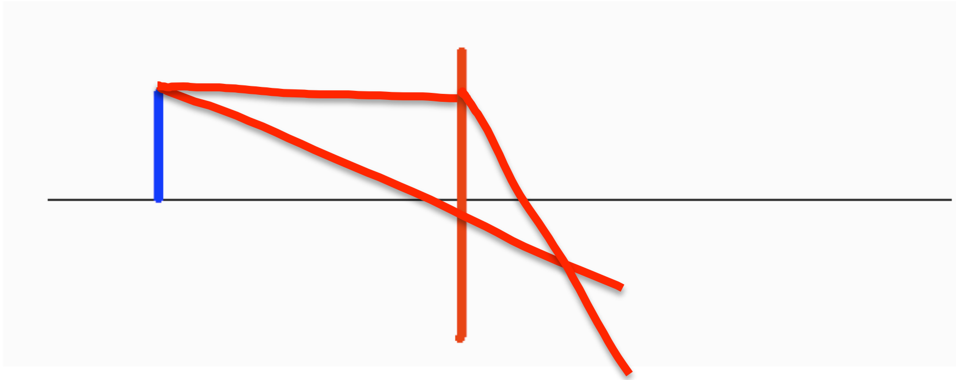
An object is placed to the left to a lens (of unknown type). Can be a *real* image formed by the lens found to the left to the lens?

1. Yes 2. No 3. Sometimes



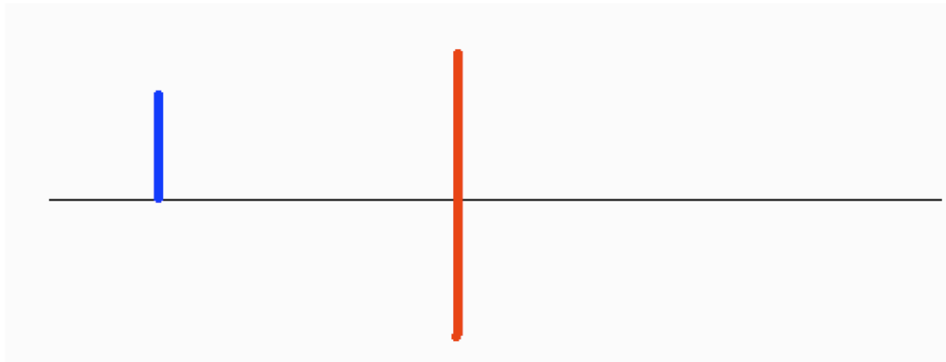
An object (the blue line) is placed to the left to a lens (of unknown type; the red line). Can be a *real* image formed by the lens found to the left to the lens?

B. No!

Light ***cannot reflect*** from the lens, it always passes through a lens, hence the real image can be built on the side which is opposite to the object, i.e. to the right to the lens (in this case).

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

1. Yes 2. No 3. Sometimes



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

A. Yes!

If an image is formed to the right to the lens, it is formed by real beams and it is a real image.

An image formed on the side of the object is formed by extensions of the beams, hence it is a virtual image.

A lens creates on a screen a clear focused image of a filament of a bulb.

The image is …

1. **Real**
2. **Virtual**
3. **It depends on other parameters of the situation**

A lens creates on a screen a clear focused image of a filament of a bulb.

The image is …

Real since it is formed on a screen;
it is formed by actual light rays
(not abstract extensions).

The lens must be converging!

Example

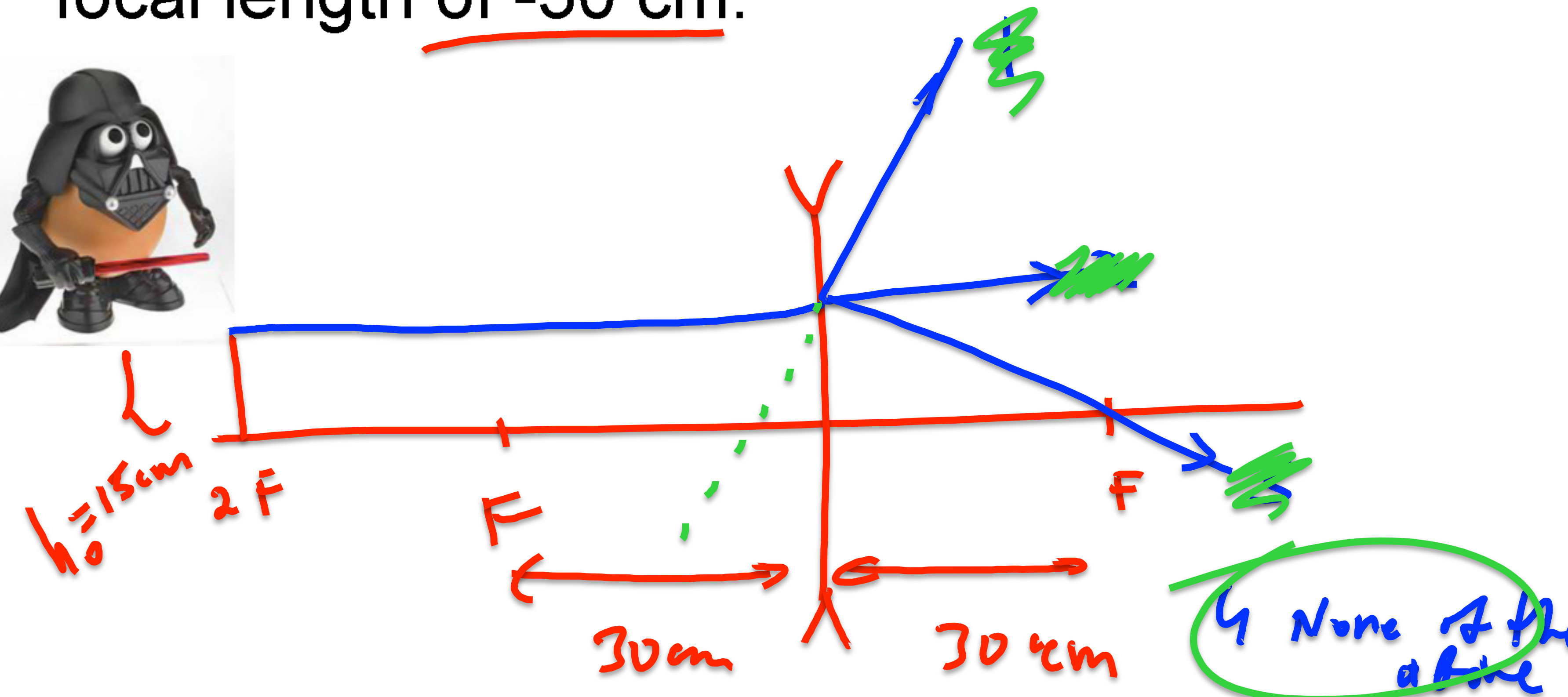
A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a diverging lens that has a focal length of -30 cm.

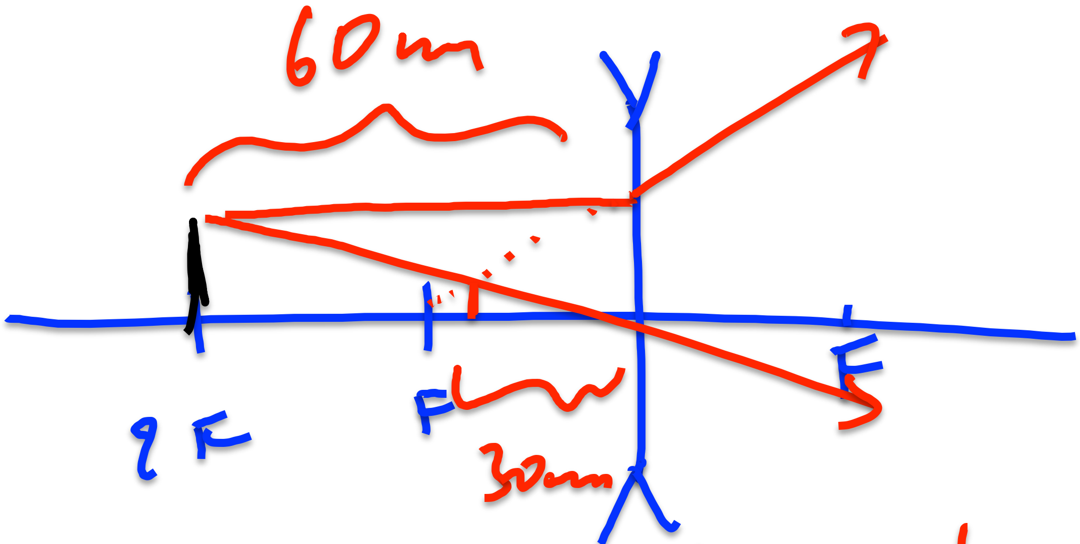
Where is the image?

How tall is the image?

What are the characteristics of the image?

A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a diverging lens that has a focal length of -30 cm.





$$\frac{1}{-30} = \frac{1}{+60} + \frac{1}{d_i} \; ; \; d_i =$$

1. 5
2. 10
3. 15
4. 20
5. 25
6. −25
7. −20

---

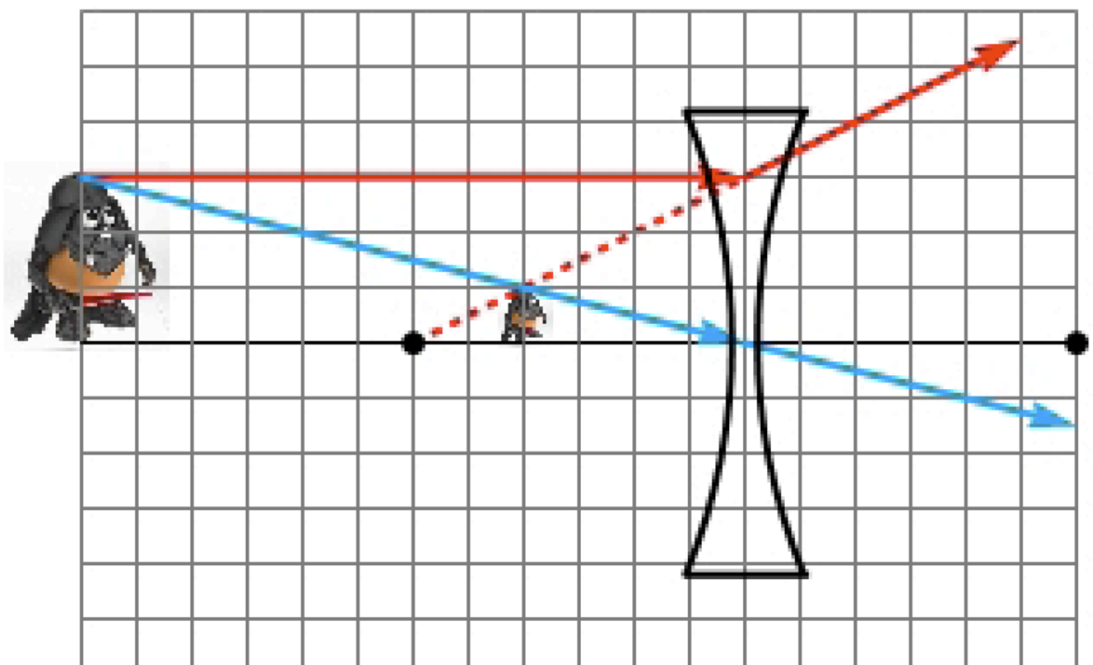
8. −15
9. −10
0. −5

A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a diverging lens that has a focal length of -30 cm.

Example

First, sketch a ray diagram.

1 grid unit = 5 cm.



Example

A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a diverging lens that has a focal length of -30 cm.

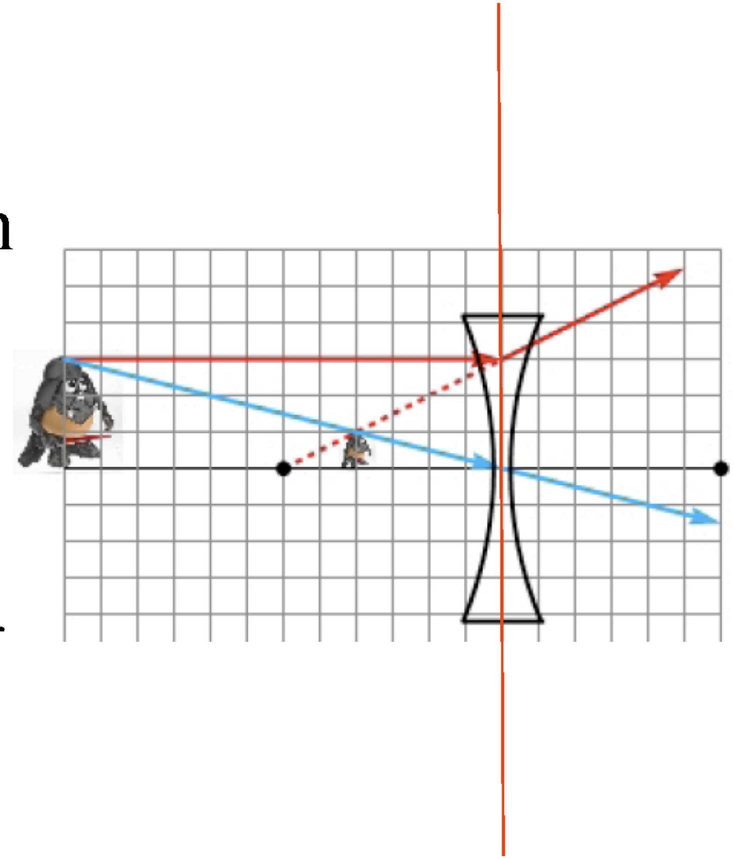
Where is the image?

$$d_o = 60 \text{ cm},\ f = -30 \text{ cm}$$

$$d_i = \frac{d_o \times f}{d_o - f}$$

$$= \frac{(60 \text{ cm}) \times (-30 \text{ cm})}{(60 \text{ cm}) - (-30 \text{ cm})}$$

$$= -20 \text{ cm}$$



A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a diverging lens that has a focal length of -30 cm.

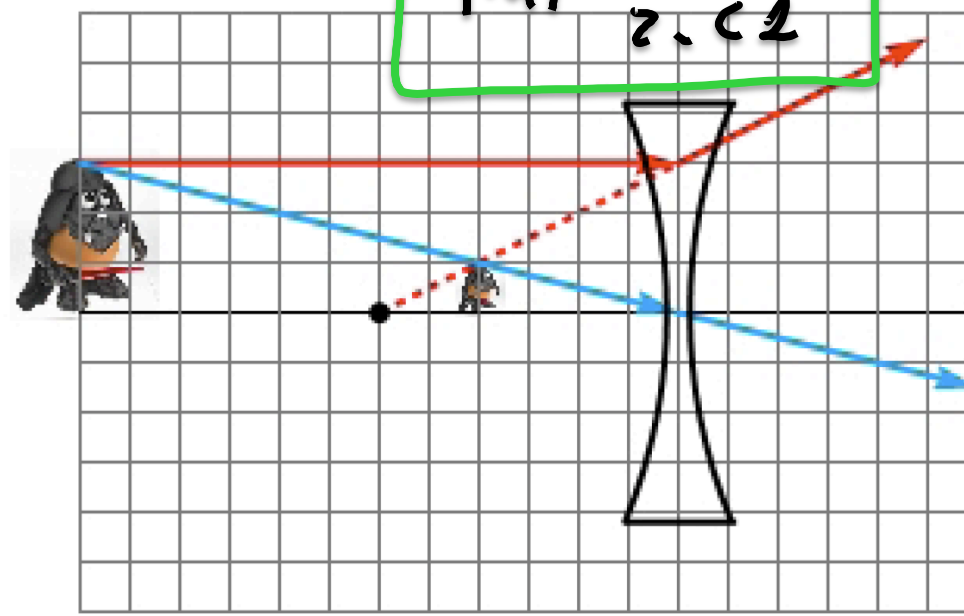
Where is the image?

$$d_o = 60 \text{ cm}, \;\; d_i = -20 \text{ cm}$$

m
1. > 0
2. < 0

|m|
1. > 1
2. < 1

This agrees with the ray diagram

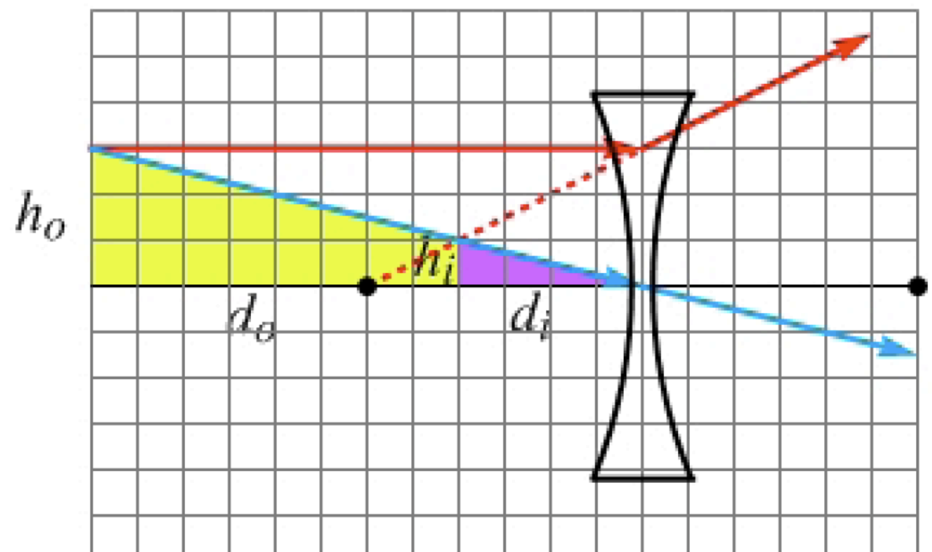


A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a diverging lens that has a focal length of -30 cm.

How tall is the image?

$$d_o = 60 \text{ cm},\ \ d_i = -20 \text{ cm},\ h_o = 15 \text{ cm}$$

The similar triangles tell us that the image is one-third the height of the object.



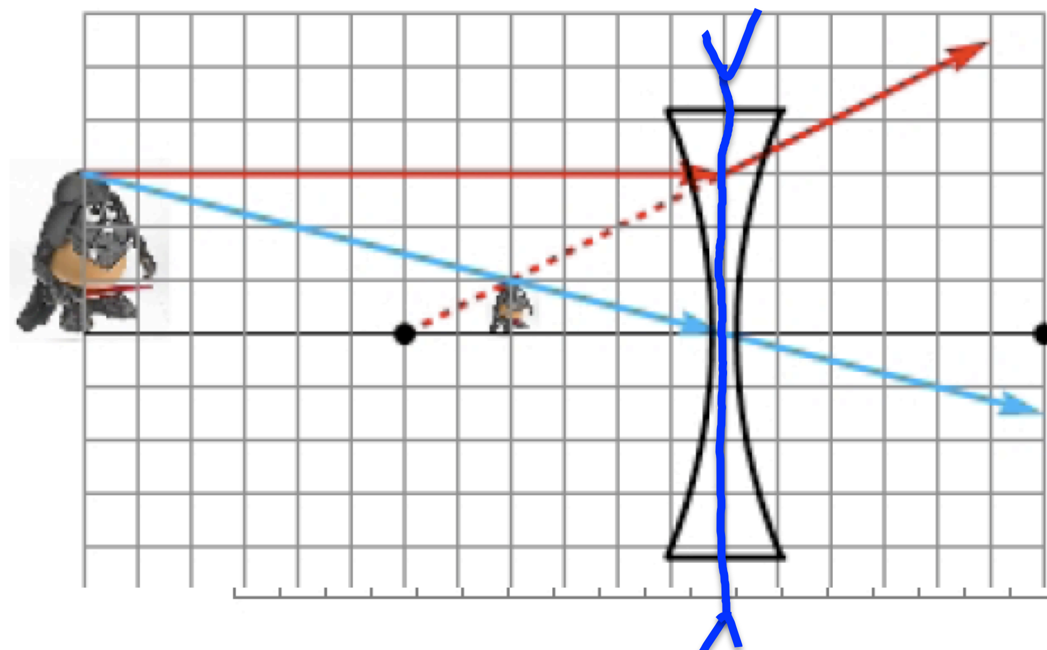
How tall is the image?

$$d_o = 60\ \text{cm},\ \ d_i = -20\ \text{cm},\ h_o = 15\ \text{cm}$$

We can also find the image height from the complete magnification equation.

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

$$h_i = 5\ \text{cm}$$

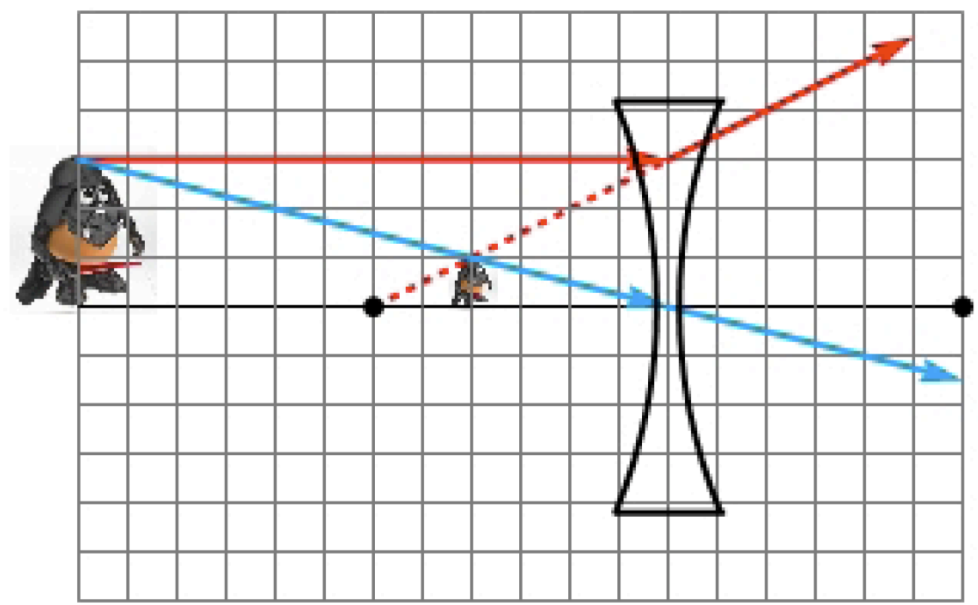


A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a diverging lens that has a focal length of -30 cm.

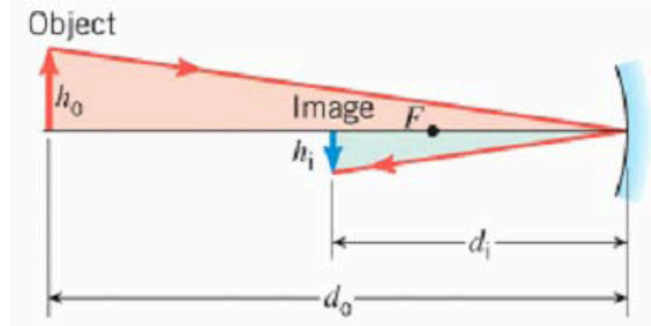
What are the image characteristics?

The image is:

- virtual
- upright
- smaller than the object



Summary of Sign Conventions for Spherical Mirrors



f is + for a concave mirror.

f is − for a convex mirror.

d_o is + (the object is in front of the mirror)

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

d_i is + if the image is in front of the mirror (real image).

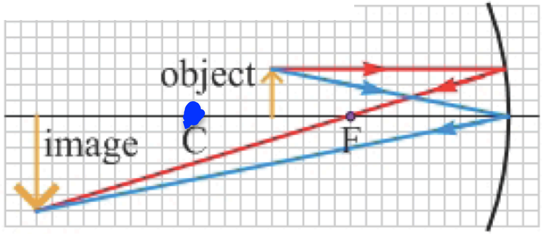
d_i is − if the image is behind the mirror (virtual image).

m is + for an upright image
m is − for an inverted image
(assuming the object is upright)

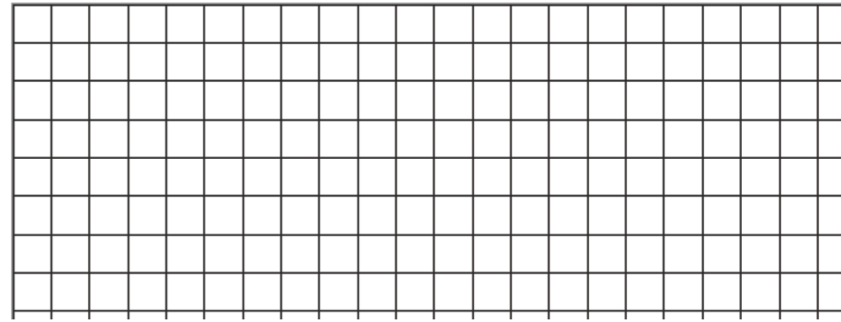
$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

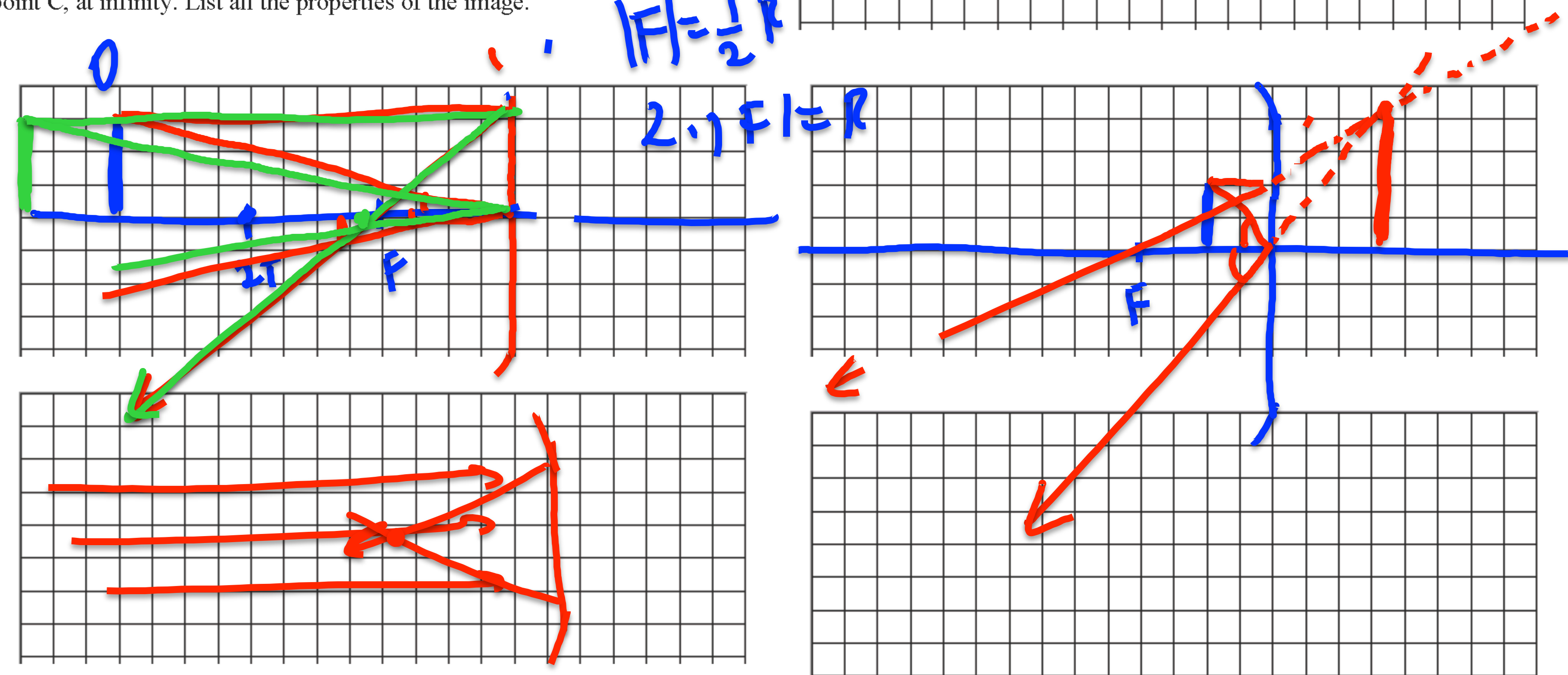
$h_{i,o}$ is + for an upright object /image

$h_{i,o}$ is − for an inverted object /image

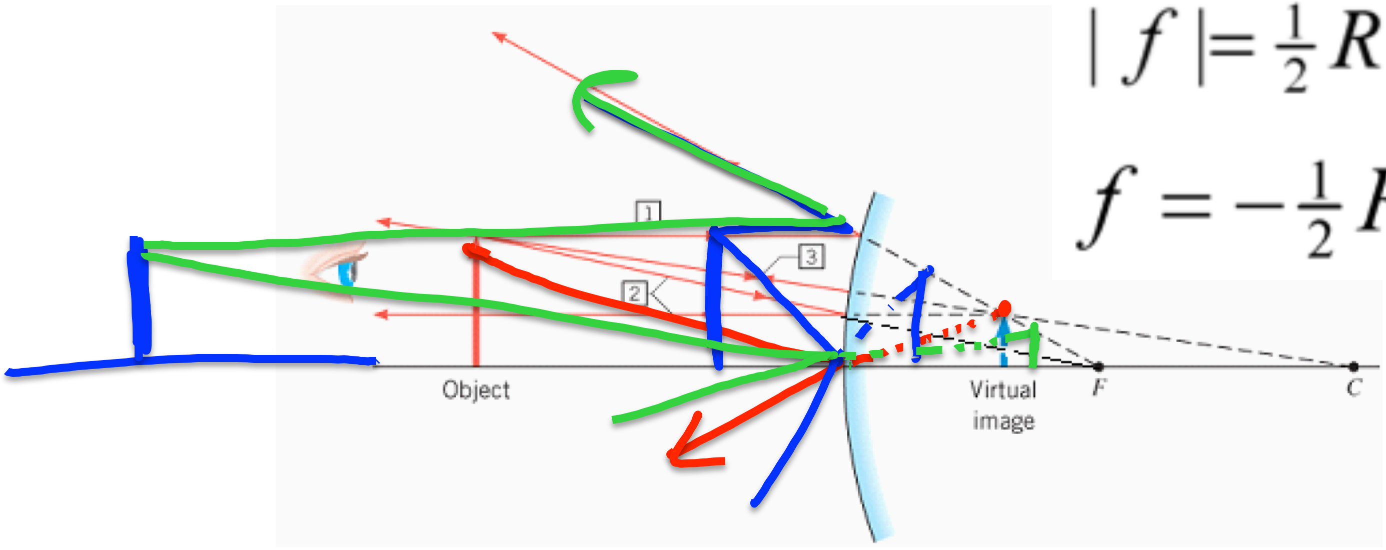


The ray diagram shows an example of an image formation by a concave mirror. Draw ray diagrams for all other possible locations of the object (i.e. between the focal point and the mirror, at focal point F, at center of the sphere C = 2F, to the left to point C, at infinity. List all the properties of the image.





CONVEX MIRRORS



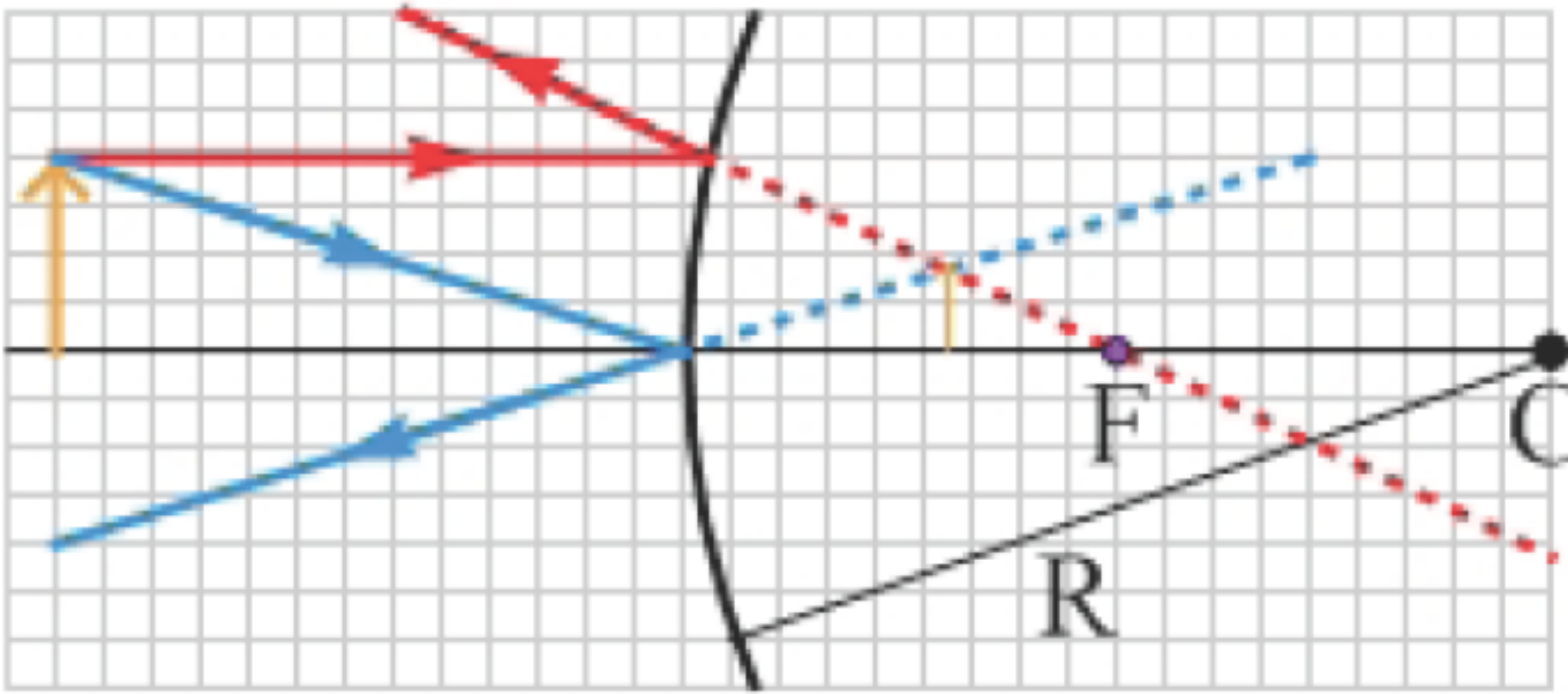
$$|f| = \frac{1}{2}R$$

$$f = -\frac{1}{2}R$$

Ray 1 is initially parallel to the principal axis and appears to originate from the focal point.

Ray 2 heads towards the focal point, emerging parallel to the principal axis.

Ray 3 travels toward the center of curvature and reflects back on itself.



ALWAYS!

A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a concave mirror that has a radius of curvature of 60 cm.

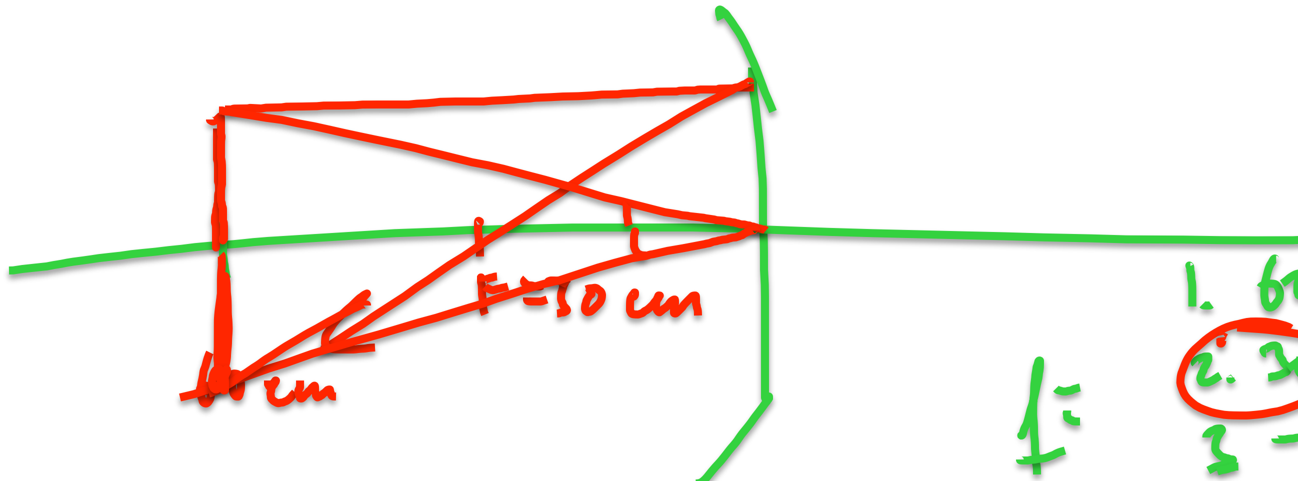
Where is the image?

How tall is the image?

What are the characteristics of the image?

A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a concave mirror that has a radius of curvature of 60 cm.

R = 60cm

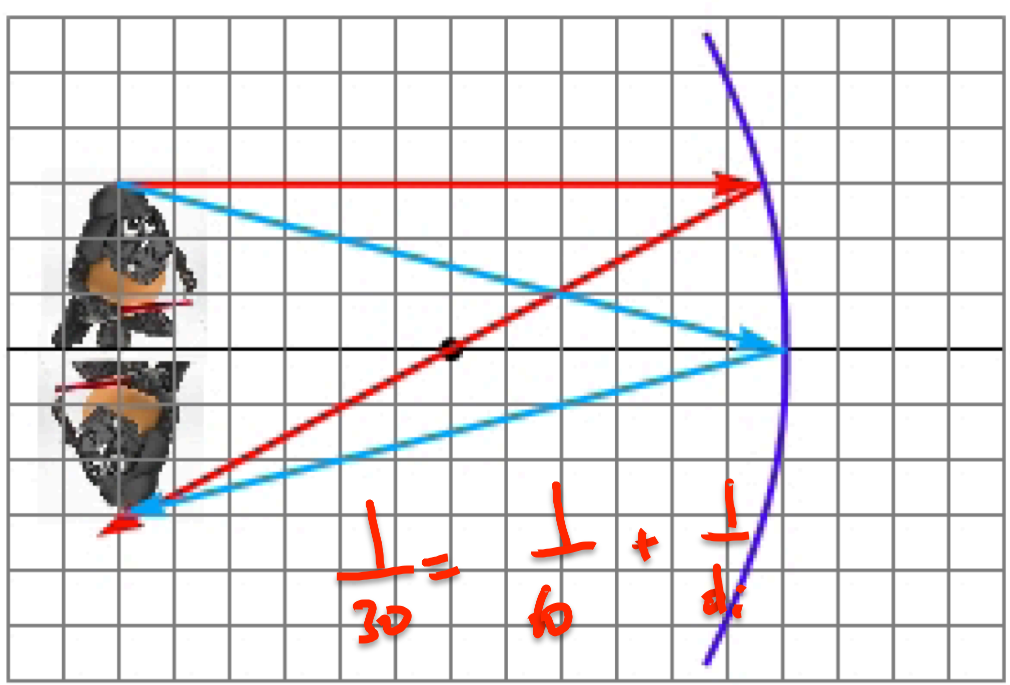


f: 1. 60
2. 30
3. -30
4. -60

A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a concave mirror that has a radius of curvature of 60 cm.

First, sketch a ray diagram. The focal point is 30 cm in front of the mirror.

1 grid unit = 5 cm.



A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a concave mirror that has a radius of curvature of 60 cm.

Where is the image?

$$d_o = 60 \text{ cm}, \; f = +30 \text{ cm}$$

$$d_i = \frac{d_o \times f}{d_o - f}$$

$$= \frac{(60 \text{ cm}) \times (30 \text{ cm})}{(60 \text{ cm}) - (30 \text{ cm})}$$

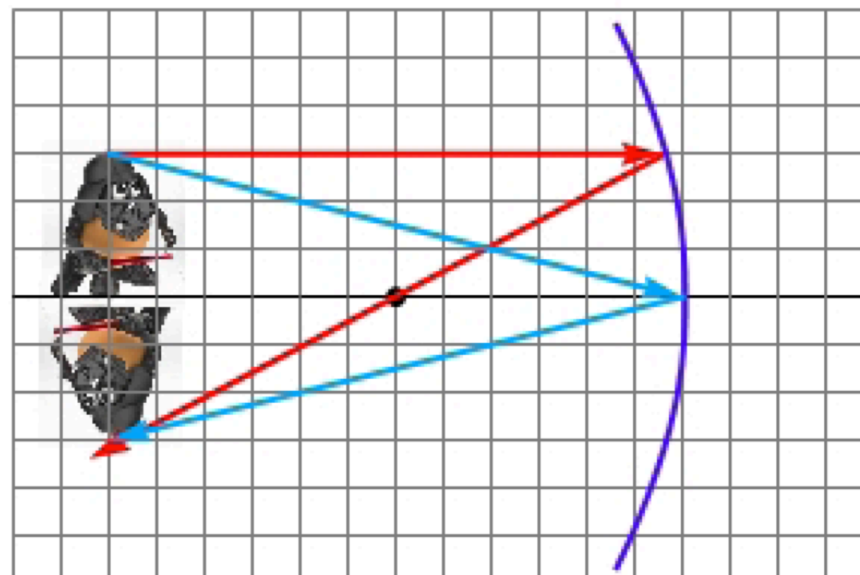
$$= +60 \text{ cm}$$

A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a concave mirror that has a radius of curvature of 60 cm.

Where is the image?

$$d_o = 60 \text{ cm}, \;\; d_i = +60 \text{ cm}$$

This agrees with the ray diagram



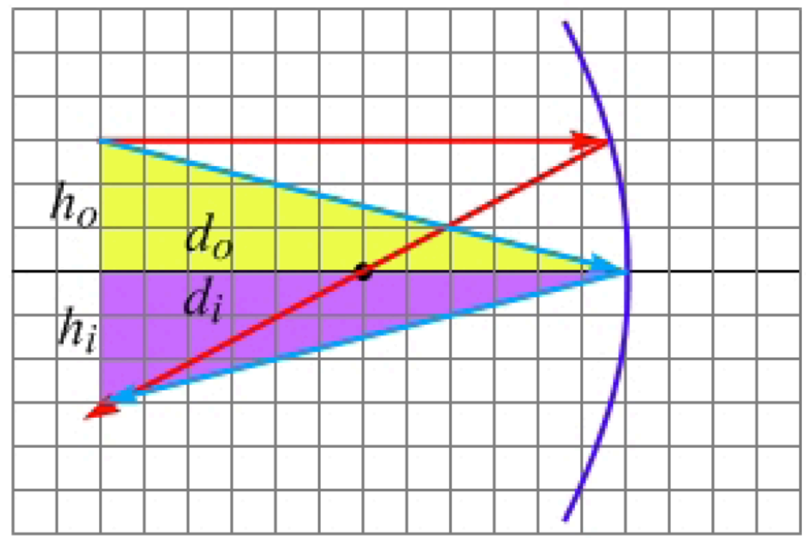
How tall is the image?

$$d_o = 60 \text{ cm}, \;\; d_i = 60 \text{ cm}, \; h_o = 15 \text{ cm}$$

We can find the image height from the similar triangles or from the magnification equation.

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

$$h_i = -15 \text{ cm}$$

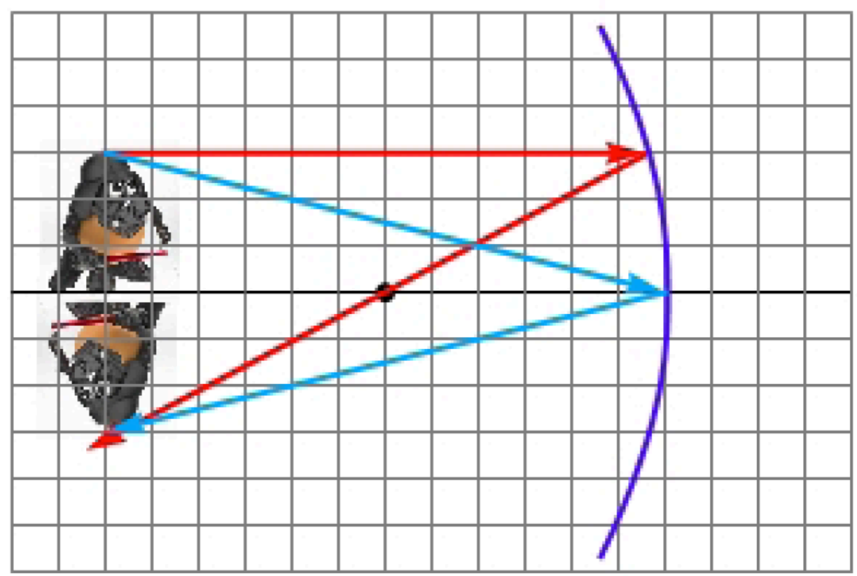


A Star Wars action figure, 15 cm tall, is placed 60 cm in front of a concave mirror that has a radius of curvature of 60 cm.

What are the image characteristics?

The image is:

- real
- inverted
- the same size as the object



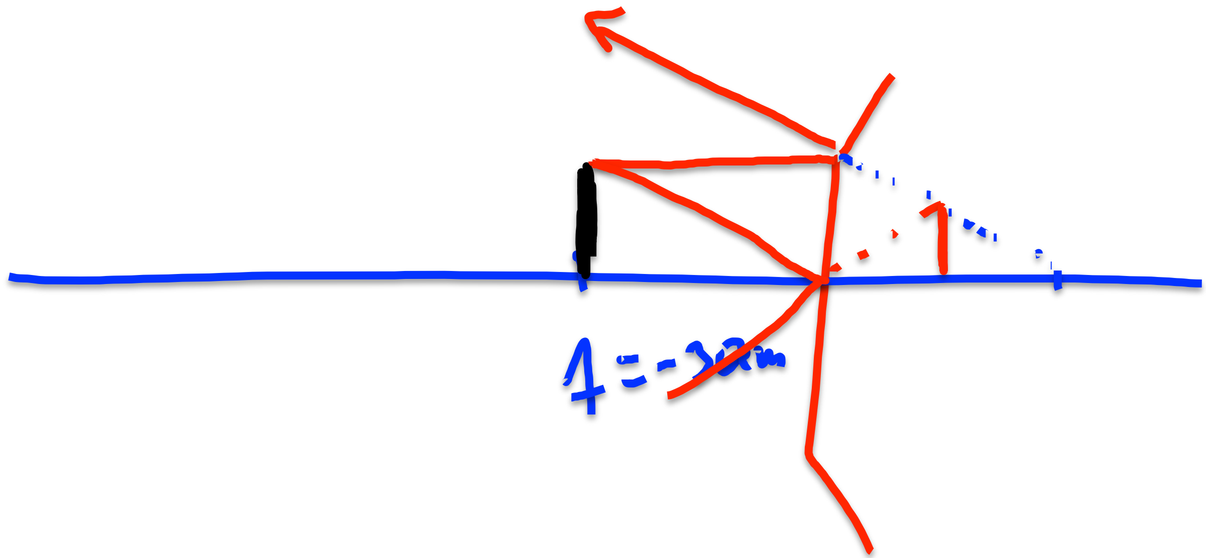
A Star Wars action figure, 15 cm tall, is placed 30 cm in front of a convex mirror that has a radius of curvature of 60 cm.

Where is the image?

How tall is the image?

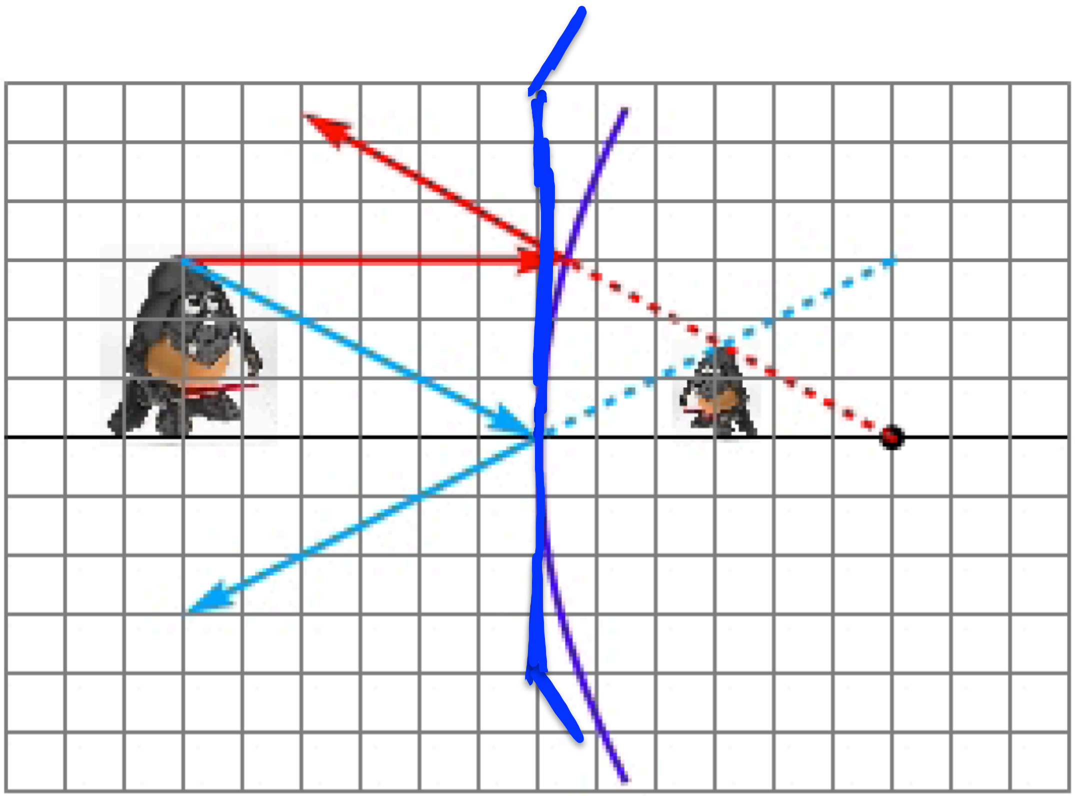
What are the characteristics of the image?

A Star Wars action figure, 15 cm tall, is placed 30 cm in front of a convex mirror that has a radius of curvature of 60 cm.



First, sketch a ray diagram. The focal point is 30 cm behind the mirror.

1 grid unit = 5 cm.



A Star Wars action figure, 15 cm tall, is placed 30 cm in front of a convex mirror that has a radius of curvature of 60 cm.

d_o

$$\frac{1}{-30} = \frac{1}{30} + \frac{1}{d_i}$$

Where is the image?

$$d_o = 30 \text{ cm}, \ f = -30 \text{ cm}$$

$$d_i = \frac{d_o \times f}{d_o - f}$$

$$= \frac{(30 \text{ cm}) \times (-30 \text{ cm})}{(30 \text{ cm}) - (-30 \text{ cm})}$$

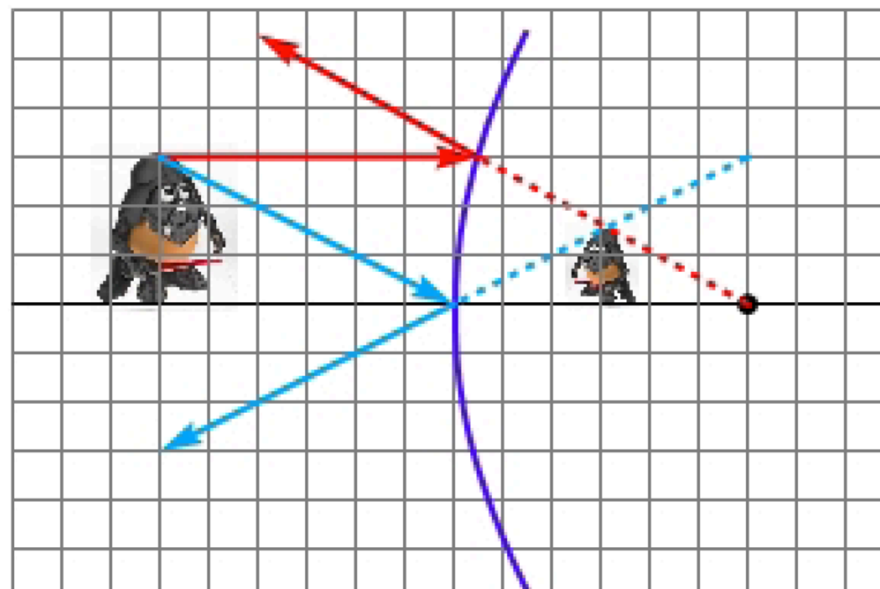
$$= -15 \text{ cm}$$

A Star Wars action figure, 15 cm tall, is placed 30 cm in front of a convex mirror that has a radius of curvature of 60 cm.

Where is the image?

$$d_o = 30\text{ cm},\ \ d_i = -15\text{ cm}$$

This agrees with the ray diagram

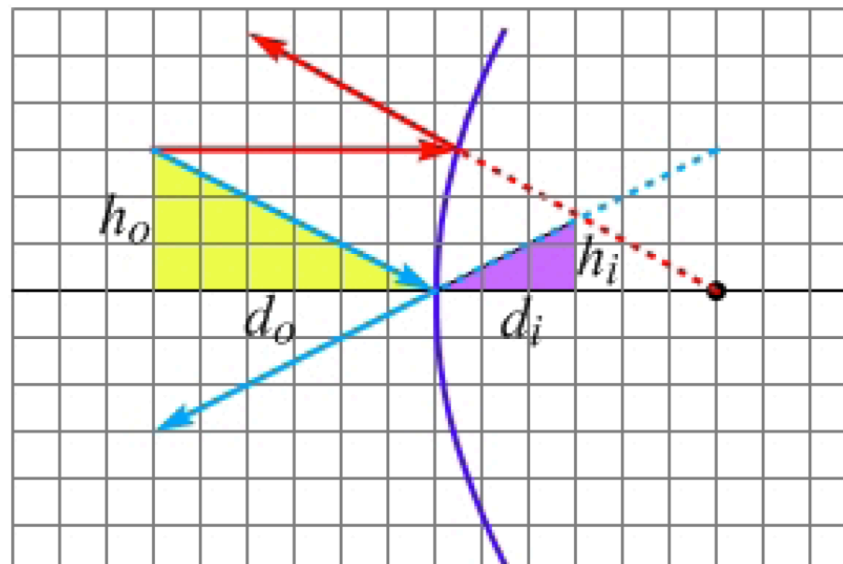


A Star Wars action figure, 15 cm tall, is placed 30 cm in front of a convex mirror that has a radius of curvature of 60 cm.

How tall is the image?

$$d_o = 30 \text{ cm}, \;\; d_i = -15 \text{ cm}, \; h_o = 15 \text{ cm}$$

The similar triangles tell us that the image is half the height of the object.



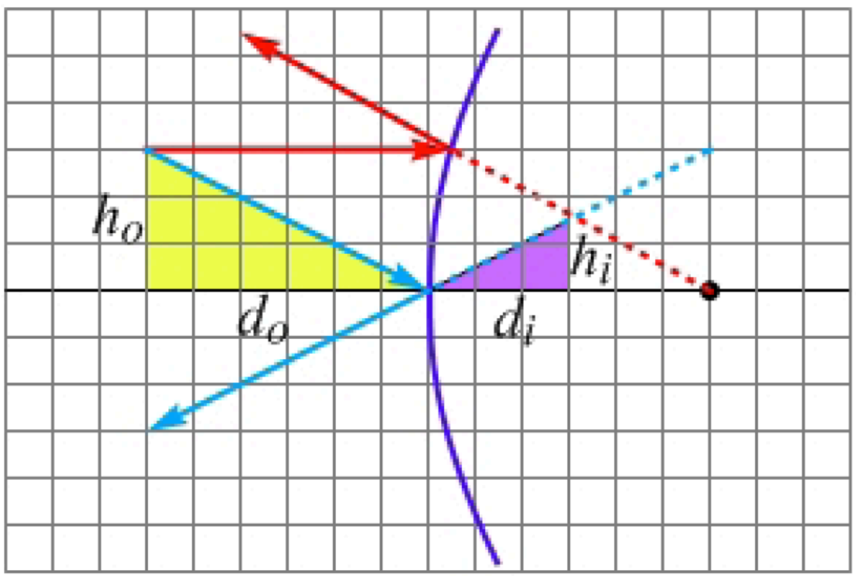
How tall is the image?

$$d_o = 30 \text{ cm}, \;\; d_i = -15 \text{ cm}, \; h_o = 15 \text{ cm}$$

We can also find the image height from the complete magnification equation.

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

$$h_i = 7.5 \text{ cm}$$

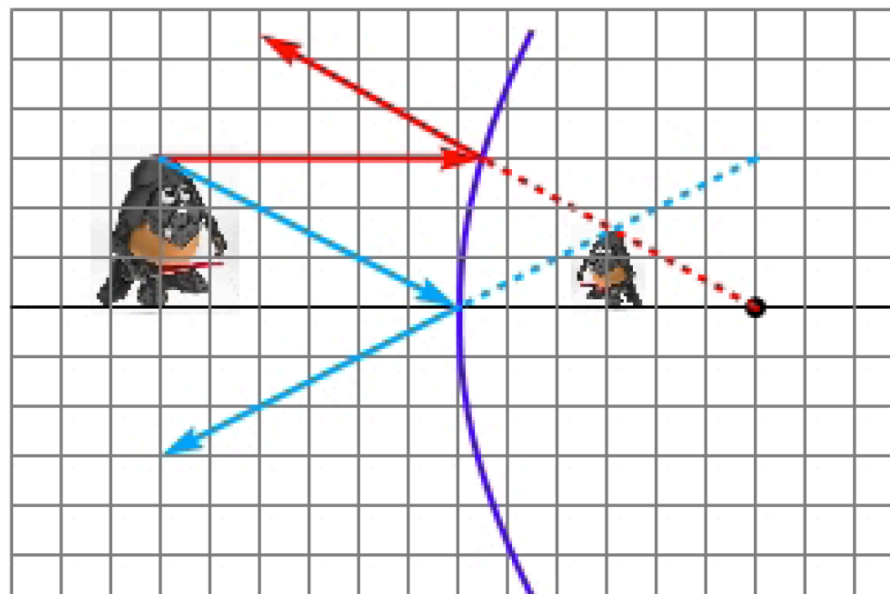


A Star Wars action figure, 15 cm tall, is placed 30 cm in front of a convex mirror that has a radius of curvature of 60 cm.

What are the image characteristics?

The image is:

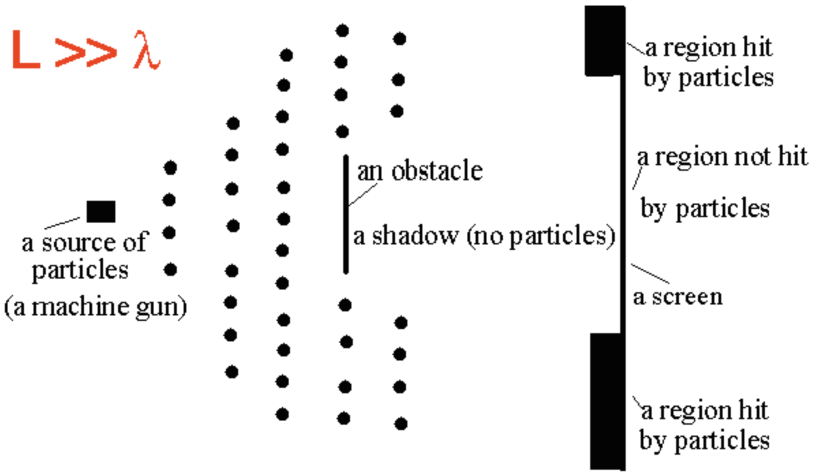
- virtual
- upright
- smaller than the object



Light is …

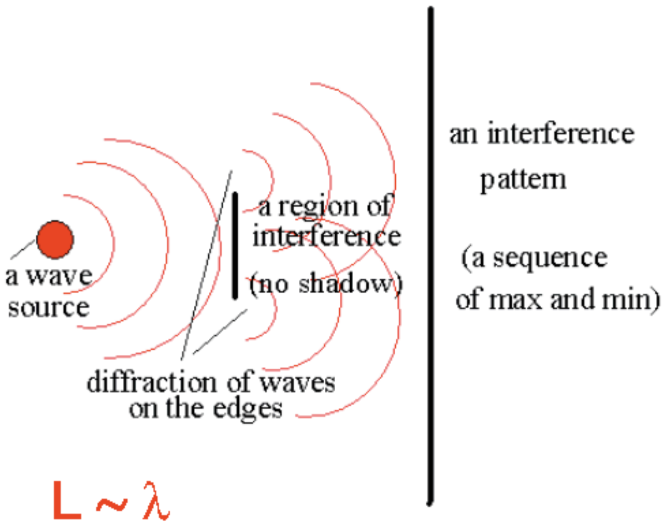
1. **A set of light particles traveling in space**
2. **A set of light waves traveling in space**
3. **Both of the above**
4. **Neither of the above**

Particles vs. Waves



Particles and waves show different patterns when encounter an obstacle.

If light were made of particles, a large shadow would be in the middle of the screen.



If light were made of waves, instead of a shadow a sequence of bright and dark regions (interference pattern) would be observed (with a bright spot in the middle of the shadow!).

OPTICS

Optics is defined as:

"the branch of physics that deals with light and vision, chiefly the generation, propagation, and detection of electromagnetic radiation."

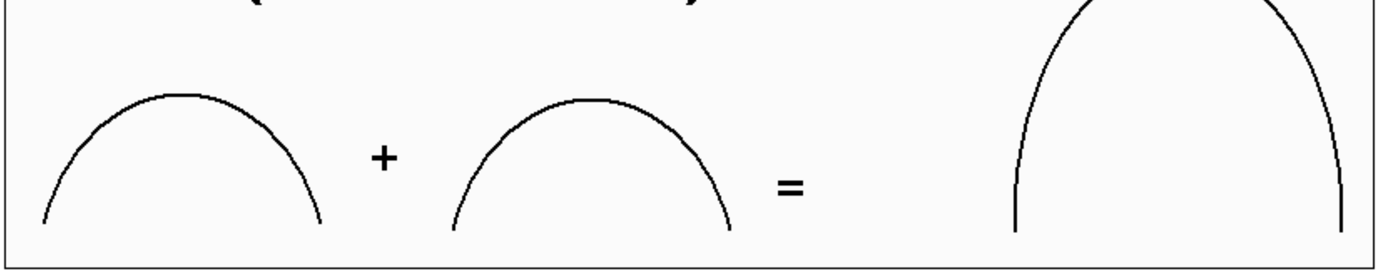
The American Heritage Dictionary

There are two branches of optics:

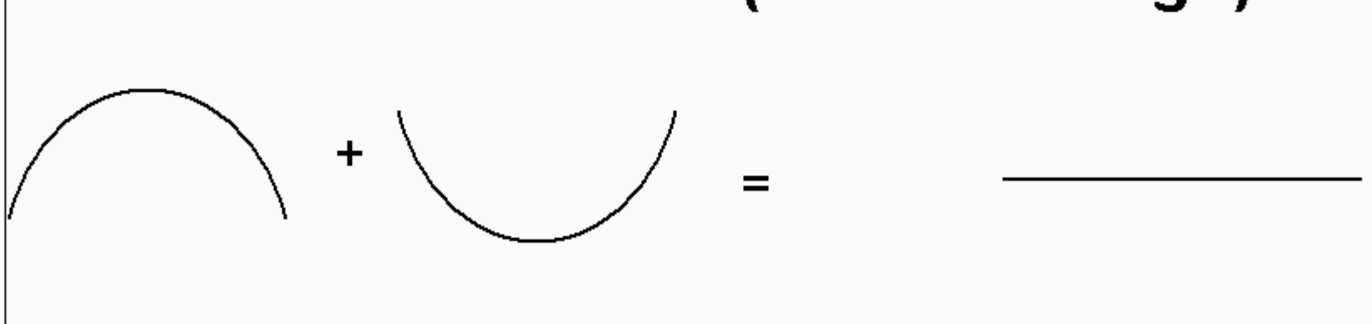
- **Geometrical Optics (light as rays = trajectories of light particles)**
- **Physical Optics (light as waves)**

When two waves meet each other they interfere with each other (superposition)

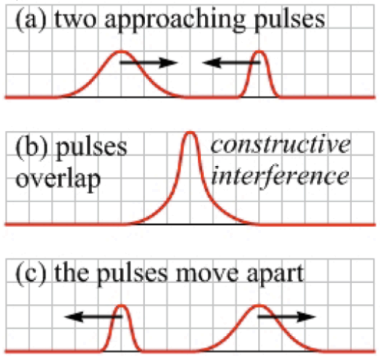
Constructive interference (crest to crest)



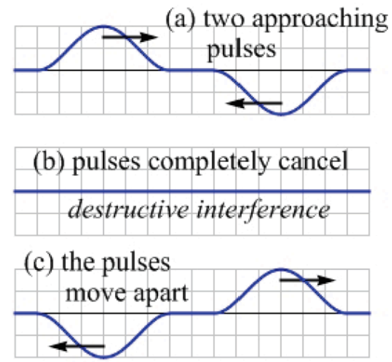
Destructive interference (crest to trough)



Constructive interference

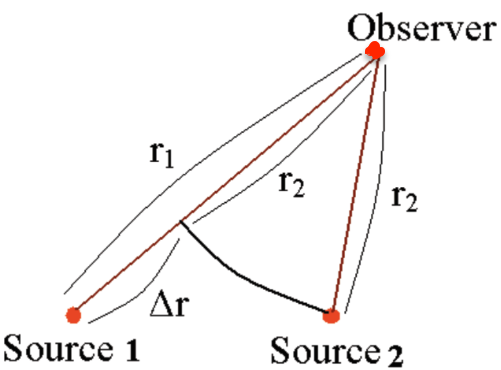


Destructive interference



Interference from two sources in phase

(For ANY two waves!)



$$\Delta r = |r_1 - r_2|$$

If:

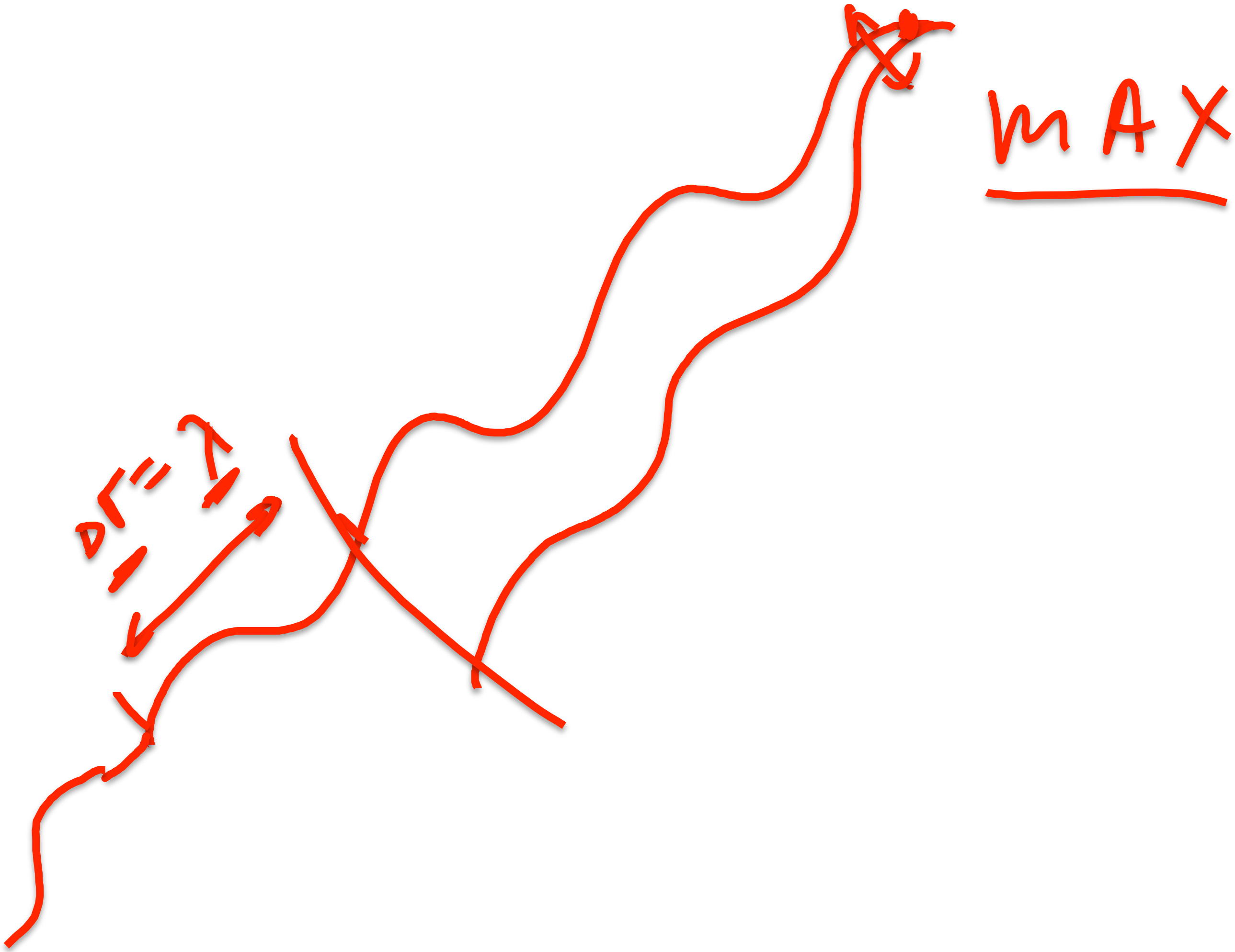
$$\mathbf{\Delta r = n\lambda} \quad \mathbf{n = 0, 1, 2, 3, ...}$$

The waves come to the observer *in phase* and the *constructive* interference is observed (louder sound).

If:

$$\mathbf{\Delta r = (2n - 1)\lambda/2 = (n - 1/2)\lambda} \quad \mathbf{n = 1, 2, 3, ...}$$

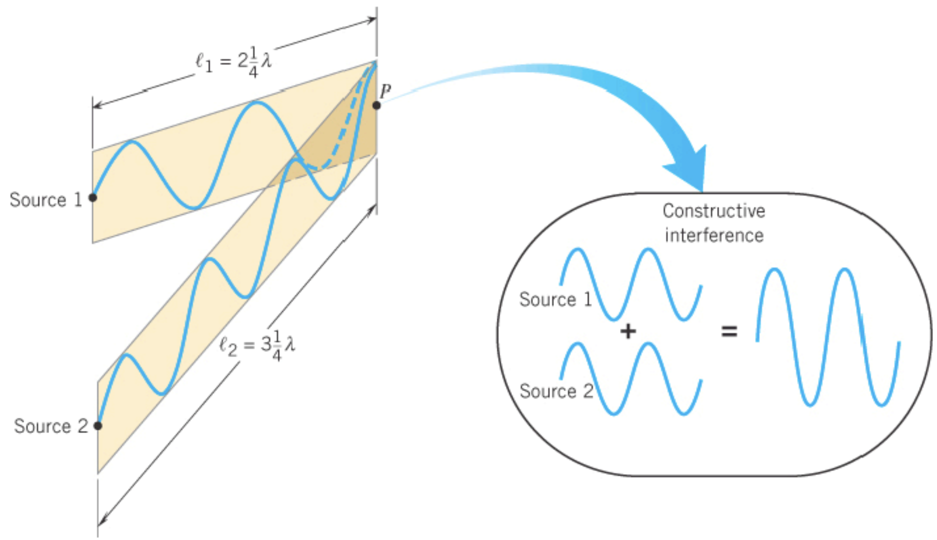
The waves come to the observer *out of phase* (the phase difference is 180^0) and the *distractive* interference is observed (no sound).


$\Delta r = \lambda$
MAX

When two or more light waves pass through a given point, their ***electric*** fields combine according to the principle of superposition.

two sources

Light is a wave, too; whatever works for sound works for light!

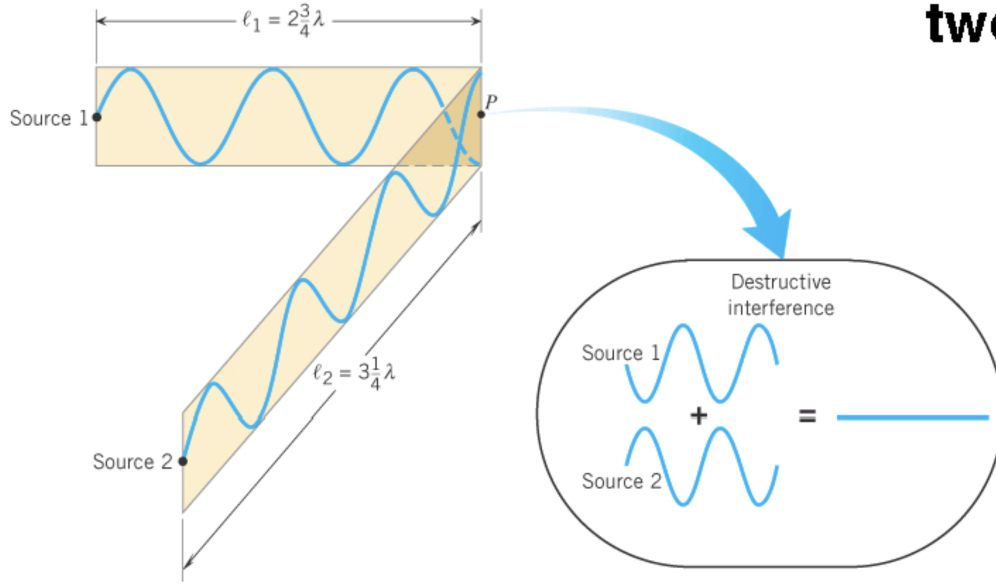


The waves emitted by the sources start out in phase and arrive at point P in phase, leading to ***constructive interference.***

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

Light is a wave, too; whatever works for sound works for light!

two sources



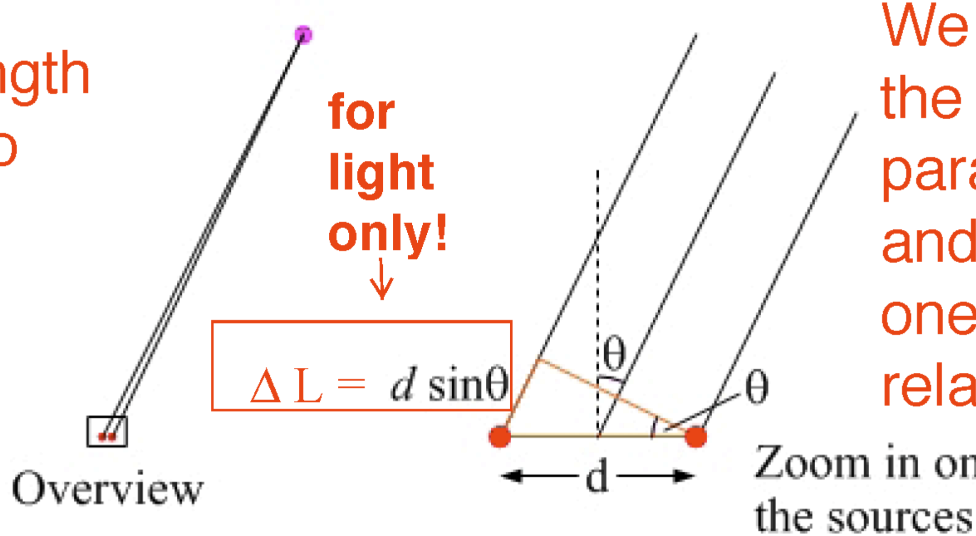
The waves emitted by the sources start out in phase and arrive at point P out of phase, leading to ***destructive interference.***

$$\left| \ell_2 - \ell_1 \right| = \left(m - \tfrac{1}{2}\right)\lambda \qquad m = 1,2,3,\ldots$$

The double-source equation

For light, the two slits are usually several wavelengths apart, which is not that far. Let's call the distance between the sources *d*. For a point a long way from the sources, the path-length difference is given by *d* sin*θ*, where *θ* is the angle between the perpendicular bisector and the line joining the point to the spot halfway between the sources.

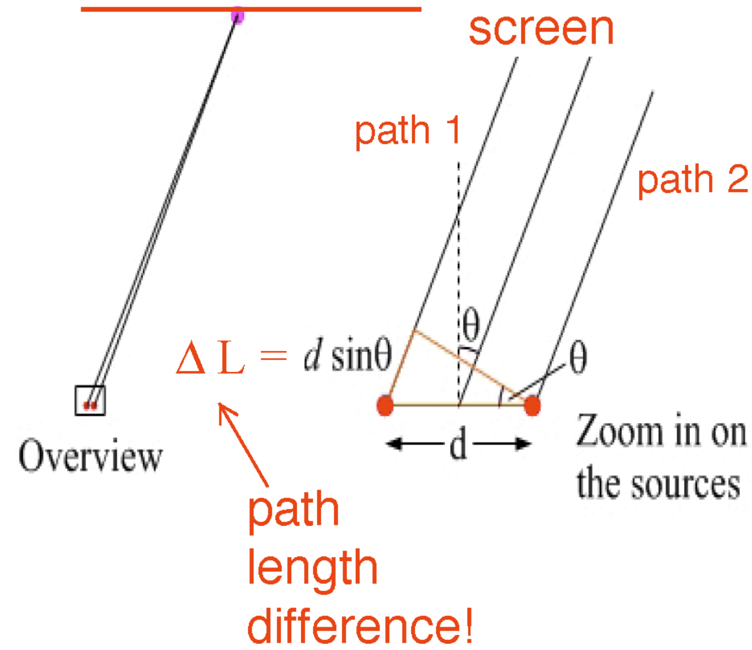
Light wavelength is so small, so any distance light travel is huge!



We can treat the rays as parallel (!) and write one more relation!

The double-source equation

For two sources sending out identical waves in phase:

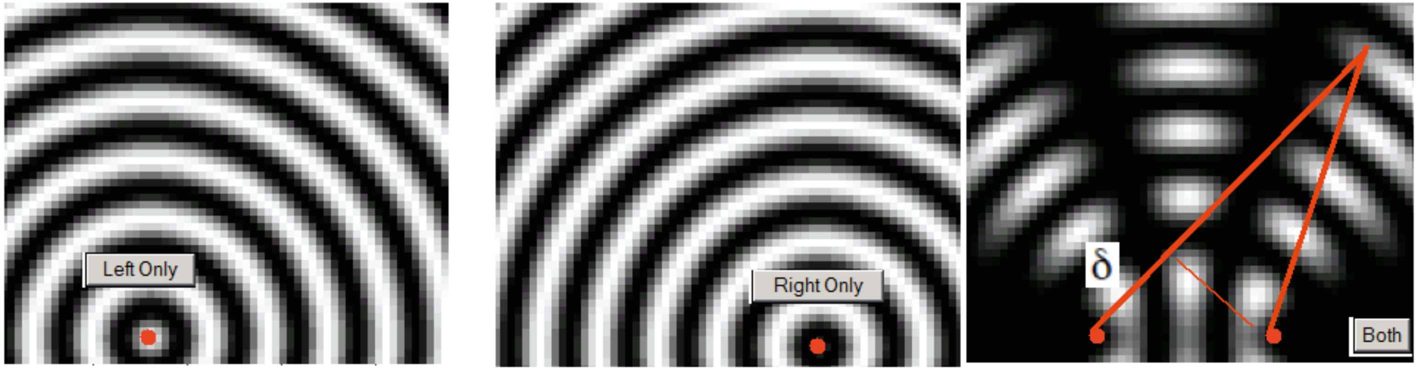


<u>Condition for constructive interference</u>

$$d \sin\theta = m\lambda$$, where m is an integer

<u>Condition for destructive interference</u>

$$d \sin\theta = (m - 1/2)\lambda$$, where m is an integer > 0



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.

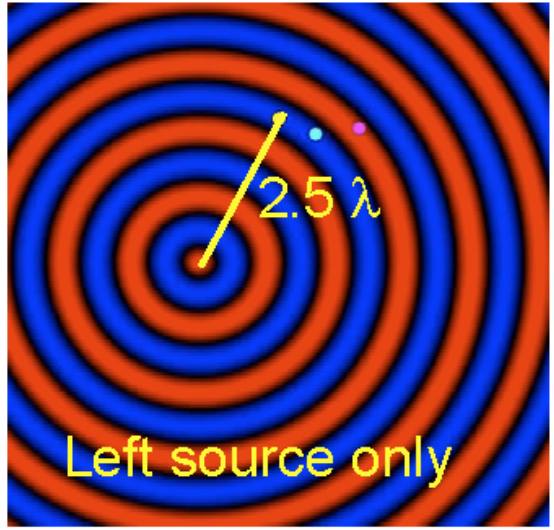
m = 0, 1, 2, 3, 4

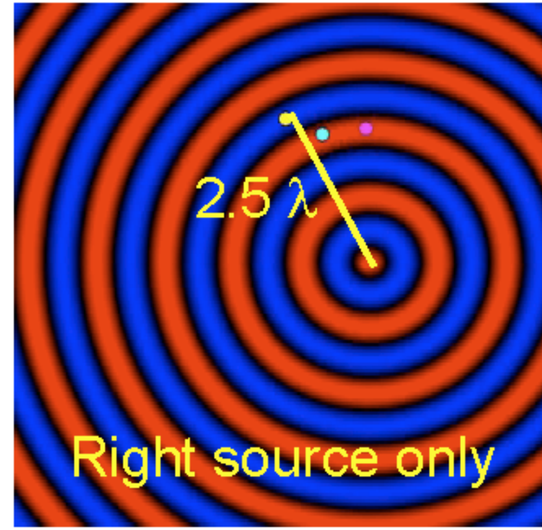
Condition for destructive interference: $\delta = (m - 1/2)\,\lambda$

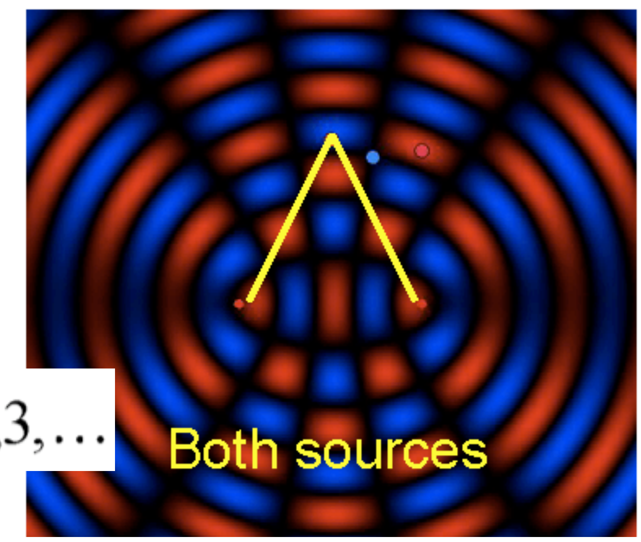
$\delta = \Delta r = |r_1 - r_2| > 0$ - **path length difference** m = 1, 2, 3, 4

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.





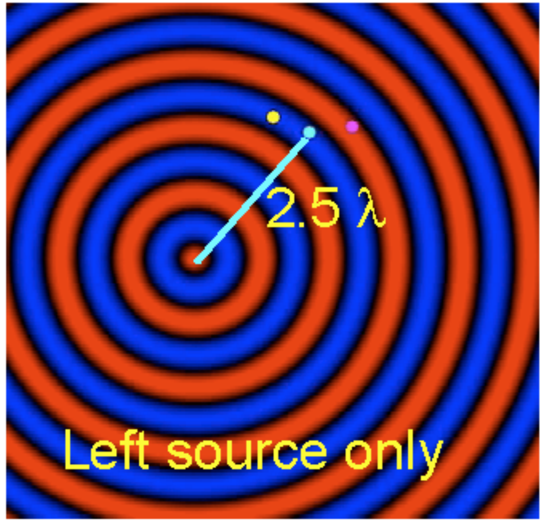


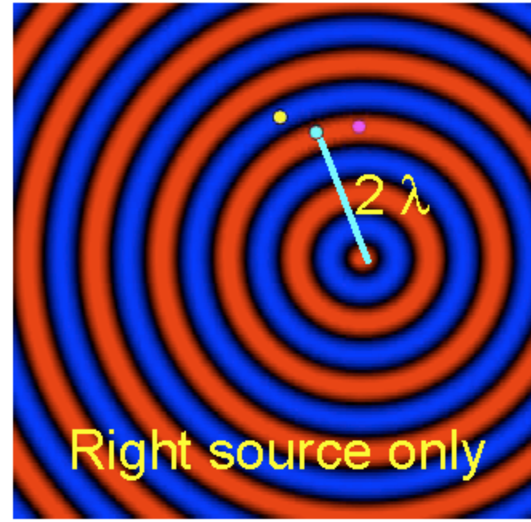
2-D standing wave!

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

Understanding the interference pattern

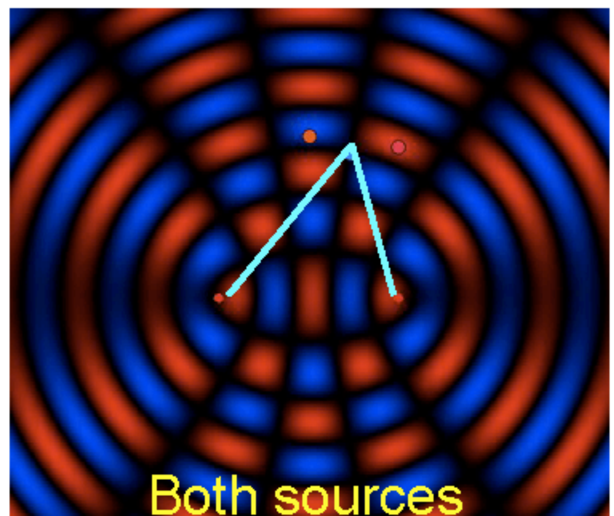
The blue point is half a wavelength farther from the left source than from the right source – giving destructive interference at that point.





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

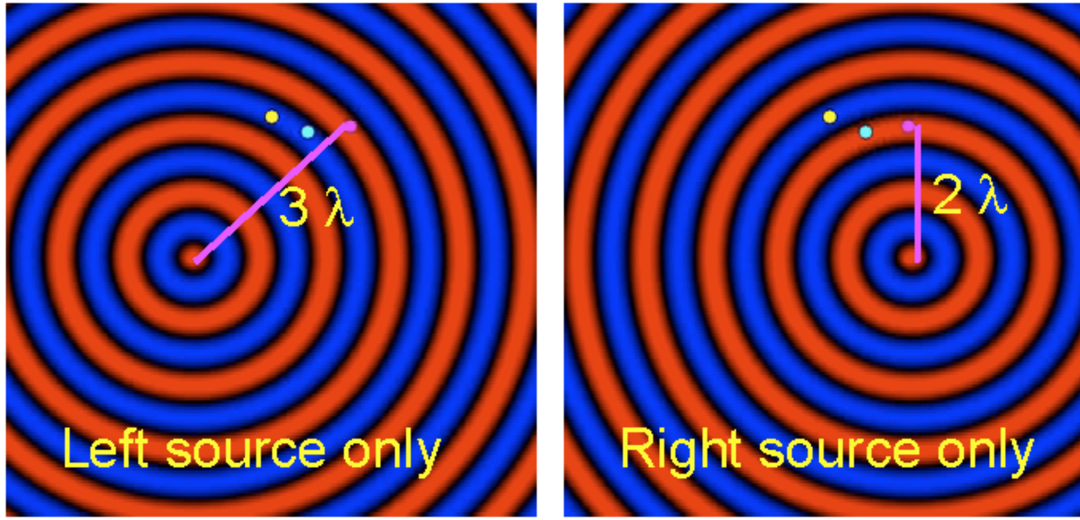
$$m = 1,2,3,\ldots$$

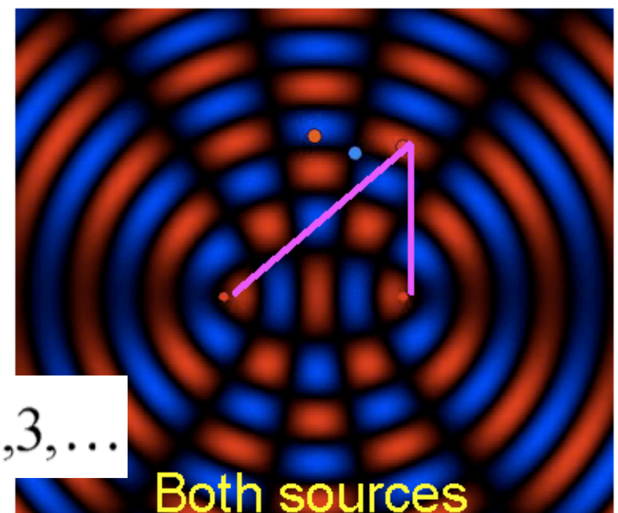


2-D standing wave!

Understanding the interference pattern

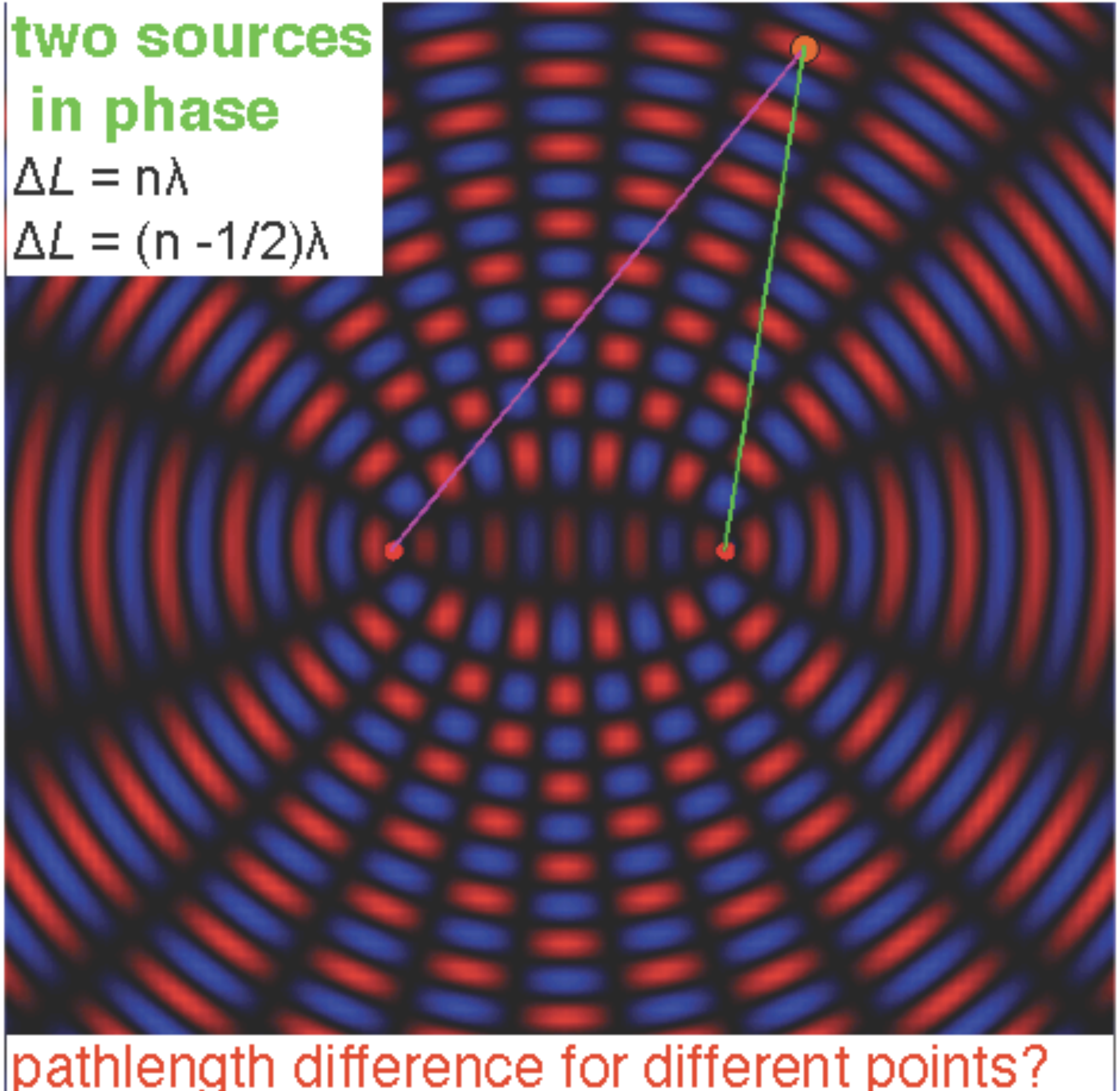
The purple point is a full wavelength farther from the left source than from the right source – giving constructive interference at that point.



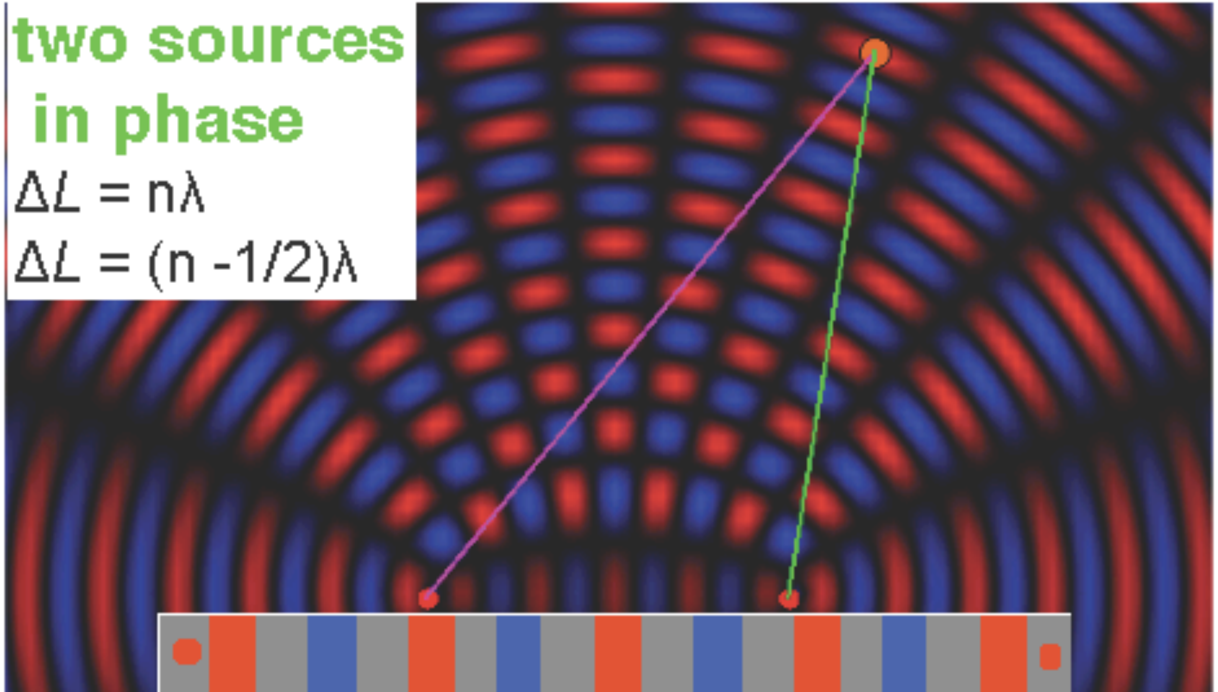


$$\left|\ell_2 - \ell_1\right| = m\lambda \qquad m = 0,1,2,3,\ldots$$

2-D standing wave!



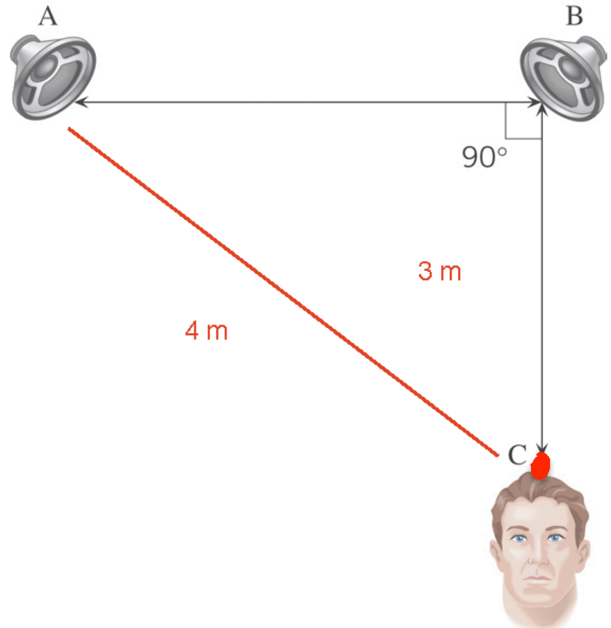
2-D standing wave!



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?

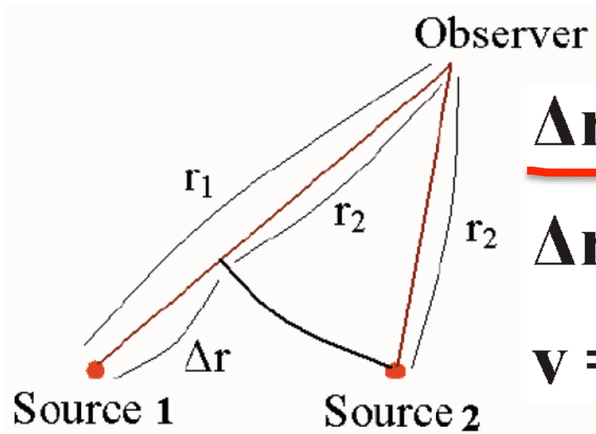


Two sources are broadcasting identical single frequency waves, in phase. You stand 3 m from one source and 4 m from the other. What is the lowest frequency at which constructive interference occurs at your location? Take the speed of sound to be 340 m/s.

n=0?

$\Delta r = 4 - 3 = 1$ m

1 m $= 1\lambda$; 2λ, 3λ



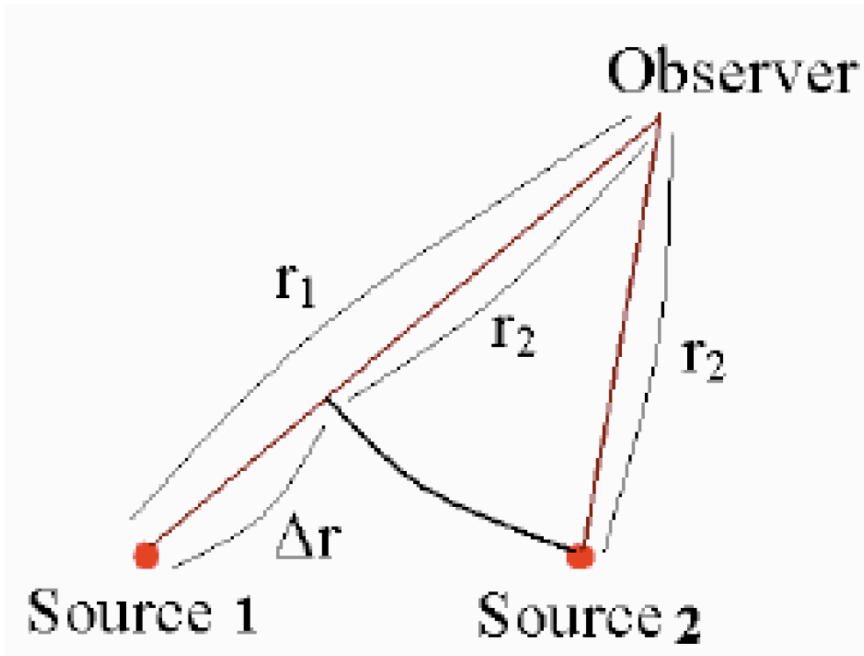
$$\Delta r = n\lambda, \; n = 0, 1, 2, \ldots$$

$$\Delta r = (2n - 1)\lambda/2 = (n - 1/2)\lambda, \; n = 1, 2, \ldots$$

$$v = f * \lambda \quad ; \quad f = \frac{v}{\lambda}$$

Two sources are broadcasting identical single-frequency waves, in phase. You stand 3 m from one source and 4 m from the other. What is the lowest frequency at which constructive interference occurs at your location? Take the speed of sound to be 340 m/s.

1. 170 Hz
2. 340 Hz
3. 680 Hz



$$\Delta \mathbf{r} = \mathbf{n}\lambda$$

$$v = f\lambda$$

First, find the path length difference - how much further are you from one source than the other? In this case it's simply 4 m – 3 m = 1 m. If that's an integral number of wavelengths, constructive interference occurs.

Constructive interference: $\Delta L = n\,\lambda$, where $n = 0, 1, 2, \ldots$

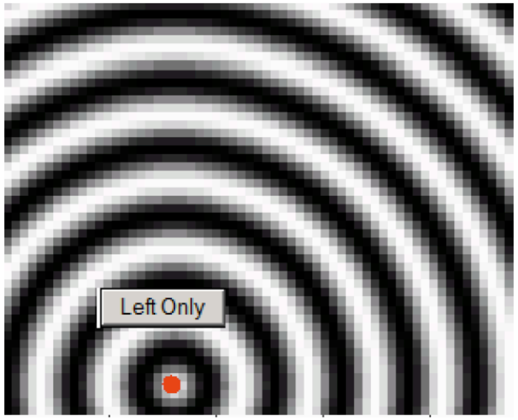
In this case: $1 \text{ meter} = n\,\lambda$ ✓

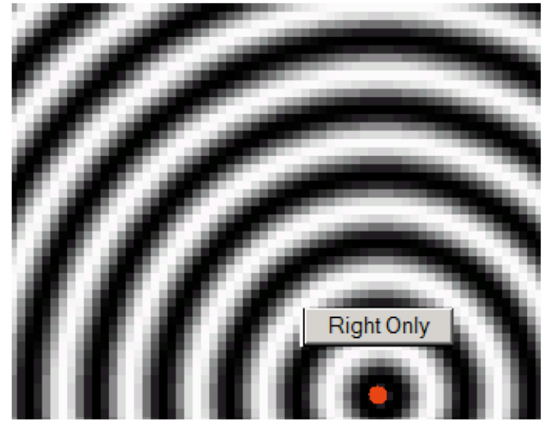
The lowest frequency corresponds to the largest wavelength, which corresponds to the smallest value of n ($n = 1$, in this case), giving a wavelength of 1 m.

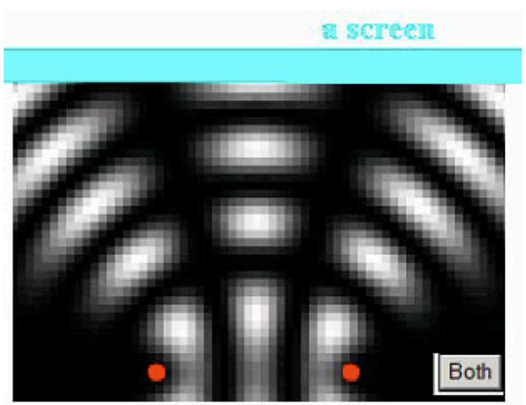
With a wavelength of 1 m and a speed of 340 m/s, the frequency is:

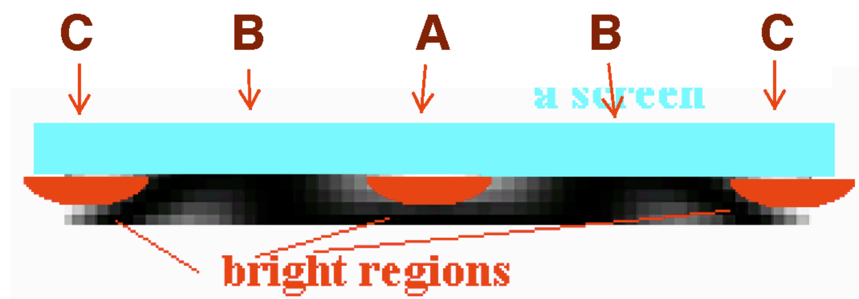
$$f = \frac{v}{\lambda} = \frac{340 \text{ m/s}}{1 \text{ m}} = 340 \text{ Hz}$$

Understanding the interference pattern









MIN = no light!

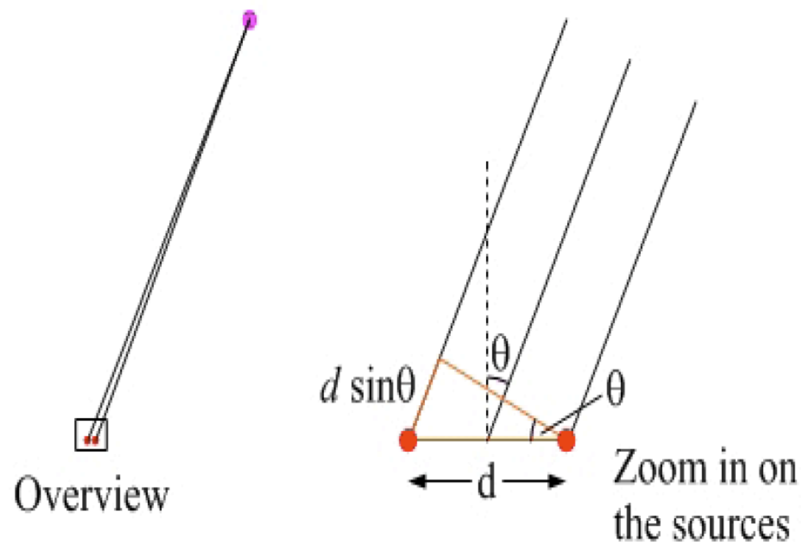
MAX = bright fringe (spot)

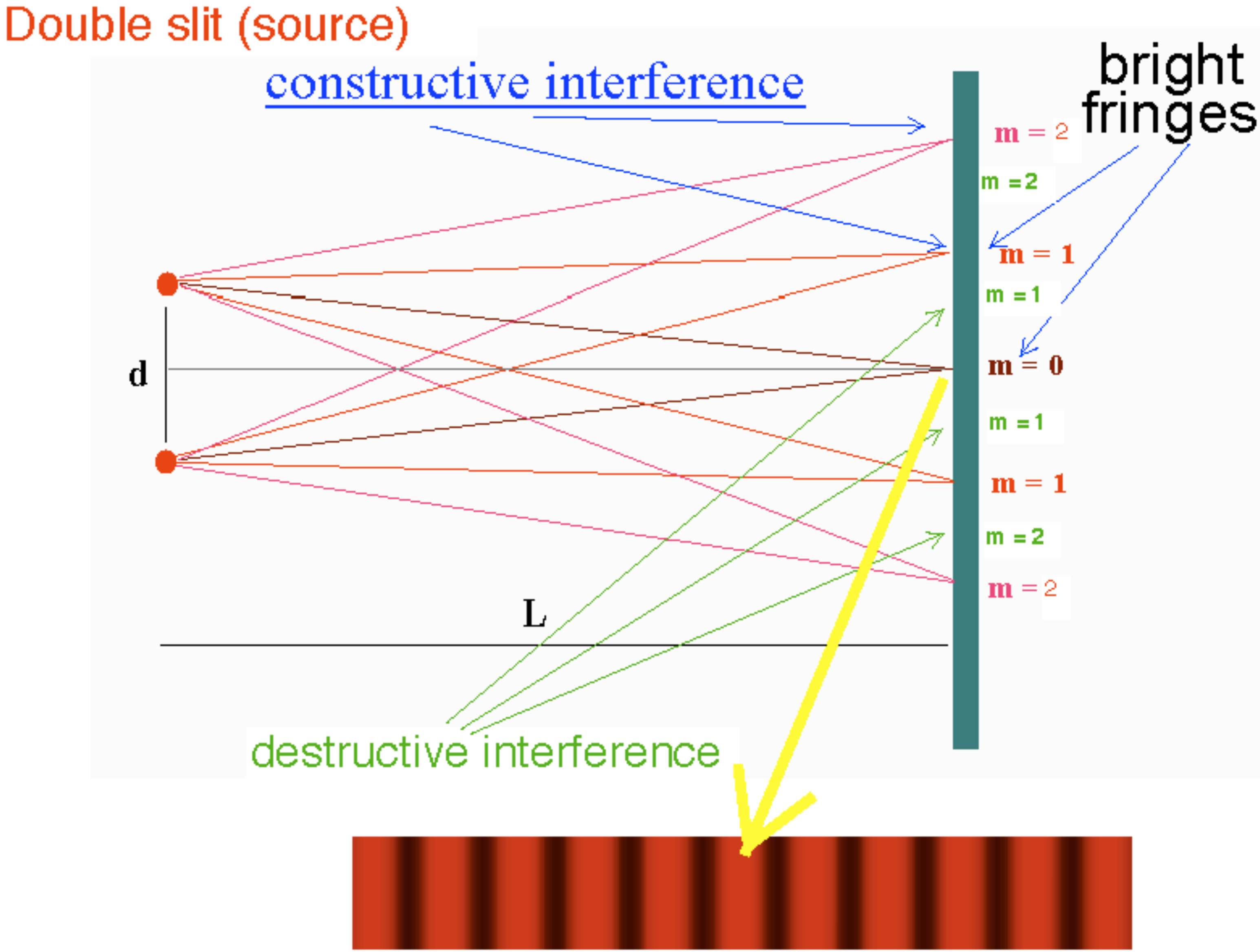
The double-source equation

Condition for constructive interference

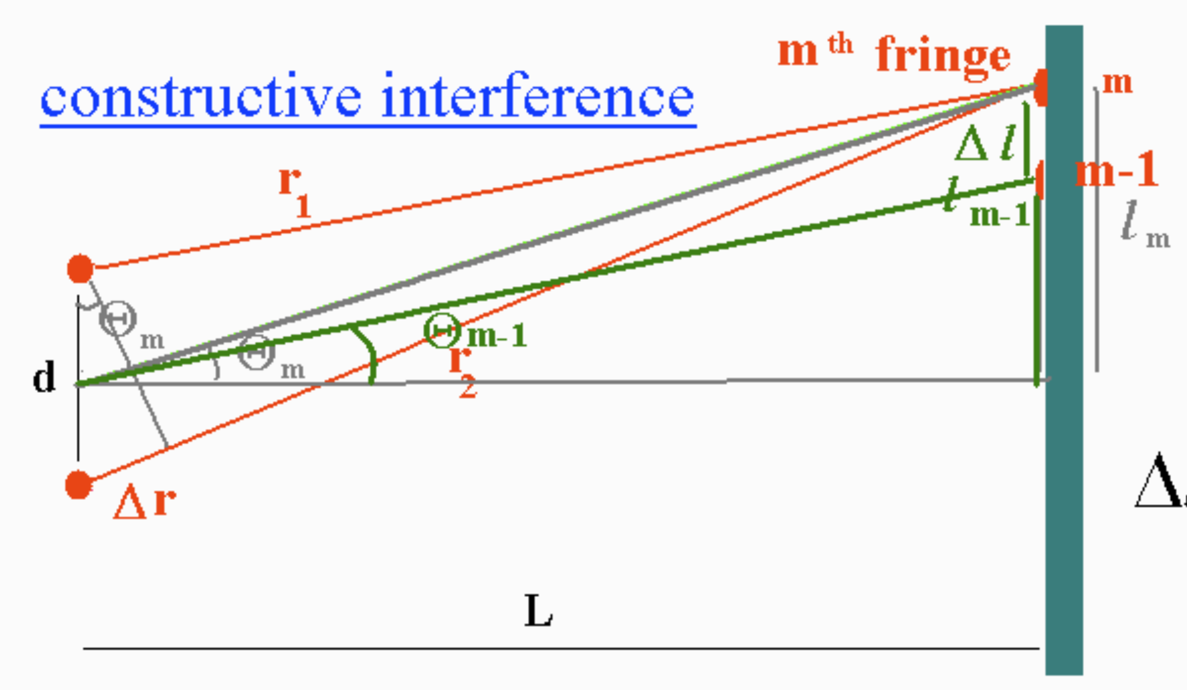
$$d \sin\theta = m\lambda \ ,$$

where m is an integer





Double slit (source)
constructive interference
bright fringes
m = 2
m = 2
m = 1
m = 1
m = 0
m = 1
m = 1
m = 2
m = 2
d
L
destructive interference



The distance between two nearest fringes is:

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

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

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

For small angles (meaning, small m)

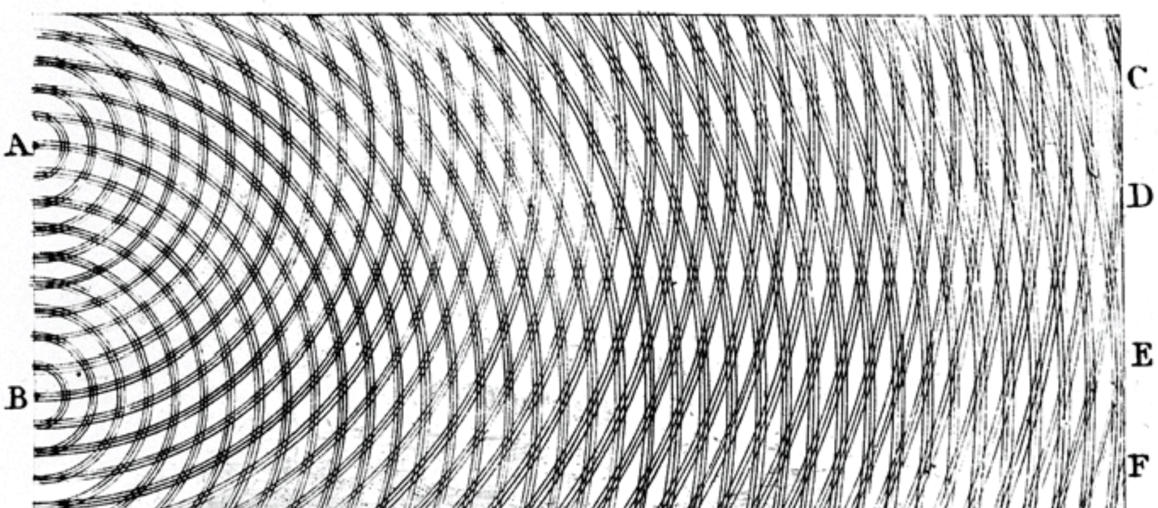
$$\sin\theta_m \approx \tan\theta_m \approx \theta_m$$

(When measured in radians)

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

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*.