Physics 280 Lecture Four: Let there be light

Summer 2016

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Objectives

- Huygen's Principle

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- Double-slit experiment and Interference

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- Reflection and Interference

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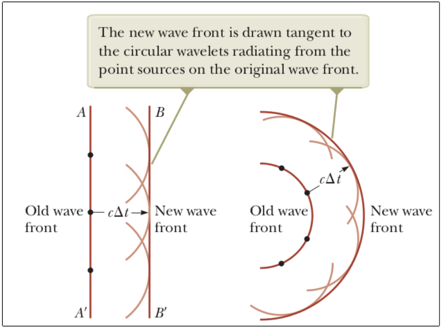
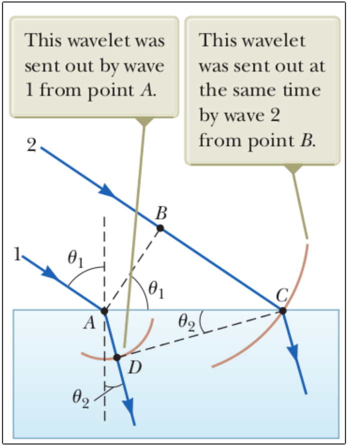
- Double-slit experiment and Interference
- Reflection and Interference
- Michelson Interferometer
- Diffraction and DNA

Huygens was the one of the earliest and most prominent proponents of light as a wave (1678). He used a geometrical construct.



Every point on a wave-front is the origin of a new wavelet; overall wave-front is tangent to the surface of the wavelets.

Huygens explains refraction!



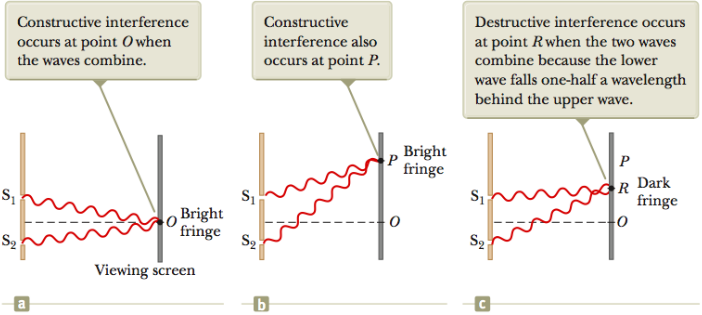
$$\sin\theta_1 = \frac{BC}{AC} = \frac{v_1 \Delta t}{AC}$$

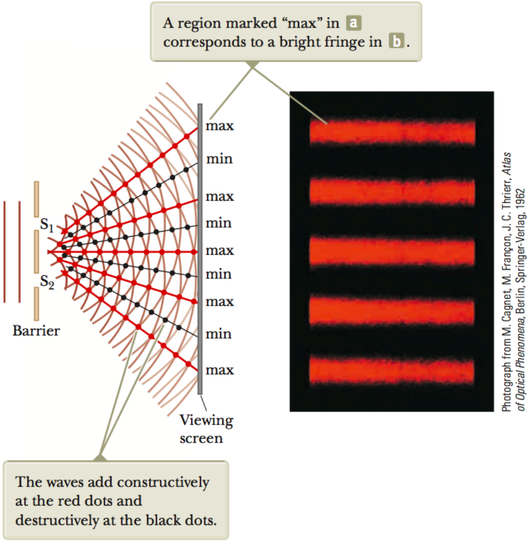
$$\sin\theta_2 = \frac{AD}{AC} = \frac{v_2 \Delta t}{AC}$$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$

Snell's Law!

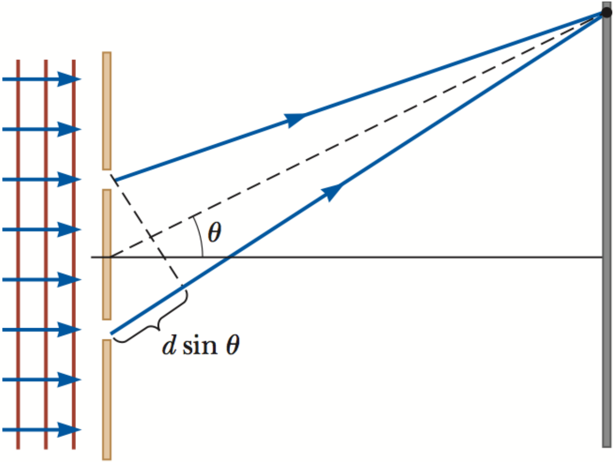
Waves can add up constructively and destructively, so we should see that in light:

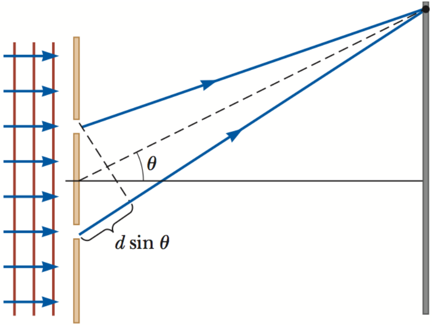


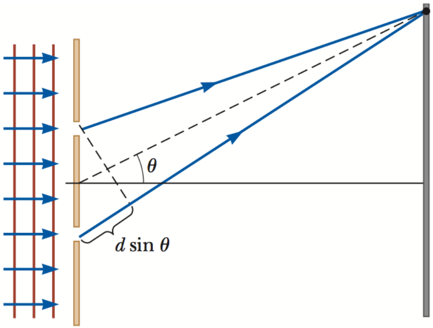


Young's Double Slit Experiment confirms, we do find patterns of **constructive** and **destructive** interference. We can predict the placement of these patterns.

Give it a try! Can you figure out the placement of bright lines by angle?



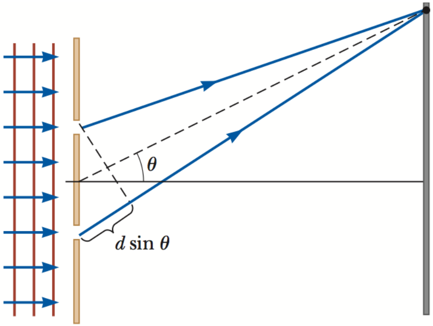

θ
d sin θ



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

where

$$m = 0, 1, 2, \cdots.$$



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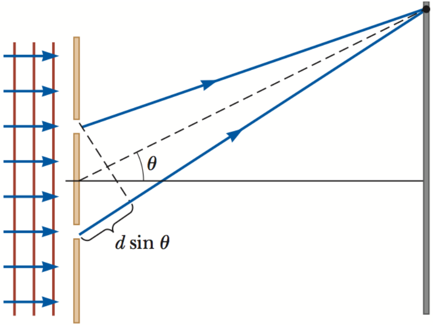
What about dark spots?



$d \sin\theta = m\lambda$
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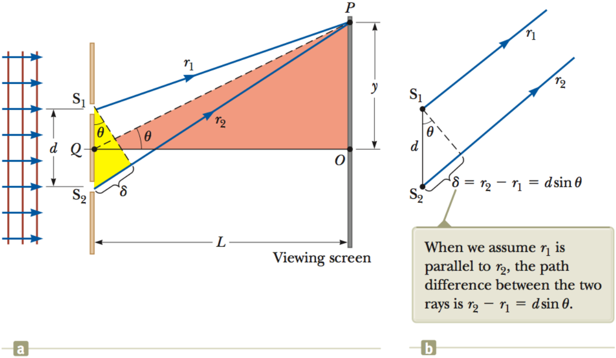
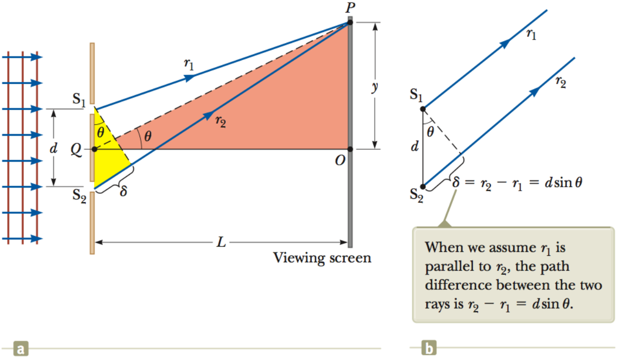
What about dark spots?

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


P
r_1
y
S_1
r_2
θ
θ
d
Q
O
S_2
δ
L
Viewing screen
a
r_1
S_1
r_2
θ
d
$\delta = r_2 - r_1 = d\sin\theta$
S_2
When we assume r_1 is parallel to r_2, the path difference between the two rays is $r_2 - r_1 = d\sin\theta$.
b



When $L \gg d$, $\sin\theta \approx \tan\theta = y/L$. Then

$$\frac{yd}{L} = m\lambda$$

Sample problem:

A viewing screen is separated from a double slit by 4.80 m. The distance between the two slits is 0.030 0 mm. Monochromatic light is directed toward the double slit and forms an interference pattern on the screen. The first dark fringe is 4.50 cm from the center line on the screen. Determine the wavelength of the light and the distance between the adjacent bright fringes.

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$$\lambda = \frac{y_{dark} d}{(m + \frac{1}{2})L} = 562nm$$

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$$y_{m+1} - y_m = L\frac{(m+1)\lambda}{d} - L\frac{m\lambda}{d} = L\frac{\lambda}{d} = 9.00cm$$

Intensity of Interference Pattern

Let's look at the electric field of the two light rays at the point they meet on the screen:

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$$E_p = 2E_0 \cos\left(\frac{\phi}{2}\right) \sin\left(\omega t + \frac{\phi}{2}\right)$$

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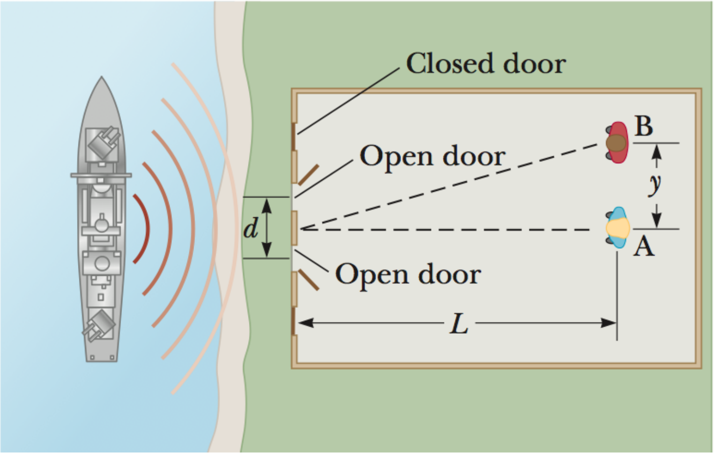
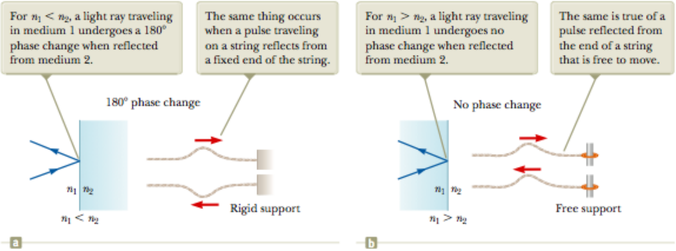
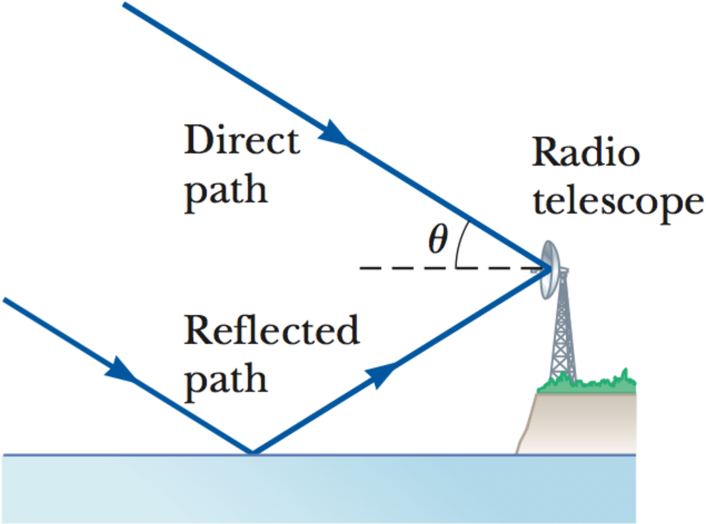
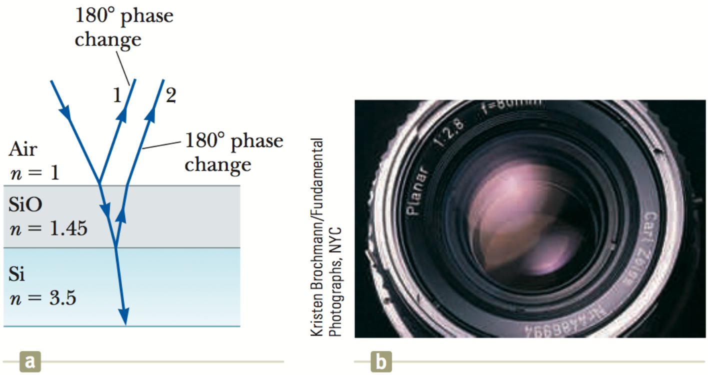
$$I = I_{max} \cos^2(\phi/2) = I_{max} \cos^2\left(\frac{\pi d \sin\theta}{\lambda}\right)$$

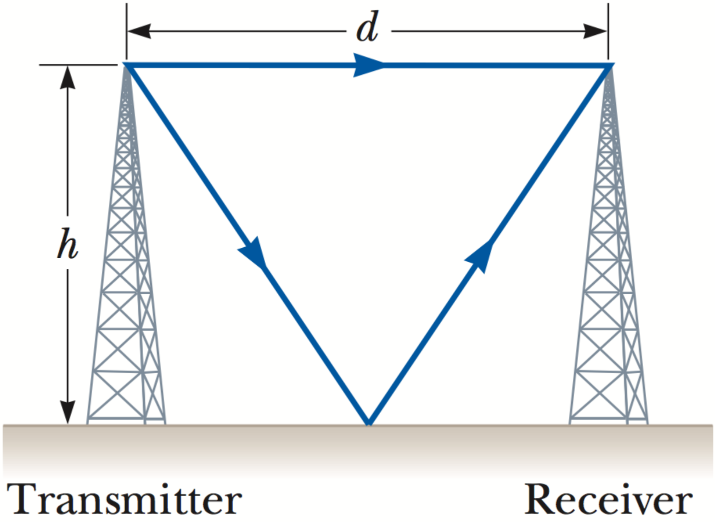

Closed door
Open door
Open door
B
A
y
d
L

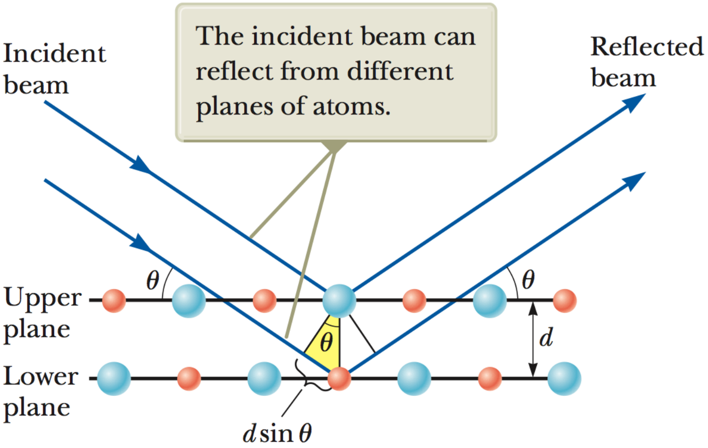

For $n_1 < n_2$, a light ray traveling in medium 1 undergoes a 180° phase change when reflected from medium 2.
The same thing occurs when a pulse traveling on a string reflects from a fixed end of the string.
For $n_1 > n_2$, a light ray traveling in medium 1 undergoes no phase change when reflected from medium 2.
The same is true of a pulse reflected from the end of a string that is free to move.
180° phase change
n_1 n_2
$n_1 < n_2$
Rigid support
No phase change
n_1 n_2
$n_1 > n_2$
Free support
a
b

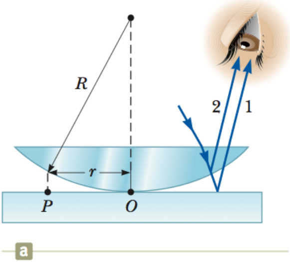

Direct
path
Radio
telescope
θ
Reflected
path

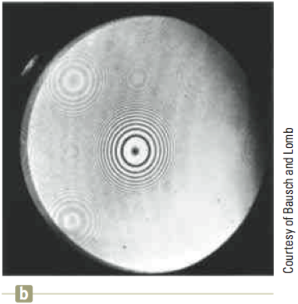


180° phase change
1
2
180° phase change
Air
n = 1
SiO
n = 1.45
Si
n = 3.5
a
Kristen Brochmann/Fundamental Photographs, NYC
Planar
1:2.8
b

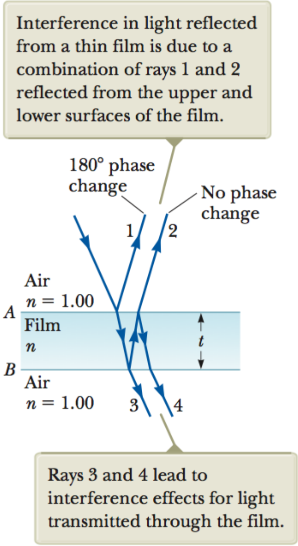

d
h
Transmitter
Receiver


The incident beam can reflect from different planes of atoms.
Incident beam
Reflected beam
Upper plane
Lower plane
θ
θ
θ
d
d sin θ

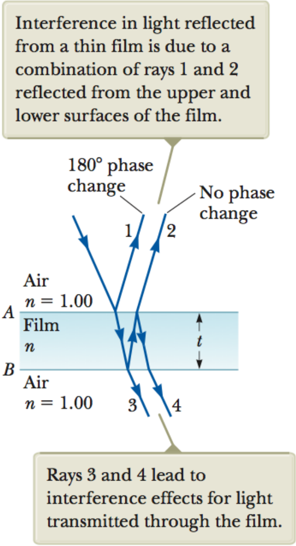

R
r
2
1
P
O
a


b
Courtesy of Bausch and Lomb

Thin film interference



Thin film interference



For rays 1 and 2:

$$\text{Constructive: } 2t = \left(m + \frac{1}{2}\right)\frac{\lambda}{n}$$

$$m = 0, 1, 2, \cdots$$

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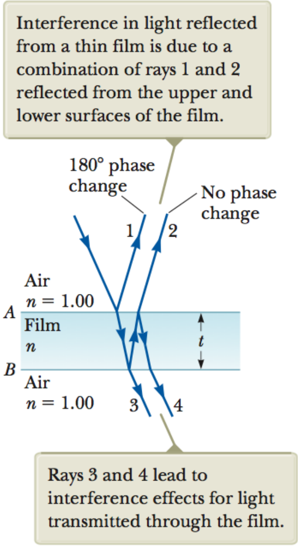

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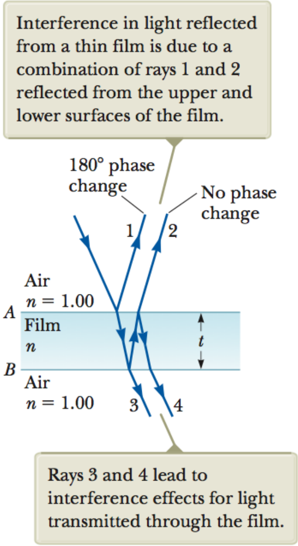

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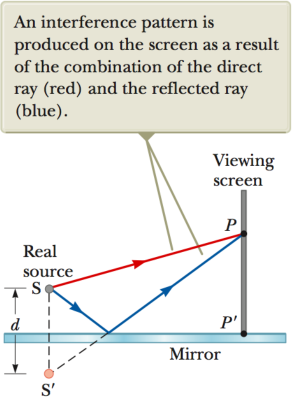
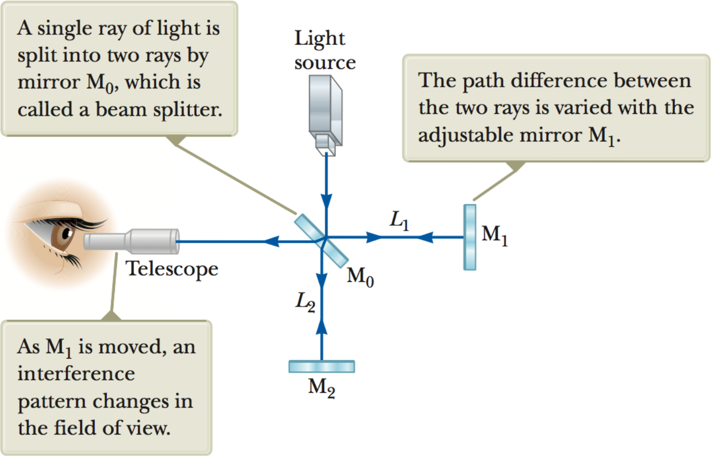
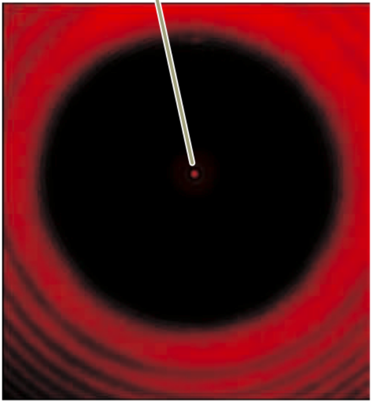
Why the 1/2?


An interference pattern is produced on the screen as a result of the combination of the direct ray (red) and the reflected ray (blue).
Viewing screen
P
Real source
S
d
P′
Mirror
S′


A single ray of light is split into two rays by mirror M_0, which is called a beam splitter.
Light source
The path difference between the two rays is varied with the adjustable mirror M_1.
L_1
M_1
Telescope
M_0
L_2
As M_1 is moved, an interference pattern changes in the field of view.
M_2

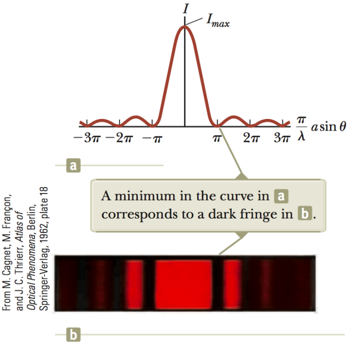
The shadow cast by a penny

Notice the bright spot at the center.

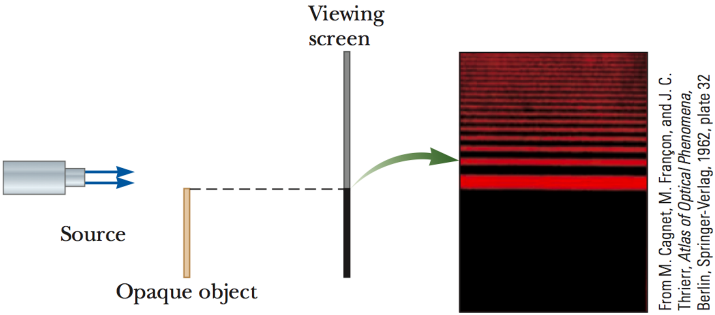


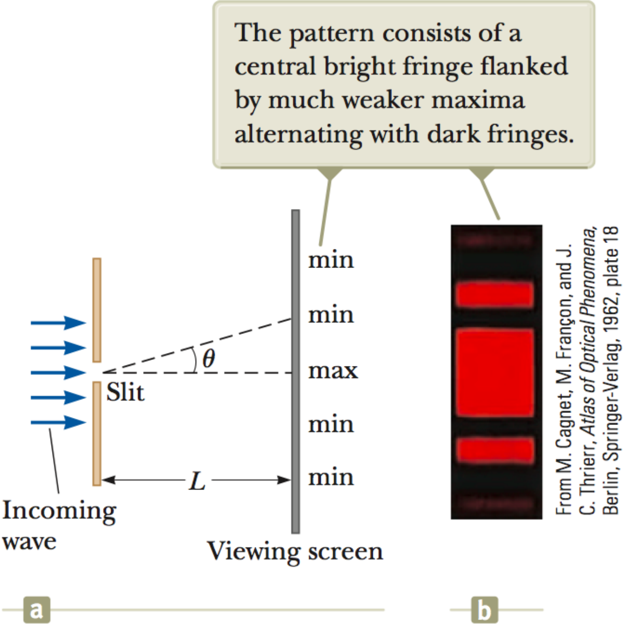
P. M. Rinard, *Am. J. Phys.* 44: 70 1976

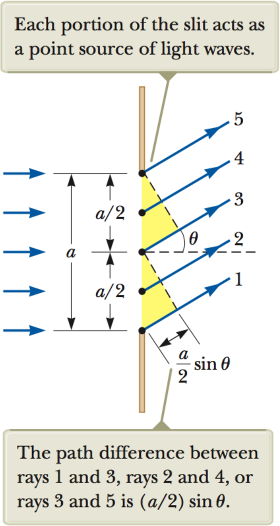
The truth about double-slit patterns



The intensity pattern described previously doesn't take into account the interference of the waves within the slit itself.


Viewing screen
Source
Opaque object
From M. Cagnet, M. Françon, and J. C. Thrierr, *Atlas of Optical Phenomena*, Berlin, Springer-Verlag, 1962, plate 32


The pattern consists of a central bright fringe flanked by much weaker maxima alternating with dark fringes.
min
min
max
min
min
θ
Slit
L
Incoming wave
Viewing screen
a
b
From M. Cagnet, M. Françon, and J. C. Thrierr, Atlas of Optical Phenomena, Berlin, Springer-Verlag, 1962, plate 18



Destructive interference occurs when

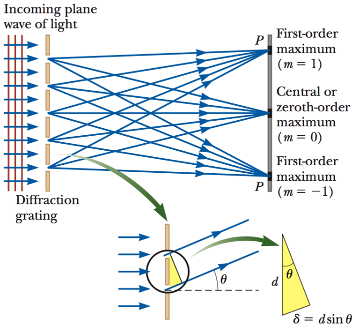
$$\frac{a}{2}\sin\theta = \pm m\frac{\lambda}{2}$$

In general,

$$\sin\theta_{dark} = m\frac{\lambda}{a}$$

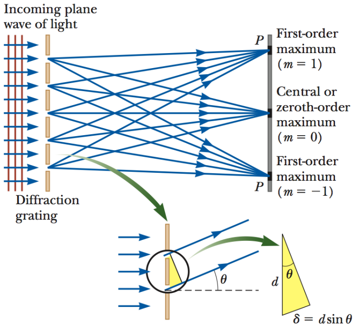
$$m = \pm 1, \pm 2, \pm 3, \cdots$$

Diffraction



Constructive interference occurs when

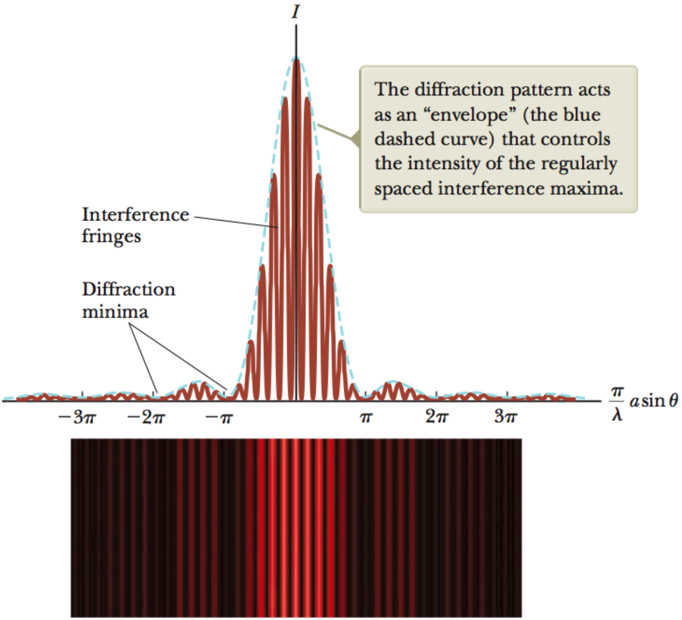
Diffraction



Constructive interference occurs when

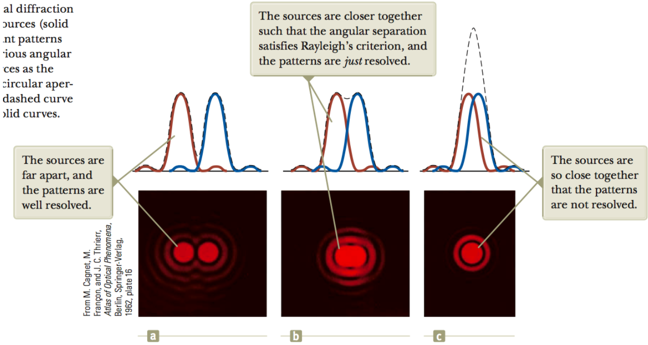
$$d \sin \theta_{bright} = m\lambda$$

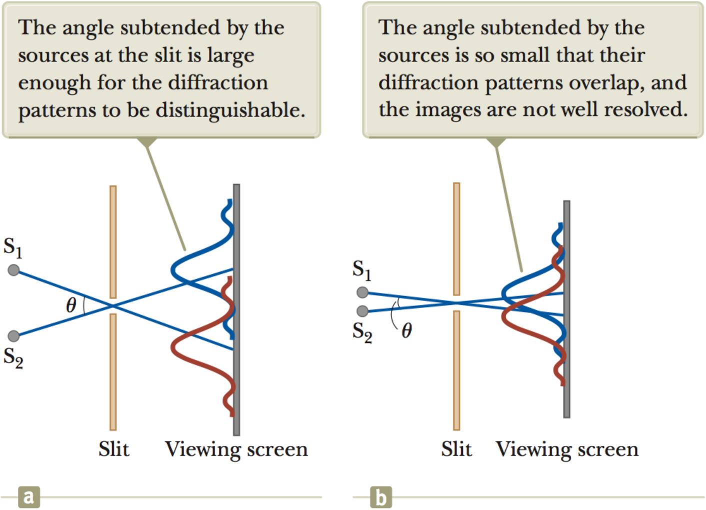
$$m = 0, \pm 1, \pm 2, \pm 3$$


I
The diffraction pattern acts as an “envelope” (the blue dashed curve) that controls the intensity of the regularly spaced interference maxima.
Interference fringes
Diffraction minima
−3π
−2π
−π
π
2π
3π
π/λ a sin θ

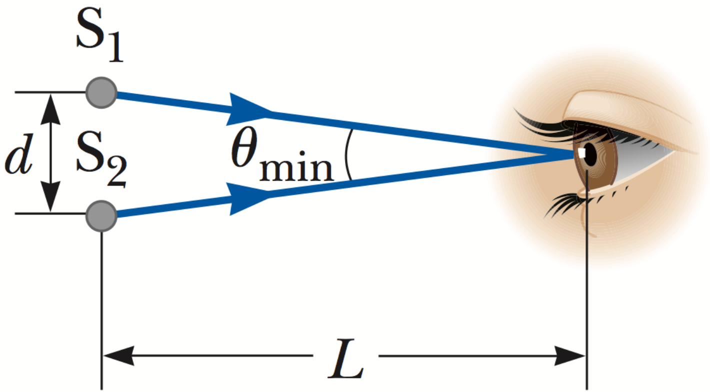
True intensity of interference patterns

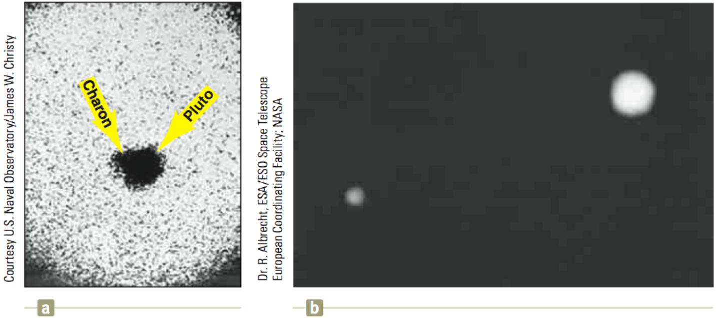
$$I = I_{max} \cos^2\left(\frac{\pi d \sin\theta}{\lambda}\right)\left(\frac{\sin(\pi a \sin\theta/\lambda)}{\pi a \sin\theta/\lambda}\right)^2$$

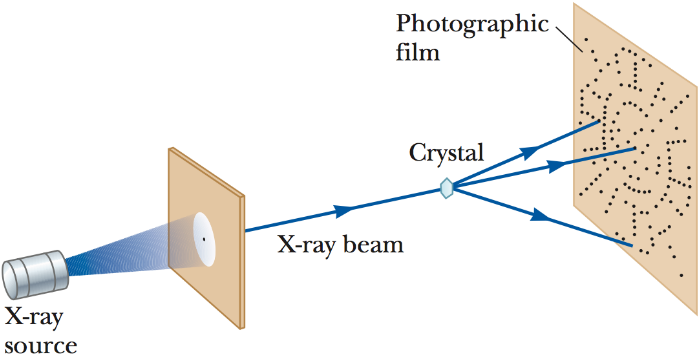

The sources are far apart, and the patterns are well resolved.
The sources are closer together such that the angular separation satisfies Rayleigh's criterion, and the patterns are *just* resolved.
The sources are so close together that the patterns are not resolved.
From M. Cagnet, M. Françon, and J. C. Thrierr, *Atlas of Optical Phenomena*, Berlin, Springer-Verlag, 1962, plate 16
a
b
c

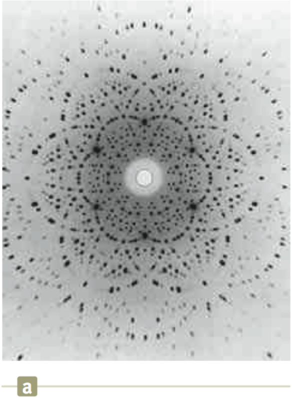


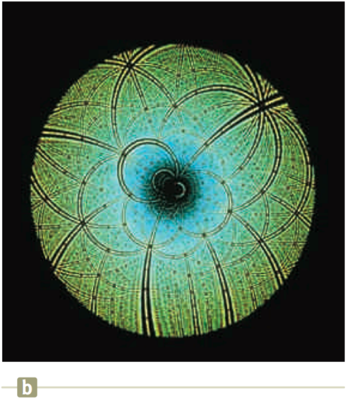
The angle subtended by the sources at the slit is large enough for the diffraction patterns to be distinguishable.
S1
S2
θ
Slit
Viewing screen
a
The angle subtended by the sources is so small that their diffraction patterns overlap, and the images are not well resolved.
S1
S2
θ
Slit
Viewing screen
b

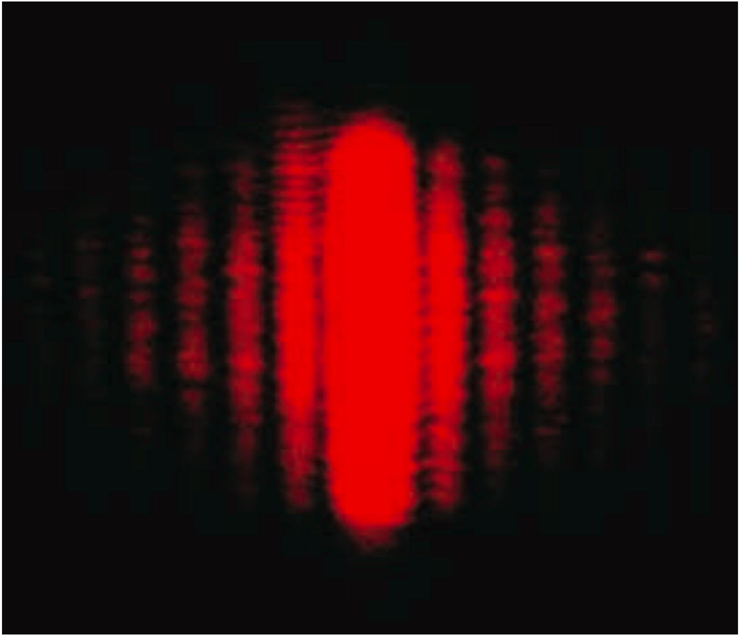

S1
d
S2
θmin
L


Courtesy U.S. Naval Observatory/James W. Christy
Charon
Pluto
a
Dr. R. Albrecht, ESA/ESO Space Telescope
European Coordinating Facility; NASA
b


Photographic film
Crystal
X-ray beam
X-ray source


a


b



Light as a particle

Light exhibits behavior that is characteristic of a particle in some circumstances, and behavior that is characteristic of a wave in other circumstances.

Light as a particle

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We have to simply accept this reality–not because somebody tells you to, but because all of the mathematics and experimental results tell us it is one of the truths of our universe.

Overview

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- A particle of light (photon) has energy E that relates to its frequency by $E = hf$ where h is Planck's constant.

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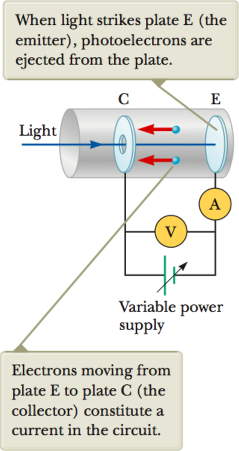
- The wave nature of light was first conclusively demonstrated by Young in 1801 with a double-slit experiment.
- Maxwell's prediction of EM radiation showed that light was an EM wave.
- Particle nature of light was re-established with Einstein's 1905 theory of photons.
- A particle of light (photon) has energy E that relates to its frequency by $E = hf$ where h is Planck's constant.
- $h = 6.626 \times 10^{-34} J \cdot s = 4.136 \times 10^{-15} eV \cdot s.$

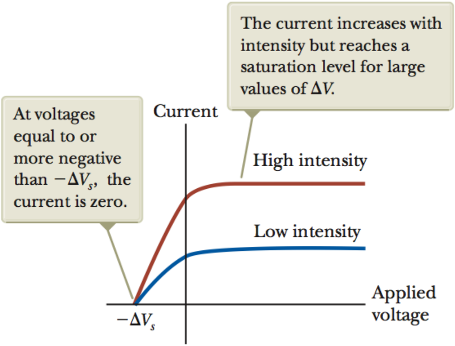
Photoelectric Effect



We can measure the maximum Kinetic energy by reversing the polarization of voltage (that is, make the plate from which electrons are emitted positive) and increasing the voltage until the current stops flowing. At this point, by conservation we know that:

$$K = e\Delta V$$

Kinetic energy of freed electrons is **not** dependent upon intensity of beam of same frequency. Explain that? **Your theories...**



Classical vs. Reality

Classical prediction	Experimental Reality
It will take time for electrons to absorb enough EM energy from wave before liberation	Wrong! They start ejecting almost immediately.
A higher intensity wave can deliver more energy per electrons, and so the kinetic energy should be stronger	Wrong! Same kinetic energy for same frequency no matter the intensity.
Frequency doesn't matter, only intensity.	Wrong! If the light falls below some cutoff frequency f_c, no electrons are liberated. The higher the frequency, the more the KE, which is not classically predicted.

- Based on what we learned in Physics II regarding EM waves and the Poynting vector, we should conclude that the higher the intensity of an EM wave, the more electrons would be kicked free.

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- The energy of a photon was $E = hf$. If that energy was not strong enough to set the electron free, nothing would happen–thus the frequency dependence.
- More photons means more free electrons, but with same KE.

Photoelectric Equation

Einstein's conclusion: Light is a stream of **individual** particles of energy. When a **single** particle is absorbed by an electron, all of its energy, hf, is donated to the electron. The electron must overcome the grip of the atoms/molecules holding it down, and this takes energy ϕ called the **work function**. Any energy left over is expressed as the kinetic energy of the electron such that:

$$K_{max} + \phi = hf$$

Work functions for select metals

Work Functions of Selected Metals

Metal	ϕ (eV)
Na	2.46
Al	4.08
Fe	4.50
Cu	4.70
Zn	4.31
Ag	4.73
Pt	6.35
Pb	4.14

The cutoff frequency can be found by setting $K_{max} = 0$: $\phi = hf_c$ so that $f_c = \phi/h$.

Photoelectric Effect for Sodium

A smooth flat surface of sodium is illuminated with light having a wavelength of 300 nm. For sodium, $\phi = 2.45$ eV is the work function. What is the maximum KE for ejected photoelectrons, and what is the cutoff wavelength λ_c? **Given:** $hc = 1240 eV \cdot nm$. Keep your answer in eV for energy units.

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$$K_{max} = hf - \phi = \frac{hc}{\lambda} - \phi = \frac{1240 eV(nm)}{300 nm} - 2.46 eV = 1.67 eV$$

and at cutoff, $KE \to 0$, so that,

$$\frac{hc}{\lambda_c} = \phi \;\to\; \lambda_c = \frac{hc}{\phi} = \frac{1240 eV(nm)}{2.46 eV} = 504 nm$$

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- This particle nature of light is a part of a bigger theory called Quantum Mechanics which we will return to later in the course.
- How can light be a particle and a wave at the same time?

Overview

As far back as Newton's time, there was debate about whether light was a particle or a wave. Newton believed light was a particle. Others such as Robert Hooke and Christian Huygens theorized that light was a wave. Turns out they were all right! (And all a little wrong.)

In this section, we talk about reflection and refraction. These are two things that can be explained best with the theory that light is a particle (for reflection) and with the theory that light is a wave (refraction), but the wave theory explains both easily.

In that sense, this section is meant to serve as a transition from our discussion of light as particles, to our discussion of light as a wave which will become even more evident next week.

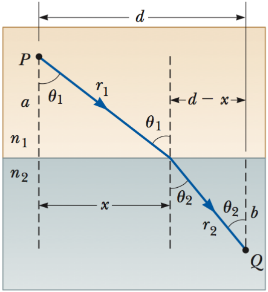
The truth is, this section is an excuse to teach you about **Fermat's Principle**, which is a result of something called the *Calculus of Variations.*

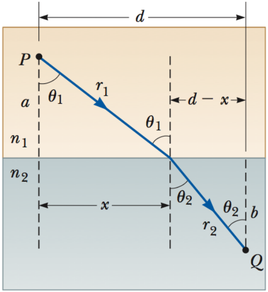
Fermat's Principle:

When light travels from point A to point B, it follows precisely that path that minimizes the amount of time it takes to get to those points.

If we add to that the idea that light slows down in non-vacuum mediums so that the speed of light in general is $v = c/n$ where $n \geq 1$ changes depending on the substance. From these rules, we can derive the laws of reflection and refraction!

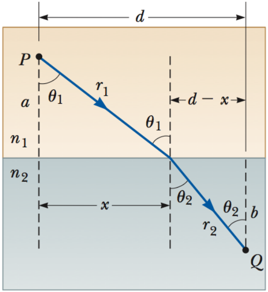
Refraction





- $t = \frac{r_1}{c/n_1} + \frac{r_2}{c/n_2} = n_1\frac{\sqrt{a^2+x^2}}{c} + n_2\frac{\sqrt{b^2+(d-x)^2}}{c}$

Refraction



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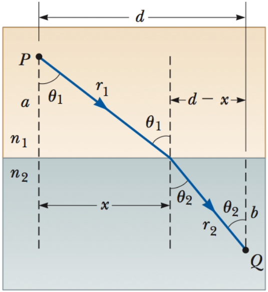

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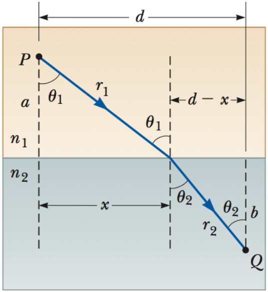

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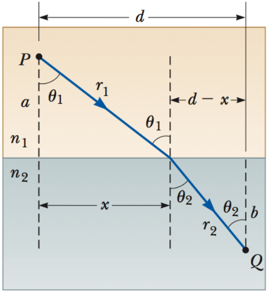

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- $n_1 \sin(\theta_1) - n_2 \sin(\theta_2) = 0$
- Snell's Law!

Example Indexes

Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473
Glass, crown	1.52	Water	1.333
Glass, flint	1.66		
Ice (H_2O)	1.309	*Gases at 0°C, 1 atm*	
Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

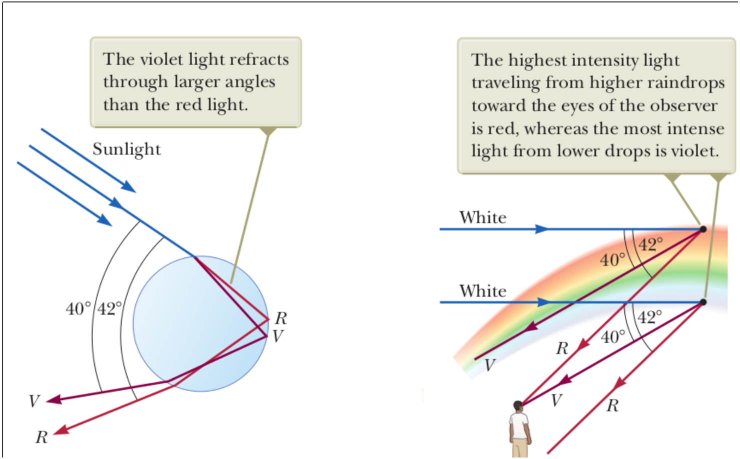
Note: All values are for light having a wavelength of 589 nm in vacuum.

Relative Intensity of Reflected Light

The calculation and resulting equations describing the intensity of light reflect vs. the intensity transmitted at the interface of two mediums with different indexes of refraction is beyond the scope of this class. However, for the special case when the light ray is normal, the intensity of reflected light is given as:

$$I = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 I_0$$

Rainbow!


The violet light refracts through larger angles than the red light.
Sunlight
40°
42°
R
V
V
R
The highest intensity light traveling from higher raindrops toward the eyes of the observer is red, whereas the most intense light from lower drops is violet.
White
White
42°
40°
42°
40°
V
R
V
R

Problem:

A light ray of wavelength 589 nm traveling through air is incident on a smooth, flat slab of crown glass at an angle of 30.0° to the normal. Find the angle of refraction, the speed of light in the glass, and the wavelength in the glass.

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$$\lambda_n = \frac{\lambda}{n} = 388 nm$$

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- we accept Fermat's Principle that light takes a path of least time,
- we get Snell's Law, which correctly predicts how refraction works.
- For reflection, since we are in the same medium, $n_1 = n_2$ so $\sin\theta_1 = \sin\theta_2$ so $\theta_2 = \theta_1$.

Nothing we have discussed so far really deviates too much from our conceptualization of light as a particle. Refraction had us thinking about how the wavelength of light comes into play in terms of the path it takes through mediums, which certainly seems wave-ish; however, we were talking about paths of rays as if they were ballistics of some sort.

Objective

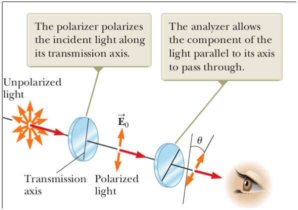
Here, we will talk about light as a wave in terms of the directions of the vibration of the EM field.

What is polarization?

Definition

The direction of the E-field of a EM wave is $\perp$ to the direction of propagation; If this direction is lined up parallel to a single line, we say it is linearly polarized.

Polarization by Absorption



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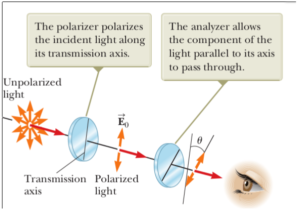

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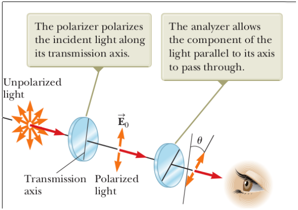

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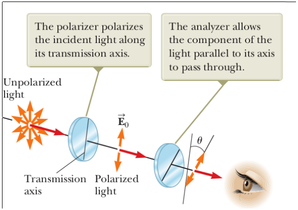

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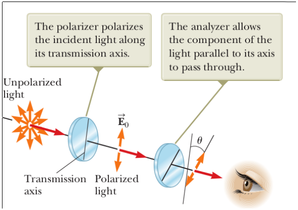

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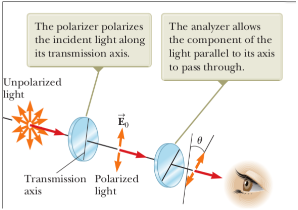

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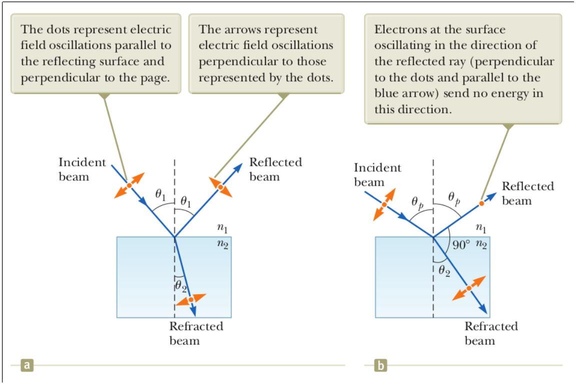
- **Law of Malus**: $I = I_0\cos^2\theta$

Polarization by Reflection



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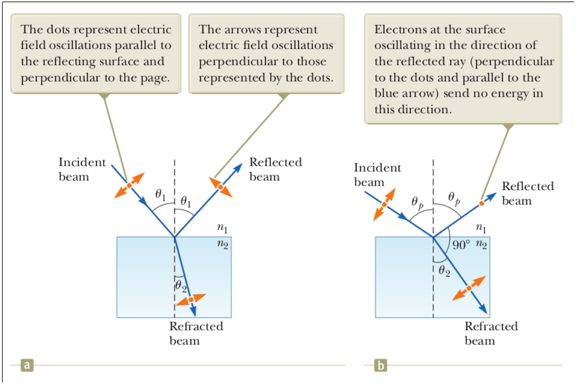

$$\theta_2 = 90 - \theta_p \;\rightarrow\; n_1 \sin\theta_p = n_2 \sin(90 - \theta_p) = n_2 \cos\theta_p$$

$$\theta_p = \tan^{-1}\frac{n_2}{n_1}$$

Other types of polarization

- **Scattering:** Absorption and re-radiation of EM waves is called scattering. Think about what happens to light that passes through muddy water. Due to effects that are beyond the scope of this current lecture (please read your book!) scattered light can be polarized.

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- **Birefringence:** Certain crystals and stressed plastics have the nature that light polarized at different angles travels at different speeds, and this results in variable refraction. (Again, read your book on this!)

Example of Birefringence

This example was created just a few hours ago: