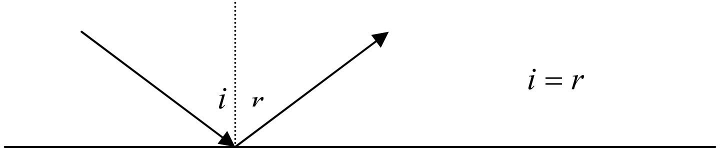
The true nature of light has been strongly debated for centuries. There have been two philosophical camps; ones who support the **corpuscular theory of light** and others that support the **wave theory**.

Corpuscular Theory

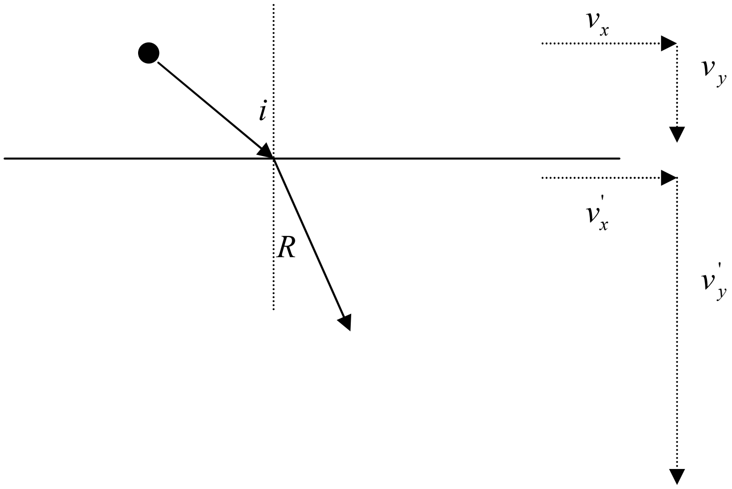
Corpuscular theory was the accepted theory 300 years ago. It was believed that light was made up of extremely light particles that were nearly mass-less. These particles would transfer energy like any moving object would (conservation of momentum and energy). It was believed that light followed the laws of mechanics and there was much evidence to support the theory at the time. Evidence to support the theory was derived directly from Newton's laws.

1) **Rectilinear Propagation** – light appeared to move in straight lines and did not seem to bend around corners or other objects.
2) **Reflection** – the reflection of light behaves as predicted for particles experiencing elastic collisions.



$$i = r$$

3) **Refraction** – refraction ***could*** be explained if light was assumed to travel faster in more optically dense media (this assumption has since been proven to be incorrect). Newton thought that the second medium attracted the light particles much the same way gravity attracts objects to the surface of the earth. Gravity does not work horizontally, only vertically, which could explain why the vertical component of velocity increases where the horizontal component is unaffected. Newton also had to justify the fact that the angle of refraction was independent of the thickness of the second medium. If the second medium had a gravity-like attraction to the corpuscles of light, the refracted beam should be a parabolic curve. This doesn't happen therefore this gravity like force only acts at the boundary, according to the theory.



4) **Partial Reflection** and **Partial Refraction** – The corpuscular theory of light was quite weak in its explanation for this phenomenon. Newton attempted to explain this by his so-called "theory of fits". His theory was that light sometimes arrived at a surface in a "fit" of reflection and other times in a "fit" of refraction… what ever that means… by Newton's own admission this was a very weak explanation.

5) **Dispersion** – The prism effect had been known for thousands of years but Newton was one of the first who tried to explain it scientifically. Newton believed that the difference in the angle of refraction for different colours of light was a result of slight differences in the masses

of each corpuscle among the different colours of light. Since red light was refracted least, Newton speculated that red light corpuscles where slightly heavier than violet corpuscles. The law of inertia states that heavier particles would be less deflected by an external force than lighter particles. As a result violet light experience more refraction then red light.

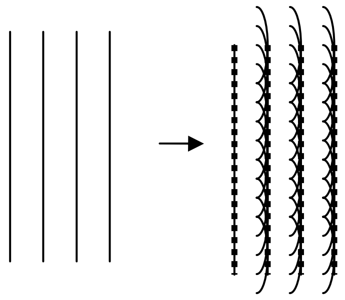
6) **Diffraction** – Newton argued that light does not bend around corners like water waves and sound. He also dismissed the work of Francesco Grimaldi, an Italian Jesuit mathematician, demonstrated that a beam of light, passing through a series of narrow slits, became slightly wider when projected on a screen some distance away. Newton argued that this was not diffraction but the result of interactions and collision between the corpuscles at the edges of the slit.

An interesting note of history, Newton was not nearly as adamant with his position on the entire wave vs. particle debate. Newton's position was based on the best evidence and best arguments at the time. Newtonian mechanics had been very well experimentally supported in other areas of physics, where wave theory had very little substantiated evidence or precedence. Naturally, one would tend to look for answer by using accepted theories in an attempt to explain new phenomena; Newton however was not completely dismissive of wave theory. He believed more experimentation was required since both theories were well supported experimentally. It was Newton's supporters that were so adamantly opposed to wave theory. Because of Newton's stature, corpuscular theory had become the accepted theory by most scientists. Even when new evidence favouring wave theory surfaced, the scientific intelligentsia at the time were still unwilling to refute the Newtonian model.

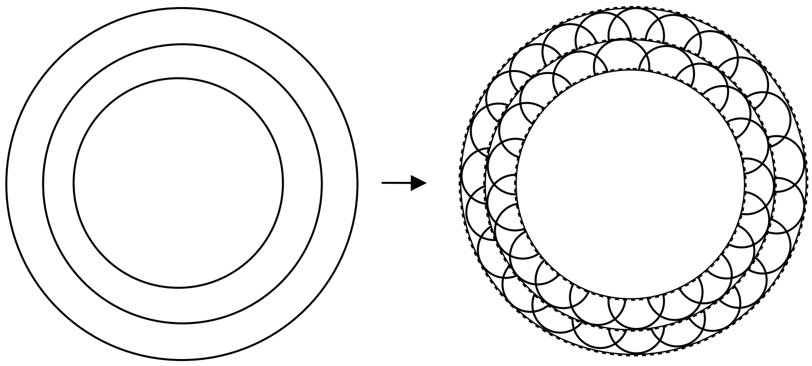
Wave Theory of Light

Wave theory was proposed by Robert Hooke in 1665 and was improved by Dutch scientist Christiaan Huygens. **Huygen's Principle** is still useful today. Huygen's principle is used to predict the future position of waves by assuming that waves are made up of an infinite number of point sources located along a wave front, generating secondary wave fronts based on the principles of superposition.

Straight Wave



Circular Wave

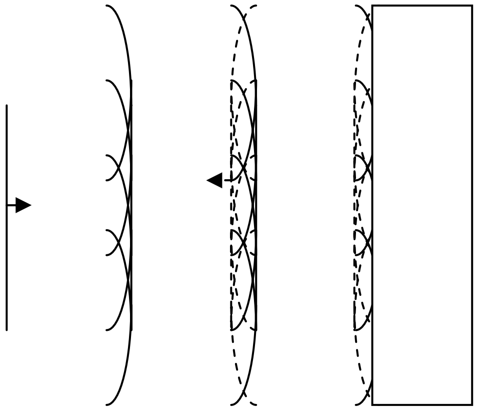


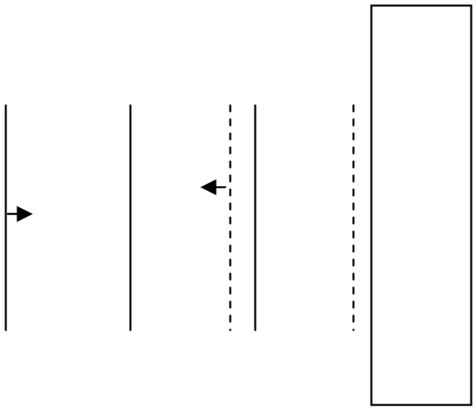
Huygen’s Principle:

> *Every point on a wavefront can be considered as a point source of tiny secondary wavelets that spread out in front of the wave at the same speed as the wave itself. The surface envelope, tangent to all the wavelets, constitutes the new wavefront.*

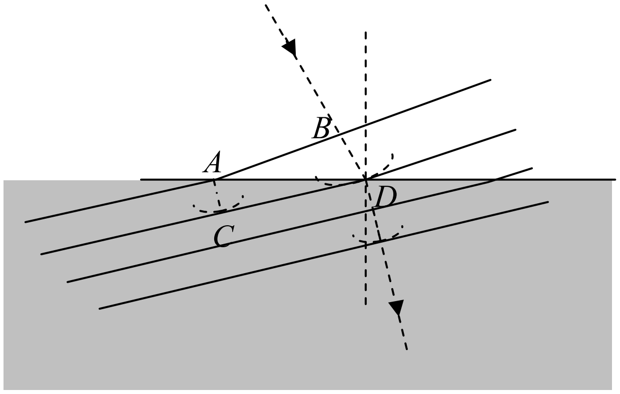
Huygen’s principle works for all manner of waves. It is a useful model for predicting transmission, reflection, and diffractions as well.

Reflection





Refraction

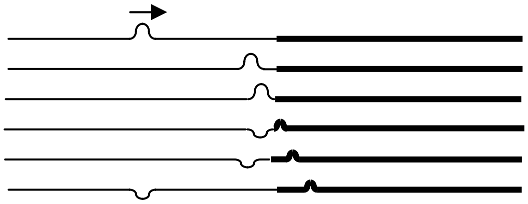


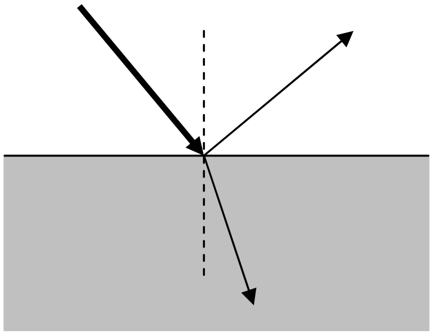
Huygen’s principle predicts that the speed of light in the second medium would be slower than in the first. This is the exact opposite to what the corpuscular theory predicts. The distance travelled by the wavelet AC is shorter than the distance traveled by the wavelet BD, implying that the wavelet AC is moving more slowly. At the time Huygen proposed his theory, it was not known if the speed of light increased or decreased as it enters the second medium. It wasn’t until 1850 when it was shown that the speed of light indeed slows down, and wave theory had become fully accepted.

Partial Reflection and Partial Refraction

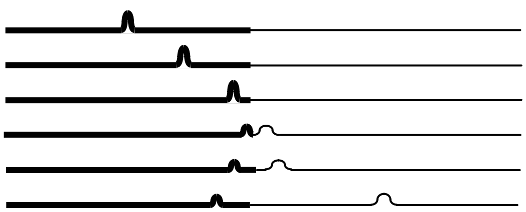
Partial reflection and partial refraction can be much better explained by wave theory. Waves moving from a slow medium to a fast, and vice versa, experience reflection and transmission.

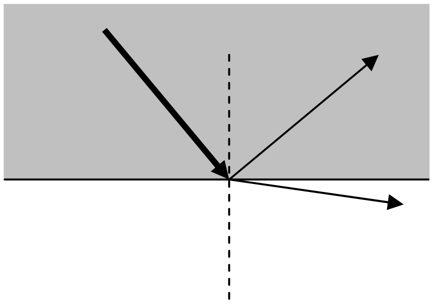
Moving from fast to slow medium





Moving from slow to fast medium





Waves in two dimensions behave similarly to waves is in one dimension with the exception of refraction, which only occurs in two dimensions. We experience this phenomenon of partial reflection and partial refraction in our everyday experiences.

Example: If you stare as a still pond you can see both reflection and refraction. As you look toward the far edge of the pond, you will see the reflection of the shoreline, but as you look down you can see the distorted images emanating from just below the surface.

Sound also experience both refraction and reflection, this is the reason why bass from home theatre systems can heard through out the entire home. The low-end frequencies transmit quite easily through walls as well as reflect from these surfaces.

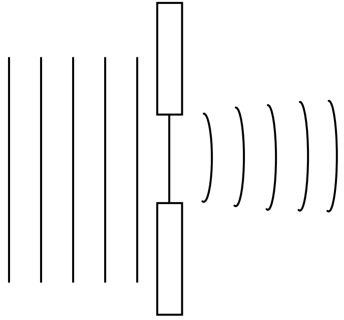
Diffraction

Waves under go diffraction, so to the proponents of wave theory, it also appeared that light also experienced diffraction. Newton, however, felt that the effect was not nearly pronounced enough to qualify as diffraction. The diffraction of water waves is quite dramatic provided that the aperture is on the same order of magnitude of the wavelength. At the time both Newton and Huygen did not realize that the wavelength of light was so small. Had the experimental apparatus been more refined, there would have been more of an observable effect.

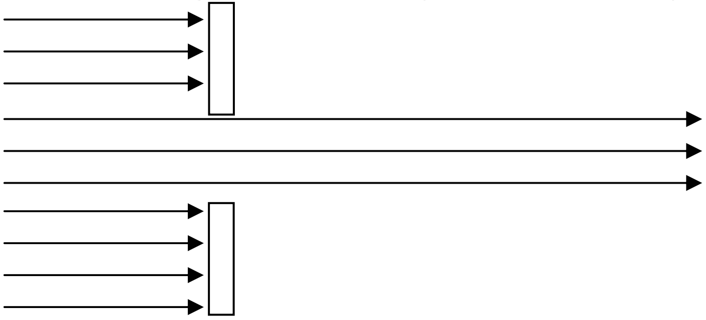
Rectilinear Propagation

Huygen's believed that rays of light only represented the direction of the wave fronts that made up the light. Newton felt this too was a weak explanation for this property of light. In this case, corpuscular theory better explains this property. A ray of light can be very easily envisioned as a stream of particles where with wave theory, one would expect the waves to spread out.

Behaviour of light as predicted by wave theory



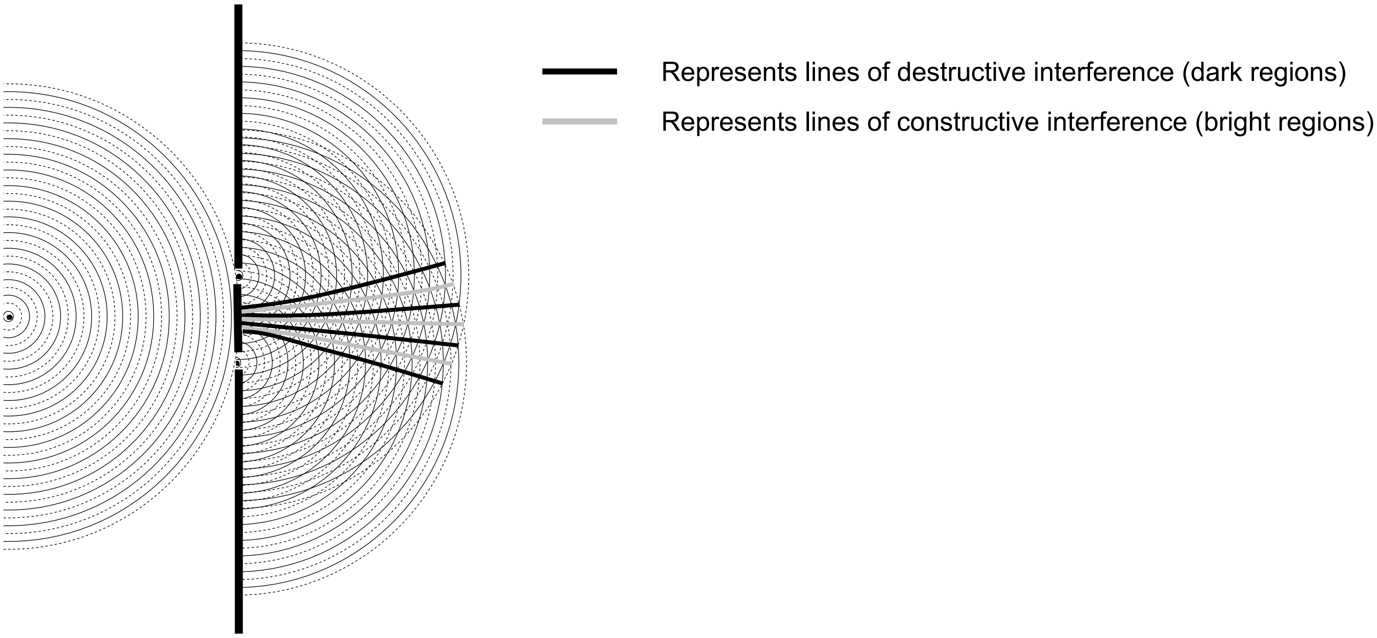
Behaviour of light as predicted by corpuscular theory



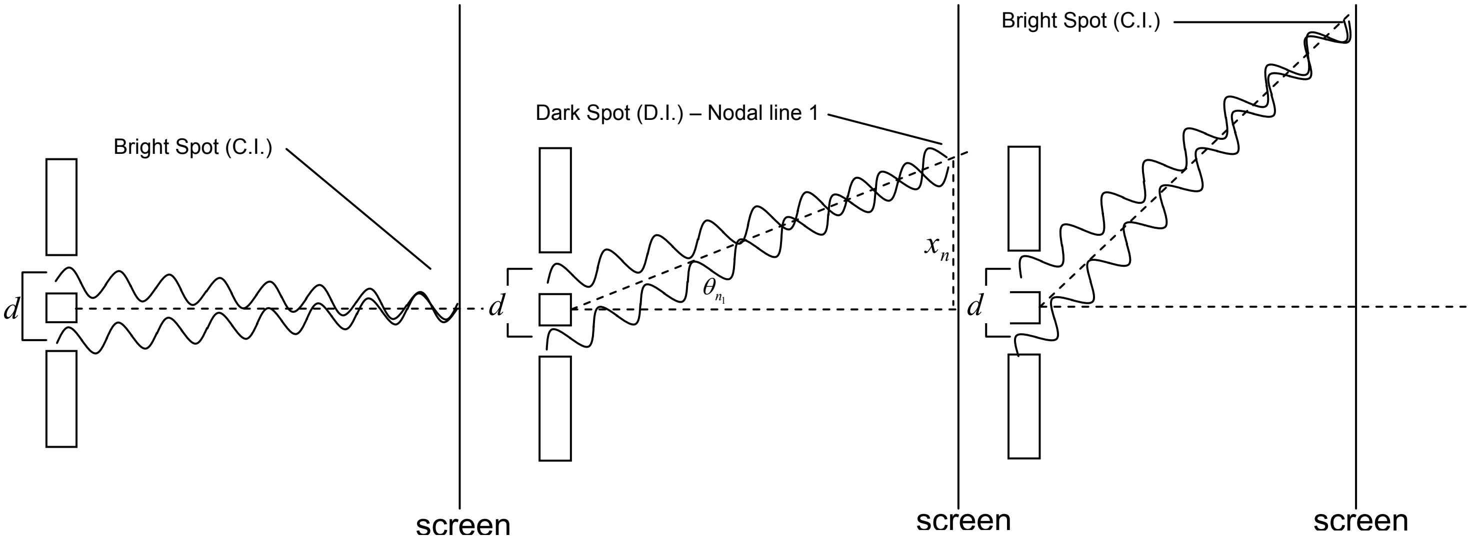
Young's Double Slit Experiments

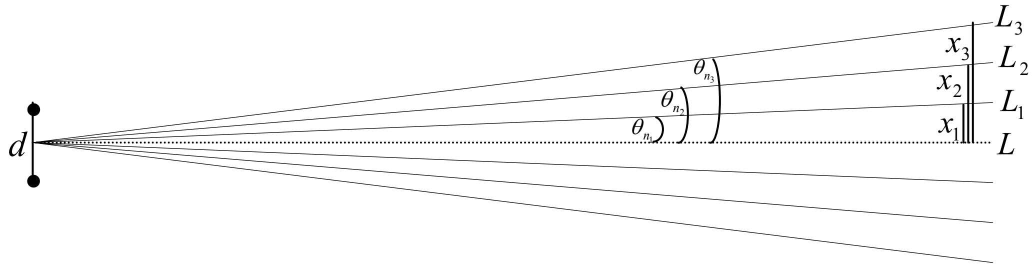
Thomas Young developed experiments that demonstrated properties of light that could not be explained by corpuscular theory but could be explained very well by wave theory.

Young discovered that shining a light through two very narrow slits would produce an interference pattern on a screen some distance from the two slits. This interference pattern could not be explained by corpuscular theory. This would be like firing a double barrel shot gun through a narrow door way and having the blast pattern take the form of as a series of concentric rings. Young was the first to observe the interference pattern because of his unique approach. By using two very narrow slits and a single light source, he was able to produce two point sources of waves in phase with each other. This was never achieved before because previous attempts of this experiment involved the use of two independent light sources. By using two independent light sources, the waves of light would have random phase angles making an inferences pattern impossible to detect.



Young successful demonstrated that light in fact behaves like a wave. Furthermore, he determined that the wave equation $\boxed{\lambda = \frac{x_n}{L}\frac{d}{\left(n-\frac{1}{2}\right)}}$ holds true of the diffraction patterns of light.





Young was able to further manipulate the above formula by making a few assumptions. L does not change significantly over the first few nodal lines since the x_n and d are small compared to L. L can be approximated to the distance from the centre of the two slits to the screen. Therefore $L_1 \cong L_2 \cong L_3 \cong L$

Rearranging the wave equation $\lambda = \frac{x_n}{L}\frac{d}{\left(n-\frac{1}{2}\right)}$ we can simplify the equation $x_n = \frac{\lambda L\left(n-\frac{1}{2}\right)}{d}$

$$x_1 = \frac{\lambda L\left(1-\frac{1}{2}\right)}{d} = \frac{\lambda L}{2d}$$

$$x_2 = \frac{\lambda L\left(2-\frac{1}{2}\right)}{d} = \frac{3\lambda L}{2d}$$

$$x_3 = \frac{\lambda L\left(3-\frac{1}{2}\right)}{d} = \frac{5\lambda L}{2d}$$

Since x_1, x_2 and x_3 are equidistant therefore

$$\left(x_2 - x_1\right) = \left(x_3 - x_2\right) = \Delta x = \frac{\lambda L}{d}$$

In general $\boxed{\Delta x = \frac{\lambda L}{d}}$

Questions:

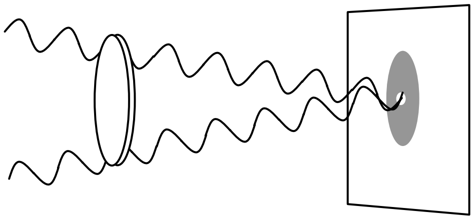
1. A student doing Young's Experiment find that the distance between the first and the seventh nodal lines is 6.0cm. If the screen is located 3.0m from two slits, whose separation is 220μm, what is the wavelength of the light? $\left(ans = 7.3\times10^{-7}\,m\right)$

2. An interference pattern is formed on a screen when helium-neon laser light $\left(\lambda = 6.328\times10^{-7}\,m\right)$is directed towards it through two slits. If the slits are 43μm apart and the screen is 2.5m away, what will be the separation of adjacent nodal lines? $\left(ans = 3.7cm\right)$

3. In an interference experiment, red light (600nm) passes through a double slit. On a screen 1.5m away, the distance between the 1st and 11th dark bands is 13.2cm. What is the separation of the slits? What would the spacing be, between adjacent nodal lines, if blue light (450nm) were used? $\left(ans = 68\mu m,\, 1.0cm\right)$

Poisson's Bright Spot

When Young put forth his arguments in support of the wave theory of light, the largely sceptical scientific community (most of who subscribed to particle theory) were unconvinced by his arguments and his work was not taken seriously. Newton's influence was still too strong. Augustin Fresnel faced similar scrutiny in 1818 when he proposed his theories in support of wave theory. The scientific community still favoured particle theory over wave theory. One mathematician in particular, by the name of Simon Poisson, used Fresnel's equations in an attempt to refute Fresnel's theories. According to the Fresnel equations, light passing by a solid disk should produce a bright spot of constructive interference in the centre of the shadow. When Poisson did not observe such a dot, he felt that he had successfully refuted wave theory.



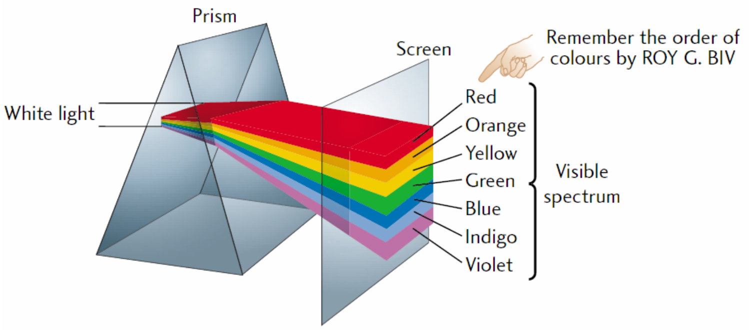
However in 1818, Poisson's prediction was tested by Dominique Arago and he did observe the dot. Inadvertently, Poisson's argument, intended to refute wave theory, was ultimately responsible for proving it. This phenomenon has come to be known as Poisson's Bright Spot. This of course begs the question of which of the following outcomes from this historic scientific debate is ultimately more ironic, that Poisson has been immortalized for having been proved wrong by his own theory or that the person whom actually observed the phenomenon has largely been ignored by history… too close to call!

Wavelength and Colour

Young's double slit experiments demonstrated that different colours of light had different wavelengths, red light having the longest wavelengths and violet having the shortest. One unexpected outcome of his work was the effect wavelength had on refraction in glass. Shorter wavelength refracted more than longer wavelengths. This was quite counter-intuitive since for sound waves and water waves, longer wavelengths refracted more.

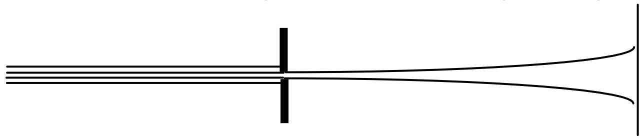
Colour	Wavelength (nm)
Violet	400-450
Blue	450-500
Green	500-570
Yellow	570-590
Orange	590-610
Red	610-750

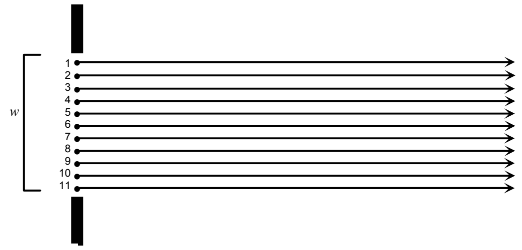
white light into its component colours



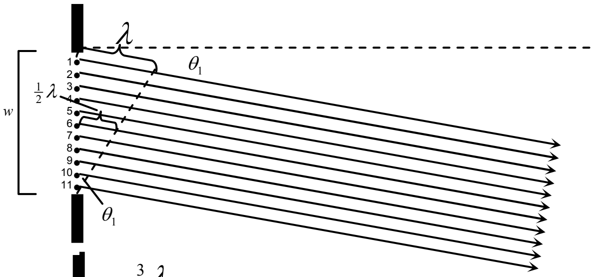
Single Slit Diffraction

An interesting phenomenon occurs when light passes through a single narrow slit. It is expected that light will diffract as it passes through the slit causing the light to disperse. However, the light emerging the other side also experiences interference. This may seem counter-intuitive at first but if we consider Huygen's principle, light as an infinite series of point sources located along the edge of a wave front, it can be demonstrated how the interference pattern does occur.

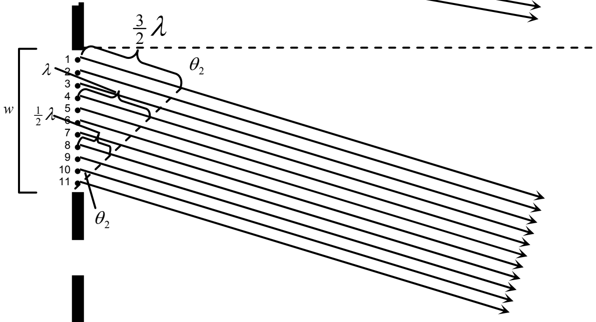




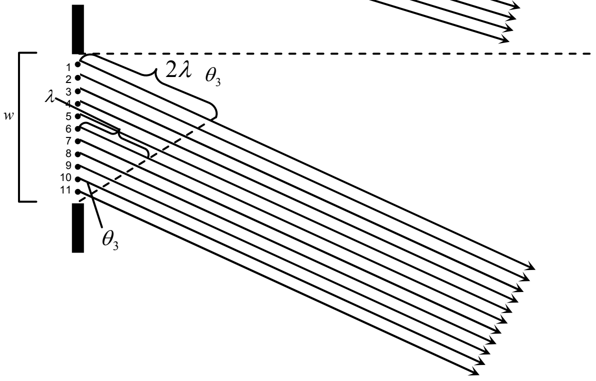
All light emanating from the point sources arrive at the screen roughly in phase. This creates the central maximum which is the brightest of all the maxima



All light emanating from the point sources arrive at the screen almost entirely out of phase. This creates a dark spot minimum. (e.g. 11-6, 10-5,9-4,8-3,7-2 cancel each other out)

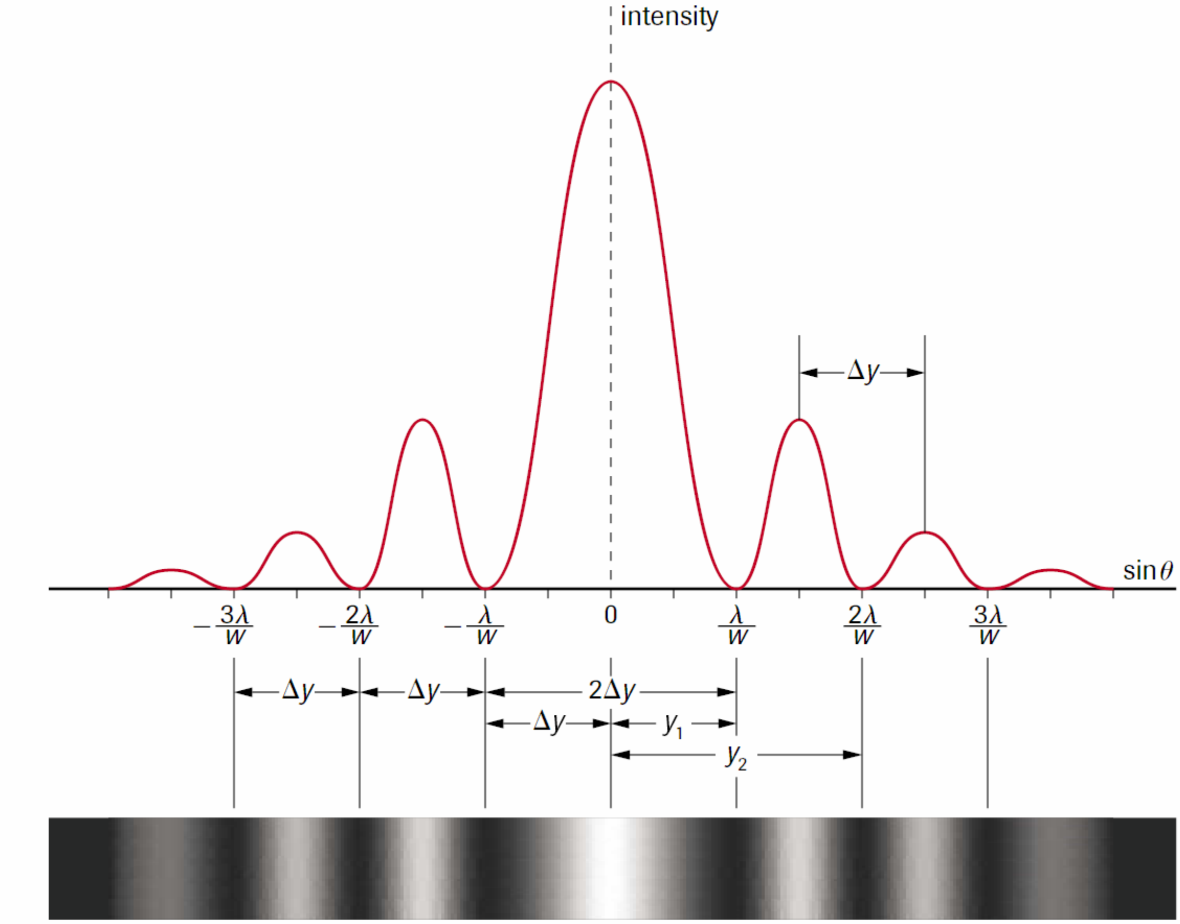


Most of the point sources in the bottom 2/3rd of the slit experience cancellation (8-4,9-5,10-6,11-7),. However the top 3rd are roughly in phase with each other (1,2 and 3). This creates a secondary maximum albeit much dimmer.

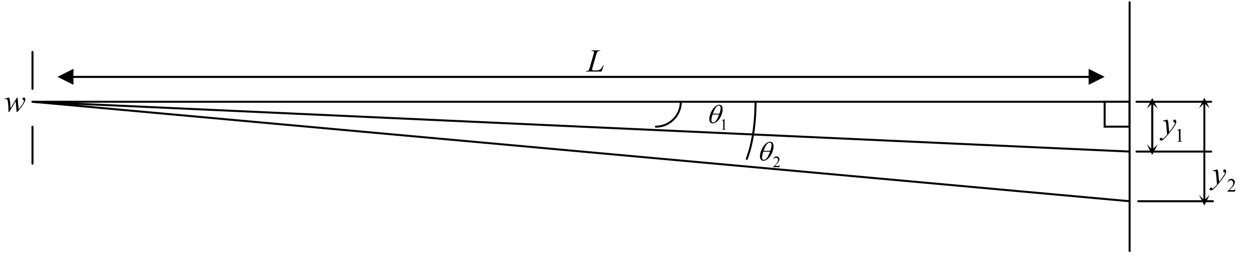


This pattern is identical to what occurs at our first minimum point (θ_1) with the exception that cancellation pattern occurs twice; once in each half of the slit. This creates a 2nd dark spot or minimum.

Dark regions occur at $\sin\theta = \frac{\lambda}{w}, \frac{2\lambda}{w}, \frac{3\lambda}{w}, etc.$, and bright regions occur at $\sin\theta = 0, \frac{3\lambda}{2w}, \frac{5\lambda}{2w}, etc.$



Therefore $\sin\theta_1 = \frac{\lambda}{w}$ is for the first minimum. By examining the geometry from the overhead perspective, we can derive the following.



Now $\tan\theta_1 = \frac{y_1}{L}$, however when $L >> y$, we can then approximate $\sin\theta = \tan\theta$. Therefore,

$$\boxed{n\lambda = \frac{wy_n}{L}}$$ for a minimum

To find the maximum we can use the following formula based on the above graph,

$$\boxed{\left(m + \tfrac{1}{2}\right)\lambda = \frac{wy_m}{L}}$$ for a maximum

Summary of equations

	nodes or minima	maxima
Double slit:	$\boxed{\left(n-\frac{1}{2}\right)\lambda=\frac{dx_n}{L}}$	$\boxed{m\lambda=\frac{dx_m}{L}}$
	$\boxed{\sin\theta_n=\frac{\left(n-\frac{1}{2}\right)\lambda}{d}=\frac{x_n}{L}}$	$\boxed{\sin\theta_m=\frac{m\lambda}{d}=\frac{x_m}{L}}$
Single slit:	$\boxed{n\lambda=\frac{wy_n}{L}}$	$\boxed{\left(m+\frac{1}{2}\right)\lambda=\frac{wy_m}{L}}$
	$\boxed{\sin\theta_n=\frac{n\lambda}{w}=\frac{y_n}{L}}$	$\boxed{\sin\theta_m=\frac{\left(m+\frac{1}{2}\right)\lambda}{w}=\frac{y_m}{L}}$

Diffraction Gratings

A diffraction grating is essentially the same as a double slit problem; but instead of a double slit, we are dealing with thousands of slits. The diffraction grating is essentially the same as the double slit equation. The equation of the maximum for a double slit problem is as follows

$$\boxed{\sin\theta_m=\frac{m\lambda}{d}=\frac{x_m}{L}}$$

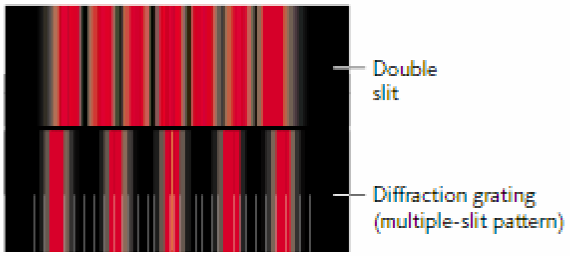


Fig.11.54 A multiple-slit pattern is sharper than a double-slit pattern

Therefore

$\boxed{m\lambda = d\sin\theta_m}$ but d is the distance the distance between consecutive slits.

For a diffraction grating, the distance between consecutive slits is defined by the following formula

$$\boxed{d=\frac{w}{N}}$$

Where d is the slit separation, w is the width of the diffraction grating, and N is the number of slits.

Note: d, w and λ must be in the same units.

Example 1:

What are the angular positions of the first-order maxima for violet light (450 nm) and red light (650 nm) when using a diffraction grating with 5400 slits over 2.8 cm?

Example 2:

Which maximum occurs closest to the central axis if the diffraction grating used has 12 678 lines in 2.40 cm: the second-order red (730 nm) maximum, the third-order violet (400 nm) maximum, or the second-order green (510 nm) maximum?