega t) + \sin(\omega t + \varphi) \]

- This can also be expressed as
  \[ E_P = 2E_0 \cos\left(\frac{\varphi}{2}\right) \sin\left(\omega t + \frac{\varphi}{2}\right) \]
  - \( E_P \) has the same frequency as the light at the slits
  - The amplitude at \( P \) is given by \( 2E_0 \cos(\varphi / 2) \)

- Intensity is proportional to the square of the amplitude:

- The intensity at \( P \) is 4 times one source.
  \[ I_P \propto E_P^2 = 4E_0^2 \cos^2\left(\frac{\varphi}{2}\right) \]
Amplitude is twice as big
But intensity is proportional to
the amplitude SQUARED so
the Intensity is four times as
big as the source. This is
energy being conserved! The
light energy is redistributed
on the screen.

\[ E_P = 2E_o \cos\left(\frac{\phi}{2}\right) \sin\left(\omega t + \frac{\phi}{2}\right) \]

\[ I_P \propto E_P^2 = 4E_o^2 \cos^2\left(\frac{\phi}{2}\right) \]
Light Intensity: Ignoring Diffraction

- The interference pattern consists of equally spaced fringes of equal intensity.
- This result is valid only if $L \gg d$ and for small values of $\theta$.

\[
I = I_{\text{max}} \cos^2\left(\frac{\Delta \phi}{2}\right)
\]

Phase Difference at P: 
\[
\Delta \phi = \frac{2\pi}{\lambda} \Delta r
\]
Intensity

In a double-slit experiment, the distance between the slits is 0.2 mm, and the distance to the screen is 150 cm. What wavelength (in nm) is needed to have the intensity at a point 1 mm from the central maximum on the screen be 80% of the maximum intensity?

\[ I = I_{\text{max}} \cos^2 \left( \frac{\pi d \sin \theta}{\lambda} \right) \approx I_{\text{max}} \cos^2 \left( \frac{\pi d}{\lambda L} y \right) \]

a. 900
b. 700
c. 500
d. 300
e. 600
Double Slit Intensity

Two slits are illuminated with green light \((\lambda = 540 \text{ nm})\). The slits are 0.05 mm apart and the distance to the screen is 1.5 m. At what distance (in mm) from the central maximum on the screen is the average intensity 50\% of the intensity of the central maximum?

a. 1
b. 3
c. 2
d. 4
e. 0.4

\[
I = I_{\text{max}} \cos^2 \left( \frac{\pi d \sin \theta}{\lambda} \right) \approx I_{\text{max}} \cos^2 \left( \frac{\pi d}{\lambda L} y \right)
\]
Double Slit Interference Reality
Combination of Single and Double
Double Slit Interference Reality

Combination of Single and Double

1. A plane wave is incident on the double slit.
2. Waves spread out behind each slit.
3. The waves interfere in the region where they overlap.
4. Bright fringes occur where the antinodal lines intersect the viewing screen.

In reality, the fringe intensity decreases because the intensity of the light from a single slit is not uniform.

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Intensity of Two-Slit Diffraction
Chapter 38

\[ I = I_{\text{max}} \cos^2 \left( \frac{\pi d \sin \theta}{\lambda} \right) \left[ \frac{\sin \left( \frac{\pi a \sin \theta}{\lambda} \right)}{\pi a \sin \theta / \lambda} \right]^2 \]
Single Slit Interference Is called Diffraction

(a) Without diffraction

(b) With diffraction
Diffraction depends on SLIT WIDTH: the smaller the width, relative to wavelength, the more bending and diffraction.
**Fraunhofer Diffraction**: screen is far away, approximate plane waves and parallel rays.

**Fresnel Diffraction**: Screen is close and curvature of wave fronts complicates the analysis.
Single Slit Diffraction

- Incident light
- Viewing screen
- 0.1-mm-wide window in an opaque screen
- The light spreads out behind the window.

(a) Greatly magnified view of slit
- Initial wave front
- Slit width $a$

The wavelets from each point on the initial wave front overlap and interfere, creating a diffraction pattern on the screen.
Light interferes with itself
Single Slit Diffraction
Single Slit Diffraction

When the path length differs by half a wavelength then the rays will interfere destructively. For Rays 1 & 3:

\[ \Delta r = \frac{a}{2} \sin \theta = \frac{\lambda}{2} \]

**Dark fringe:** \( \sin \theta = m \frac{\lambda}{a} \)

\( m = \pm 1, \pm 2, \pm 3, \ldots \)
Dark fringe: \( \sin \theta = m \frac{\lambda}{a} \) \( m = \pm 1, \pm 2, \pm 3, \ldots \)
Compare Fringe Equations for Single and Double Slits

maxima: $d \sin \theta = m\lambda \quad (m = 0, \pm 1, \pm 2 \ldots)$

minima: $d \sin \theta = \left( m + \frac{1}{2} \right)\lambda \quad (m = 0, \pm 1, \pm 2 \ldots)$

minima: $a \sin \theta_{\text{dark}} = m\lambda, \; m = \pm 1, \pm 2, \pm 3, \ldots$
Dark fringe: \( \sin \theta \approx \theta = m \frac{\lambda}{a} \)

Single Slit Diffraction for Different Slit Widths

These single slit diffraction patterns were photographed with a helium-neon laser as the light source and a micrometer-controlled single slit. The sketches of the slit widths at right were scaled to the difference between the first minima of the diffraction patterns. If the geometry is such that the small angle approximation is valid, the width of the pattern is inversely proportional to the slit width.
A narrow slit is illuminated with sodium yellow light of wavelength 589 nm. If the central maximum extends to ±30°, how wide is the slit?

a. 0.50 mm  
b. $2.2 \times 10^{-6}$ m  
c. $3.3 \times 10^{-5}$ m  
d. 1.18 µm  
e. 5.89 µm

Dark fringe: $\sin \theta = m \frac{\lambda}{a}$
Width of the Central Maximum

Dark fringe: \[ \sin \theta = m \frac{\lambda}{a} \quad m = 1, 2, 3, \ldots \]

\( y \): the distance from the center of the central maximum to the fringe \( m \)

\[ y_m = L \tan \theta_m \]

\[ w = 2y \]
Single Slit Problem

If the incident light has $\lambda=690\text{nm}$ (red) and $a = 4 \times 10^{-6}\text{m}$, find the width of the central bright fringe when the screen is $0.4\text{m}$ away.

Dark fringe: $\sin \theta = m \frac{\lambda}{a} \quad m = 1, 2, 3, \ldots$

$$y_m = L \tan \theta_m$$

$$w = 2y$$
Single Slit Intensity

- The intensity can be expressed as

\[ I = I_{\text{max}} \left[ \frac{\sin(\pi a \sin \theta / \lambda)}{\pi a \sin \theta / \lambda} \right]^2 \]

- \( I_{\text{max}} \) is the intensity at \( \theta = 0 \)
  - This is the central maximum

- Minima occur at

\[
\frac{\pi a \sin \theta_{\text{dark}}}{\lambda} = m\pi \quad \text{or} \quad \sin \theta_{\text{dark}} = m\frac{\lambda}{a}
\]
Combined Effects

Interference maximum coincides with the first diffraction minimum.
Two-Slit Diffraction Patterns, Maxima and Minima

- To find which interference maximum coincides with the first diffraction minimum

\[
\frac{d \sin \theta}{a \sin \theta} = \frac{m \lambda}{\lambda} \quad \Rightarrow \quad \frac{d}{a} = m
\]

- The conditions for the first interference maximum
  - \( d \sin \theta = m \lambda \)
- The conditions for the first diffraction minimum
  - \( a \sin \theta = \lambda \)
Intensity of Two-Slit Diffraction

\[ I = I_{\text{max}} \cos^2 \left( \frac{\pi d \sin \theta}{\lambda} \right) \left[ \frac{\sin \left( \frac{\pi a \sin \theta}{\lambda} \right)}{\pi a \sin \theta / \lambda} \right]^2 \]

- The broken blue line is the diffraction pattern
- The red-brown curve shows the \( \cos^2 \) term
  - This term, by itself, would result in peaks with all the same heights
  - The uneven heights result from the diffraction term (square brackets in the equation)

Interference maximum coincides with the first diffraction minimum.
Under the **Fraunhofer conditions**, the light curve of a multiple slit arrangement will be the interference pattern multiplied by the single slit diffraction envelope. This assumes that all the slits are identical.
Double Slit Diffraction

Under the **Fraunhofer conditions**, the light curve of a multiple slit arrangement will be the interference pattern multiplied by the single slit diffraction envelope. This assumes that all the slits are identical.
Under the **Fraunhofer conditions**, the light curve of a multiple slit arrangement will be the interference pattern multiplied by the single slit diffraction envelope. This assumes that all the slits are identical.
Hyperphysics

Five Slit Diffraction

Under the Fraunhofer conditions, the light curve of a multiple slit arrangement will be the interference pattern multiplied by the single slit.
Multiple Slits: Diffraction Gratings

For N slits, the intensity of the primary maxima is $N^2$ times greater than that due to a single slit.

For any value of $N$, the decrease in intensity in maxima to the left and right of the central maximum, indicated by the blue dashed arcs, is due to *diffraction patterns* from the individual slits, which are discussed in Chapter 38.
Diffraction Grating

- The condition for maxima is:
  \[ d \sin \theta_{\text{bright}} = m\lambda \]
  - \( m = 0, \pm 1, \pm 2, \ldots \)
- \( d \) is the slit spacing
- The integer \( m \) is the order number of the diffraction pattern
Dispersion via Diffraction

Constructive: \[ d \sin \theta = m \lambda, \quad m = 0, 1, 2, 3 \]
Diffraction Gratings

constructive: $d \sin \theta = m\lambda, \quad m = 0,1,2,3$

Note: The greater the wavelength, the greater the angle.
Hydrogen Spectra
Helium Spectra
Mercury Spectra
Neon Spectrum
Oxygen Spectrum
Argon Spectrum
• Cosmological Redshift: Expanding Universe
• Stellar Motions: Rotations and Radial Motions
• Solar Physics: Surface Studies and Rotations
• Gravitational Redshift: Black Holes & Lensing
• Exosolar Planets via Doppler Wobbler
• **Red Shift**: Moving Away
• **Blue Shift**: Moving Toward
A mixture of violet light (410 nm in vacuum) and red light (660 nm in vacuum) fall on a grating that contains $1.0 \times 10^4$ lines/cm. For each wavelength, find the angle and the distance from the central maximum to the first order maximum.
Diffraction Grating Problem

White light is spread out into spectral hues by a diffraction grating. If the grating has 1000 lines per cm, at what angle will red light ($\lambda = 640$ nm) appear in first order?

a. 14.68°
b. 7.35°
c. 17.73°
d. 3.67°
e. 1.84°
Resolving Power of a Diffraction Grating

- For two nearly equal wavelengths, $\lambda_1$ and $\lambda_2$, between which a diffraction grating can just barely distinguish, the **resolving power**, $R$, of the grating is defined as

$$R \equiv \frac{\lambda}{\lambda_2 - \lambda_1} = \frac{\lambda}{\Delta \lambda}$$

- Therefore, a grating with a high resolution can distinguish between small differences in wavelength
Resolving Power of a Diffraction Grating

- The resolving power in the \( m \)th-order diffraction is \( R = Nm \)
  - \( N \) is the number of slits
  - \( m \) is the order number

- Resolving power increases with increasing order number and with increasing number of illuminated slits
Grating Resolution

Determine the number of grating lines necessary to resolve the 589.59 nm and 589.00 nm sodium lines in second order.

a. 999  
b. 680  
c. 500  
d. 340  
e. 380
Michelson Interferometer

The fringe pattern shifts by one-half fringe each time $M1$ is moved a distance $\lambda/4$

http://www.youtube.com/watch?v=ETLG5SLFMZo
http://www.youtube.com/watch?v=Z8K3gcHQiqk&feature=related
James Clerk Maxwell
1860s

Light is wave. The medium is the Ether.

\[ c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3.0 \times 10^8 \text{ m/s} \]
The Luminiferous Aether was imagined by physicists since Isaac Newton as the invisible "vapor" or "gas aether" filling the universe and hence as the carrier of heat and light.
Rotate arms to produce interference fringes and find different speeds of light caused by the Ether Wind, due to Galilean Relativity: light should travel slower against the Ether Wind. From that you can find the speed of the wind.
http://www.youtube.com/watch?v=XavC4w_Y9b8&feature=related

http://www.youtube.com/watch?v=4KFMeKJySwA&feature=related
Michelson-Morely Experiment 1887

The speed of light is independent of the motion and is always $c$. The speed of the Ether wind is zero.

OR....

Lorentz Contraction

The apparatus shrinks by a factor:

$$\sqrt{1 - \frac{v^2}{c^2}}$$
Clocks slow down and rulers shrink in order to keep the speed of light the same for all observers!
Time is Relative! Space is Relative! Only the SPEED OF LIGHT is Absolute!
On the Electrodynamics of Moving Bodies
1905
LIGO in Richland, Washington

http://www.youtube.com/watch?v=RzZgFKolfQI&feature=related
LISA

http://www.youtube.com/watch?v=DrWwWcA_Hgw&feature=related
Diffraction of a Penny

Central Bright Spot: Poisson Spot
Light from a small source passes by the edge of an opaque object and continues on to a screen. A diffraction pattern consisting of bright and dark fringes appears on the screen in the region above the edge of the object.
Circular Aperature

Dark fringe: \( \sin \theta = m \frac{\lambda}{D} \quad m = 0, 1, 2, 3, \ldots \)

If light travels in straight lines, the image on the screen is the same size as the hole. Diffraction will not be noticed unless the light spreads over a diameter larger than \( D \).
Circular Aperture Diffraction

Circular aperture
\[ \sin \theta = \frac{m \lambda}{d} \]
\[ d = \text{aperture diameter} \]

\[ y \approx D \frac{m \lambda}{d} \text{ for maxima and minima} \]

Relative Intensity
0.0175
0.0042
0.00078

m values for:
Minima | Maxima
---|---
1 | 1.220 | 1.635
2 | 2.233 | 2.679
3 | 3.238 | 3.69

\[ \frac{y}{D} = \tan \theta \approx \sin \theta \approx \theta \]
for small angles \( \theta \)
Resolution

- The ability of optical systems to distinguish between closely spaced objects is limited because of the wave nature of light.
- If two sources are far enough apart to keep their central maxima from overlapping, their images can be distinguished.
  - The images are said to be resolved.
- If the two sources are close together, the two central maxima overlap and the images are not resolved.
Diffraction Resolution

(a)  
(b)  
(c)
Resolving Power

The diffraction limit: two images are just resolvable when the center of the diffraction pattern of one is directly over the first minimum of the diffraction pattern of the other.

**Rayleigh Criterion**

\[ \theta_{\text{min}} = 1.22 \frac{\lambda}{D} \]

D: Aperture Diameter
Standing back from a Georges Seurat painting, you can cannot resolve the dots but a camera, at the same distance can. Assume that light enters your eyes through pupils that have diameters of 2.5 mm and enters the camera through an aperture with diameter of 25 mm. Assume the dots in the painting are separated by 1.5 mm and that the wavelength of the light is 550 nm in vacuum. Find the distance at which the dots can just be resolved by a) the camera b) the eye.
Space Shuttle Resolution

What, approximately, are the dimensions of the smallest object on Earth that the astronauts can resolve by eye at 200 km height from the space shuttle? Assume $l = 500$ nm light and a pupil diameter $D = 0.50$ cm. Assume eye fluid has an average $n = 1.33$.

a. 150 m
b. 100 m
c. 250 m
d. 25 m
e. 18 m
The diffraction pattern from a hexagonally-shaped hole. Note the six-fold symmetry of the pattern. Observation of such complex patterns can reveal the underlying symmetry structure of the object that diffracts the light. This is the basis for many physical techniques that study patterns in the microscopic world.
Crystallography

The International Union of Crystallography has redefined the term *crystal* to mean `any solid having an essentially discrete diffraction pattern.`
Diffraction of X-Rays by Crystals

- X-rays are electromagnetic waves of very short wavelength
- Max von Laue suggested that the regular array of atoms in a crystal could act as a three-dimensional diffraction grating for x-rays
- Laue Pattern for Beryl
Diffraction of X-Rays by Crystals, Set-Up

- A collimated beam of monochromatic x-rays is incident on a crystal
- The diffracted beams are very intense in certain directions
  - This corresponds to constructive interference from waves reflected from layers of atoms in the crystal
- The diffracted beams form an array of spots known as a *Laue pattern*
Laue Pattern for Rubisco
X-Ray Diffraction: Bragg’s Law

- This is a two-dimensional description of the reflection of the x-ray beams.
- The condition for constructive interference is
  \[ 2d \sin \theta = m\lambda \]
  where \( m = 1, 2, 3 \)
- This condition is known as Bragg’s law
- This can also be used to calculate the spacing between atomic planes.
X-Ray Diffraction

In an X-ray diffraction experiment using X-rays of \( \lambda = 0.500 \times 10^{-10} \) m, a first-order maximum occurred at 5.00°. Find the crystal plane spacing.

a. \( 2.87 \times 10^{-10} \) m  
b. \( 1.36 \times 10^{-10} \) m  
c. \( 6.24 \times 10^{-9} \) m  
d. \( 1.93 \times 10^{-9} \) m  
e. \( 5.74 \times 10^{-9} \) m
Limits of Vision

Electron Waves

\[ \lambda_e = 2.4 \times 10^{-11} \text{ m} \]
Electron Diffraction

The diffraction pattern on the left was made by a beam of x-rays passing through thin aluminum foil. The diffraction pattern on the right was made by a beam of electrons passing through the same foil.

by S. Ritsch and C. Beeli

Type I superstructure
Electron Microscope

Stem Cells

Salmonella Bacteria

The fossilized shell of a microscopic ocean animal is magnified 392 times its actual size.
Electron Microscope

Electron microscope picture of a fly.
The resolving power of an optical lens depends on the wavelength of the light used. An electron-microscope exploits the wave-like properties of particles to reveal details that would be impossible to see with visible light.
Polarization of Light Waves

- The *direction of polarization* of each individual wave is defined to be the direction in which the electric field is vibrating.
- In this example, the direction of polarization is along the *y*-axis.
Unpolarized Light

• All directions of vibration from a wave source are possible
• The resultant em wave is a superposition of waves vibrating in many different directions
• This is an unpolarized wave
• The arrows show a few possible directions of the waves in the beam
Circularly Polarized EM Wave
Elliptically Polarized EM Wave
Polarization of Light

• A wave is said to be *linearly polarized* if the resultant electric field $\mathbf{E}$ vibrates in the same direction *at all times* at a particular point.

• The plane formed by $\mathbf{E}$ and the direction of propagation is called the *plane of polarization* of the wave.
Polarization of Light

Plane Polarized

Circular Polarized

Polarization upon Reflection
Intensity of Polarized Light, Examples

- On the left, the transmission axes are aligned and maximum intensity occurs.
- In the middle, the axes are at $45^\circ$ to each other and less intensity occurs.
- On the right, the transmission axes are perpendicular and the light intensity is a minimum.
Polarization by Selective Absorption

- The most common technique for polarizing light
- Uses a material that transmits waves whose electric field vectors lie in the plane parallel to a certain direction and absorbs waves whose electric field vectors are perpendicular to that direction
Malus’ Law

\[ I = I_0 \cos^2 \theta \]
Polarization

\[ I = I_0 \cos^2 \theta \]

The intensity of unpolarized light passing through a polarizer will be reduced by \( \frac{1}{2} \), because the average value of the cosine squared term over all directions is \( \frac{1}{2} \).
Example

If the incident beam is linearly polarized along the vertical direction and has an intensity of $50 \text{ W/m}^2$ and the angle is 30 degrees, which set up transmits more light? Determine the average intensity of the transmitted beam for both setups.

If the light is unpolarized, which set up transmits the most light?
Polarization Problem

Unpolarized light is passed through three successive Polaroid filters, each with its transmission axis at 45° to the preceding filter. What percentage of light gets through?

a. 0%
b. 12.5%
c. 25%
d. 50%
e. 33%
Methods of Polarization

• It is possible to obtain a linearly polarized beam from an unpolarized beam by removing all waves from the beam except those whose electric field vectors oscillate in a single plane.

• Processes for accomplishing this include:
  – selective absorption
  – reflection
  – double refraction
  – scattering
Polarization by Reflection

- When an unpolarized light beam is reflected from a surface, the reflected light may be
  - Completely polarized
  - Partially polarized
  - Unpolarized

- It depends on the angle of incidence
  - If the angle is 0°, the reflected beam is unpolarized
  - For other angles, there is some degree of polarization
  - For one particular angle, the beam is completely polarized
Polarization by Reflection, Partially Polarized Example

• Unpolarized light is incident on a reflecting surface

• The reflected beam is partially polarized

• The refracted beam is partially polarized
Polarization by Reflection, Completely Polarized Example

- Unpolarized light is incident on a reflecting surface
- The reflected beam is completely polarized
- The refracted beam is perpendicular to the reflected beam
- The angle of incidence is Brewster’s angle
Polarization by Reflection

- The angle of incidence for which the reflected beam is completely polarized is called the **polarizing angle**, $\theta_p$

- **Brewster’s law** relates the polarizing angle to the index of refraction for the material

$$n = \frac{\sin \theta_p}{\cos \theta_p} = \tan \theta_p$$

- $\theta_p$ may also be called **Brewster’s angle**
Brewster’s Angle

\[ n = \frac{\sin \theta_p}{\cos \theta_p} = \tan \theta_p \]

Sunlight reflected from a smooth ice surface is completely polarized. Determine the angle of incidence. \((n_{\text{ice}} = 1.31)\)

a. 52.6°
b. 25.6°
c. 65.2°
d. 56.2°
e. 49.8°
Polarization by Double Refraction: Birefringence

- In certain crystalline structures, the speed of light is not the same in all directions.
- Such materials are characterized by two indices of refraction.
- They are often called double-refracting or birefringent materials.
Optical Stress Analysis

- Some materials become birefringent when stressed
- When a material is stressed, a series of light and dark bands is observed
  - The light bands correspond to areas of greatest stress
- Optical stress analysis uses plastic models to test for regions of potential weaknesses
Polarization by Scattering

• When light is incident on any material, the electrons in the material can absorb and reradiate part of the light
  – This process is called scattering

• An example of scattering is the sunlight reaching an observer on the Earth being partially polarized
Polarization by Scattering, cont.

- The horizontal part of the electric field vector in the incident wave causes the charges to vibrate horizontally.
- The vertical part of the vector simultaneously causes them to vibrate vertically.
- If the observer looks straight up, he sees light that is completely polarized in the horizontal direction.
Light is in a Superposition of Polarization States! This is a Quantum Effect.
Three Polarizers Paradox

You have a field with cows. To make sure that now cows get out, you put up two fences. They stay in their field. But you're really paranoid, so you put a third fence in between the two. Now, all of a sudden, one fourth of your cows are wandering in your neighbor's field.