Laser Light (Online)

Purpose   To study basic properties of light and its interaction with matter using a laser.

INTRODUCTION

Reflection and Refraction

Snell's Law, $n_1sin\theta_1 = n_2sin\theta_2$, relates the index of refraction n_1 of one medium, the angle of incidence of light θ_1 from that medium and the index of refraction n_2 of the other medium, and the angle of refraction θ_2 in that medium. A consequence of Snell's Law is that if $n_1 > n_2$ then $\theta_1 < \theta_2$. This is fine for small angles, but for some angle of incidence θ_1, the angle of refraction θ_2 will be 90^0. When this happens, $\theta_1 = \theta_c$ where θ_c is called the critical angle, and a so-called "evanescent" wave can travel along the interface. For incident angles larger than θ_c, the light is totally internally reflected and no light passes through the interface.
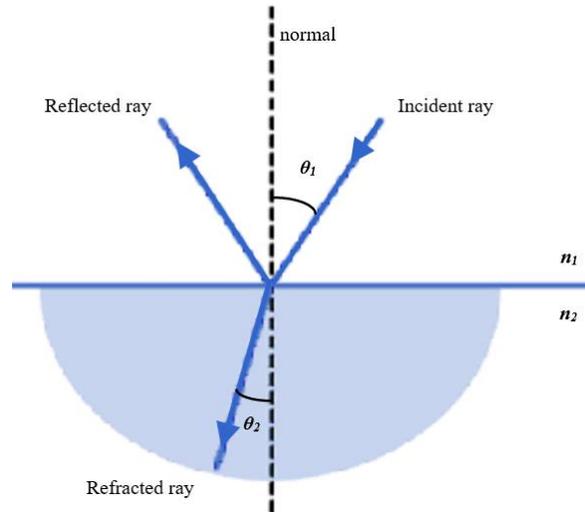

Fig. 1 – Reflection and Refraction of Light

Interference and Diffraction

For two sources of coherent light separated by distance d (as sketched in Fig. 1), light will destructively or constructively interfere on a screen placed far from the source. Light constructively interferes where the distance from one source to the screen is different from the distance of the other source to the screen by an integral number of wavelengths of the light illuminating the sources. That is, the **path length difference** $d\sin\theta$ for the two beams equals $m\lambda$, where m is an integer (0, 1, 2, ...), λ is the wavelength of light and θ is the angle to the position of interest on the screen as seen in Fig. 2. For destructive interference, this path length difference $d\sin\theta$ must be $(m + \frac{1}{2})\lambda$ and the light is out of phase.
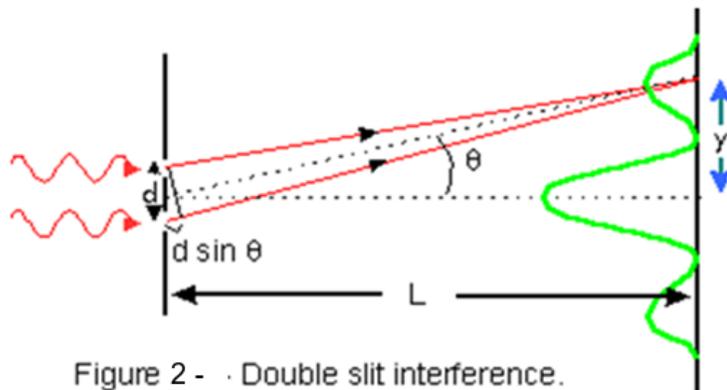

Figure 2 - · Double slit interference.

For a single slit of width D, light from the edges of the slit can interfere with light from the center of the slit, either destructively or constructively. This is called single slit diffraction. The condition for a **_minimum_** in intensity (a dark fringe) is $D\sin\theta = m\lambda$. If there are two or more slits, you can observe the single slit diffraction pattern superimposed on the multiple slit interference pattern. Typically, D, the width of the slits, is much less than d, the spacing between slits, so the single slit diffraction pattern is broader than the multiple slit interference pattern.

Diffraction gratings have thousands of lines per inch patterned onto a film. The gap between each line acts as a source. The same multiple slit interference formula applies as described above, with d the distance between lines.

Polarization

Light is a transverse electromagnetic wave, and both its electric and magnetic field amplitudes oscillate perpendicular to its direction of travel. Consider the electric field vector of a plane wave propagating in the x direction $E(x,t) = E_o\sin(kx- t)$. The orientation of E_o is always in the yz plane. If a beam of light is composed of electric field vectors with a uniform distribution in the yz plane, it is unpolarized. If one direction for E_o is favored the light is partially polarized. Tools have been made which can isolate one polarization from another.

Activity 1 – Calculating the Index of Refraction and the Critical Angle

Open this link to a simulation.
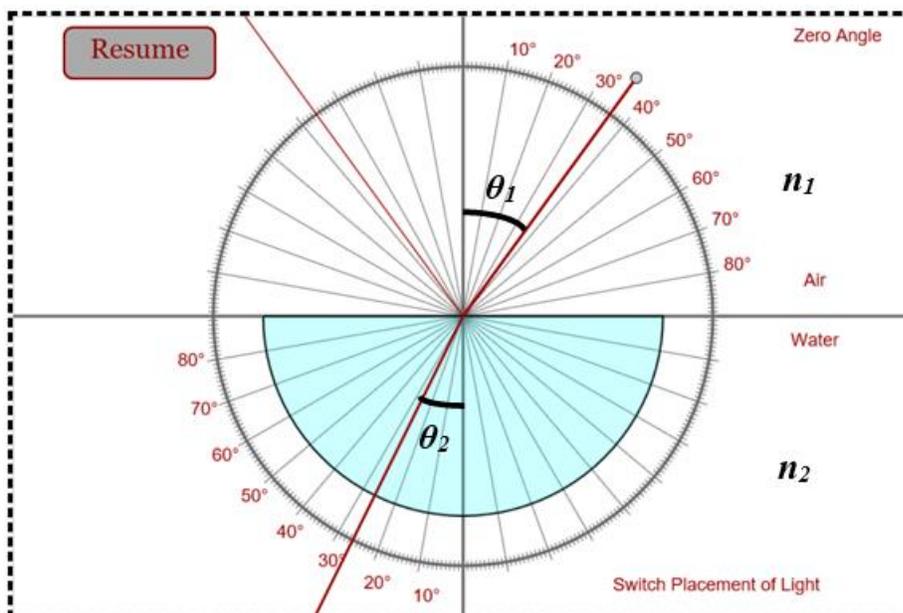
Using the simulation, we will look at how light is reflected and refracted as it goes from one medium to another and using Snell's Law, $n_1sin\theta_1 = n_2sin \theta_2$, find the index of refraction of the different materials in the simulation. We will also look for the critical angle θ_c and observe total internal reflection in these materials.

Fig. 3 - Simulation to get angle of incidence θ_1 and angle of refraction θ_2
(*credit: thephysicsaviary.com*)

The upper region in Fig. 3 contains air and $n_1 = n_{air}$ which is equal to 1. The lower region

contains water hence $n_2 = n_{water}$. The incident ray is coming from a laser indicated by the gray circle ⌕ pointed towards the water. Click on "Zero Angle" to start the laser from the vertical position then watch the reflected ray and the refracted ray as the position of the incident ray moves from 0 to 90°.

Questions:
1. Hit the "*Pause*" button to stop the incident ray at some angle. Carefully read and record the values of θ_1 and θ_2. Take a screenshot of the simulation screen for your report. Calculate the index of refraction of water. Compare your result (get % error) to the actual index of refraction of water which is 1.33.

2. Click on "Water" and change the second medium to "Air". Describe what you observe with the incident and refracted rays. Explain your result.

3. Change the second medium then follow the procedure in Question 1 to calculate the index of refraction for **glass**, **diamond**, **amber** and **glycerol**. Compare your results to the known indices of the materials.

Index of Refraction (n) of Some Common Materials	
Air	1.00
Amber	1.55
Diamond	2.417
Glass	1.52
Glycerol	1.473
Ice	1.31
Water	1.33

When light goes from a medium with a higher index of refraction to a medium with a lower index of refraction, i.e. $n_1 > n_2$, the refracted ray bends away from the normal line. A special case happens when the angle of refraction θ_2 reaches 90^0. In this case, the angle θ_1 is called the critical angle θ_c and the light undergoes total internal reflection and there is no refracted ray. At the critical angle, $\theta_1 = \theta_c$ and $\theta_2 = 90^0$ (see Fig. 4). If the light went from a high index medium to air, Snell's Law is then written as $n_{medium}sin\theta_c = n_{air}sin90^0$ and θ_c can be obtained for a given medium.

Reflection and Refraction

Total Internal Reflection

When the angle of incidence equal the critical angle, the angle of refraction is 90-degrees.

When the angle of incidence is greater than the critical angle, all the light undergoes reflection.
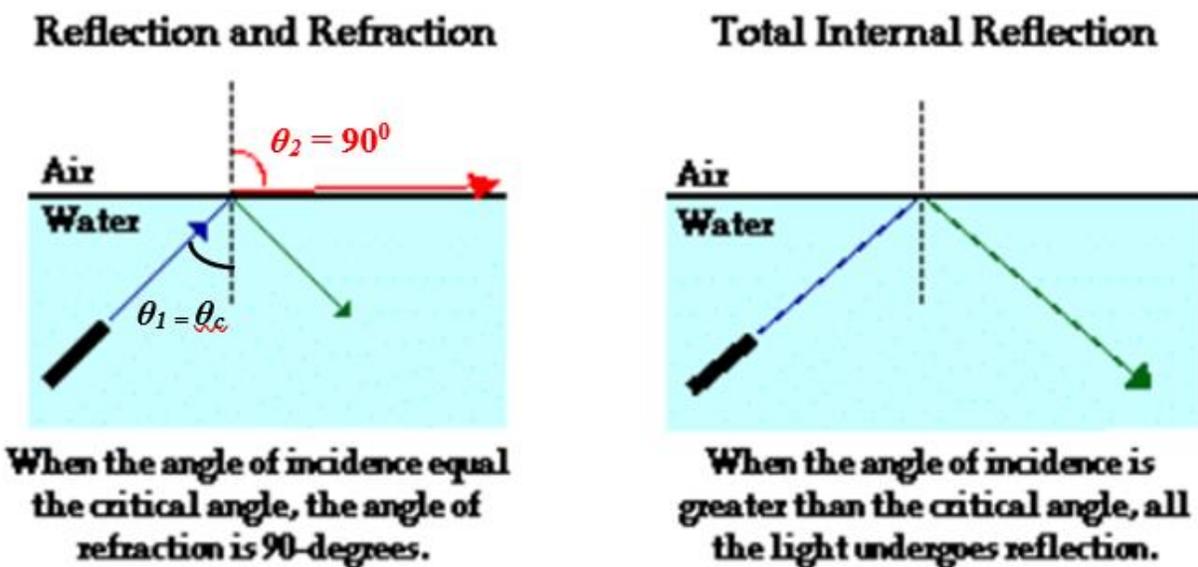
Fig. 4 – The critical angle and total internal reflection (*credit: physicsclassroon.com*)

In the simulation, reset the lower medium to "*Water*" and click on "*Switch Light Placement*" to make the light go from water to air.

Questions:

4. Click on "*Zero Angle*" then click "*Resume*" and watch as θ_2 approaches 90^0. Quickly click on "*Pause*" as θ_2 reaches 90^0 and the light undergoes total internal reflection (try to get as close as possible to the first angle at which the total internal reflection is observed). Read and record the value of θ_1 at this position. This should be very close to the critical angle θ_c for water. Try to repeat this a few times to get a consistent result.

5. Repeat the steps in Question 4 using **glass**, **diamond**, **amber** and **glycerol** as the higher index medium. Remember to start at "*Zero Angle*" each time you take the observation.

6. Using Snell's Law, calculate θ_c for each of these 5 materials and discuss how close these values are to the ones you have obtained from the simulation. Explain the cause for the differences.

Activity 2 – Understanding Interference and Diffraction

A. Click on this link to the simulation.

This simulation shows light waves passing through a double slit and shows how the waves interfere. The locations where constructive interference happens are indicated with their corresponding index values (m = 0, 1, 2, …) on the screen at the right.

The scale indicated on the screen is 1 micron = 1 x 10^{-6} meters.
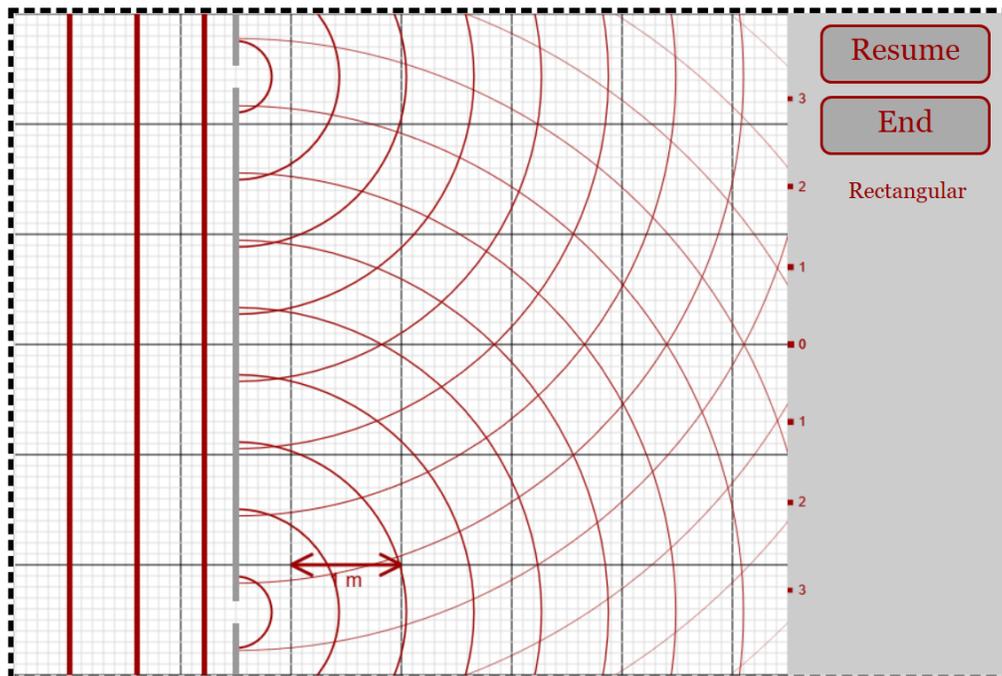

Fig. 5 - Calculating the wavelength (*credit: thephysicsaviary.com*)

Click on "*New d*" to set the slit separation to about 4 microns or more. Click on "*Start*" and observe how the waves come together forming constructive interferences (bright spots) on the screen. You should have index values of m = 2 or higher, if not, "*End*" the simulation then click on "*New λ*" to try a different wave and start it over. Once you get m's of 2 or higher, "*Pause*" the screen. Take a screenshot of the simulation screen to be included in your report.

The wavelength of the light can be obtained using $d sin\theta = m\lambda$, where d is the distance between slit centers, θ is the angle to the mth maximum and λ is the wavelength of the laser (see Fig. 2). You can measure the angle θ by measuring the distance L from the slit to the central spot of the laser on the wall, and measuring the distance y perpendicular to the beam, from the central spot to the mth maximum. Then $tan\theta = y/L = sin\theta$ for small angles. Hence, $\boldsymbol{dy/L = m\lambda}$.

Questions:
   7. Calculate the wavelength of the light used in your simulation screen. Express your answer in nanometers (nm).

B. Click on this next link to learn more about interference and diffraction.
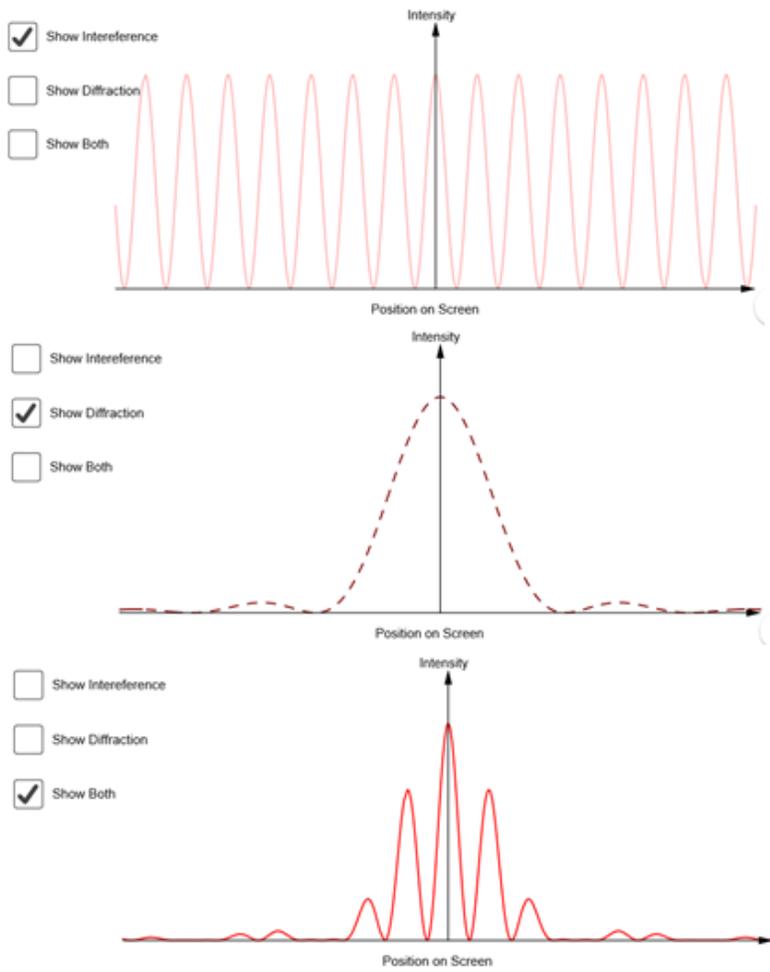
When light passes through a double slit, bright and dark spots formed is a combination of an interference pattern (see top image, Fig. 6) and a diffraction pattern (see middle image, Fig. 6). The combination of these two results in the double slit pattern shown in the bottom image of Fig. 6.

Individually click on "*Show Interference*", "*Show Diffraction*" and "*Show Both*" to get an understanding of how the double slit interference pattern is produced

Vary the parameters
a (slit width),
d (slit separation),
λ (wavelength),
D (distance from slits to screen) using the sliders.

Fig. 6 - How the double slit pattern is produced. (*credit: geogebra.org*)

Questions:
   8. Looking at the interference pattern, what parameter is it independent of? Looking at the
       diffraction pattern, what parameter is it independent of?

   9. What happens to the pattern when the parameter *a* is reduced?

   10. Set λ = 400 nm, *a* = 1 µm, *D* = 10 m. When the slit separation *d* is 4 times the slit widfh
       a, which interference maximum is missing in the double slit pattern?

   11. Continue to adjust the slit separation *d* and find two more values of *d* that will result in
       missing maxima. Write down your results for *d* and the missing maxima. Can you see a
       pattern? Take a screenshot of one of your patterns and include it in your report.

C. Click on this link to observe interference/diffraction pattern formed by various slits.
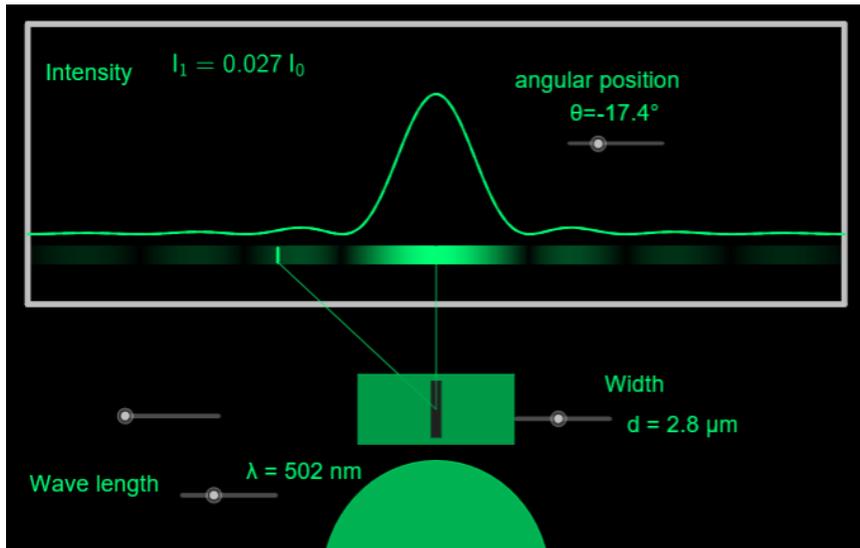
This simulation shows how the interference and diffraction patterns (shown in the previous activity as graphs) actually look like as bright and dark sport on a screen. Allow the simulation to completelt sweep from left to right to see the full set of brigh and dark spots produced by the slit starting with a single slit.

Fig. 7 - Single Slit Diffraction (credit: geogebra.org)

Observe the patterns formed by a single slit, double slit and a multiple slit (5 slits). Move the
slider button [slider image] to the left of the slit to increase the number of slits.

Questions:
   12. Describe the pattern formed by a single slit. How does the pattern change when we use a
        double slit? How does it change further when we increase the number of slits to 5?

D. Open this simulation to look at diffraction grating patterns

A diffraction grating consists of many parallel scratches (typically ~500 lines/mm) on a flat
transparent surface which then act as a multitude of parallel slits when laser shines on it. The

rays emerging from a diffraction grating also follows the equation $dsin\theta = m\lambda$.

Place the diffraction grating in front of the laser by clicking on "*Grating in Place*". Note the interference pattern on the screen. A blown up view of the pattern can be seen with a corresponding scale to show the actual distances between the bright spots or peaks. Observe what happens to the interference patterns when you vary the parameters one at a time (keep the other two parameters constant). For example, start with varying "*Lens to Grating Distance*" while keeping the "*Grating Lines/mm*" and "*Wavelength*" constant.

Questions:
13. Describe how the number of peaks and the distances between them vary with
   a) Distance to the grating
   b) Number of grating lines/mm
   c) Wavelength

Activity 3 - Polarization Effects

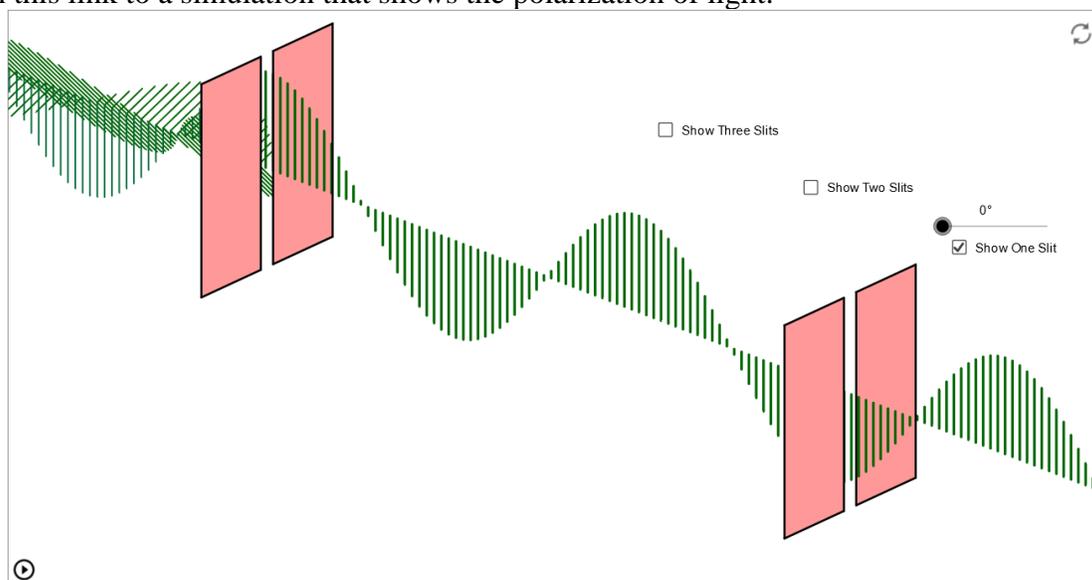Open this link to a simulation that shows the polarization of light.

Fig.   – Light passing through multiple polarizers (*credit: ophysics.com*)

This simulation helps visualize polarization. A polarizer has a particular transmission axis and only allows light waves aligned with that axis to pass through. In this simulation, unpolarized waves come in from the left side and pass through a polarizer with a vertical transmission axis. Note that the light that passed through has only vertical components. Observe what happens as this vertical transverse wave passes through two or three polarizers at various angles.

Use the check boxes to add one or two polarizers and the slider button to rotate the polarizers. Press the button at the bottom left to start or pause the animation.

Click on "*Show One Slit*" to add one polarizer on the right side of the screen. Rotate this

polarizer from 0^0 to 90^0.

Questions:

14. Observe the variation in intensity as you rotate a polarizer in the beam. What does that imply about the polarization of the laser?

15. What happens to the light when you rotate the polarizer on the right from 0^0 to 90^0? At what position is the light completely blocked?

Click on "*Show Two Slits*" to have two polarizer on the right side of the screen. Rotate each polarizer individually from 0^0 to 90^0.

16. Describe what happens when (a) the rightmost polarizer is at 0^0 and the polarizer in the middle is at 90^0? (b) the rightmost polarizer is at 90 and the polarizer in the middle is at 0^0

17. From the position given in 3.b above, rotate the middle polarizer from 0^0 to 90^0. For what orientations is the beam transmitted? At what angle do we see the maximum transmission?

18. How is it possible that rotating the polarizer in the middle can allow light to be transmitted?