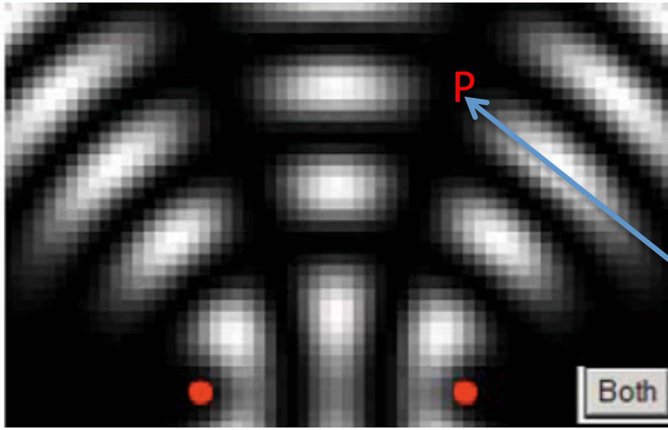
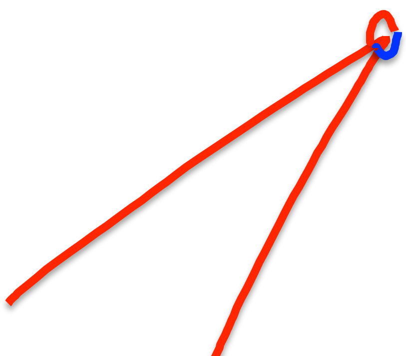


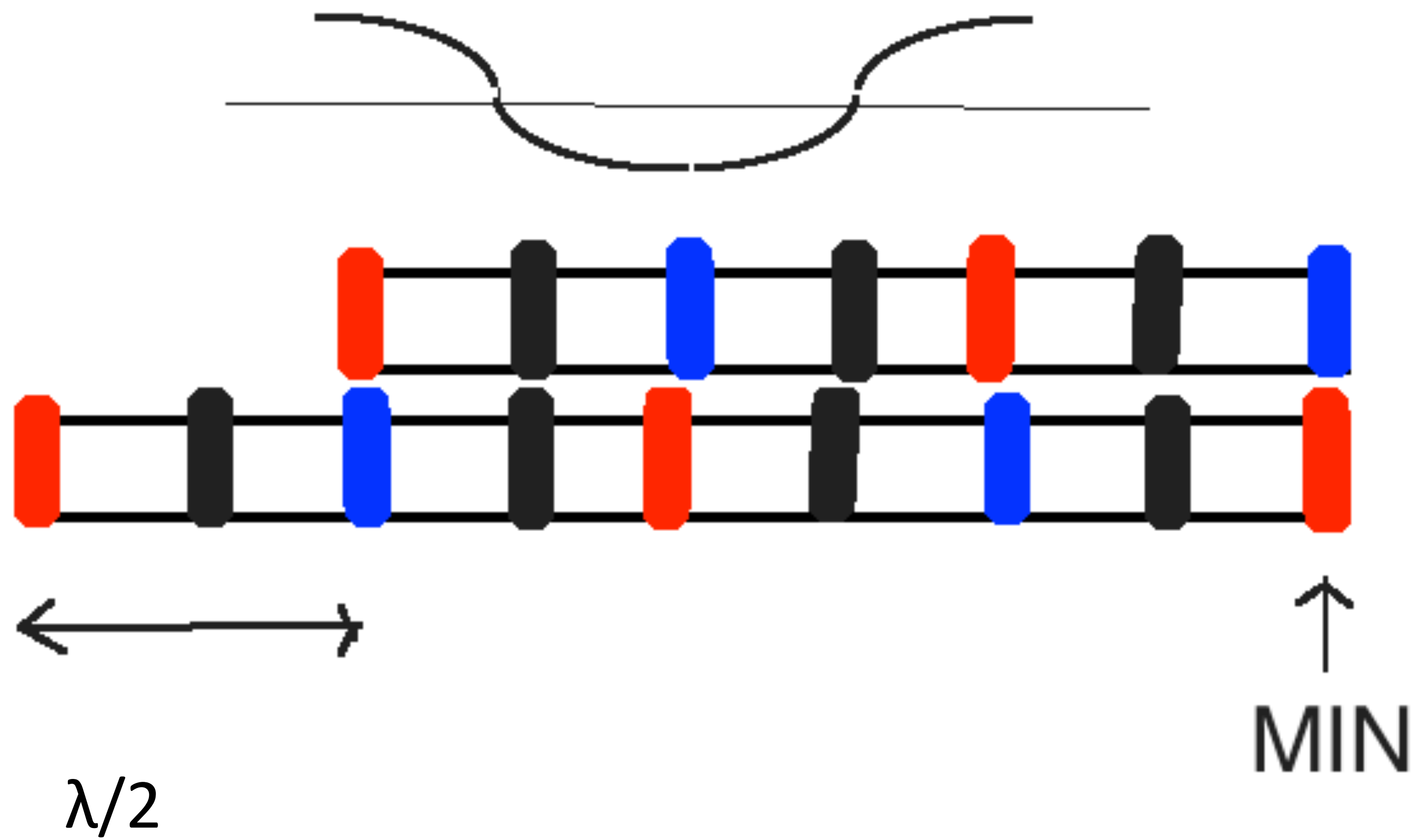


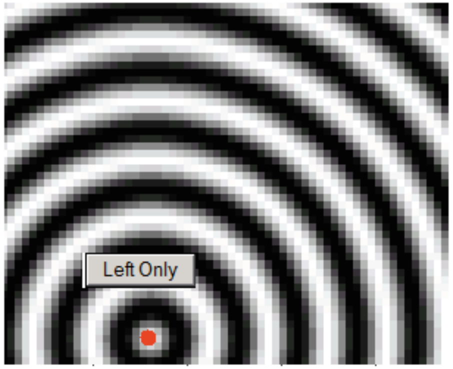
2-D standing wave!

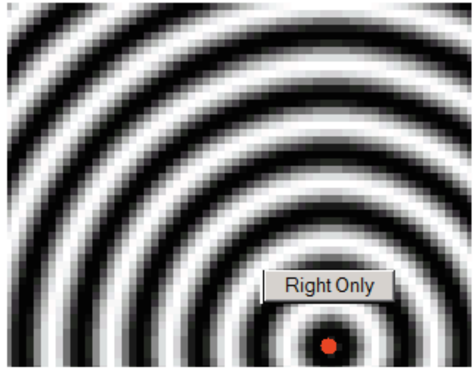
At point P we observe:

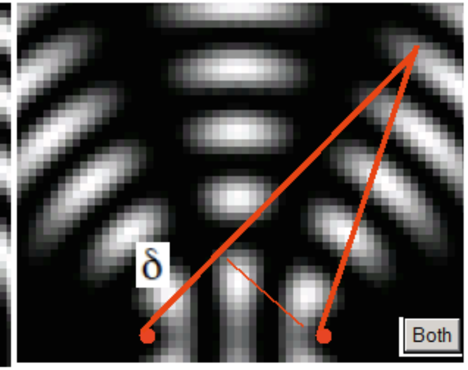
1. MAX (constructive int.)

2. MIN (destructive int.)


MIN
λ/2







2-D standing wave!

Conditions for interference

When waves come together they can interfere constructively or destructively. To set up a stable and clear interference pattern, two conditions must be met:

1. The sources of the waves must be ***coherent***, which means they emit identical waves with a constant phase difference.

2. The waves should be ***monochromatic*** - they should be of a single wavelength.

Let's say we have two sources sending out identical waves in phase. Whether constructive or destructive interference occurs at a point near the sources depends on the path-length difference, δ, which is the distance from the point to one source minus the distance from the point to the other source.

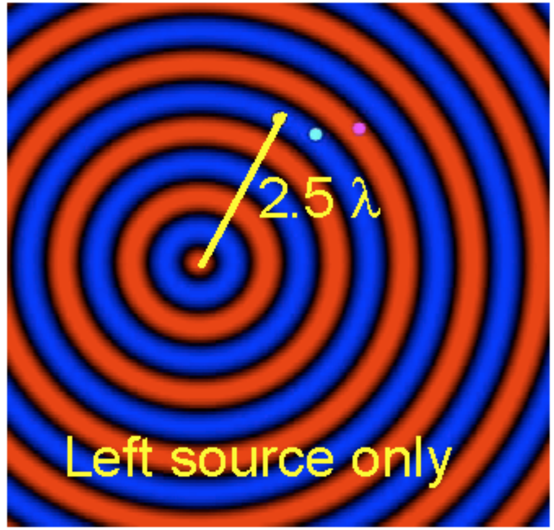
Condition for constructive interference: $\delta = m\lambda$, where m is any integer.
m = 0, 1, 2, 3, 4

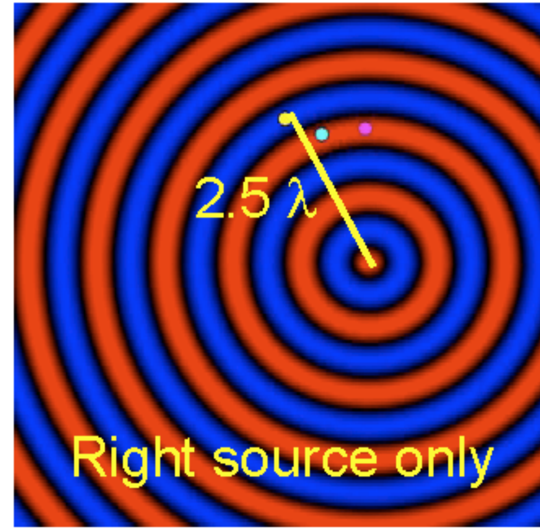
Condition for destructive interference: $\delta = (m - 1/2)\lambda$
m = 1, 2, 3, 4

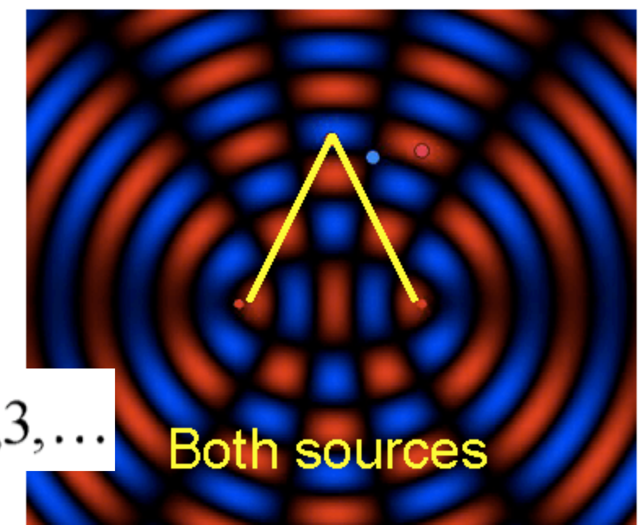
$\delta = \Delta r = |r_1 - r_2| > 0$ - **path length difference**

Understanding the interference pattern

At any point on the perpendicular bisector to the line joining the sources (like the yellow point) we get constructive interference – the path-length difference is zero.





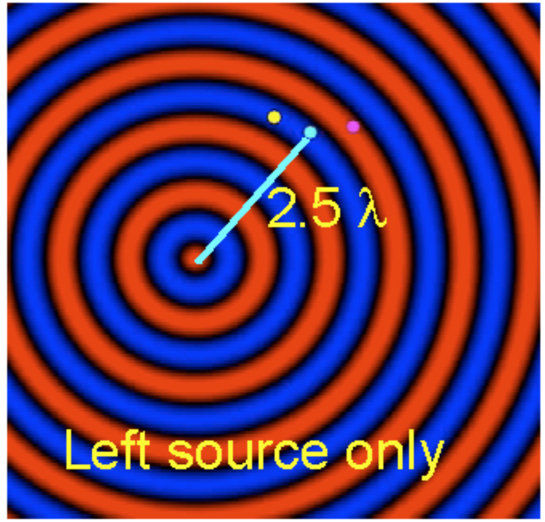


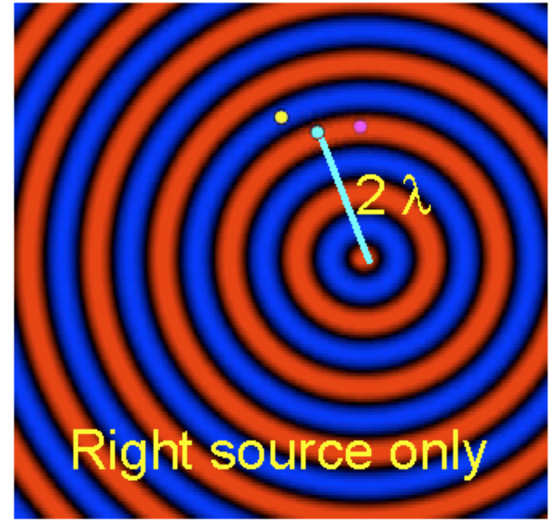
$$|\ell_2 - \ell_1| = m\lambda \qquad m = 0,1,2,3,\ldots$$

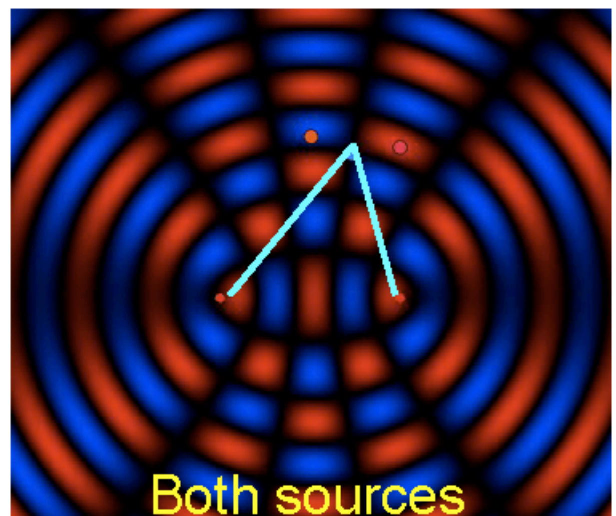
2-D standing wave!

Understanding the interference pattern

The blue point is half a wavelength farther from the left source than from the right source – giving destructive interference at that point.







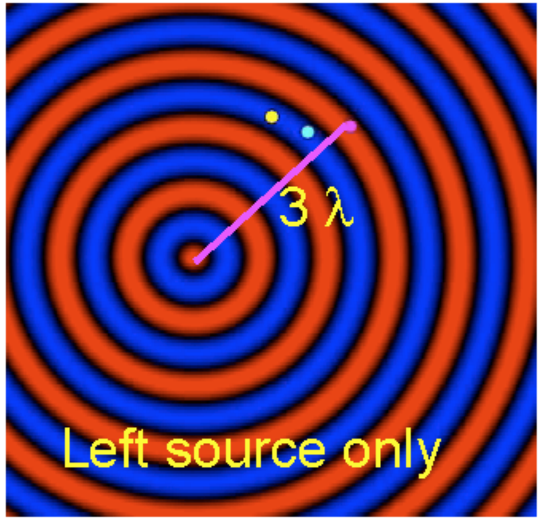
$$\left|\ell_2 - \ell_1\right| = \left(m - \tfrac{1}{2}\right)\lambda$$

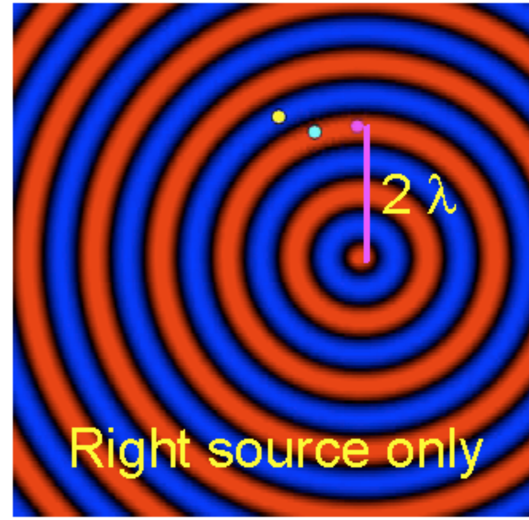
$$m = 1,2,3,\ldots$$

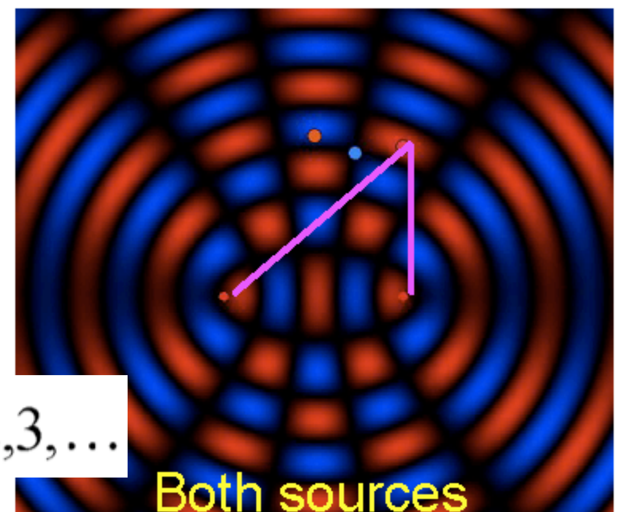
2-D standing wave!

Understanding the interference pattern

The purple point is a full wavelength farther from the left source than from the right source – giving constructive interference at that point.

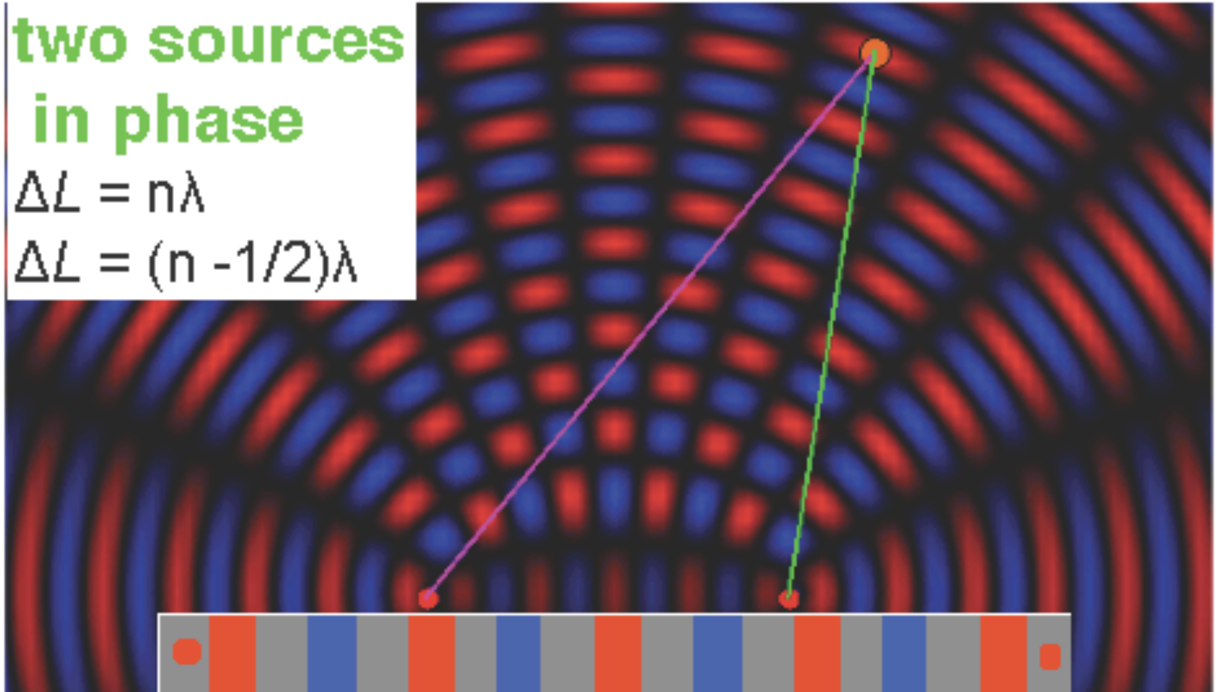






$$|\ell_2 - \ell_1| = m\lambda \qquad m = 0,1,2,3,\ldots$$

2-D standing wave!

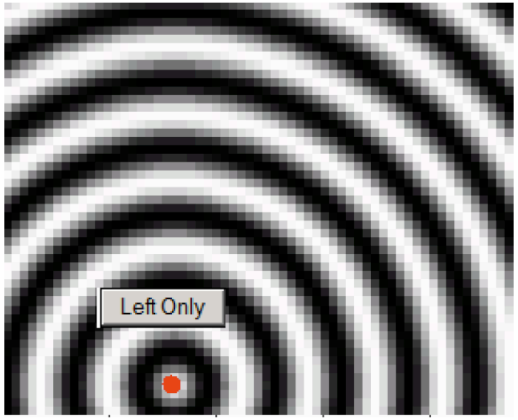


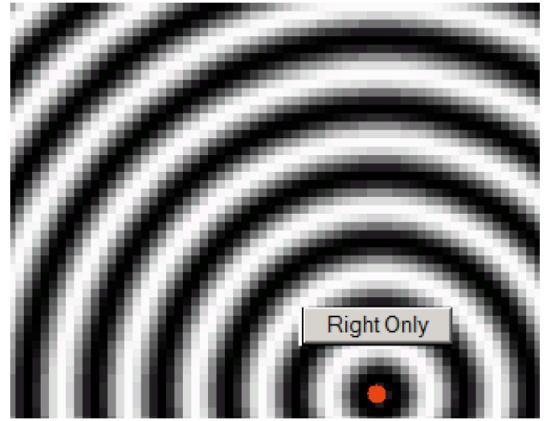
**In space:
2-D
standing
wave!**

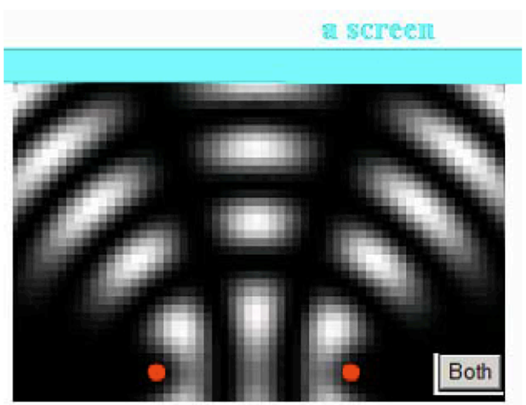
**Between the sources:
1-D
standing
wave!**

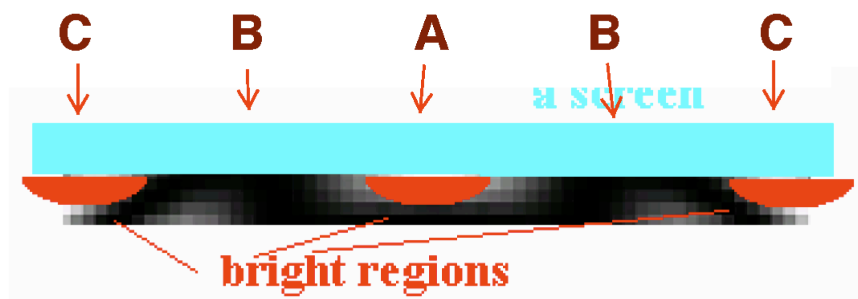
The enlarged picture of the pattern between the sources.
Can we draw a transversal representation for this pattern?

Understanding the interference pattern









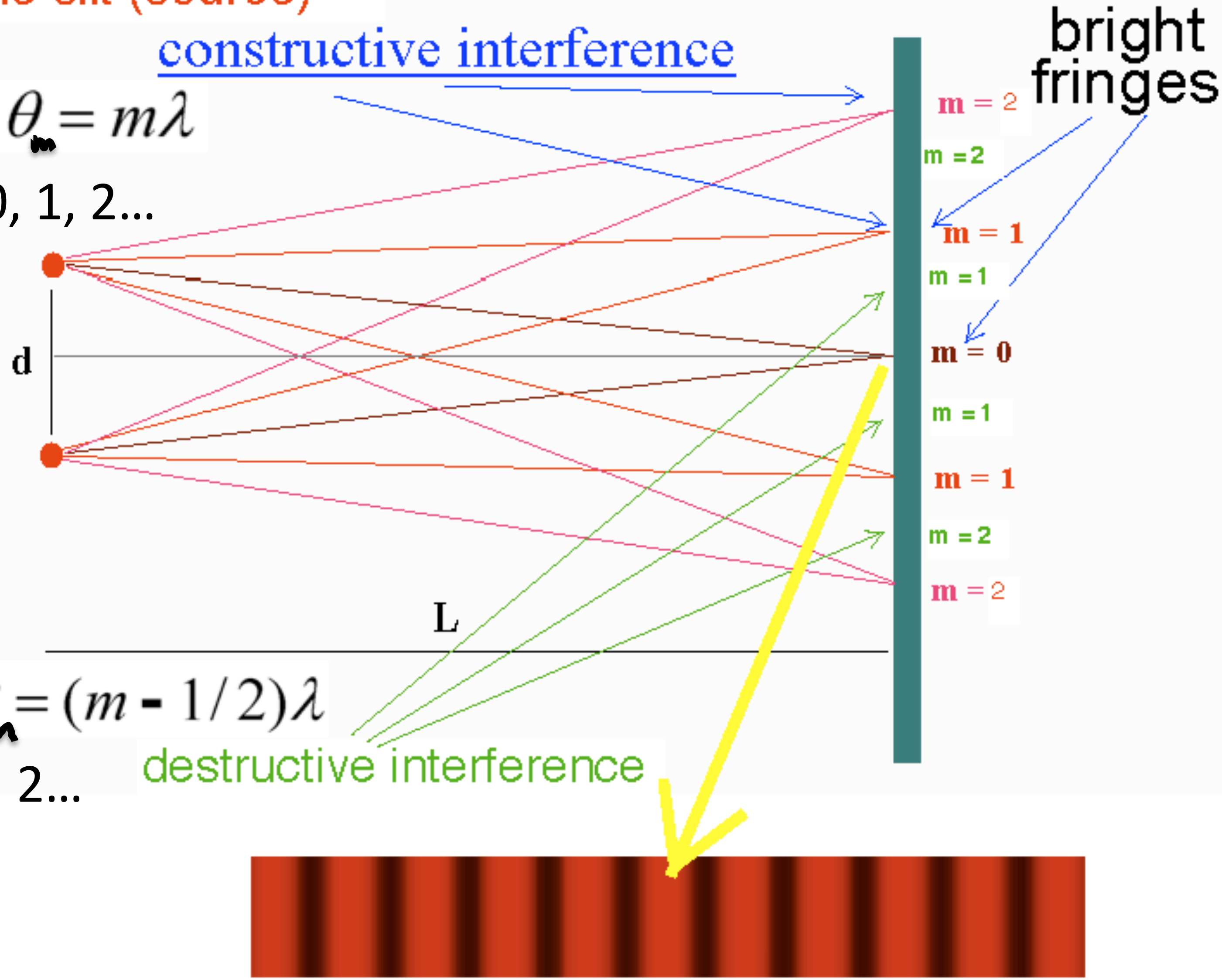
MIN = no light!

MAX = bright fringe (spot)

Double slit (source)

$$d \sin \theta_m = m\lambda$$

m = 0, 1, 2...

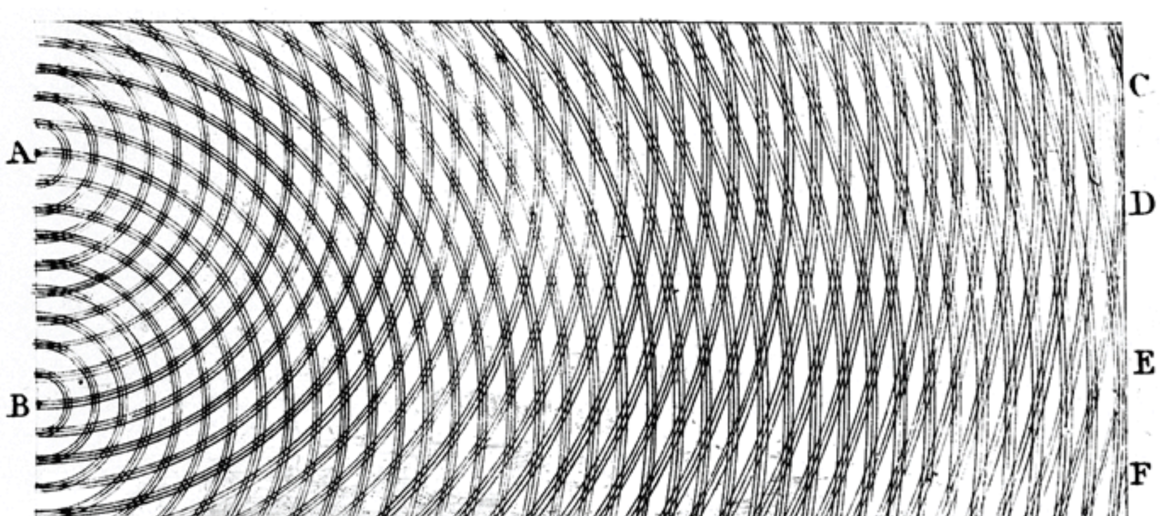


$$d \sin \theta_m = (m - 1/2)\lambda$$

m = 1, 2...

The nature of light

In 1801, Thomas Young carried out a famous experiment (Young's double slit) that showed very clearly that light acted as a wave.



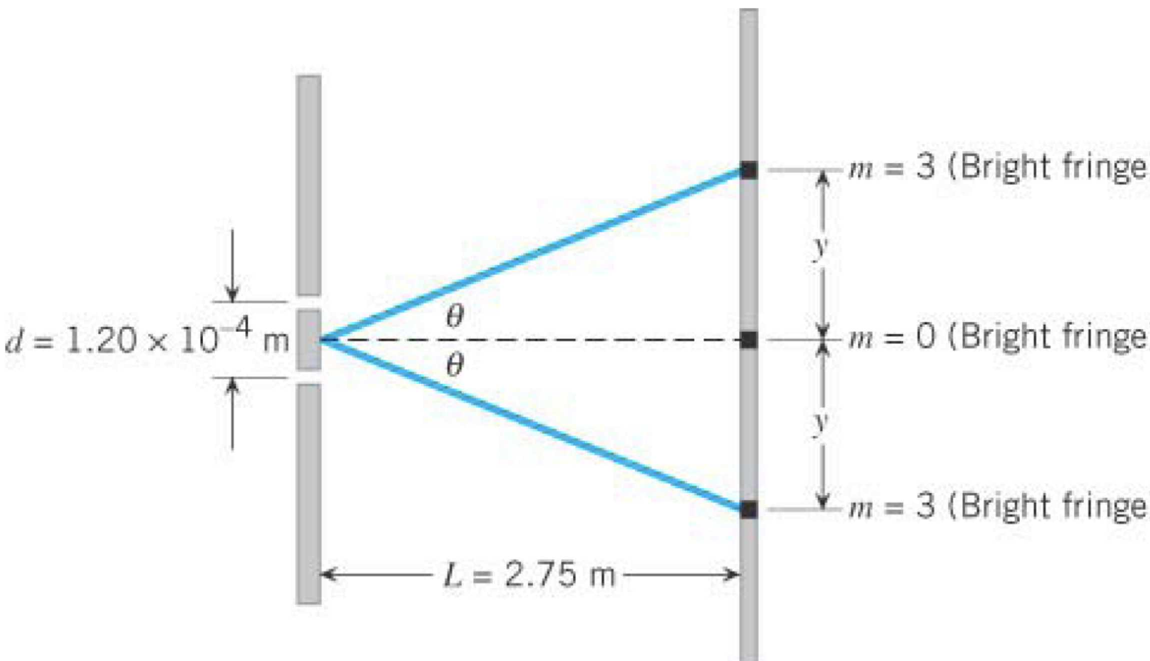
Thomas Young's own diagram of double-slit interference. *Diagram from Wikipedia.*

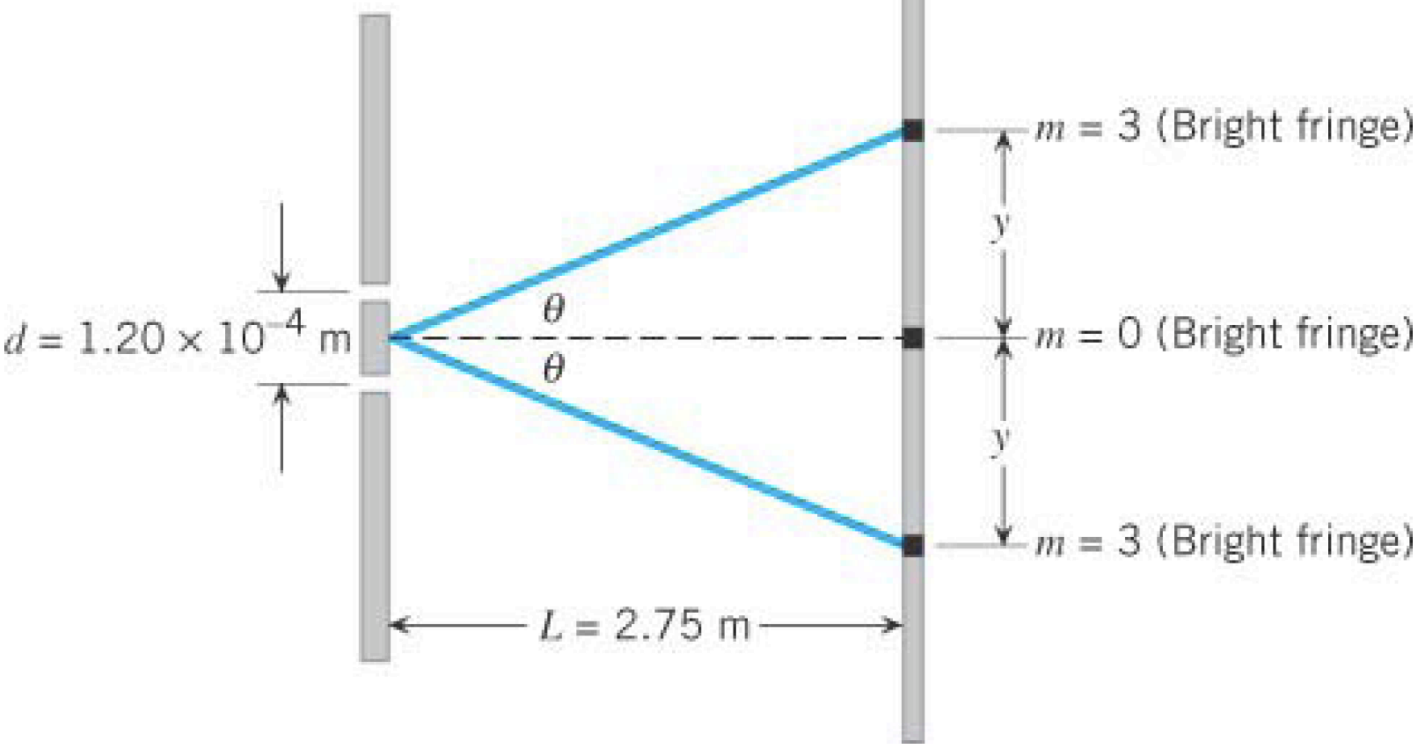
Young's Double-Slit Experiment

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

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.

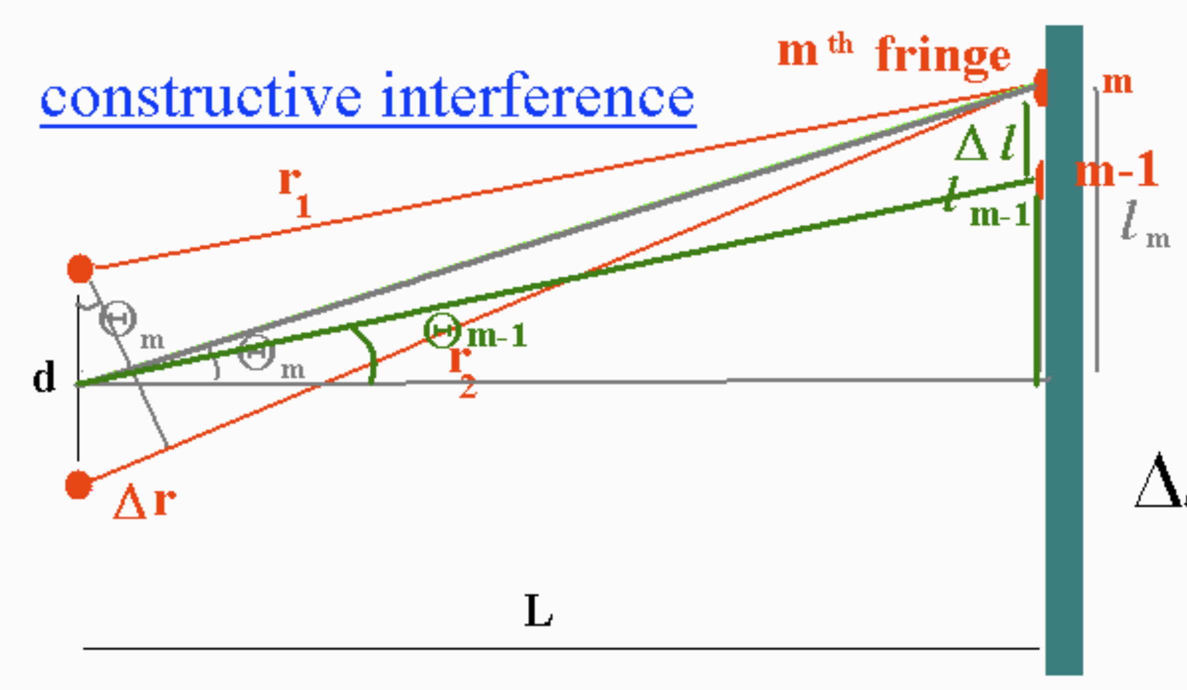
Find the distance on the screen between the central bright fringe and the third-order bright fringe.





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

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



The distance between two nearest fringes is:

$$\Delta l = l_m - l_{m-1}$$

$$m\lambda = \mathrm{d}\sin\theta_m$$

$$\frac{l_m}{L} = \tan\theta_m$$

For small angles (meaning, small m)

$$\sin\theta_m \approx \tan\theta_m \approx \theta_m$$

(When measured in radians)

$$\Rightarrow \quad \Delta l \approx L(\theta_m - \theta_{m-1}) = L\left(\frac{m\lambda}{d} - \frac{(m-1)\lambda}{d}\right) = \frac{L\lambda}{d}$$

Changing the wavelength

If the wavelength is *decreased*, what happens to the lines of constructive and destructive interference in the pattern?

1. They get farther apart
2. They get closer together
3. They stay the same

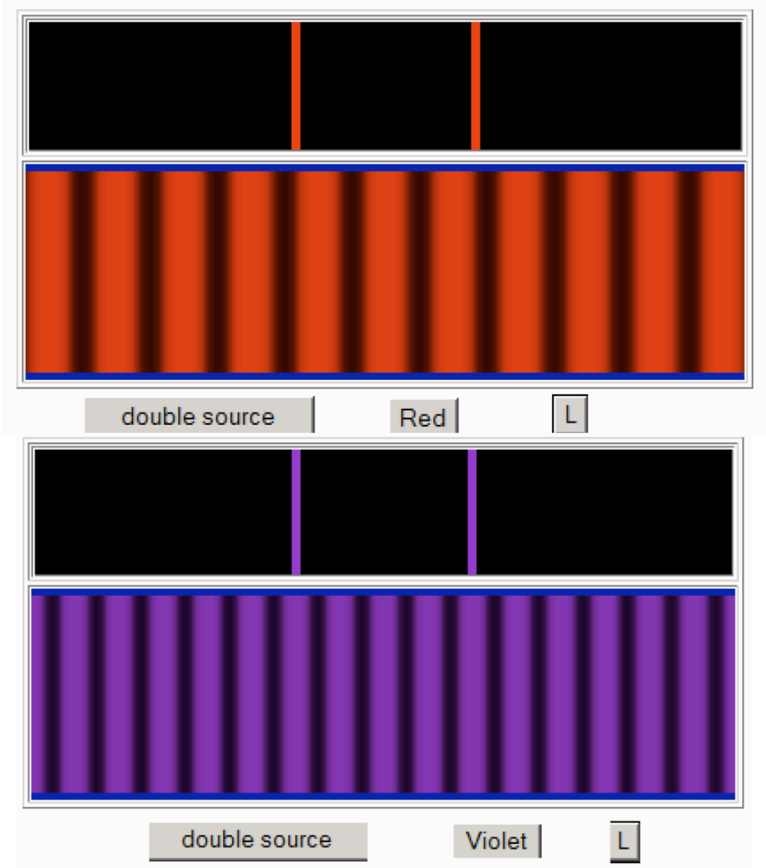
$$\sin\theta = \frac{m\lambda}{d}$$

The screen with the fringes making a pattern

Changing the wavelength

$$\Delta l = \frac{L\lambda}{d}$$

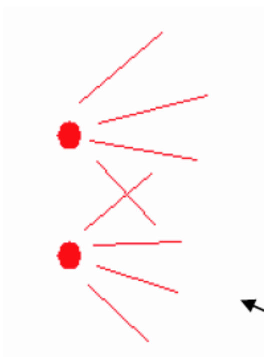
$$\sin\theta = \frac{m\lambda}{d}$$

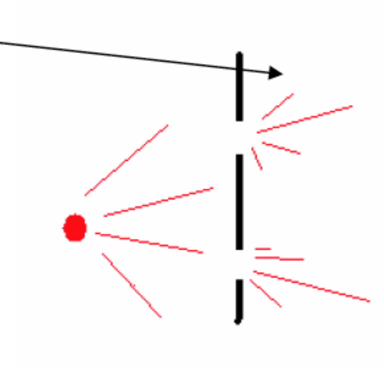


Decreasing the wavelength decreases the *angles* at which constructive and destructive interference happens, and decreases the distance between the fringes, so the lines in the pattern get closer together.

The double slit vs. two sources

The double slit creates the same pattern as the double source pattern, but the intensity gradually decreases to the edges of the screen.

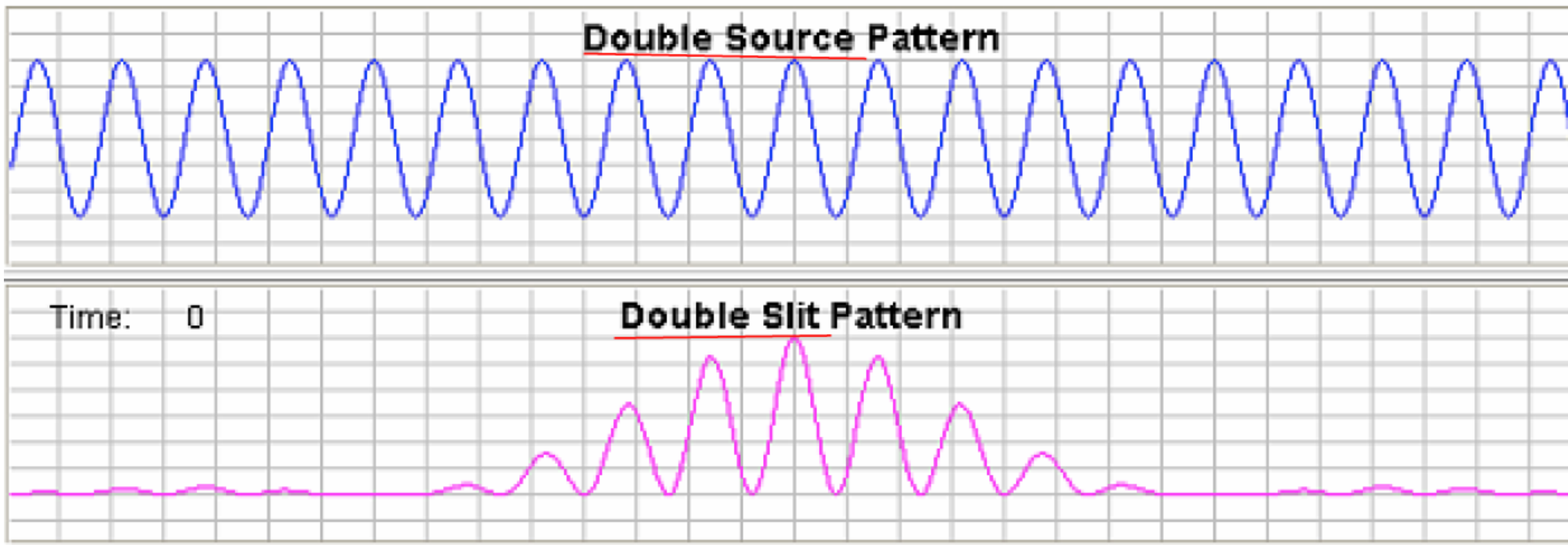




If each slit sent out light *uniformly in all directions (as each source does)*, the peaks in the pattern would be equally bright, as in the “Double Source” picture.

The double slit

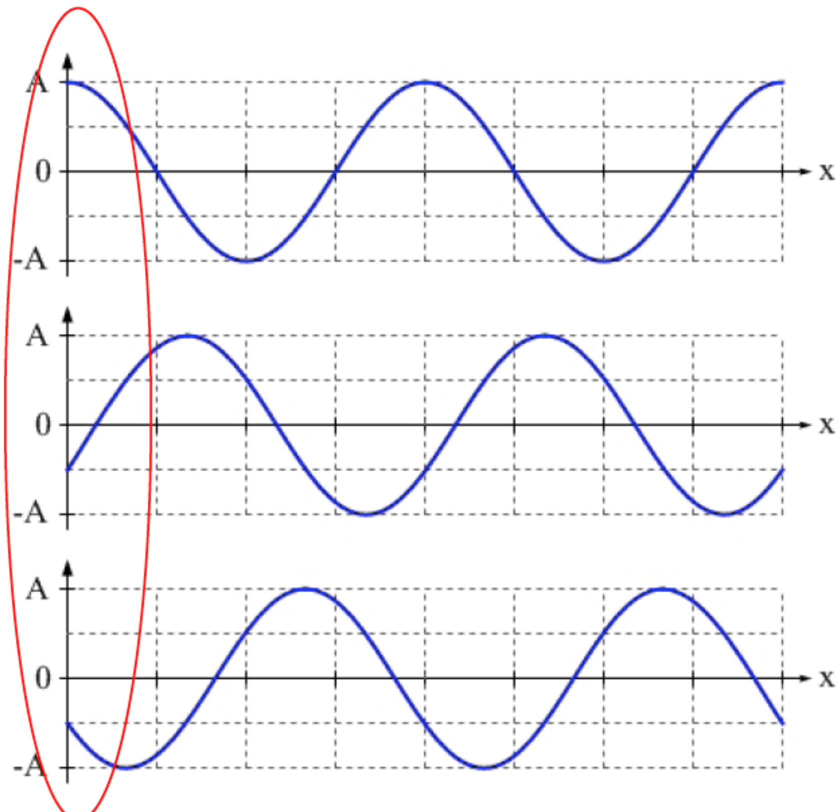
The double slit creates the same pattern as the double source pattern, but the intensity gradually decreases to the edges of the screen.



If each slit sent out light *uniformly in all directions*, the peaks in the pattern would be equally bright, as in the “Double Source” picture.

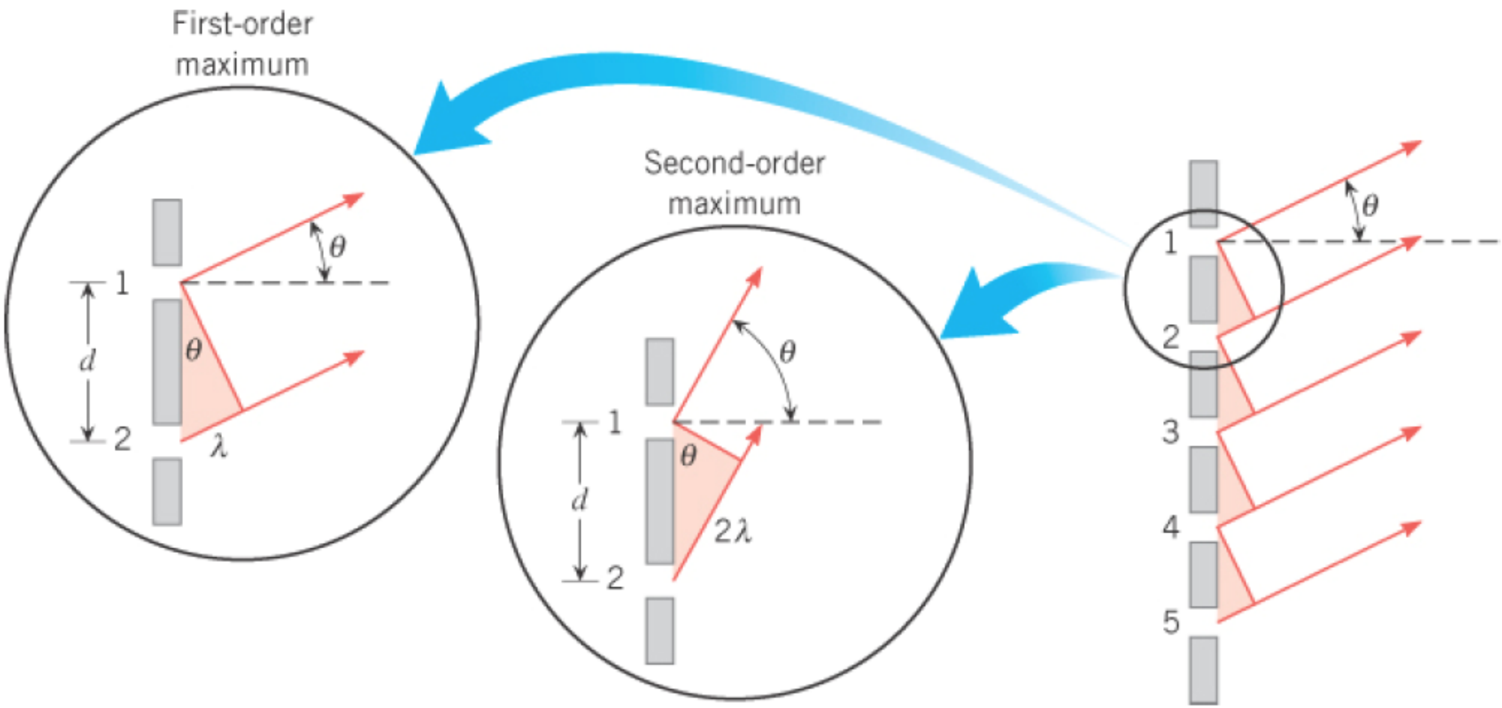
Adding sources

To get *three* waves to cancel, the path-length difference is one-third or two-thirds of a wavelength, not half a wavelength.



a regular minima condition does not work any more!

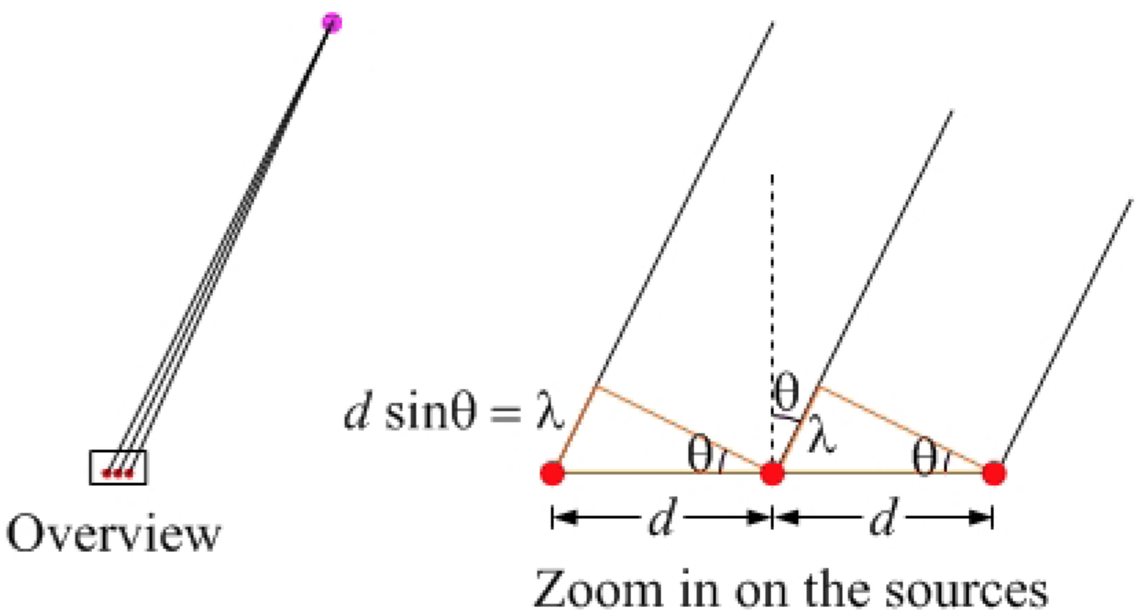
~~$d \sin\theta = (m - 1/2)\lambda$~~



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

Adding sources

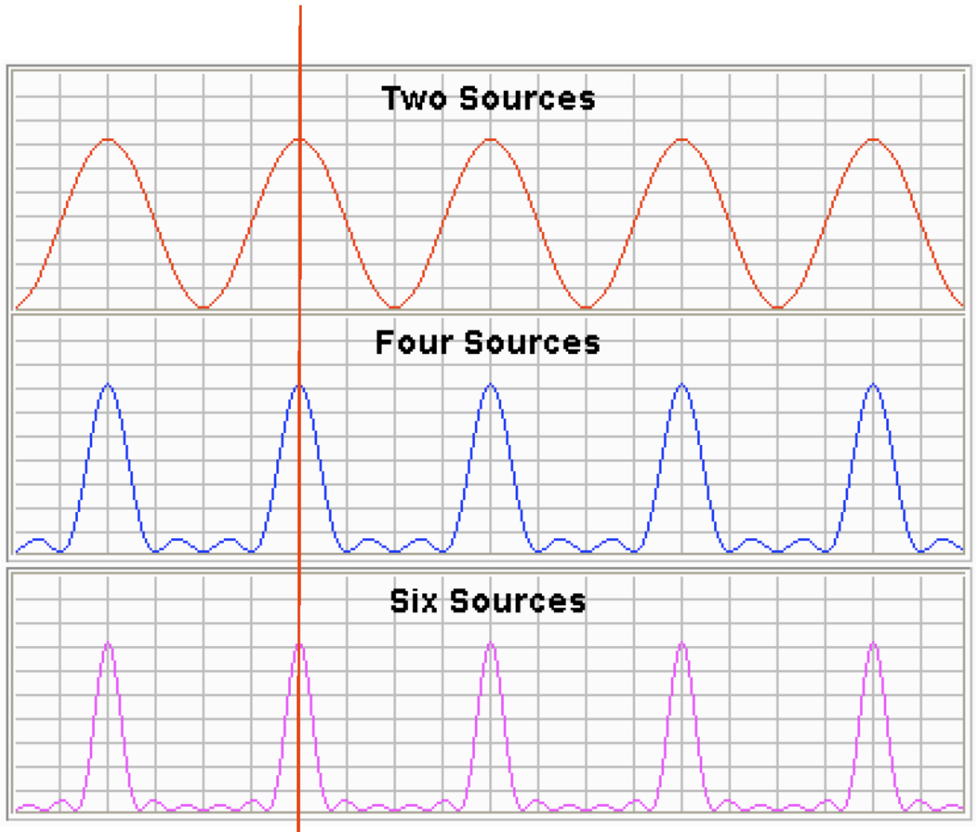
the constructive interference equation ***applies for any number of sources separated by a distance d*** : $d \sin(\theta) = m\lambda$. We're are simply adding more waves in phase instead of two (for N sources we'd add N waves in phase).

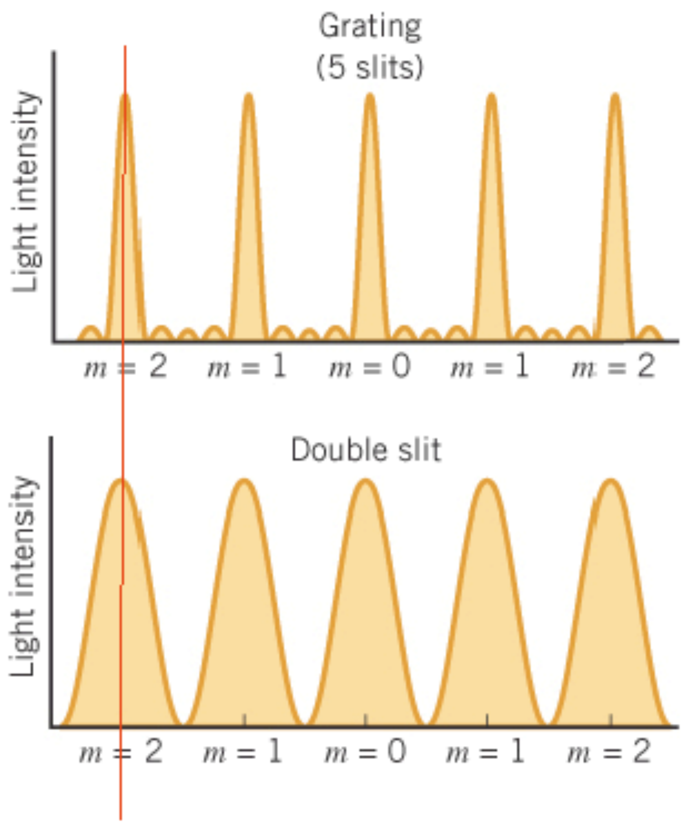


Adding slits or sources

For light, adding sources really means adding slits (openings) for the laser light to pass through – each slit acts as a source.

By adding more slits, the interference maxima are much brighter, and a lot sharper but at the same locations!





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

Principal maxima of a diffraction grating

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

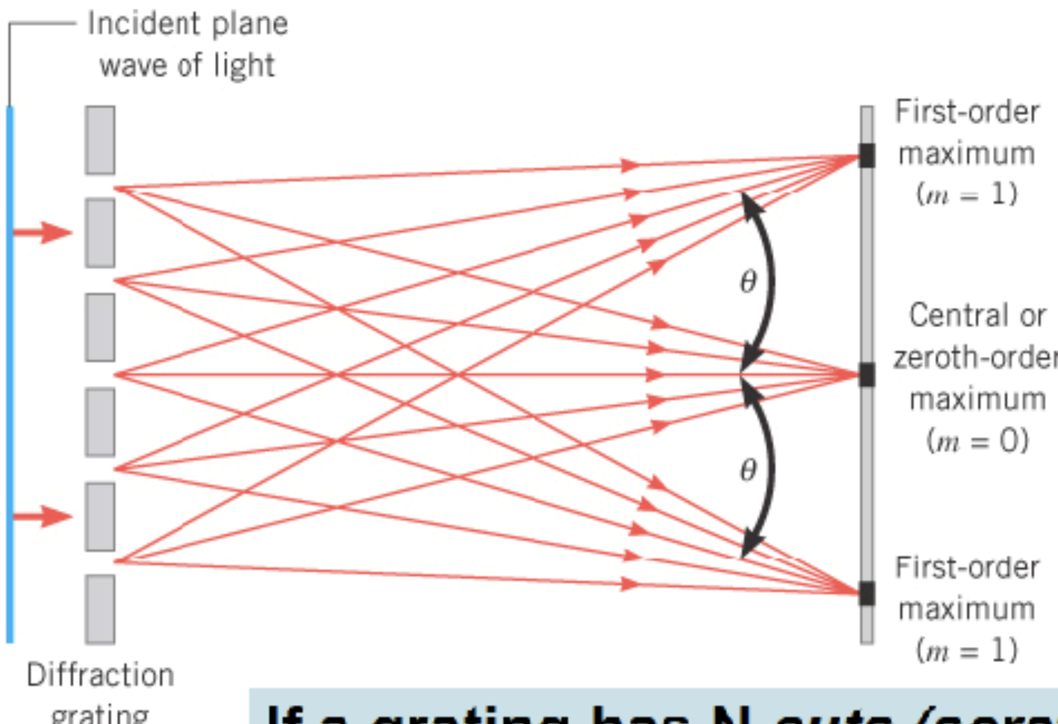
distance between slits

Maxima have the same locations!
Minima gradually disappear

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

A regular minima condition does not work any more!

But it still works for maxima!



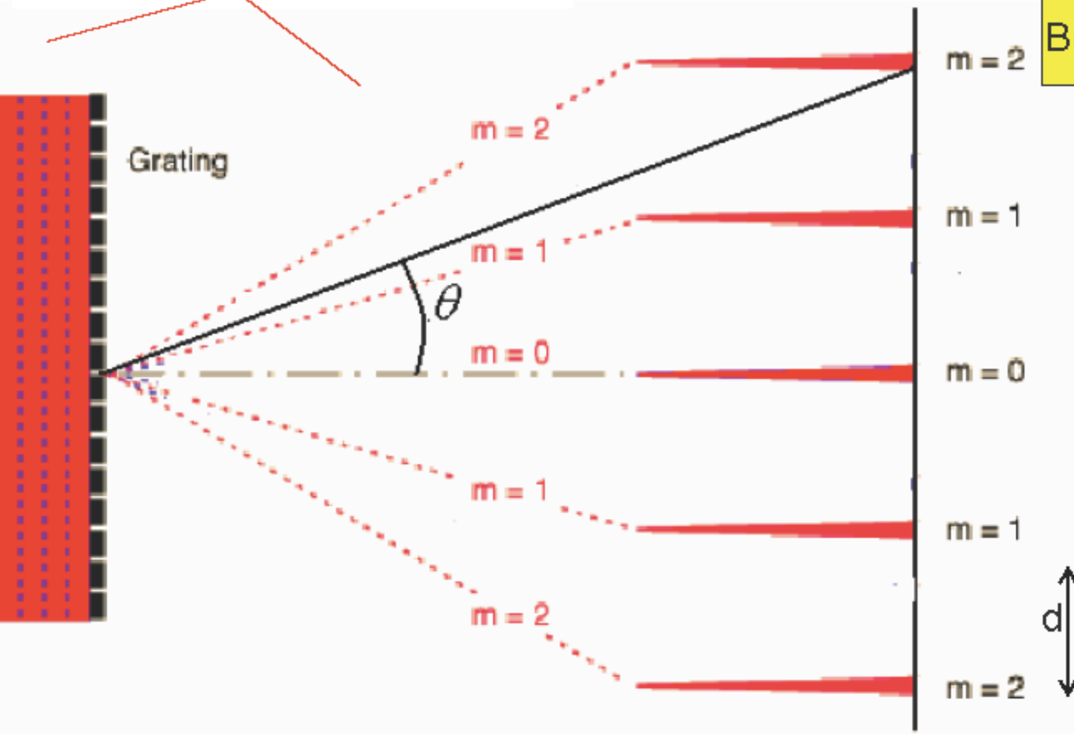
If a grating has N *cuts (scratches)* *per a meter*, so d = 1/N

~~$\sin\theta = (m - \frac{1}{2})\frac{\lambda}{d}$ $m = 1, 2, 3, 4,$~~

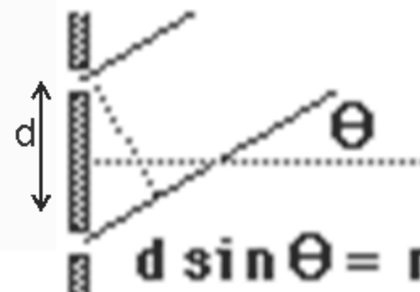
A grating

A regular minima condition does not work any more!

But it still works for maxima!



Maxima condition ONLY!

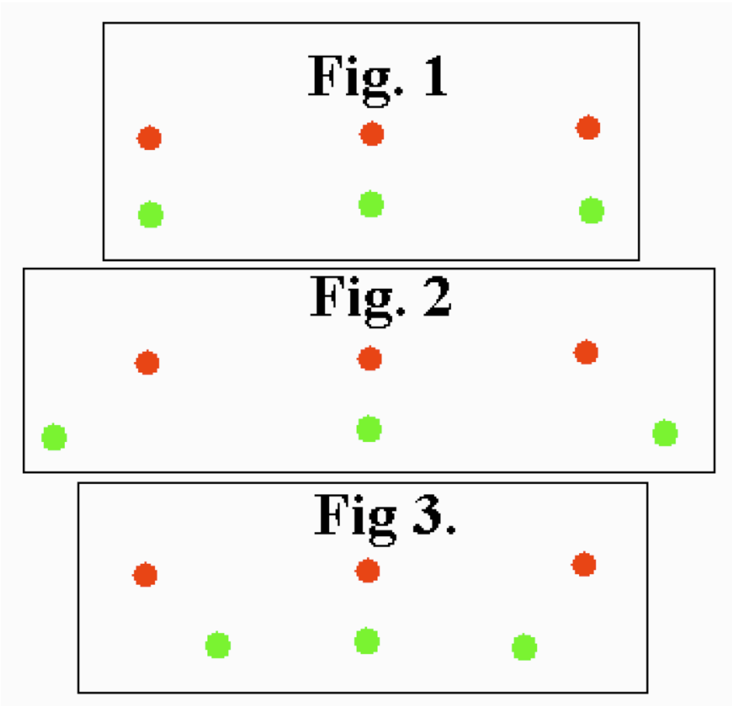


$$d \sin\Theta = m\lambda$$

Θ is NOT small!

d is grating spacing

the number of slits per unit length = 1/d

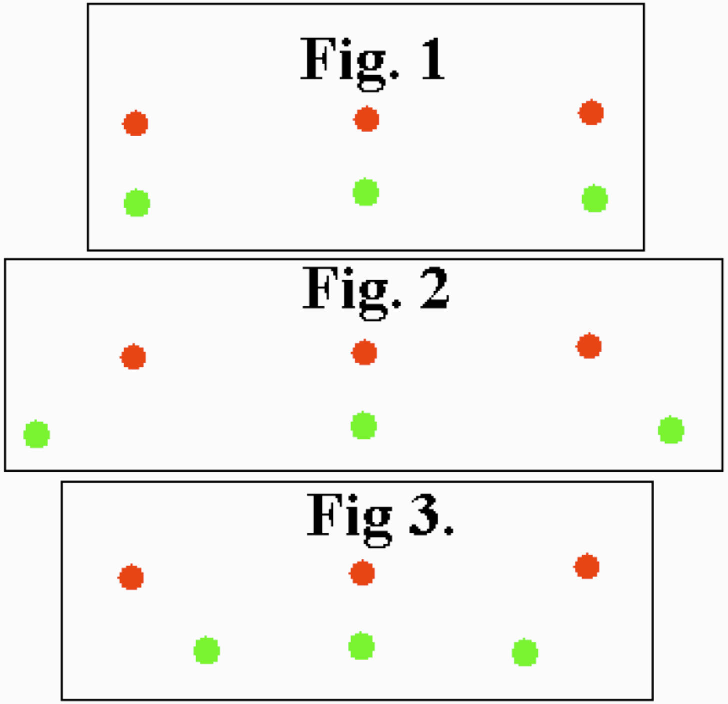


Red and green lasers are shining at the diffraction grating.

Which of the figures on the left is correct?

1. 1
2. 2
3. 3

$$\sin\theta = m\frac{\lambda}{d}$$

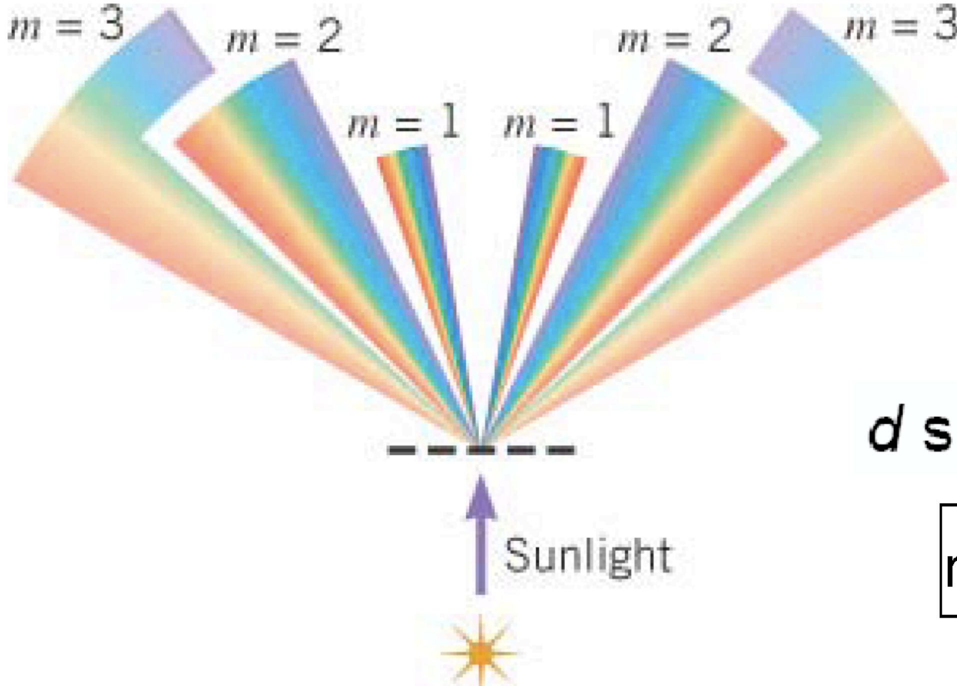


Red and green lasers are shining at the diffraction grating.

Which of the figures on the left are correct?

1. 1
2. 2
3. 3

for maxima: $d \cdot \sin\theta = m\lambda$; $\lambda \uparrow \Rightarrow \theta \uparrow$



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

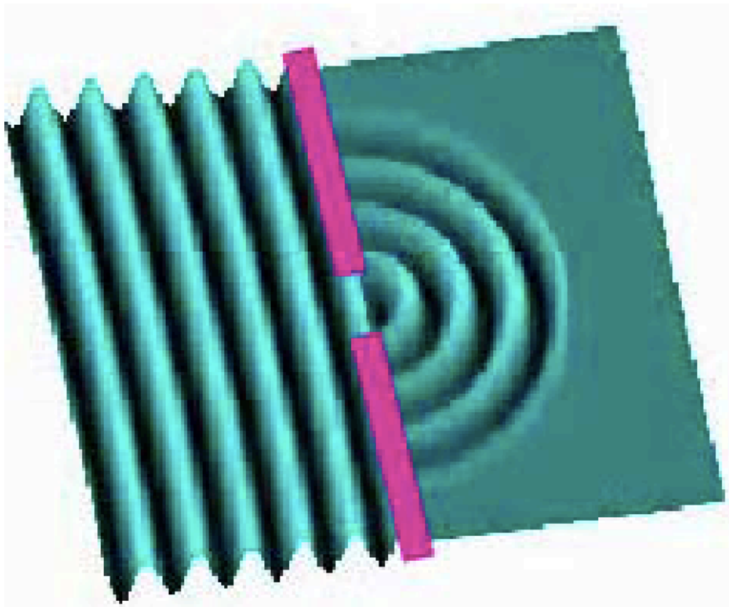
m = 1

$$\theta = \sin^{-1}\left(\frac{\lambda_{\text{violet}}}{d}\right) = \sin^{-1}\left(\frac{410\times10^{-9}\,\text{m}}{1.0\times10^{-6}\,\text{m}}\right) = 24^{\circ}$$

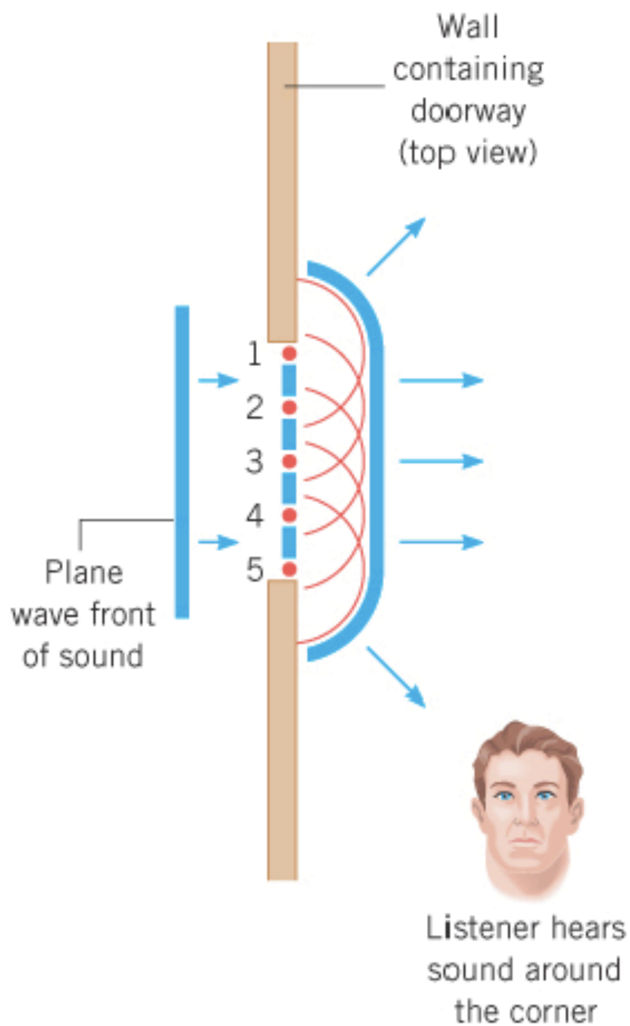
$$\theta = \sin^{-1}\left(\frac{\lambda_{\text{red}}}{d}\right) = \sin^{-1}\left(\frac{660\times10^{-9}\,\text{m}}{1.0\times10^{-6}\,\text{m}}\right) = 41^{\circ}$$

Diffraction is an ability of light

to bend around edges.



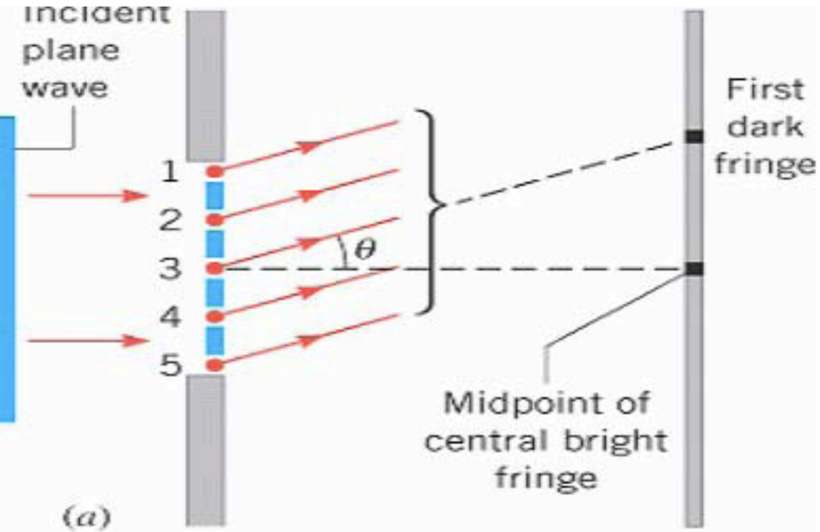
Diffraction is the spreading out of a wave when it encounters a single object or opening.

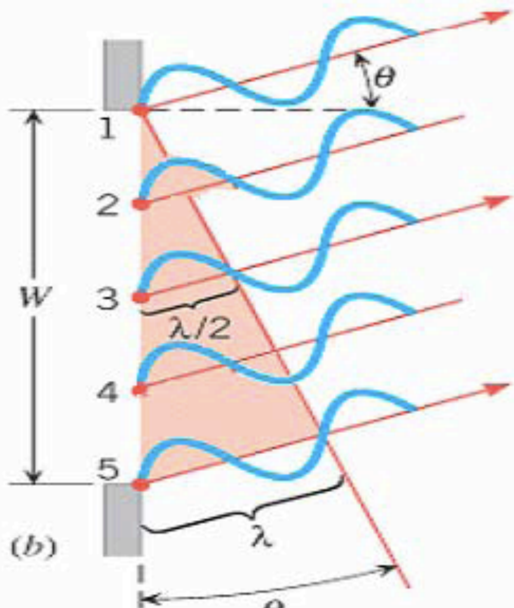


Diffraction is the bending of waves around obstacles or the edges of an opening.

<u>Huygens' principle</u>

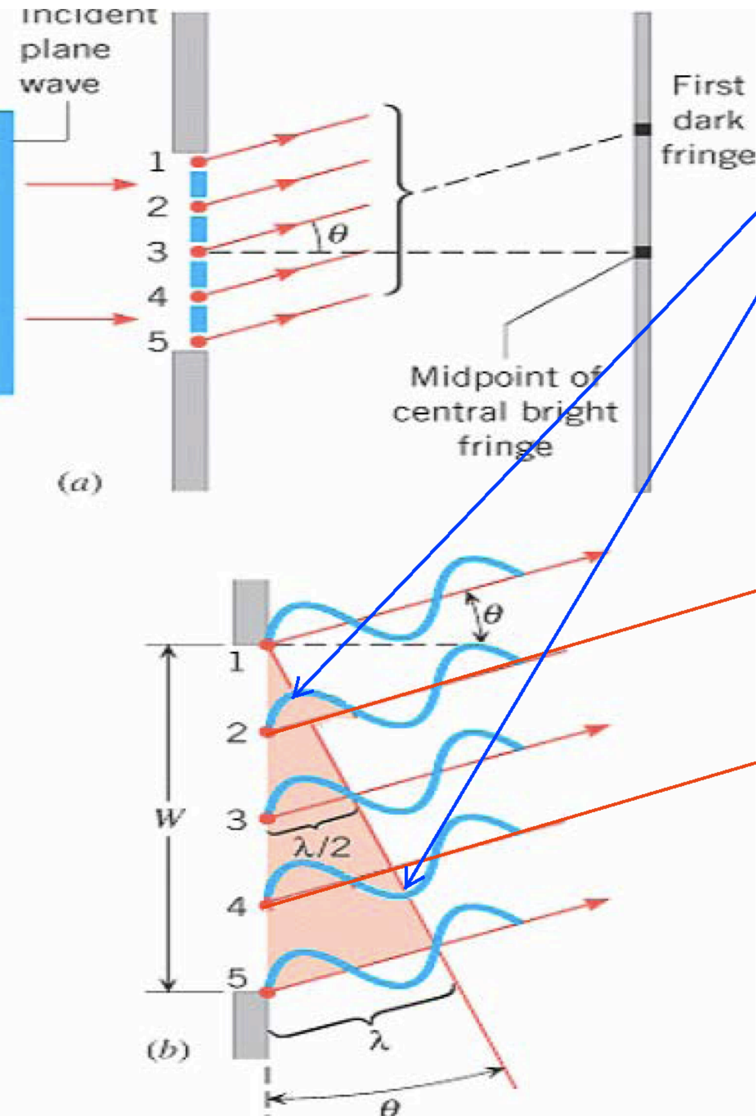
Every point on a wave front acts as a source of tiny wavelets that move forward with the same speed as the wave; the wave front at a latter instant is the surface that is tangent to the wavelets.





Beams 1 and 5 are in phase, but have an intensity of a half of the beam 3, which cancels them out.

Beams 1 and 3 are completely out of phase, so do beams 2 and 4, or *any two beams starting from the points separated by* ½w!



Out of phase!!

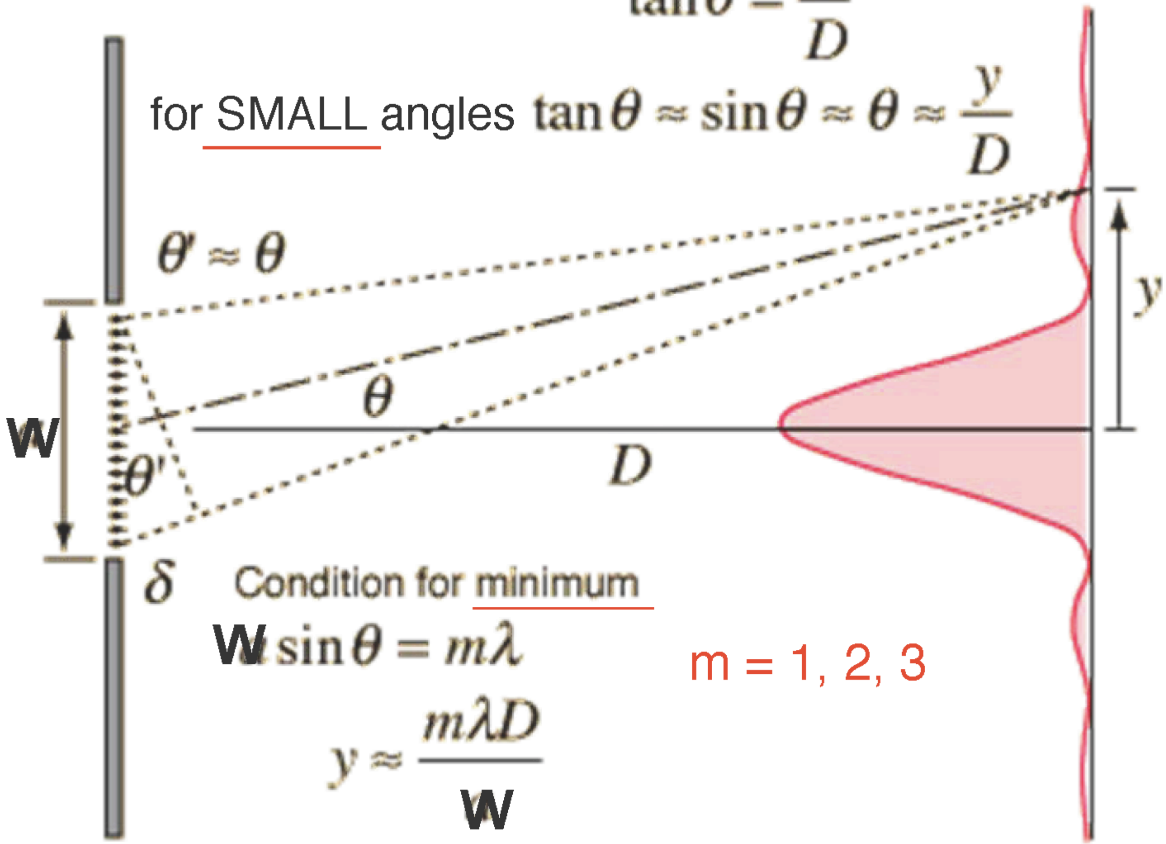
These drawings show how **destructive interference** leads to the first dark fringe on either side of the central bright fringe.

$$w \sin\theta = m\lambda \qquad m = 1, 2, 3, \ldots$$

A single slit

$$\tan\theta = \frac{y}{D}$$

for SMALL angles $\tan\theta \approx \sin\theta \approx \theta \approx \frac{y}{D}$

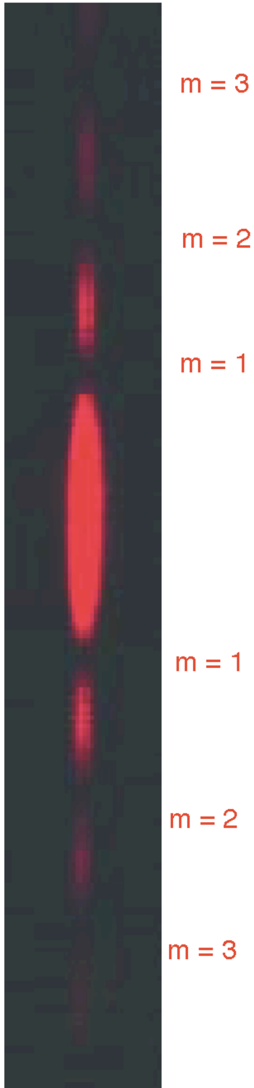


Condition for minimum

$$W \sin\theta = m\lambda$$

m = 1, 2, 3

$$y \approx \frac{m\lambda D}{W}$$



$\frac{y}{D}$ =tan(Θ) ~ Θ (in rad; for small angles)

$$\boxed{w \sin\theta = m\lambda} \qquad m = \underline{1}, 2, 3, \ldots$$

Light of wavelength 632 nm illuminates a single slit of width 0.1 mm.

What is the width of the central maximum formed on a screen placed 2 m beyond the slit?

$\frac{y}{D}$ =tan(Θ) ~ Θ (in rad; for small angles)

$$w \sin\theta = m\lambda \qquad m = 1, 2, 3, \ldots$$

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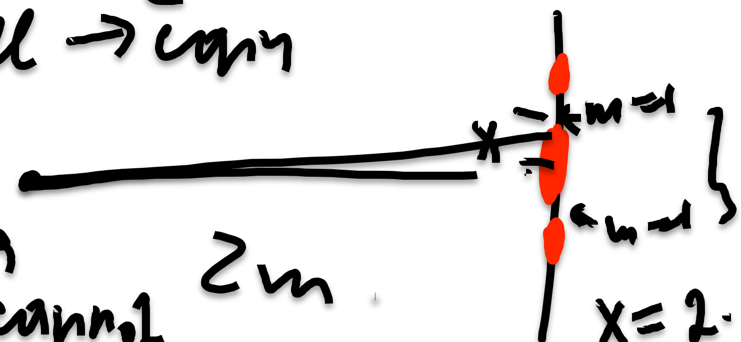

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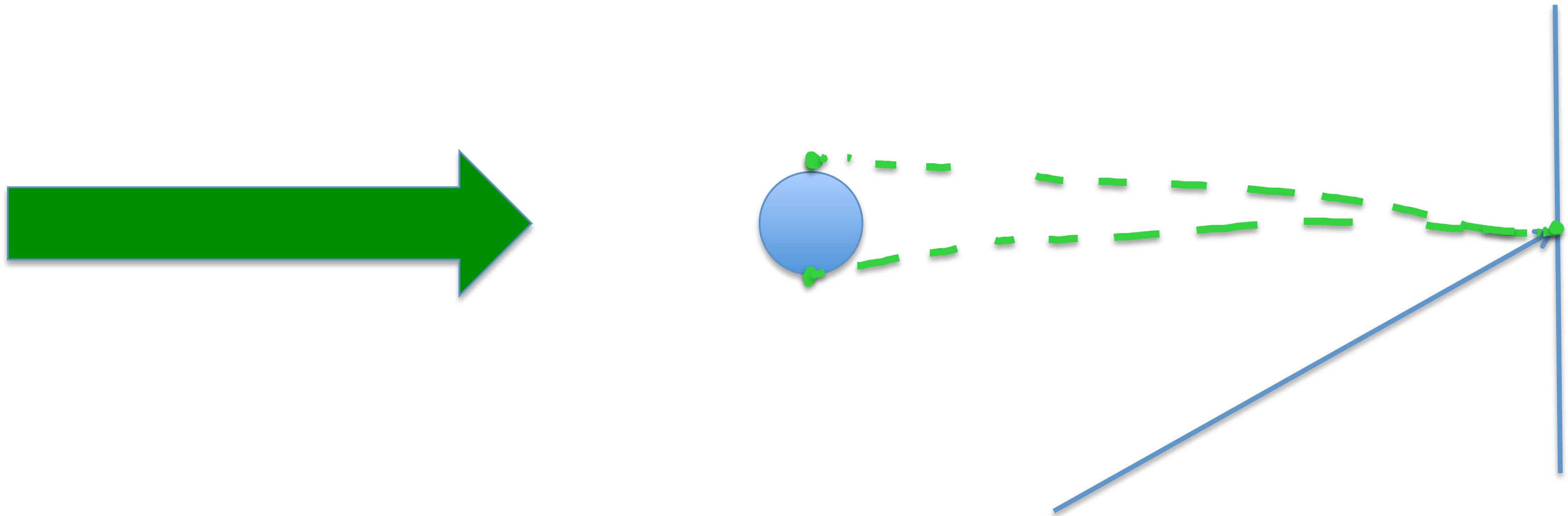
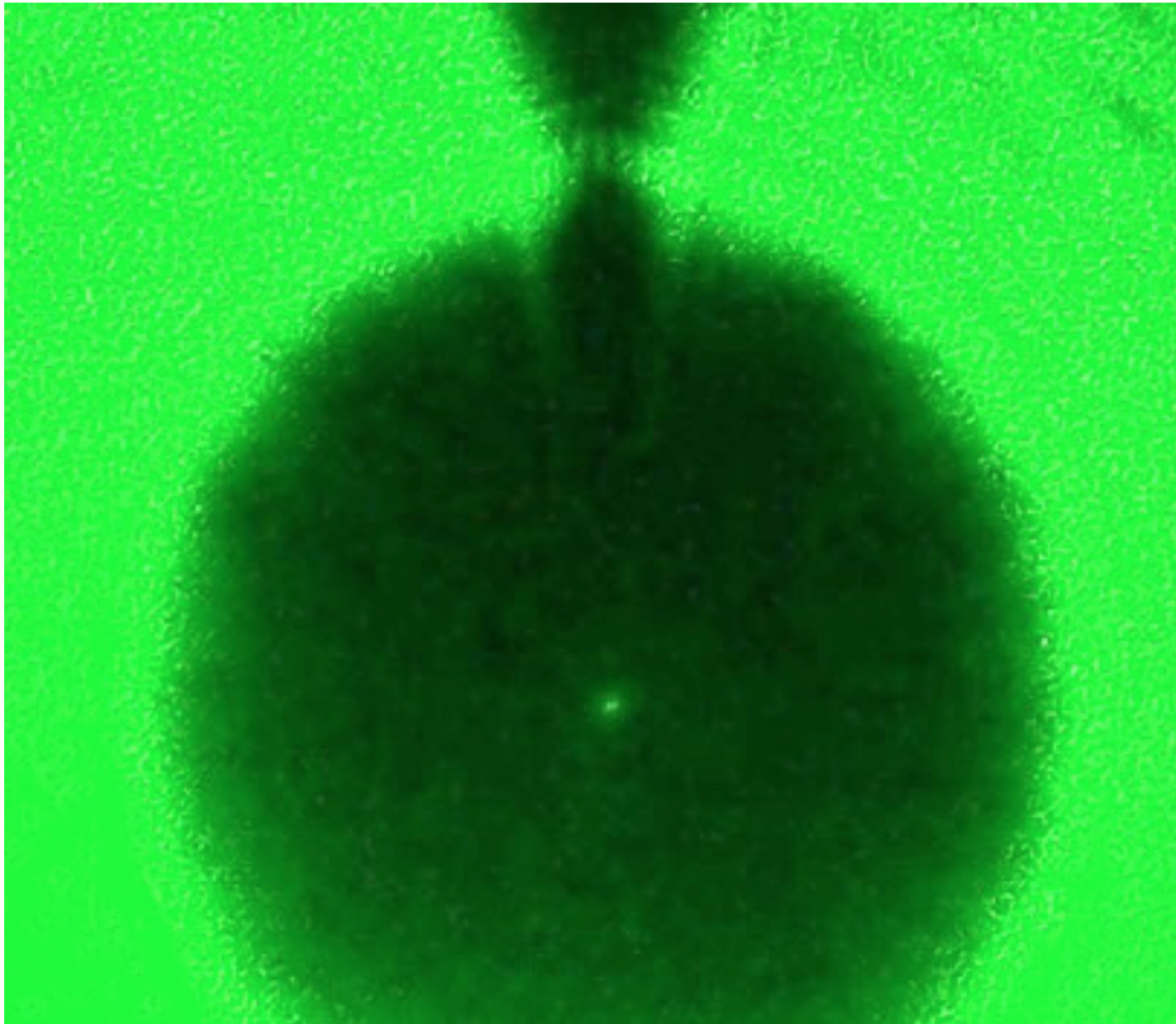


A beam of a green light generated by a laser pointer impinges upon small metal ball. What will we see in the middle of the shadow?

1. Nothing 2. A green dot 3. ??

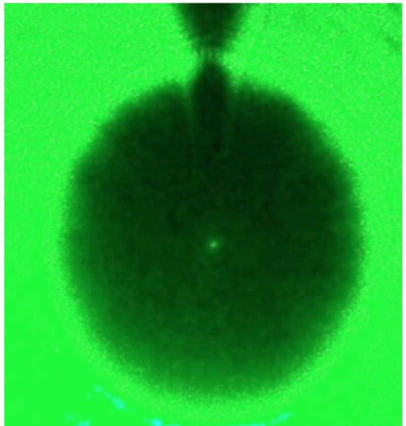
The bright spot at the center



A bit of history

The French scientist Augustin Fresnel presented his work on diffraction to the French Academy in 1818. Siméon Poisson, who did not believe the wave theory, was there. Poisson realized that, if the wave theory was correct, there should be a bright spot at the center of the shadow of a round object. Waves leaving the edge of the object would all be the same distance from the center of the shadow, and would thus interfere constructively – what nonsense!

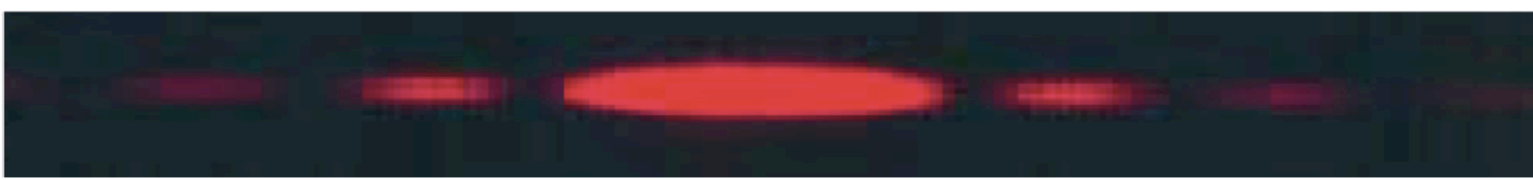
Dominique Arago showed that there is such a bright spot, providing compelling evidence for the wave theory.



A diffraction grating interference pattern

A double slit interference pattern

A single slit interference pattern



Geometry:

$\tan\theta = y/L$

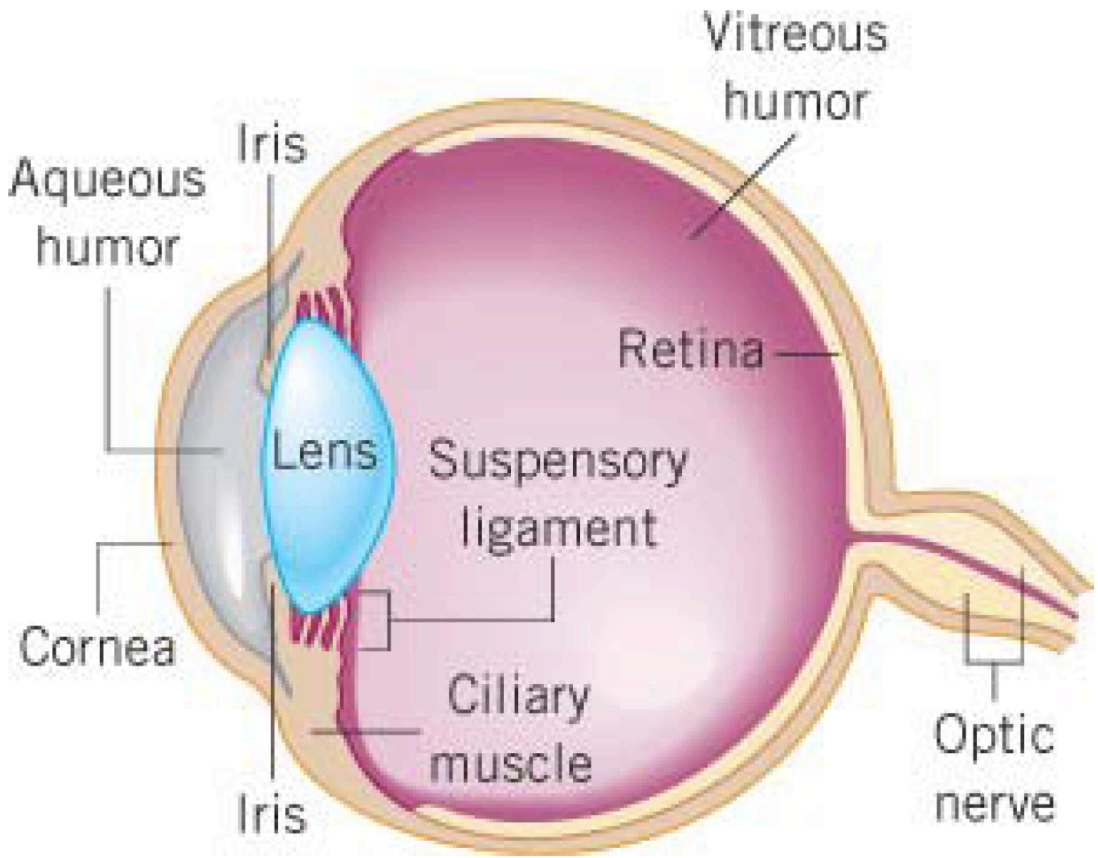
L – the distance from the slit(s) to the screen

m = 0,1,2,… order number

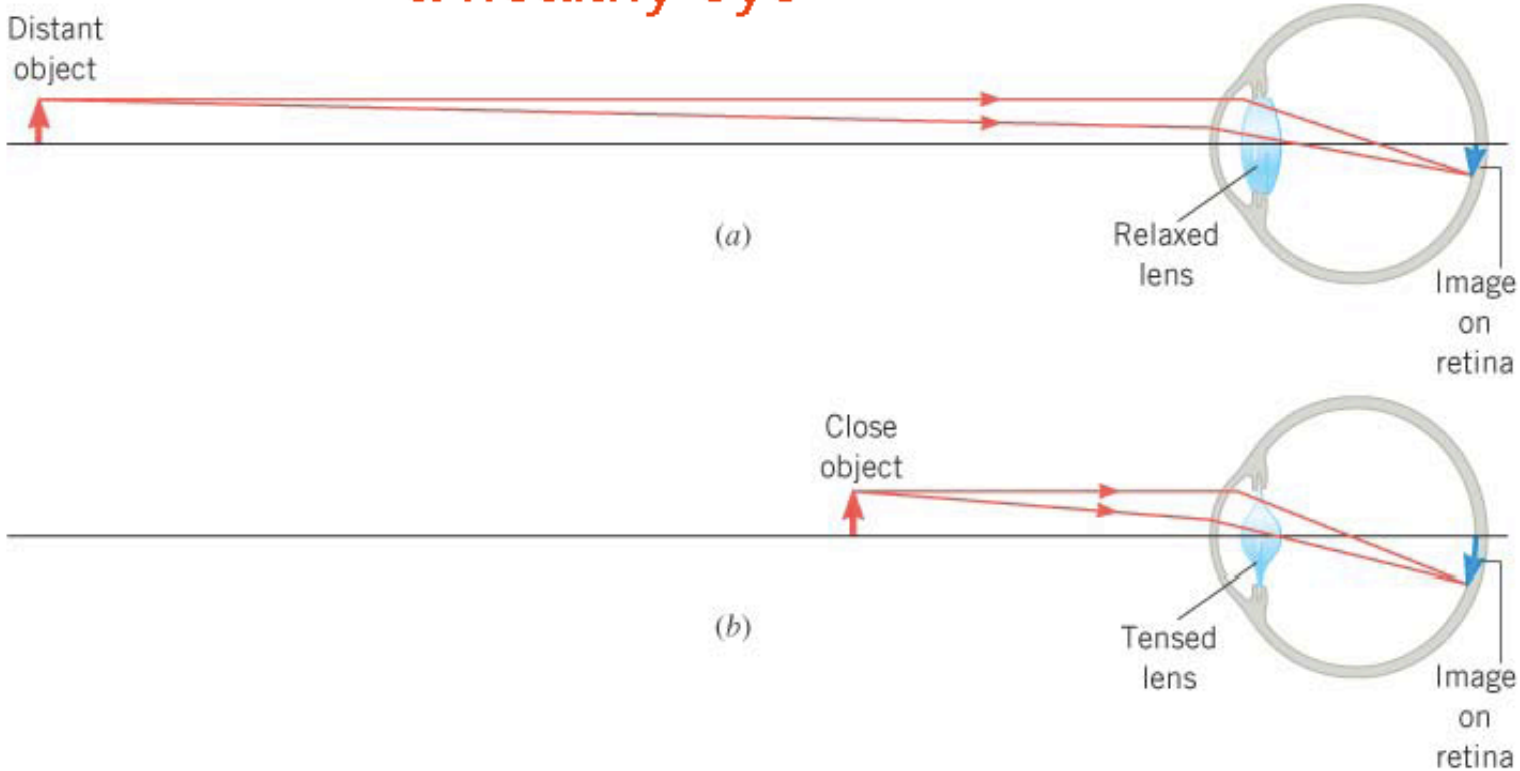
Θ – an angular position of a maximum or a minimum

A single slit	Two slits or sources	A grating
<u>Minimum:</u> $w\sin\theta = m\lambda$ <u>Notations:</u> l – the distance from the center to the m-th minimum w – the size of the slit m = 1,2,…	<u>Maximum:</u> m = 0,1,2, $d\sin\theta = m\lambda$ <u>Minimum:</u> m = 1,2,… $d\sin\theta = (m - 1/2)\lambda$ <u>Notations:</u> d – the distance between the slits	<u>Principal Maximum:</u> $d\sin\theta = m\lambda$ $d = 1/N$ m = 0,1,2, N – the number of slits per a unit length

ANATOMY


Vitreous
humor
Iris
Aqueous
humor
Retina
Lens
Suspensory
ligament
Cornea
Ciliary
muscle
Optic
nerve
Iris

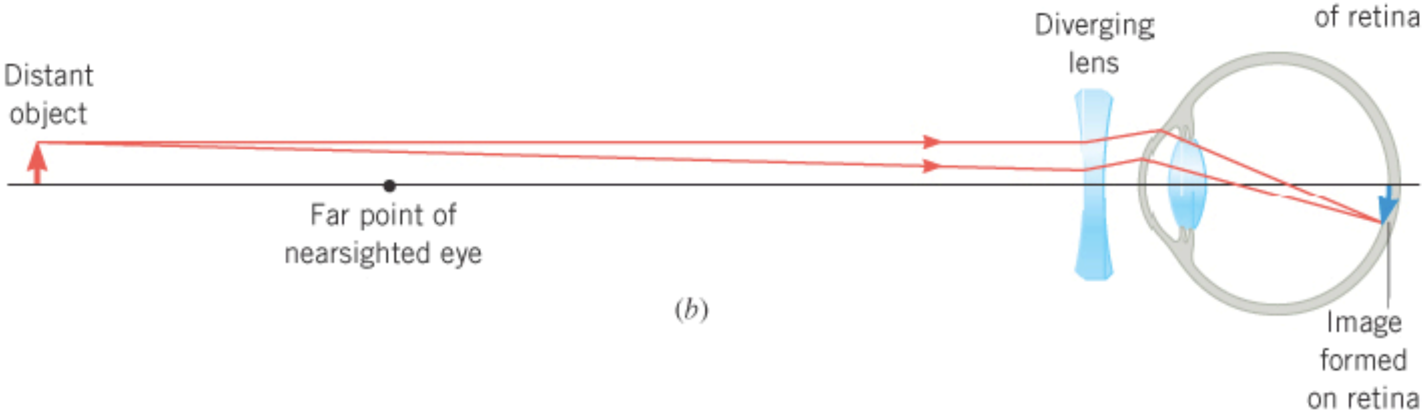
a healthy eye



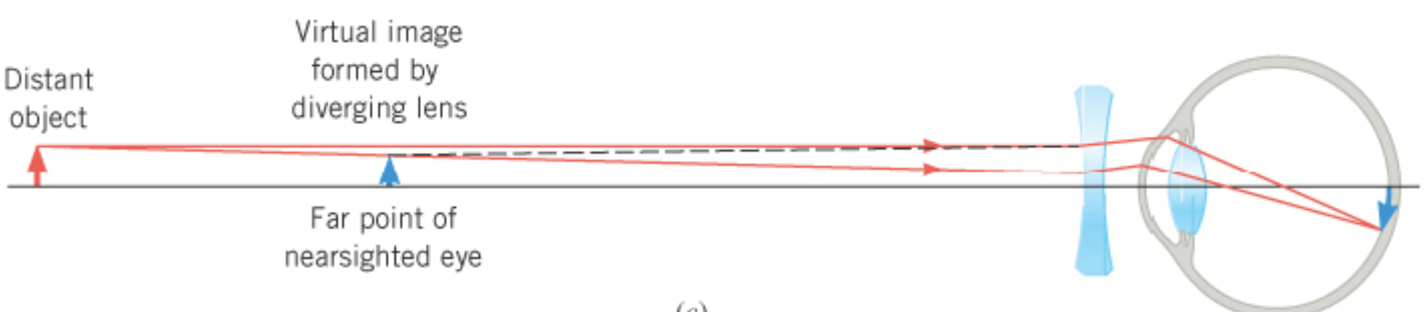
The lens only contributes about 20-25% of the refraction, but its function is important.

NEARSIGNTEDNESS

(a)



(b)



(c)

FARSIGNTEDNESS

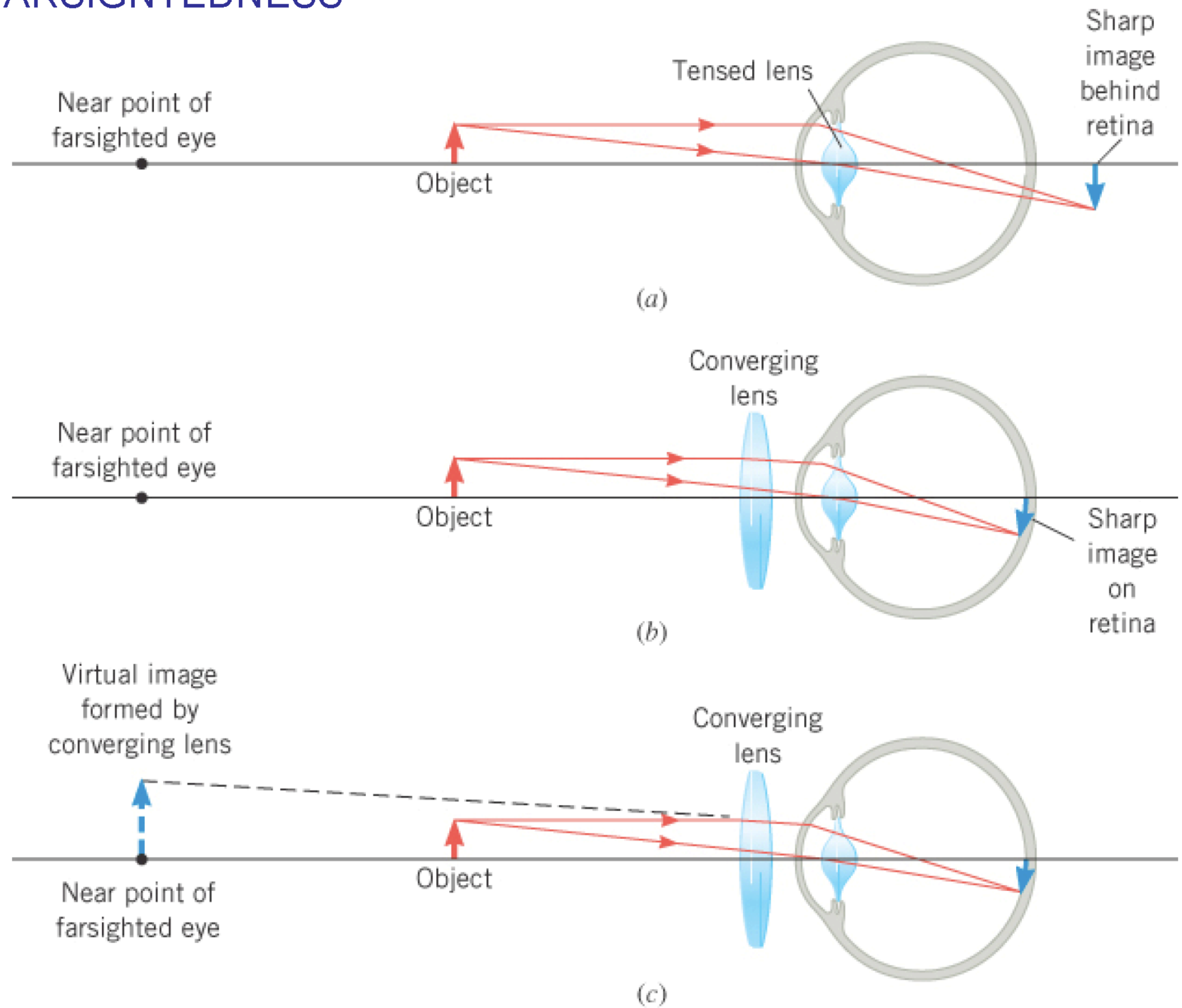
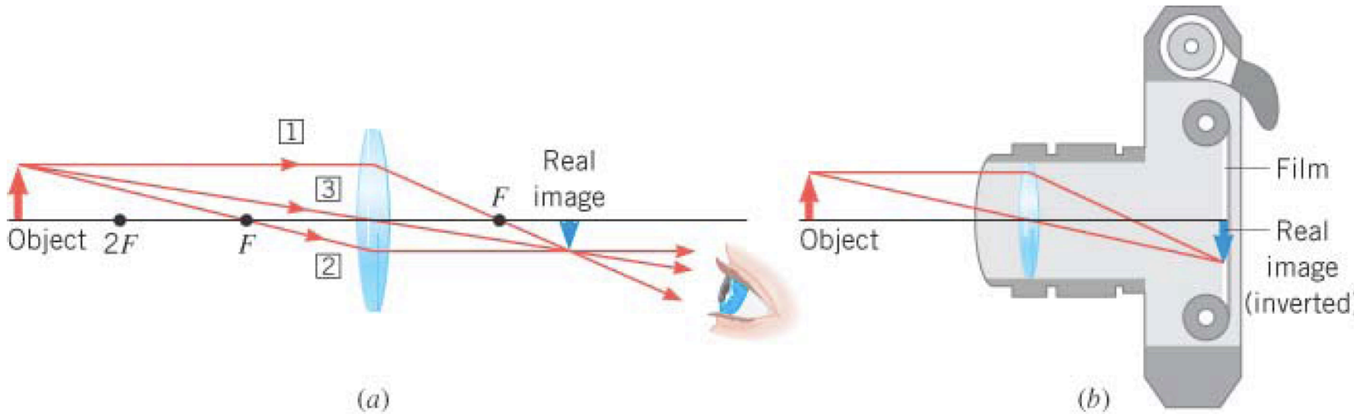


IMAGE FORMATION BY A CONVERGING LENS

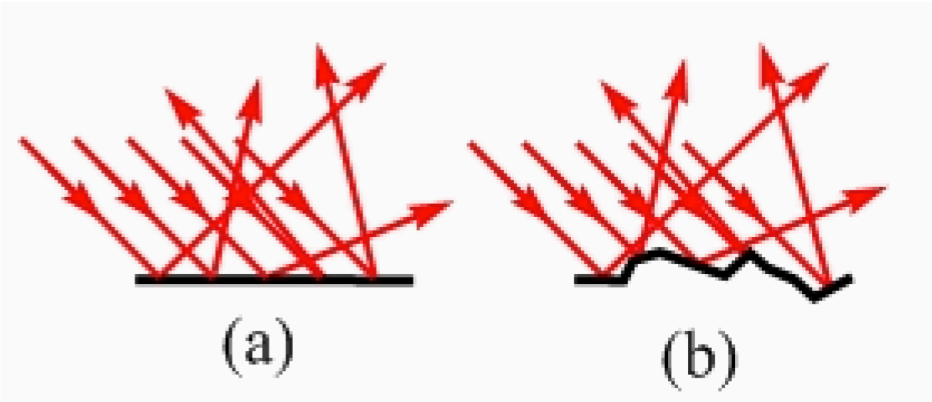


In this example, when the object is placed further than twice the focal length from the lens, the real image is inverted and smaller than the object.

looking at the object vs. looking at the image

Reflection

Most objects exhibit diffuse reflection, with light being reflected in all directions, as in (a) below. The irregularities on the surface of an object are larger than the wavelength of light, which is usually the case, and the light reflects off in all directions (see the Pic. (b)).



(How do particles reflect off a surface?)

(Why do we see colors?)

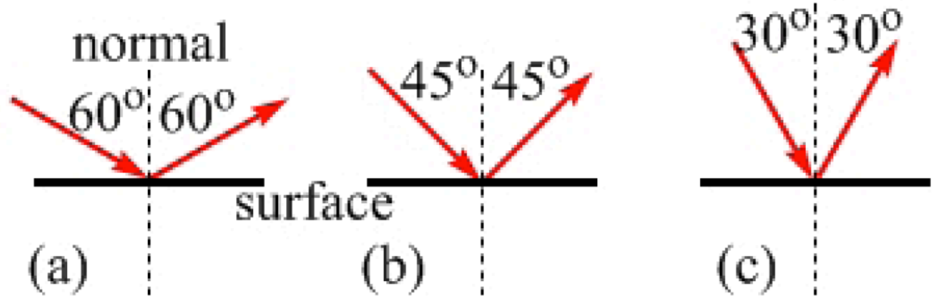
Reflection

The ***Law of Reflection*** –

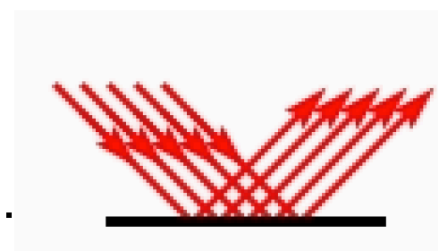
the angle of reflection

equals the angle of incider

(part 2 of the law)



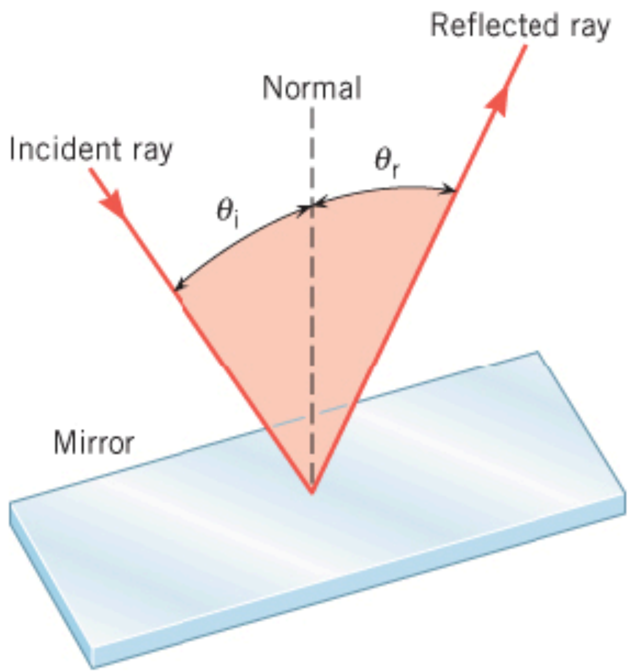
For objects such as flat mirrors, with surfaces so smooth that any hills or valleys on the surface are smaller than the wavelength of light, the law of reflection applies on a large scale. The EMW (including a light) traveling in one direction and reflecting from a flat (or plane) mirror is reflected in one direction; reflection from such objects is known as specular reflection.



LAW OF REFLECTION

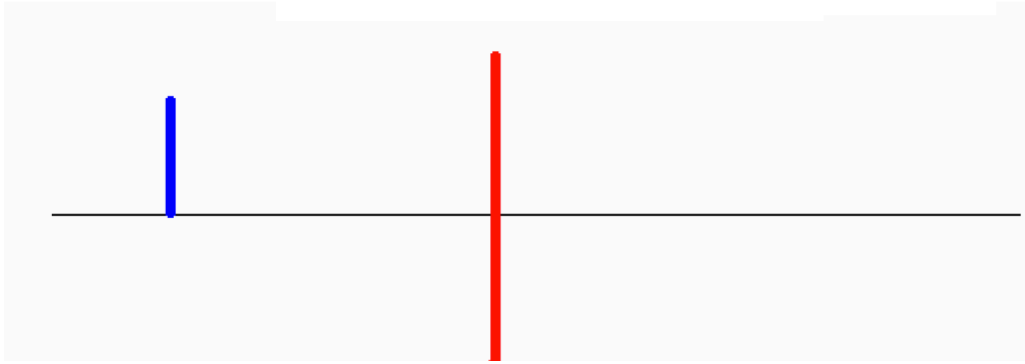
1.The incident ray, the reflected ray, and the normal to the surface all lie in the same plane, and

2. The angle of incidence equals the angle of reflection.



An object is placed to the left to a mirror (of unknown type). Can be a *real* image formed by the mirror found to the right to the mirror?

1. Yes 2. No 3. Sometimes



An object (the blue line) is placed to the left to a mirror (the red line; of unknown type). Can be a *real* image formed by the mirror found to the right to the mirror?

2. **No!**

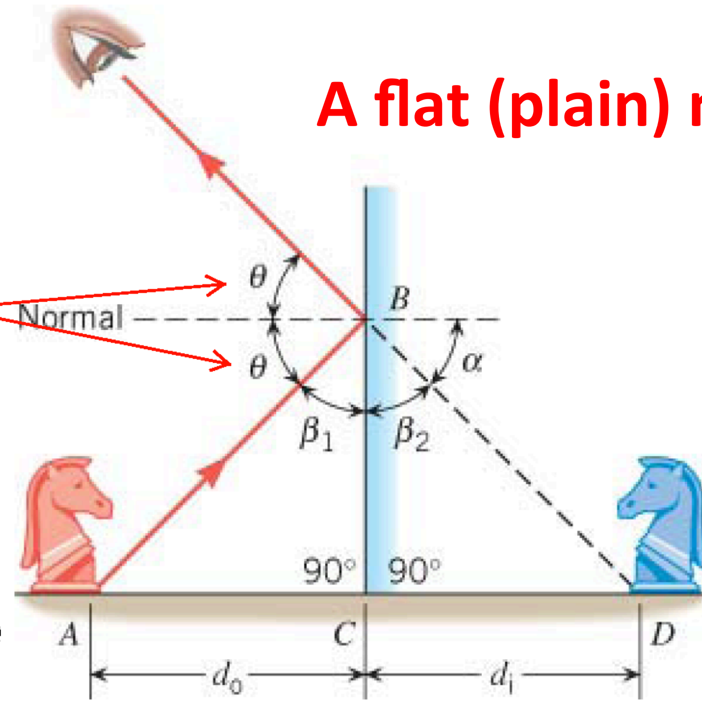
There is no light behind the mirror, only virtual image can be formed there!

A ray of light from the top of the chess piece reflects from the mirror. To the eye, the ray seems to come from behind the mirror.

Because none of the rays actually emanate from the image, it is called a ***virtual image.***

The geometry used to show that the image distance is equal to the object distance.

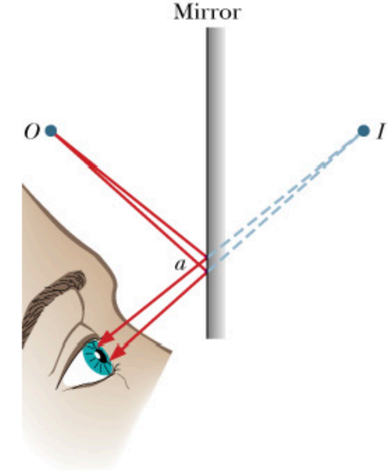
A flat (plain) mirror



Why are theses angles equal? Because ...

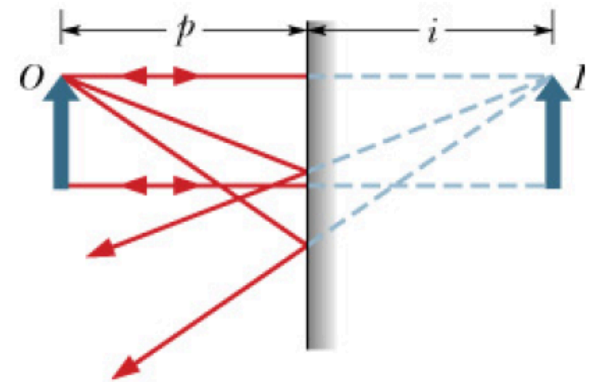
1. we use a right triangle
2. $\sin(90^0) = 1$
3. an observer is looking at the mirror
4. none of the above

Images



Rays from *O* reflect on the surface of the plane mirror.

Extending the rays beyond the surface of the mirror, they meet at *I*, where the imaginary image is located behind the mirror. **(i.e. virtual)**



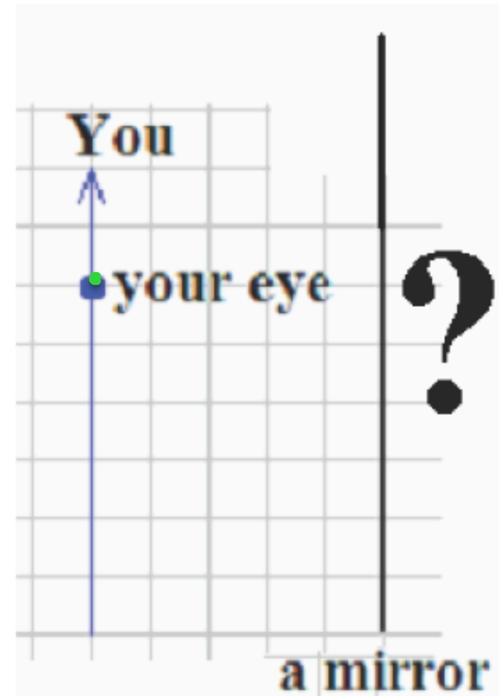
- ***O*** represents the object
- ***P*** represents the distance from the object to the surface of the mirror
- ***I*** is the image of this object
- ***i*** represents the distance from the surface of the mirror to the image

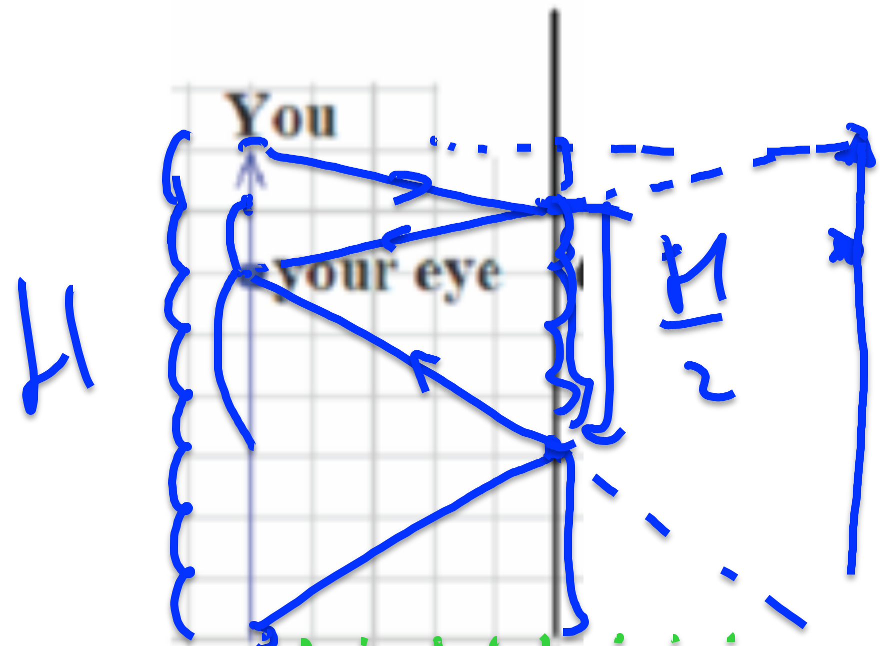
You have a height *h*. What is the minimum height possible for a plane mirror so that you can see your entire reflection in it without moving?

1. Draw an image of your top

2. Draw an image of your feet

3. See how much of the mirror you need to make the reflected rays reaching your eye.

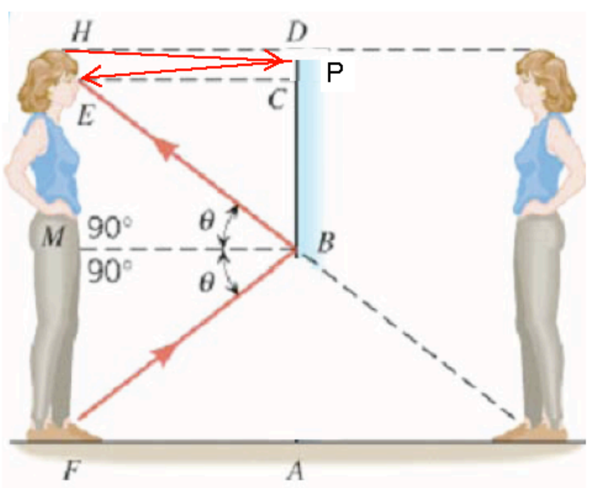


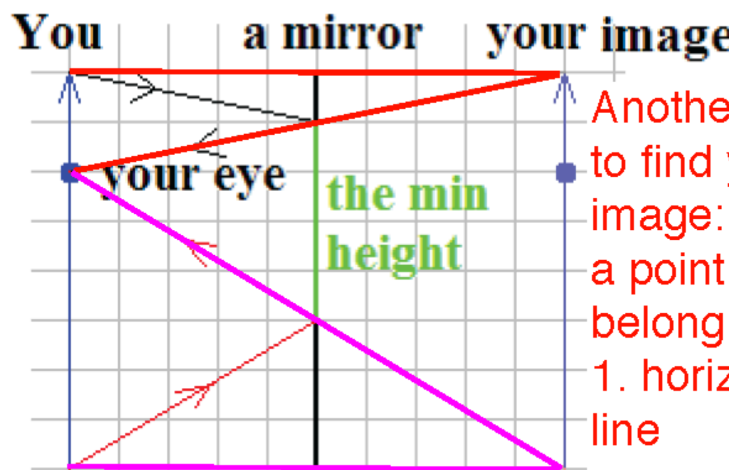

You
your eye

No matter how far you are from the mirror, the minimum height necessary is $h/2$.

It should be placed halfway between the top of your head and your eye level!

The bottom of the mirror should be at
a height equal to half the distance between
your eyes and the floor.





Another way to find your image:
a point should belong to
1. horizontal line
2. the line passing the eye and has to be at the same distance from the mirror as you are