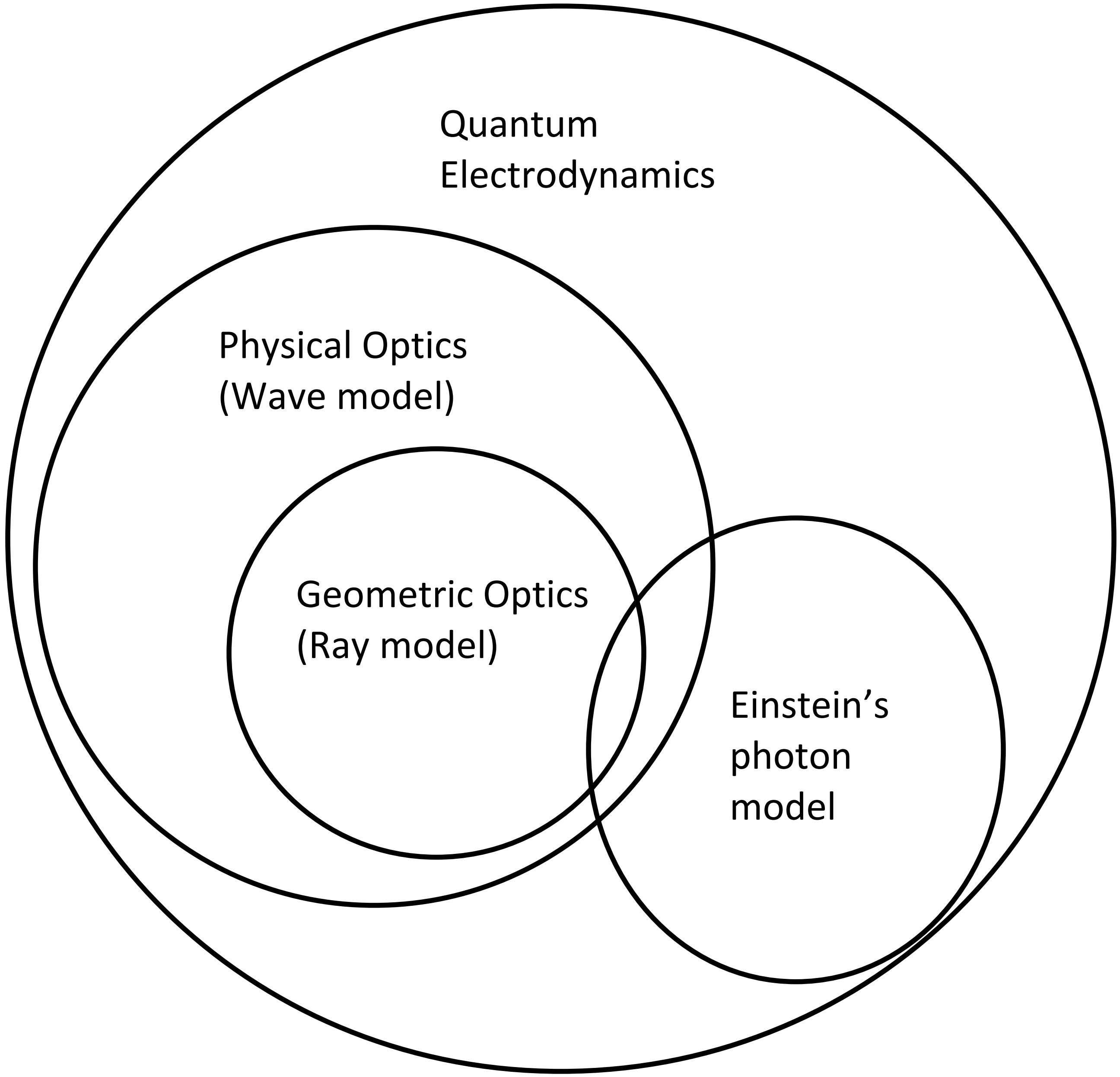
Chapter 10 - Light

Light: Three models

- Newton's particle model (rays)
  - Models light as bits of energy traveling very fast in straight lines. Each bit has a color. Intensity is the number of bits you get.
- Huygens's/Maxwell wave model
  - Models light at waves (transverse EM waves). Color determined by frequency, intensity by square of a total oscillating amplitude. (Allows for cancellation – interference.)
- Einstein's photon model
  - Models light as "wavicles" == quantum particles whose energy is determined by frequency and that can interferer with themselves.

Venn Diagram



Classical Electromagnetism - Maxwell's Equations

Everything in models (1) and (2) is contained in Maxwell's Equations

$$\nabla \cdot \vec{\mathbf{E}} = \frac{\rho}{\varepsilon_0}$$

Charge density

$$\nabla \times \vec{\mathbf{E}} = -\frac{\partial \vec{\mathbf{B}}}{\partial t}$$

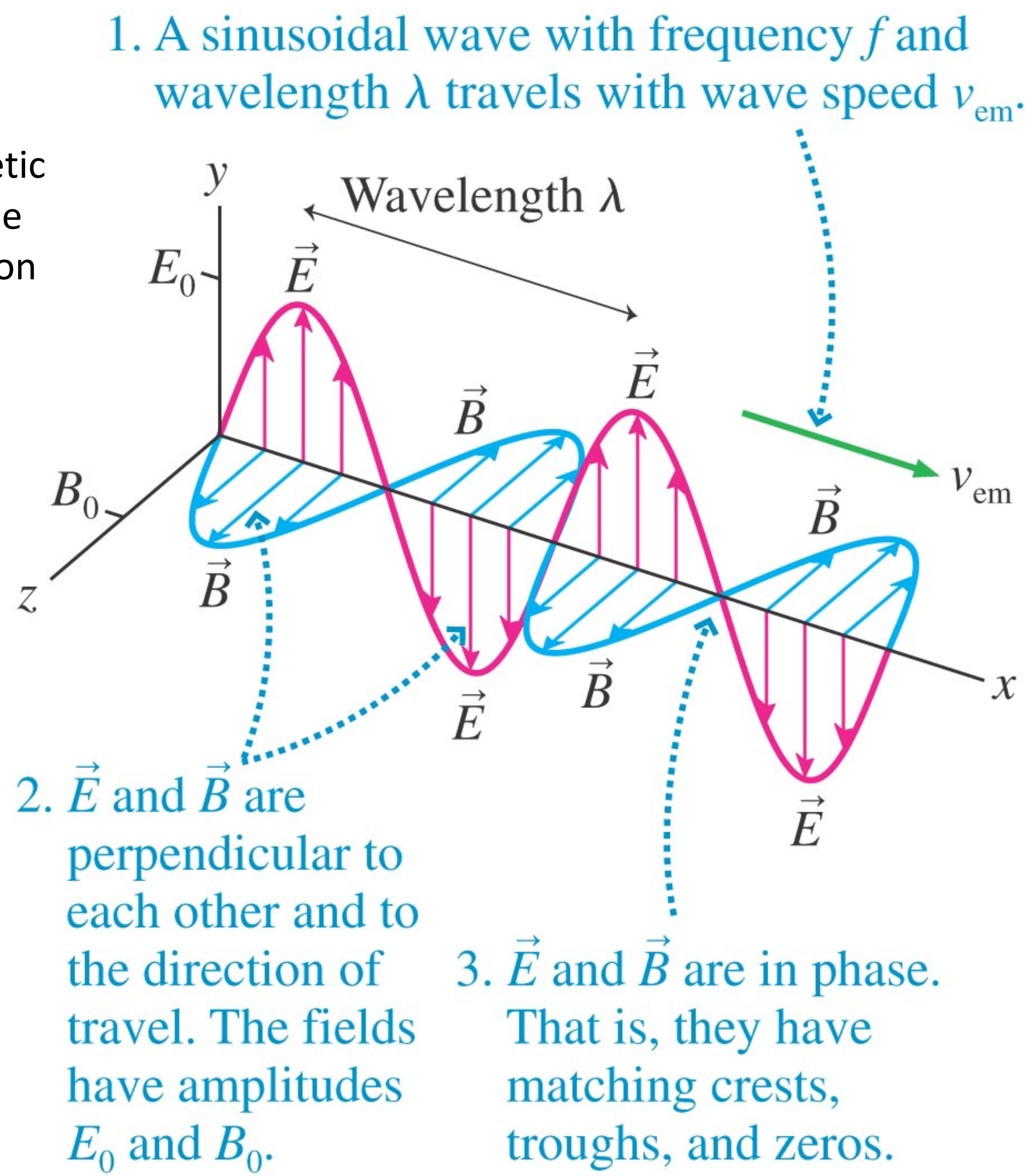
$$\nabla \cdot \vec{\mathbf{B}} = 0$$

$$\nabla \times \vec{\mathbf{B}} = \mu_0 (\vec{\mathbf{J}} + \varepsilon_0 \frac{\partial \vec{\mathbf{E}}}{\partial t})$$

Current density

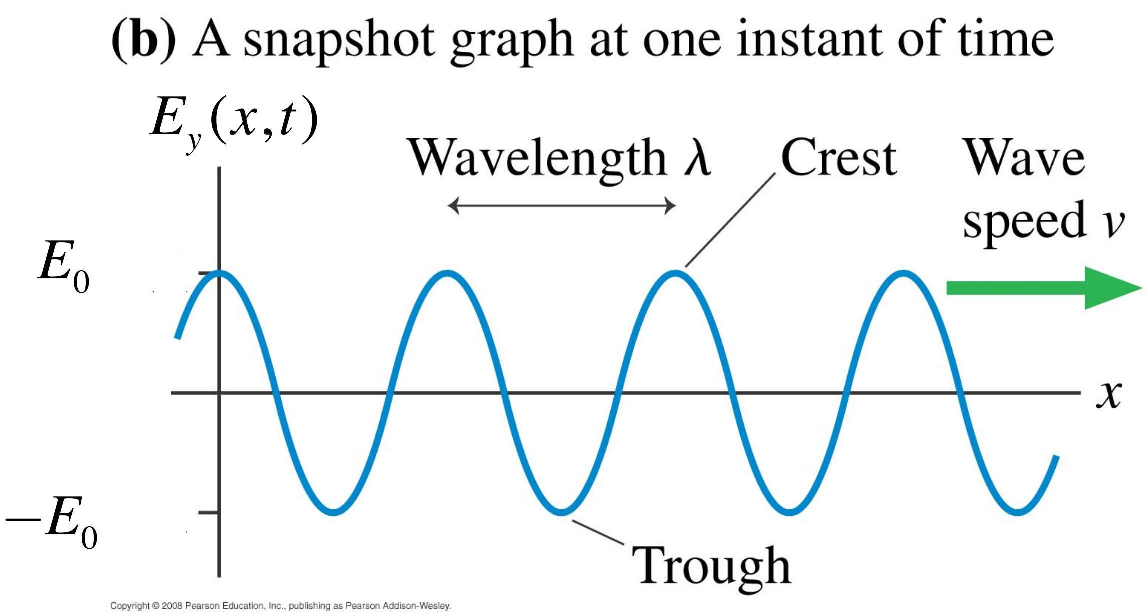
You are not expected to know these. Just know they exist.

Electromagnetic Waves are one type of solution to Maxwell's equations



Special Case Sinusoidal Waves

$$E_y(x,t) = f_+(x - v_{em}t) = E_0 \cos\left[k(x - v_{em}t)\right]$$



Wavenumber and wavelength

$$k = 2\pi / \lambda$$

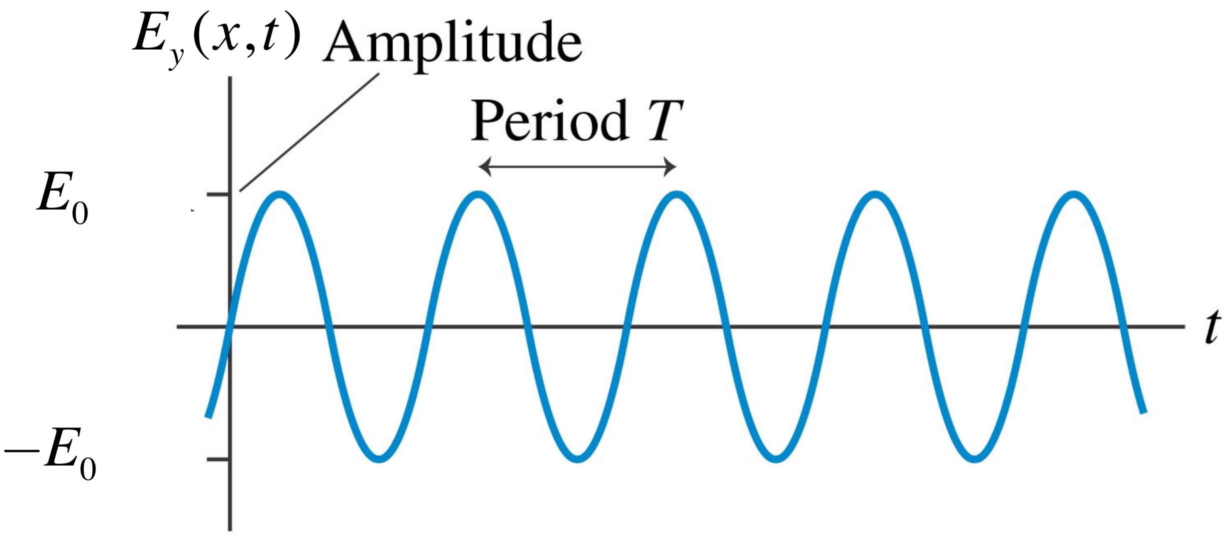
$$\lambda = 2\pi / k$$

These two contain the same information

Special Case Sinusoidal Waves

$$E_y(x,t) = f_+(x - v_{em}t) = E_0 \cos\left[k(x - v_{em}t)\right]$$

(a) A history graph at one point in space



$2\pi = kv_{em}T$

Introduce

$\omega = 2\pi / T$

$f = 1/T$

Different ways of saying the same thing:

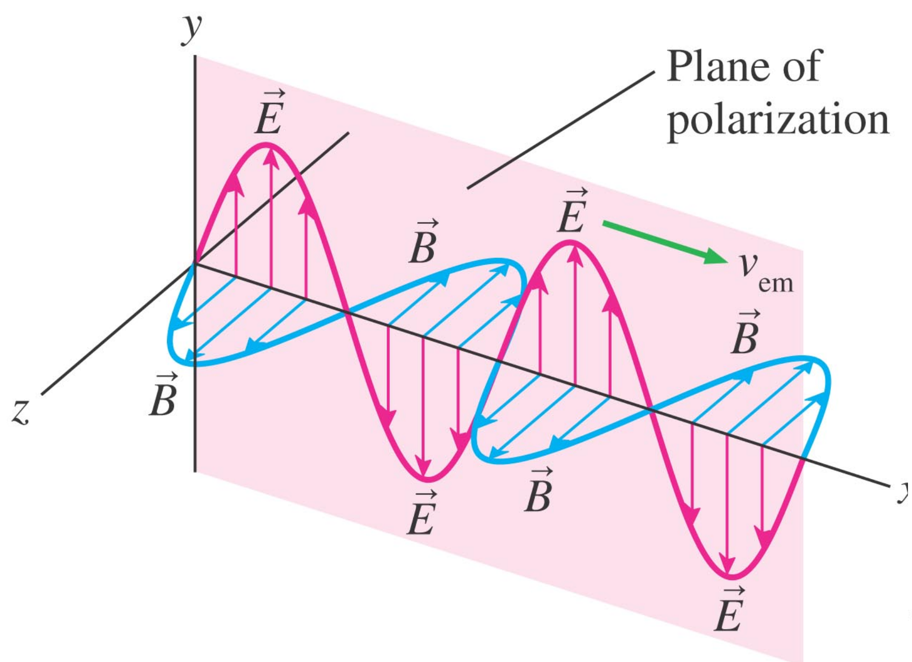
$$\omega / k = v_{em} \qquad f\lambda = v_{em}$$

Polarizations

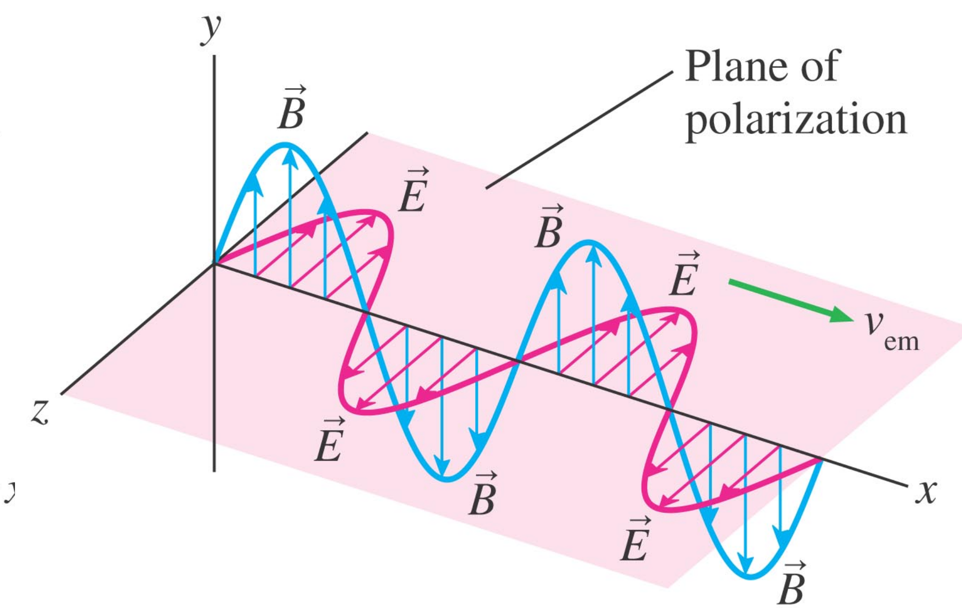
We picked this combination of fields: E_y - B_z

Could have picked this combination of fields: E_z - B_y

(a) Vertical polarization

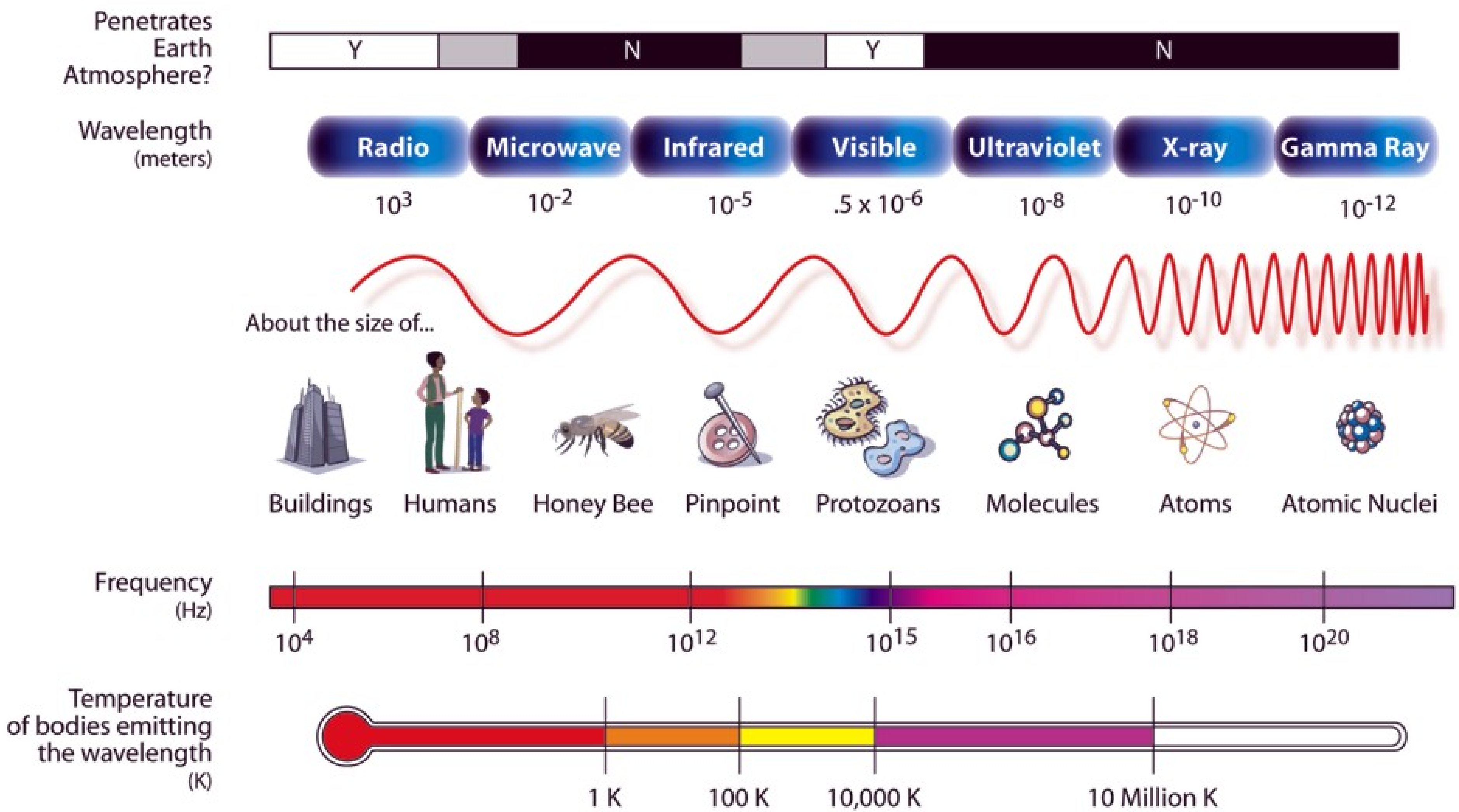


(b) Horizontal polarization

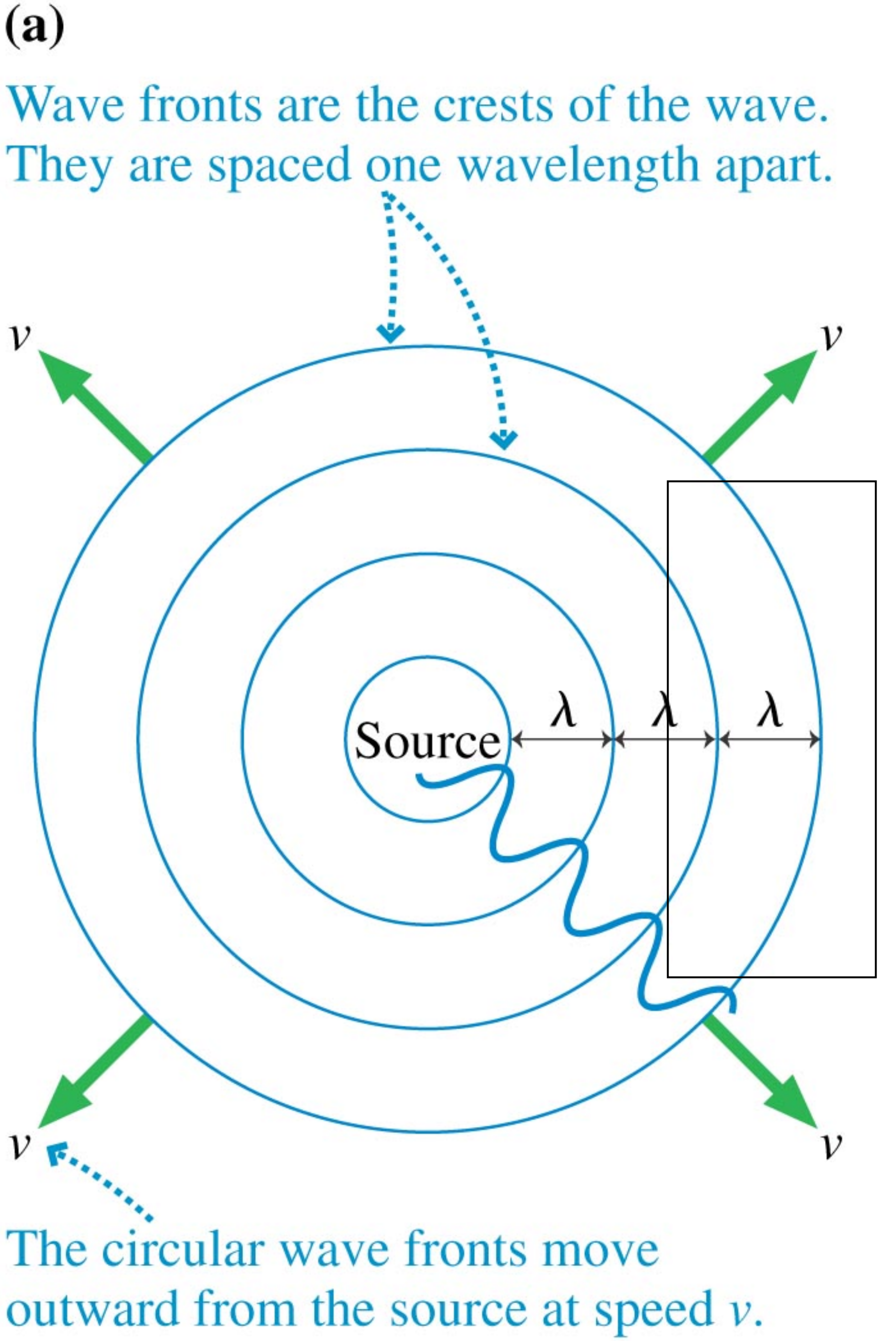


These are called plane polarized. Fields lie in plane

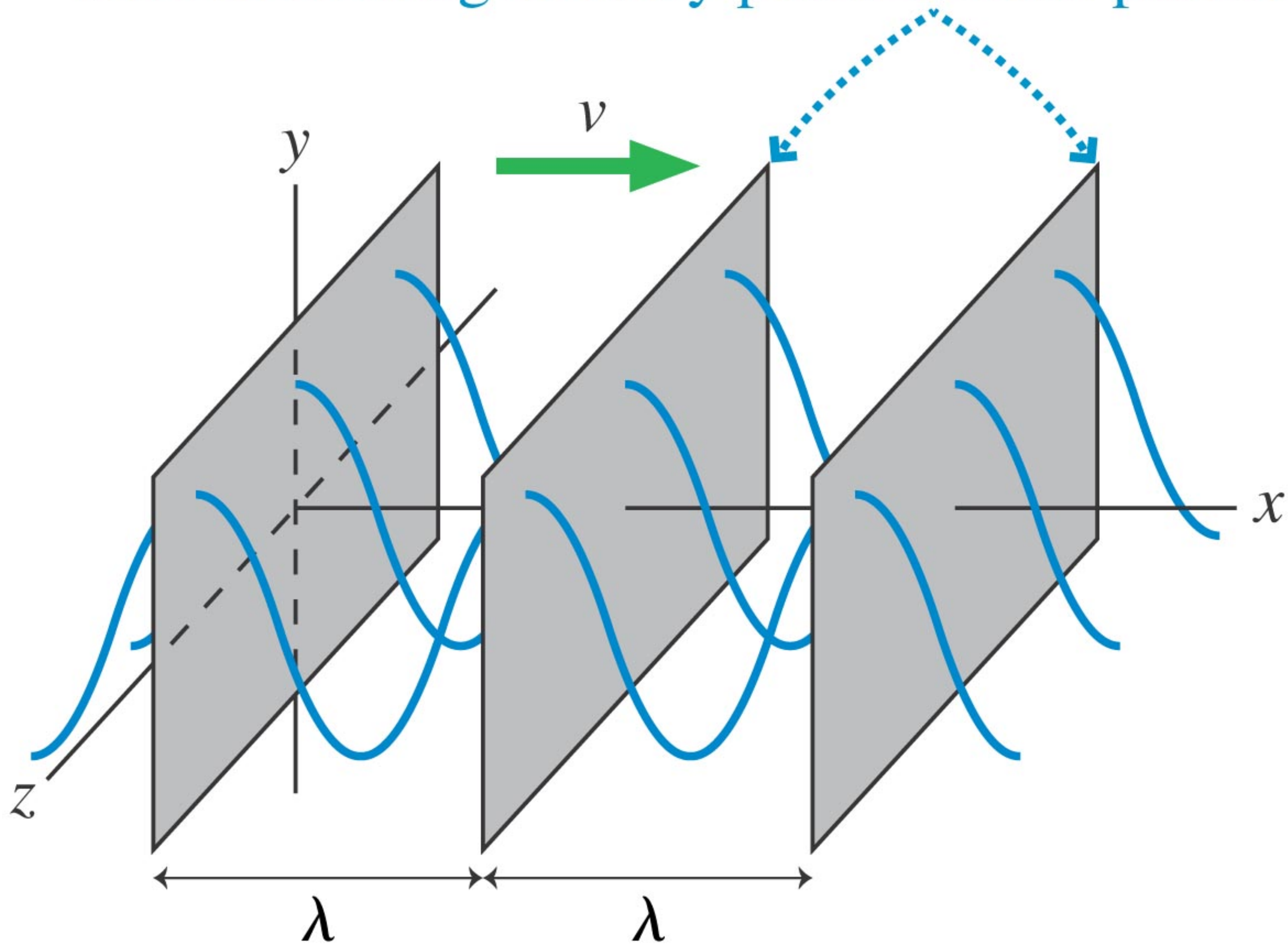
THE ELECTROMAGNETIC SPECTRUM

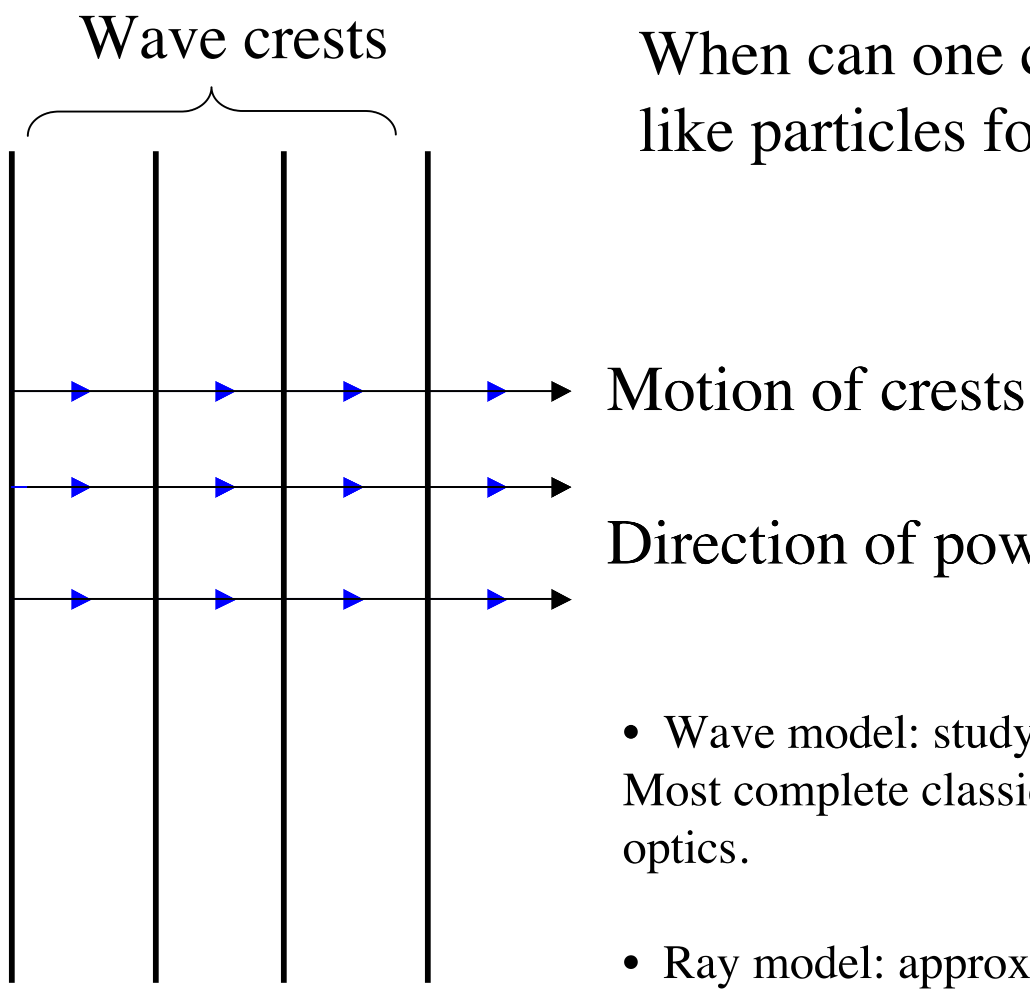


Waves emanating from a point source



Very far from the source, small segments of spherical wave fronts appear to be planes. The wave is cresting at every point in these planes.



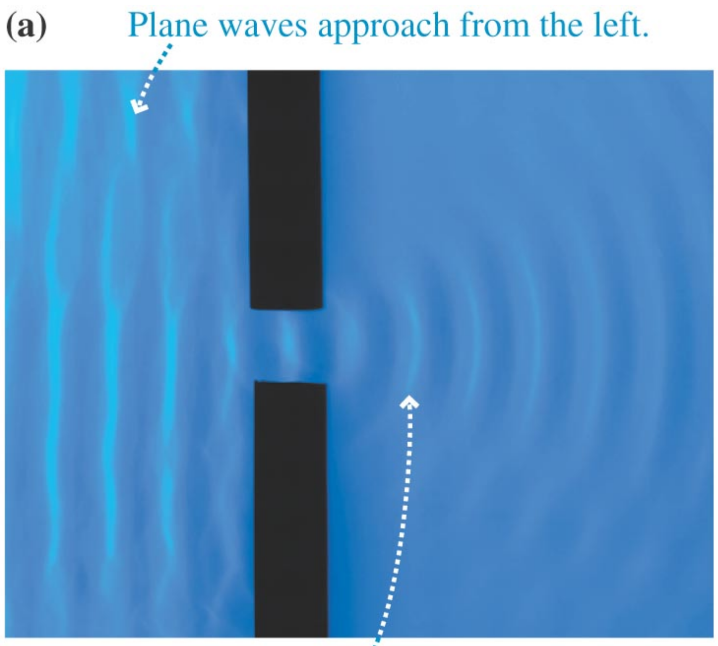


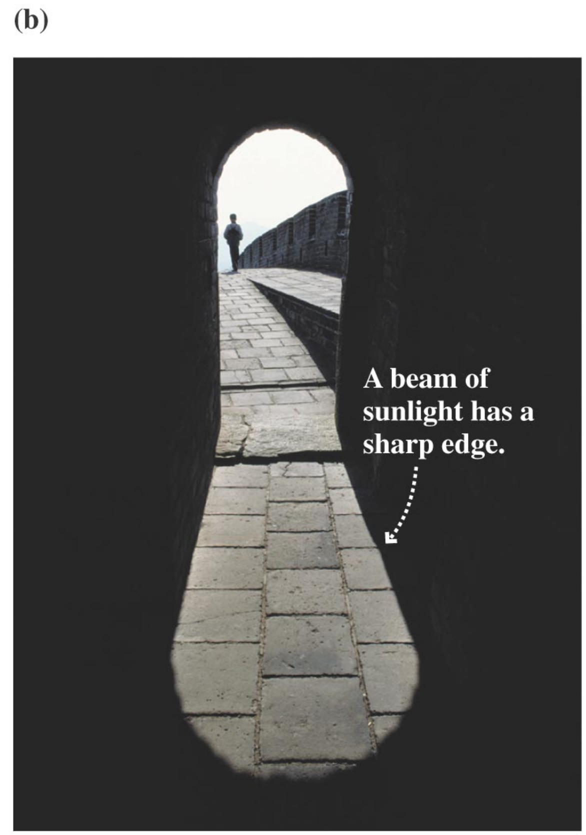
When can one consider waves to be like particles following a trajectory?

- Wave model: study solution of Maxwell equations. Most complete classical description. Called physical optics.

- Ray model: approximate propagation of light as that of particles following specific paths or “rays”. Called geometric optics.

- Quantum optics: Light actually comes in chunks called photons





λ

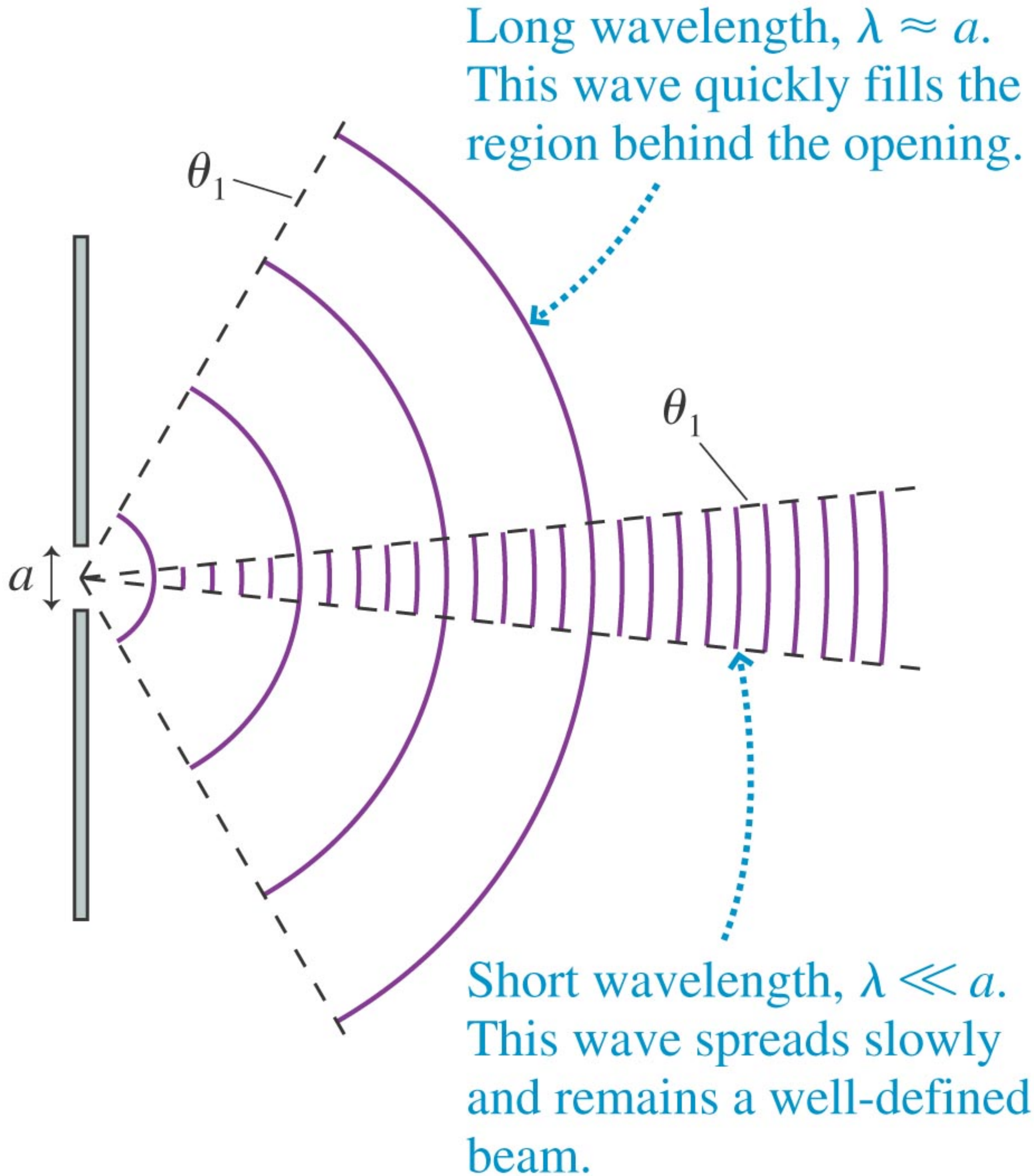
Comparable to opening size

What is the difference?
Diffraction.

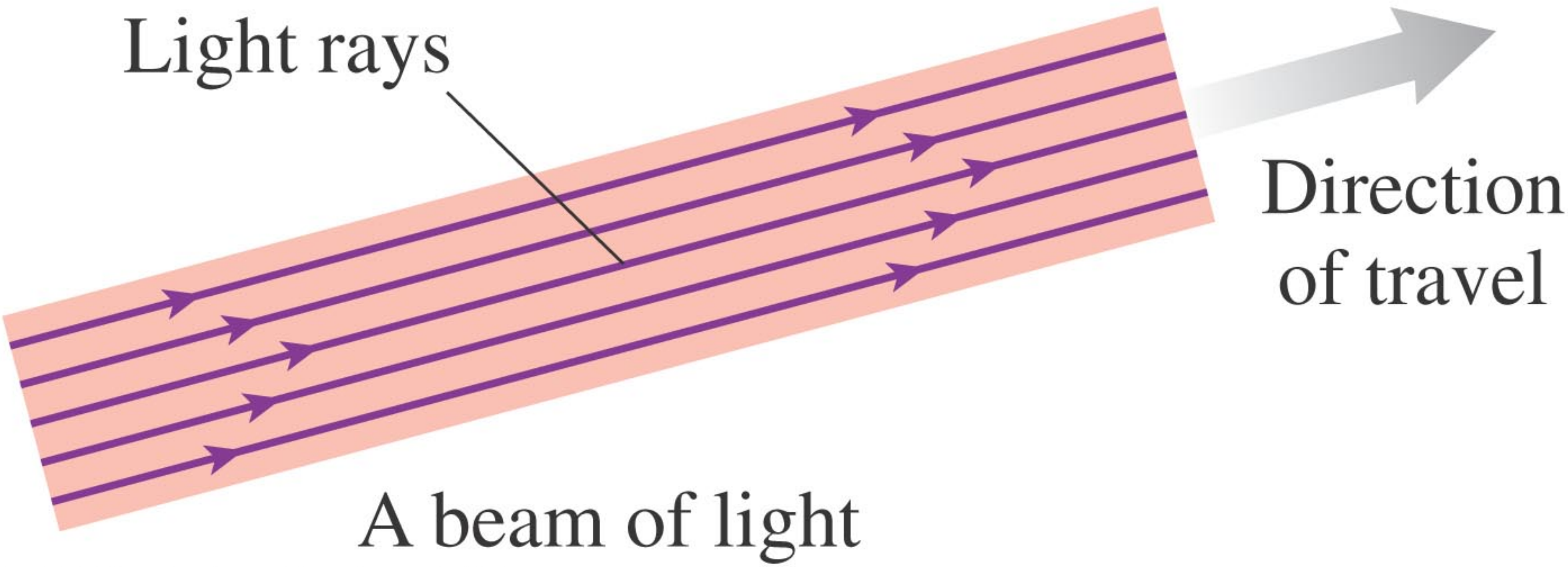
λ

Much smaller than opening size

Diffraction

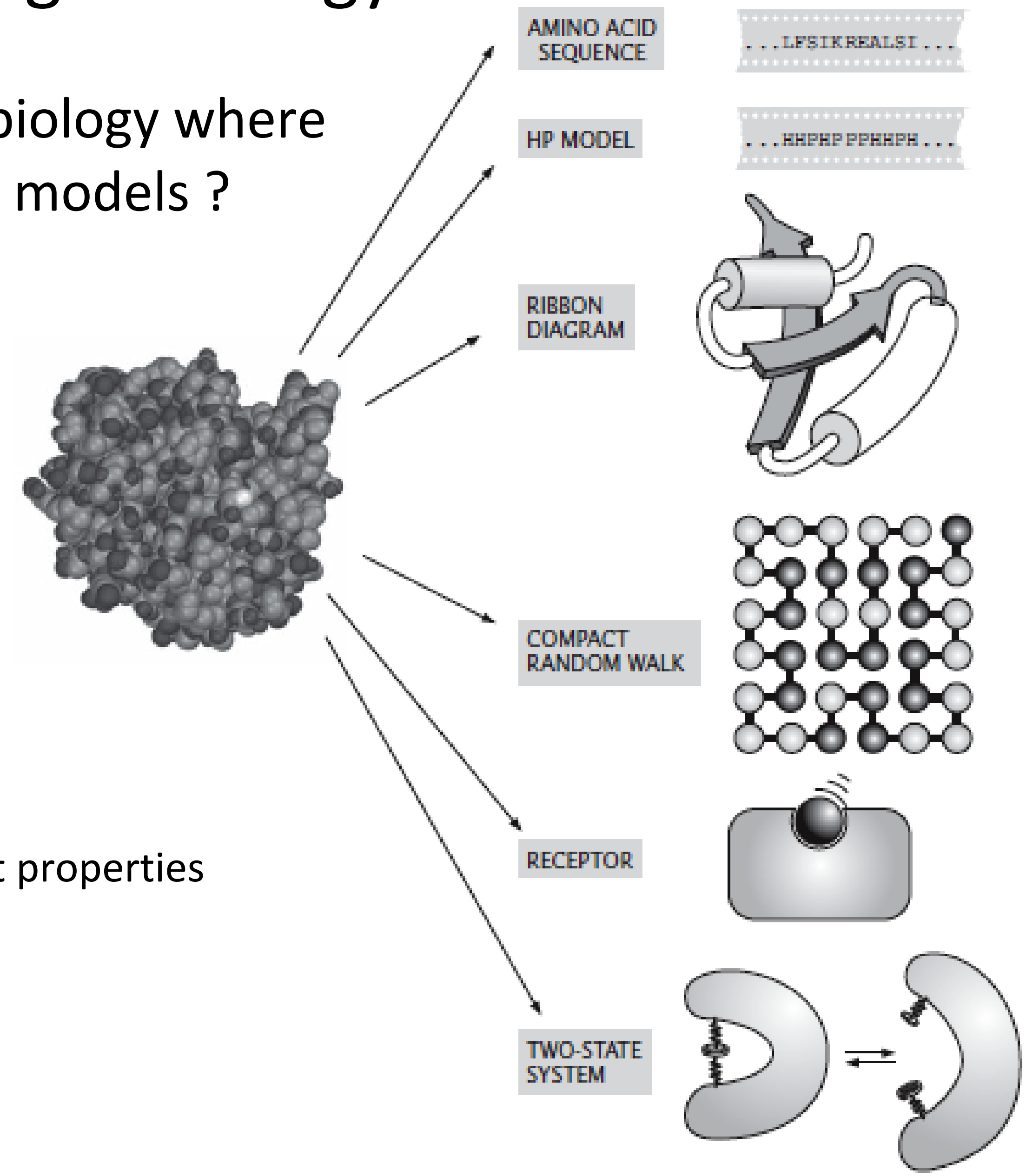


In the Ray Picture a beam of light is a bundle of parallel traveling rays



Modeling in Biology

Are there examples in biology where you also need different models ?



Each model highlights different properties of the protein

-Hydrophobic character

-Folding property

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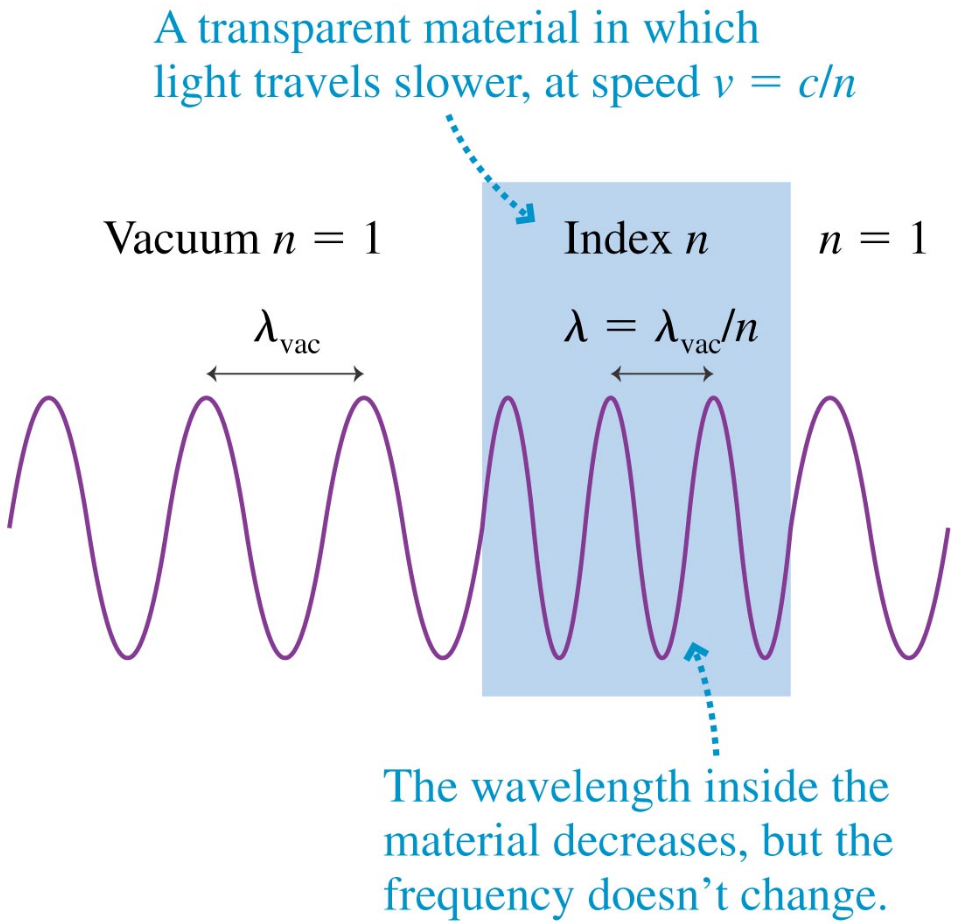
Index of refraction

$$n = \frac{speed\ of\ light\ in\ vacuum}{speed\ of\ light\ in\ material} = \frac{c}{v_{em}} = \sqrt{\kappa}$$

TABLE 20.2 Typical indices of refraction

Material	Index of refraction
Vacuum	1 exactly
Air	1.0003
Water	1.33
Glass	1.50
Diamond	2.42



For sinusoidal waves the following is still true

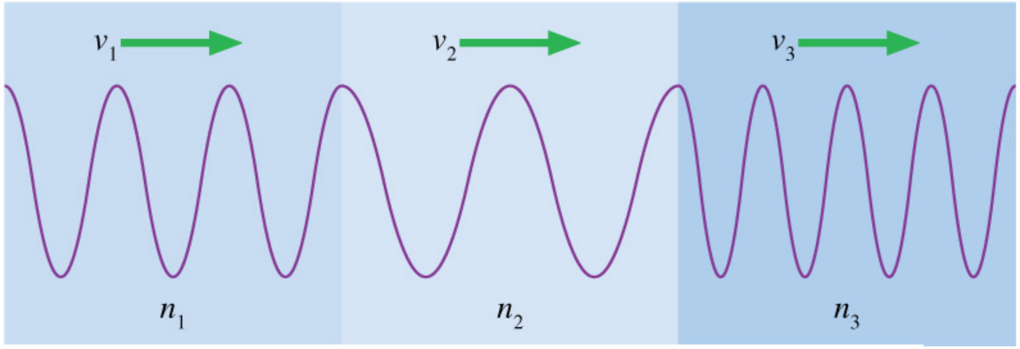
$$f\lambda = v_{em}$$

$$\omega / k = v_{em}$$

Frequency is the same in both media

Wavelength changes

A light wave travels through three transparent materials of equal thickness. Rank in order, from the largest to smallest, the indices of refraction n_1, n_2, and n_3.



A. $n_1 > n_2 > n_3$

B. $n_2 > n_1 > n_3$

C. $n_3 > n_1 > n_2$

D. $n_3 > n_2 > n_1$

E. $n_1 = n_2 = n_3$

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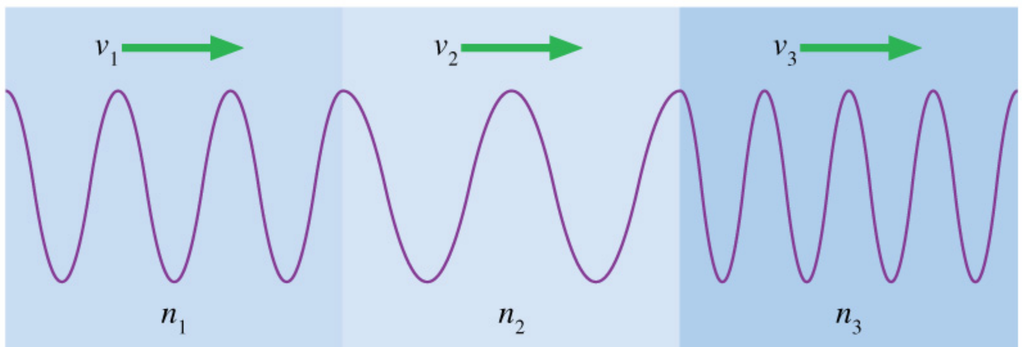


A. $n_1 > n_2 > n_3$

B. $n_2 > n_1 > n_3$

✔ **C. $n_3 > n_1 > n_2$**

D. $n_3 > n_2 > n_1$

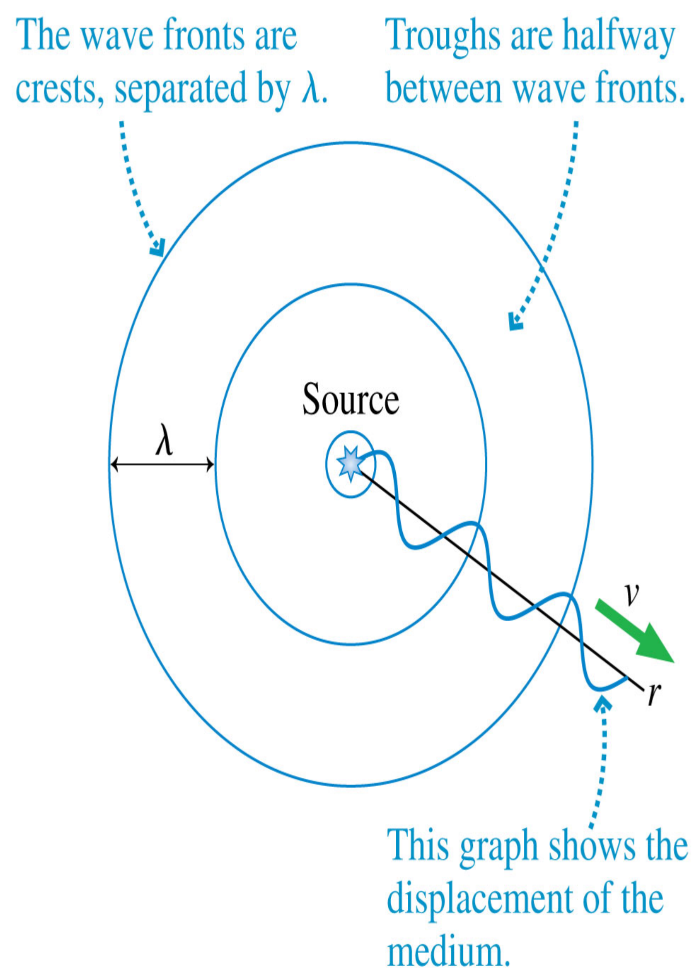
E. $n_1 = n_2 = n_3$

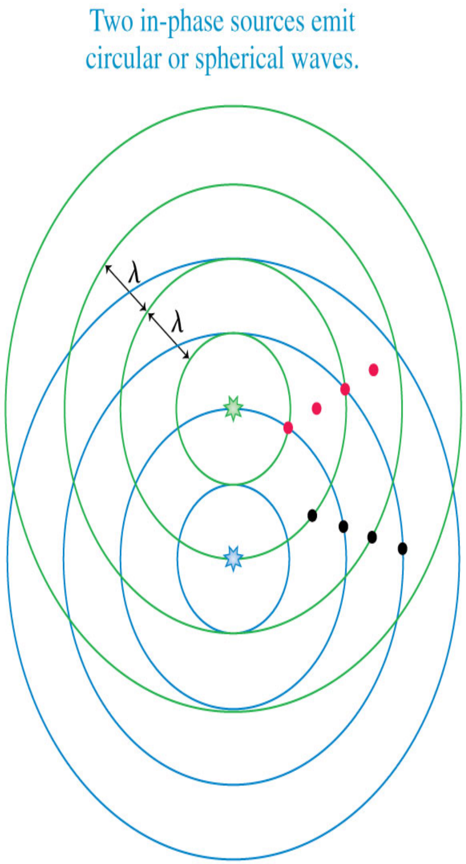
- A circular or spherical wave can be written:

$$D(r, t) = a \sin(kr - \omega t + \phi_0)$$

where r is the distance measured outward from the source.

- The amplitude a of a circular or spherical wave diminishes as r increases.





• = Points of constructive interference. A crest is aligned with a crest, or a trough with a trough.

• = Points of destructive interference. A crest is aligned with a trough of another wave.

- The mathematical description of interference in two or three dimensions is very similar to that of one-dimensional interference.
- The conditions for constructive and destructive interference are:

Maximum constructive interference:

$$\Delta\phi = 2\pi\frac{\Delta r}{\lambda} + \Delta\phi_0 = m \cdot 2\pi$$

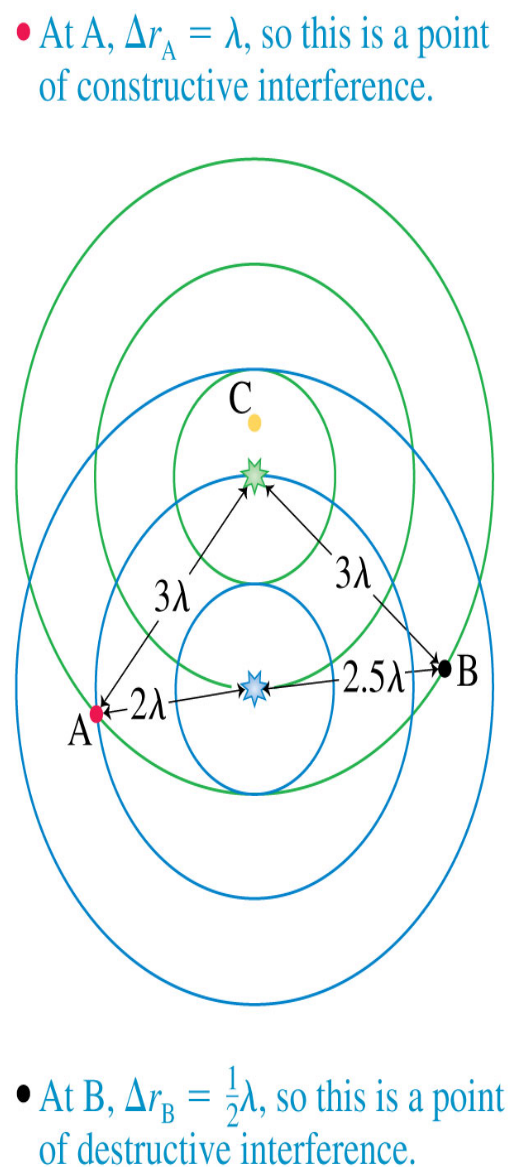
Perfect destructive interference:

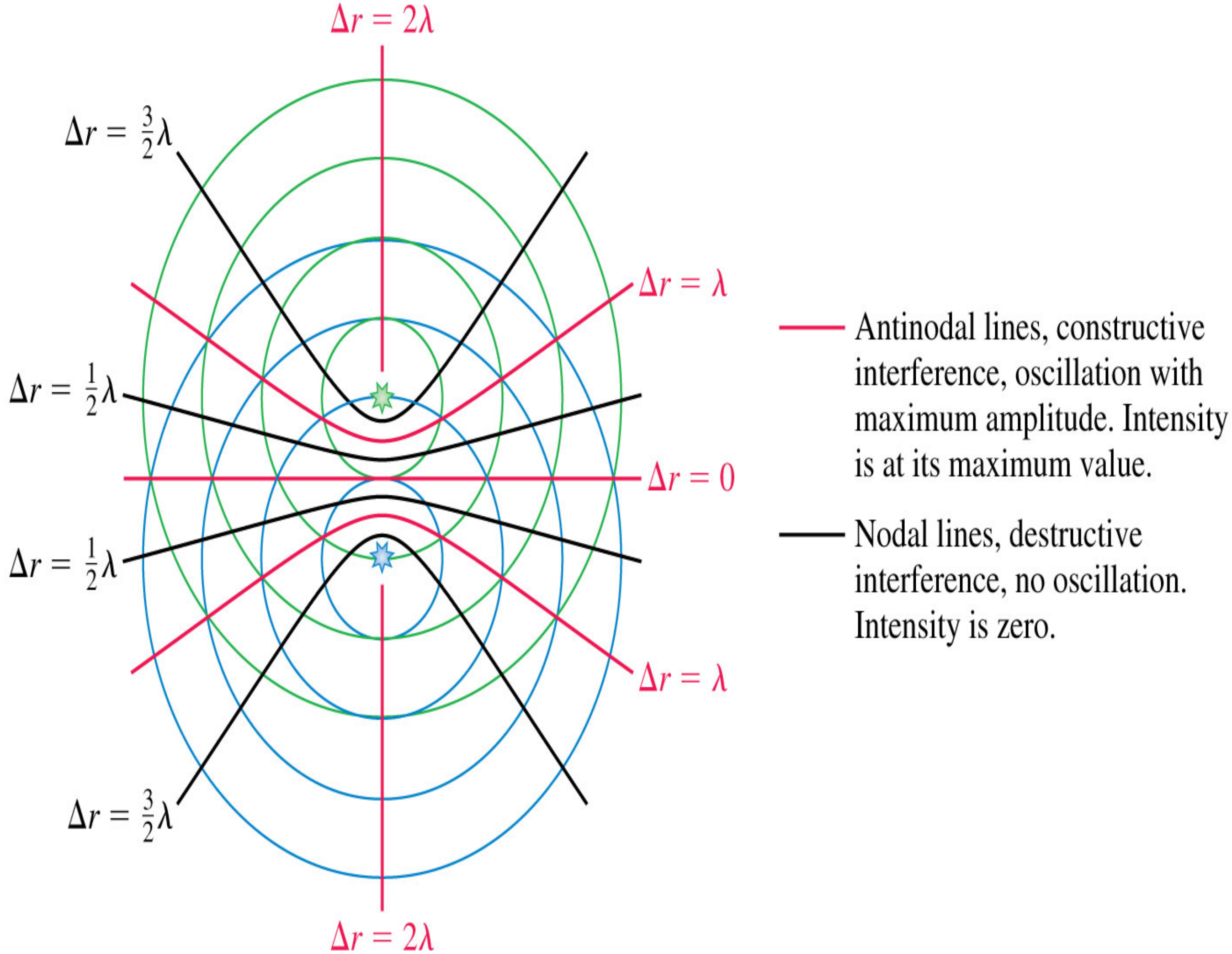
$$\Delta\phi = 2\pi\frac{\Delta r}{\lambda} + \Delta\phi_0 = \quad m + \frac{1}{2} \quad \cdot 2\pi$$

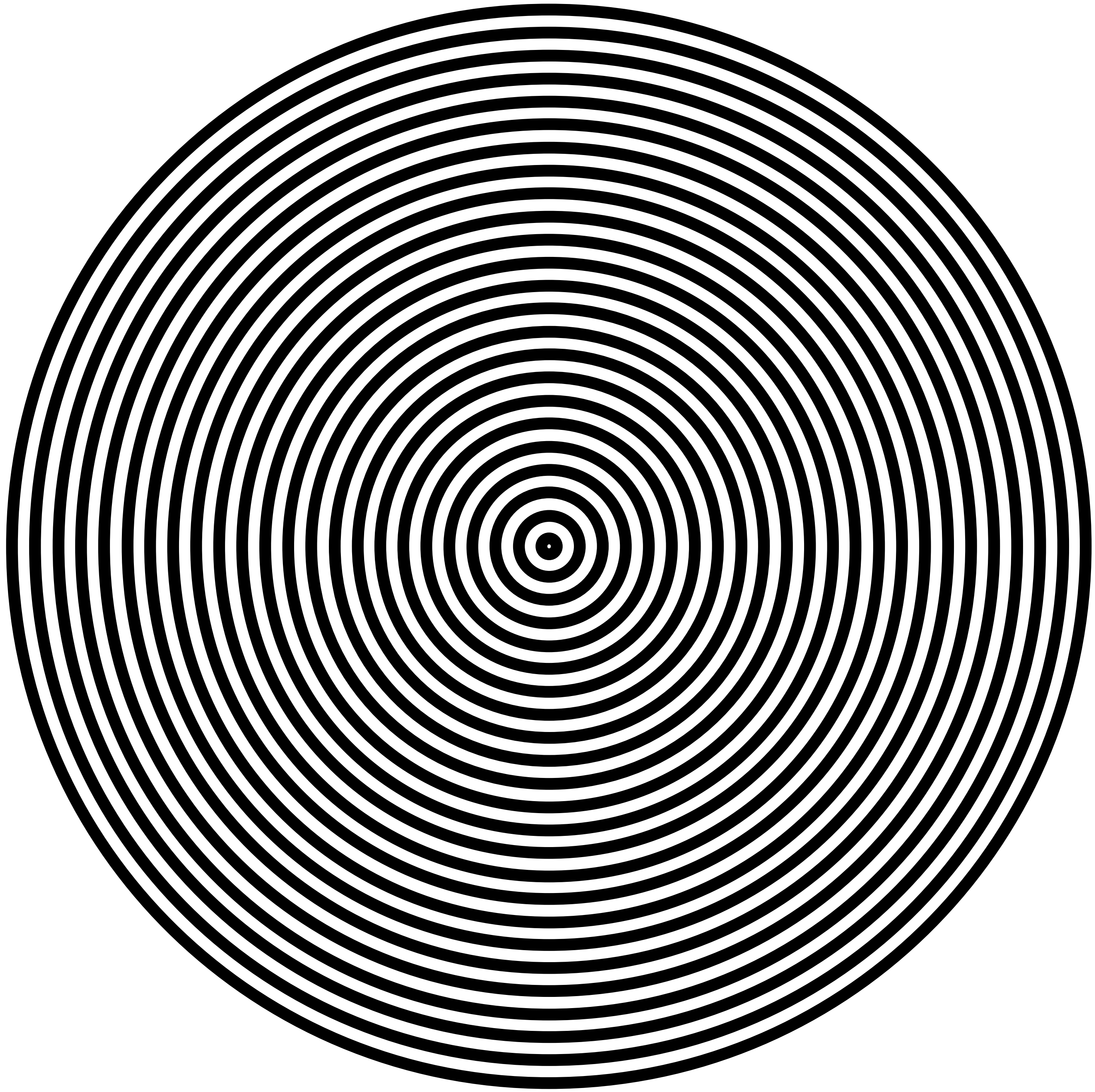
$$m = 0, 1, 2, \ldots$$

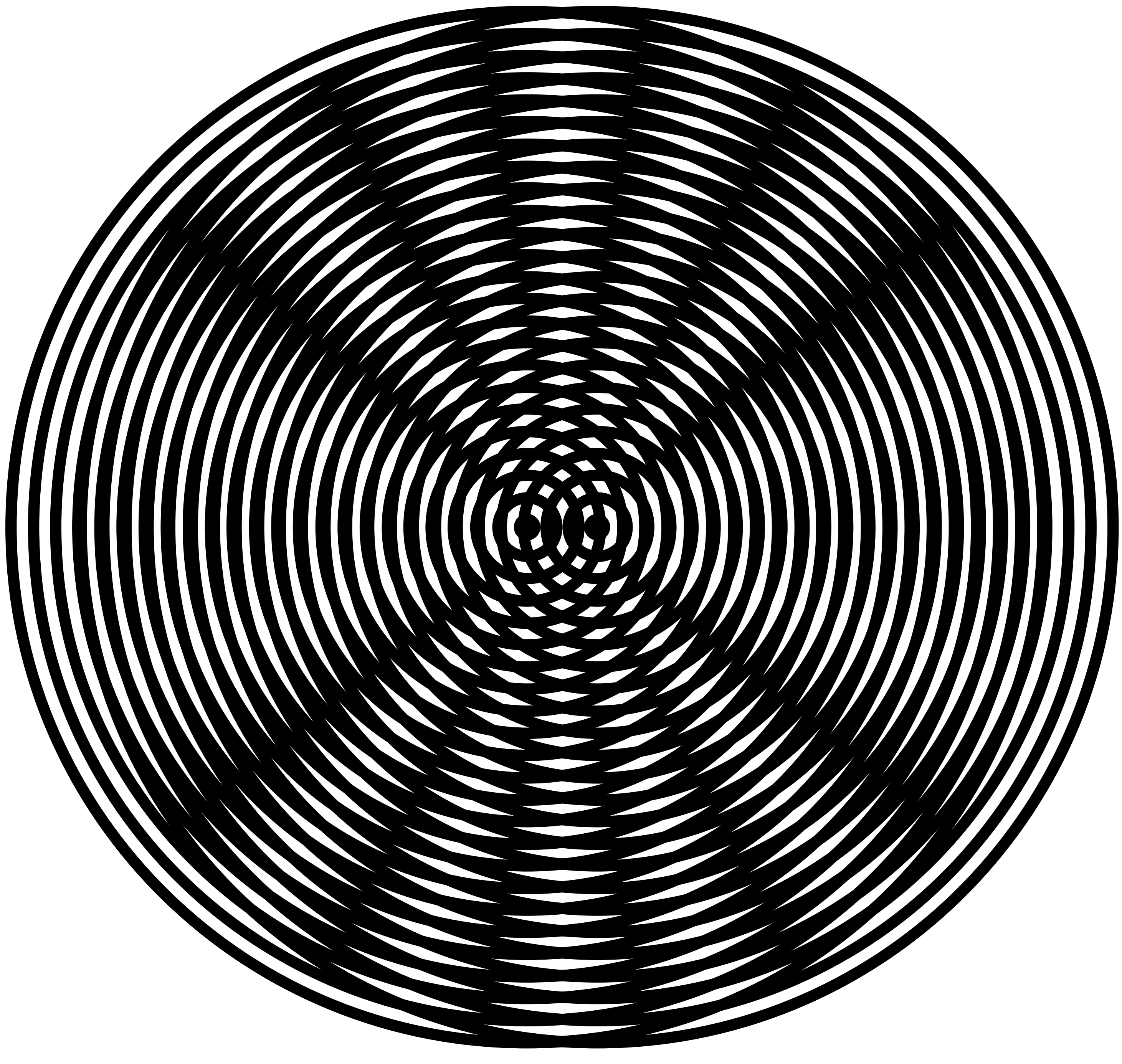
where Δr is the *path-length difference*.

- The figure shows two identical sources that are in phase.
- The path-length difference Δr determines whether the interference at a particular point is constructive or destructive.




$\Delta r = 2\lambda$
$\Delta r = \frac{3}{2}\lambda$
$\Delta r = \lambda$
$\Delta r = \frac{1}{2}\lambda$
$\Delta r = 0$
$\Delta r = \frac{1}{2}\lambda$
$\Delta r = \lambda$
$\Delta r = \frac{3}{2}\lambda$
$\Delta r = 2\lambda$
Antinodal lines, constructive interference, oscillation with maximum amplitude. Intensity is at its maximum value.
Nodal lines, destructive interference, no oscillation. Intensity is zero.





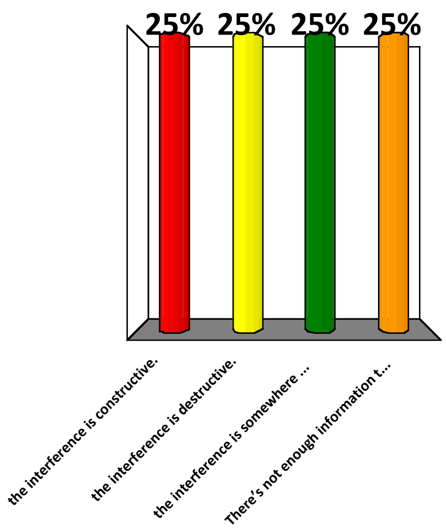
Two in-phase sources emit sound waves of equal wavelength and intensity. At the position of the dot,

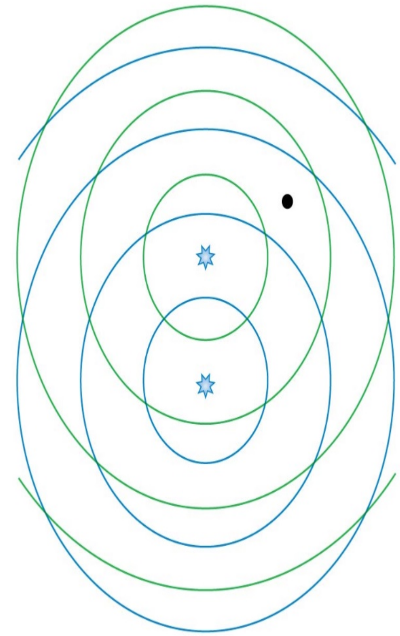
A. the interference is constructive.

B. the interference is destructive.

C. the interference is somewhere between constructive and destructive.

D. There's not enough information to tell about the interference.





Two in-phase sources emit sound waves of equal wavelength and intensity. How many antinodal lines (lines of constructive interference) are in the interference pattern?

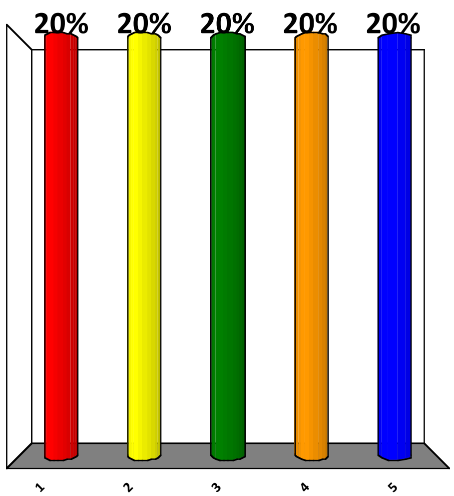
A. 1

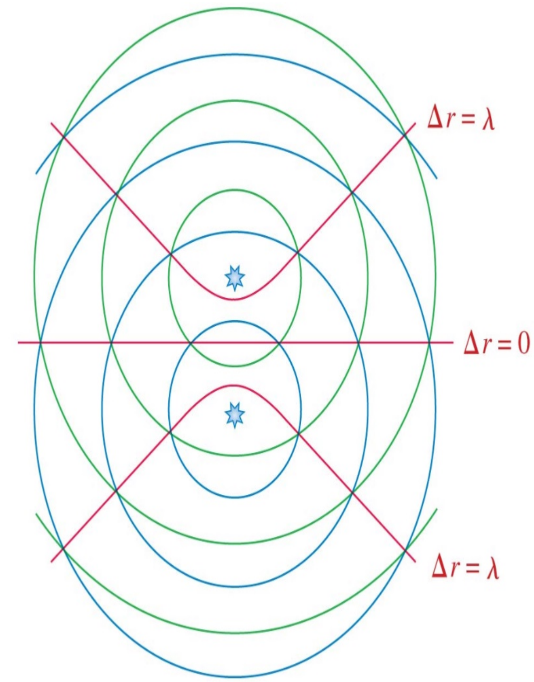
B. 2

C. 3

D. 4

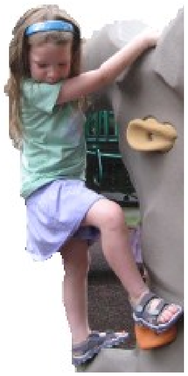
E. 5





Sources are 1.5λ apart, so no point can have Δr more than 1.5λ.

Foothold Ideas 1:
Light as Rays - The Physics



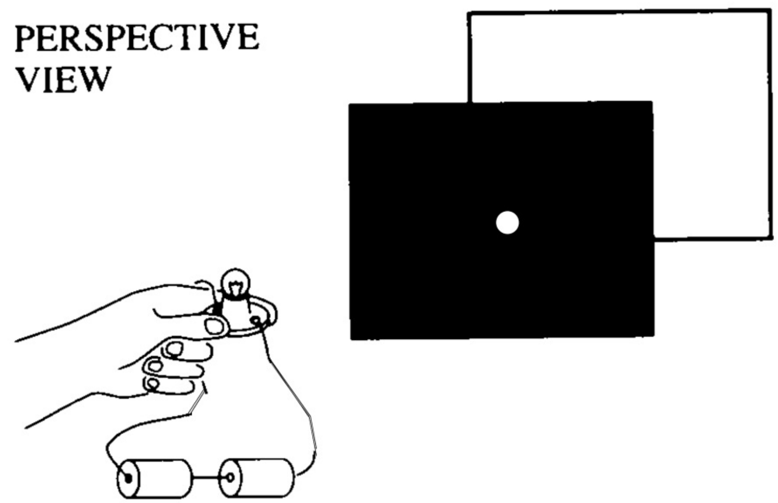
- Through empty space (or ~air) light travels in straight lines.
- Each point on an object scatters light, spraying it off in all directions.
- A polished surface reflects rays back again according to the rule: *The angle of incidence equals the angle of reflection*.

Foothold Ideas 2:
Light as Rays - the perception

- We only see something when light coming from it enters our eyes.
- Our eyes identify a point as being on an object when rays traced back converge at that point.

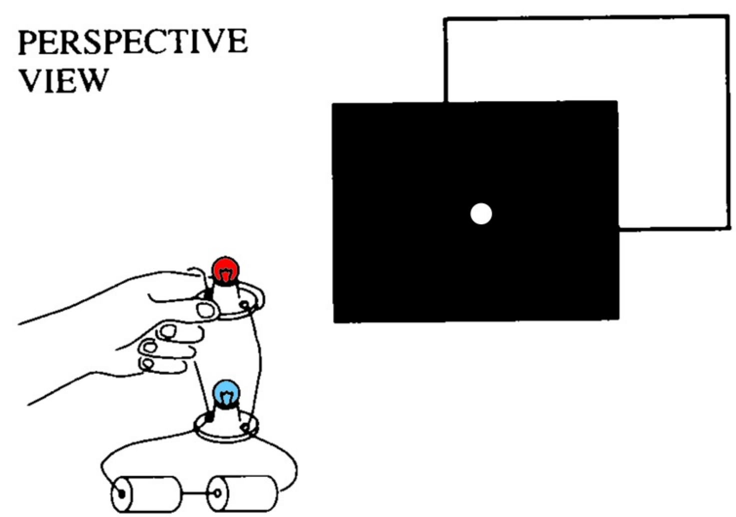
Suppose you have a small brightly lit bulb, a mask (a cardboard screen with a small circular hole cut in it), and a screen. You see a small circle of light on the screen. What would happen to the spot if you moved the bulb straight upward a bit?

1. The spot would stay where it was.
2. The spot would move up a bit.
3. The spot would move down a bit.
4. The spot would move left a bit.
5. The spot would move right a bit.
6. Something else



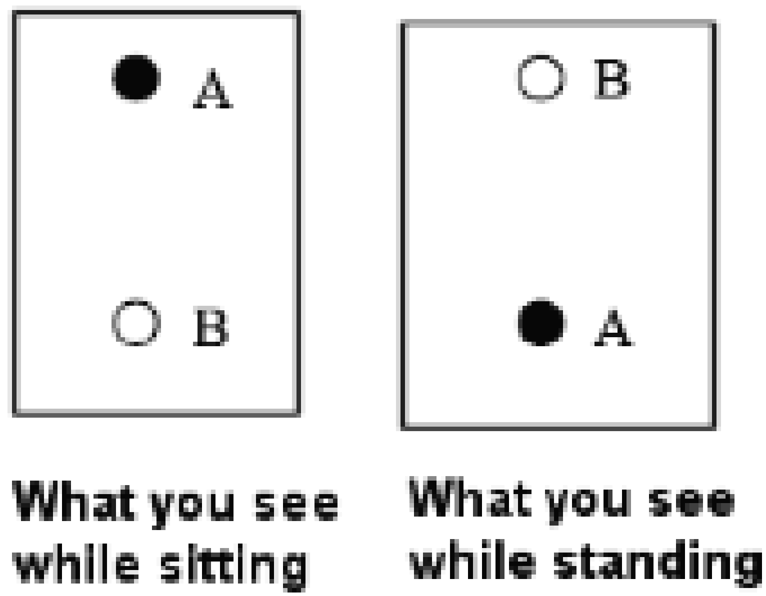
Suppose you have two lit bulbs, the top one red and the bottom one blue, a mask (a cardboard screen with a small circular hole cut in it), and a screen, as shown. What would you see on the screen if you held the bulbs one over the other as shown?

1. One purple circle.
2. Two circles, one above the other with the top one red, the lower one blue.
3. Two circles, one above the other with the top one blue the lower one red.
4. Something else.



You are sitting in a chair looking at two objects that are suspended from the ceiling. It appears to you that object A is above object B. When you stand up, object A appears to be below object B. Which of the two objects is farther away from you?

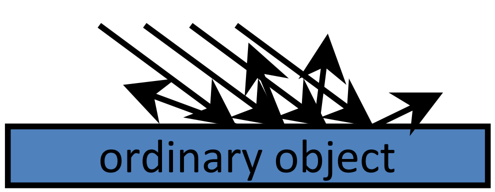
1. Object A
2. Object B
3. They are both the same distance.
4. You can't tell. It could be either one

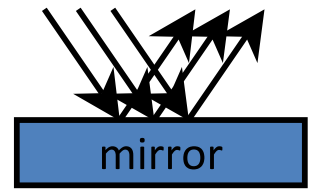


When I arrived in New York for the first time, we flew low over Manhatten and I was impressed with the view of the city lights in the dark. Being tired after a long flight, I tried to take a picture through the window using my flash. Explain why this is a bad idea and what the picture was likely to show.

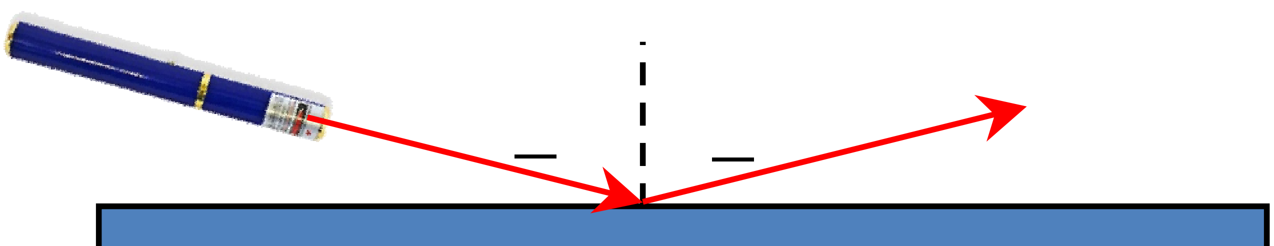
Foothold Ideas 3: Mirrors

- For most objects, light scatters in all directions. For some objects (mirrors) light scatters from them in controlled directions.

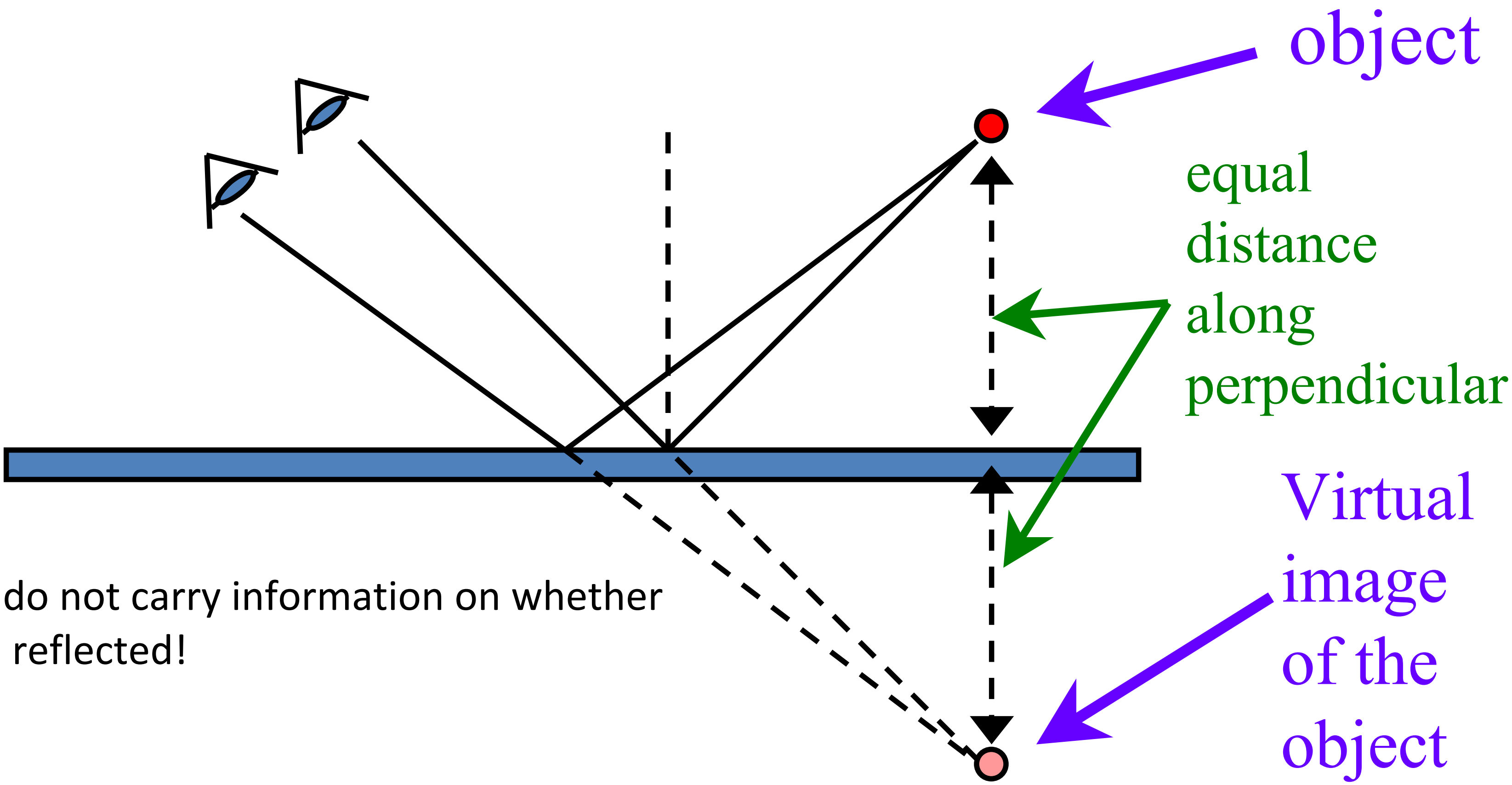




- A polished surface reflects rays back again according to the rule: *The angle of incidence equals the angle of reflection*.



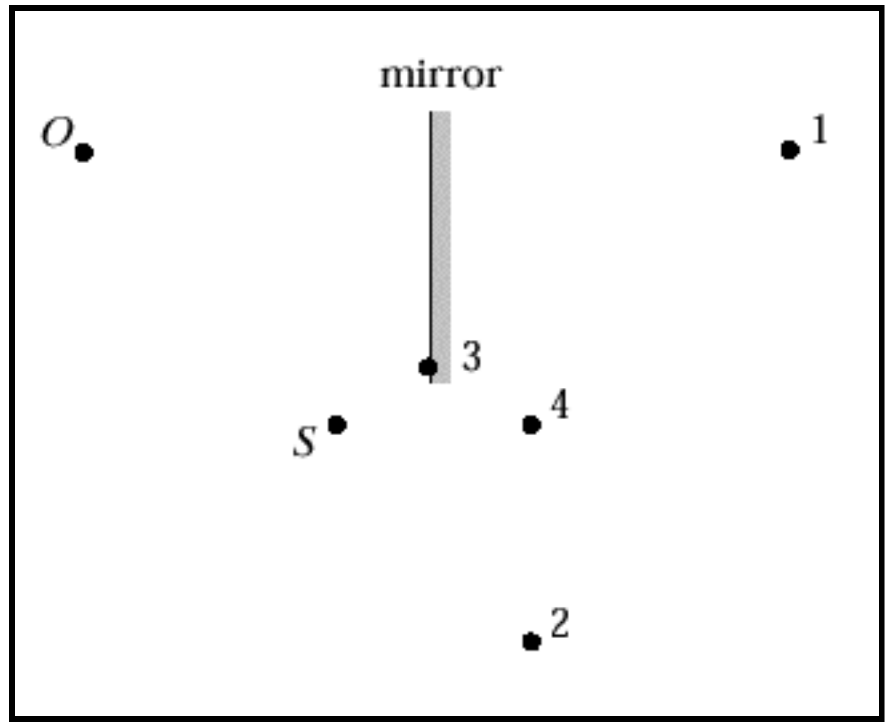
Where does an object seen in a mirror appear to be?



Light rays do not carry information on whether they were reflected!

An observer O, facing a mirror, observes a light source S. Where does *O* perceive the mirror image of *S* to be located?

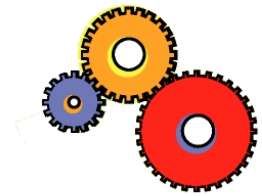
1. 1
2. 2
3. 3
4. 4
5. Some other location
6. *O* cannot see *S* in the mirror when they are as shown.



Kinds of Images: Virtual

- In the case of the previous slide, the rays seen by the eye do not actually meet at a point – but the brain, only knowing the direction of the ray, assumes it came directly form an object.
- When the rays seen by the eye do not meet, but the brain assumes they do, the image is called *virtual*.
- If a screen is put at the position of the virtual image, there are no rays there so nothing will be seen on the screen.

I have a small mirror – about 8 inches high – hanging on my wall. When I'm standing right in front of it, I can only see my head. Can I see all of myself at once by moving far back enough?



1. Yes
2. No
3. I can if I …

You want to put a “full length mirror” on the wall of your room; that is, a mirror that is large enough so that you can see your whole self in it all at the same time. How big should the mirror be?

1. You can see yourself in any size mirror if you go back far enough.
2. It depends on the size of your room and whether you can step back far enough from the mirror.
3. The mirror needs to be about half your size.
4. The mirror needs to be as big as you are.
5. Some other answer.

What does a mirror do to the image?

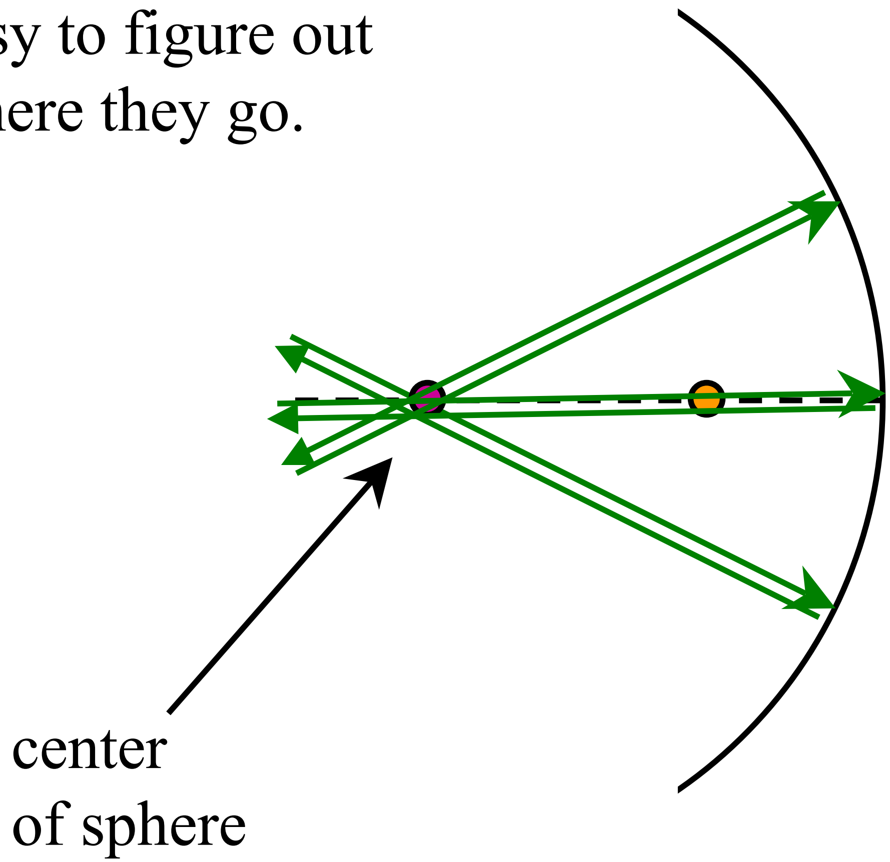
1. Flips it left to right.
2. Flips it upside down.
3. Does both.
4. Does something else.

What will a real image look like if there is no screen?

1. Nothing. You won't be able to see the image without the screen.
2. You will still see the image, but it will appear to be floating in front of the mirror.
3. You will still see the image, but it will appear to be on the mirror.
4. You will still see the image, but it will appear to be behind the mirror like it is with a flat mirror.

A Spherical Mirror: Central Rays

A few rays are easy to figure out where they go.



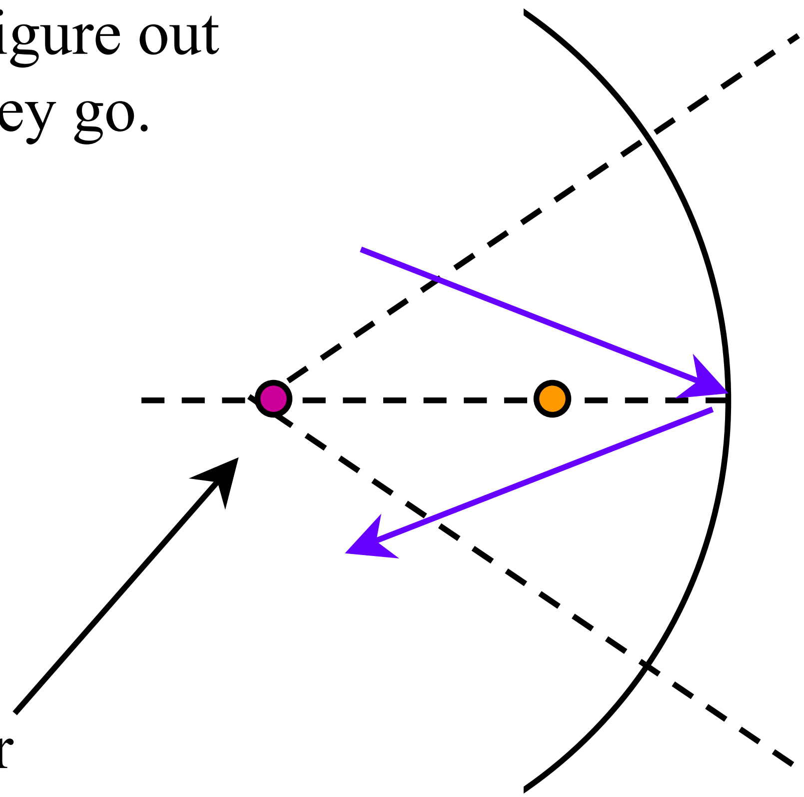
All rays satisfy the "angle of incidence = angle of reflection" measured to the normal to the surface

All rays through the center strike the mirror perpendicular to the surface and bounce back along their incoming path.

A Spherical Mirror: Central Ray

A few rays are easy to figure out where they go.

All rays satisfy the “angle of incidence = angle of reflection” measured to the normal to the surface

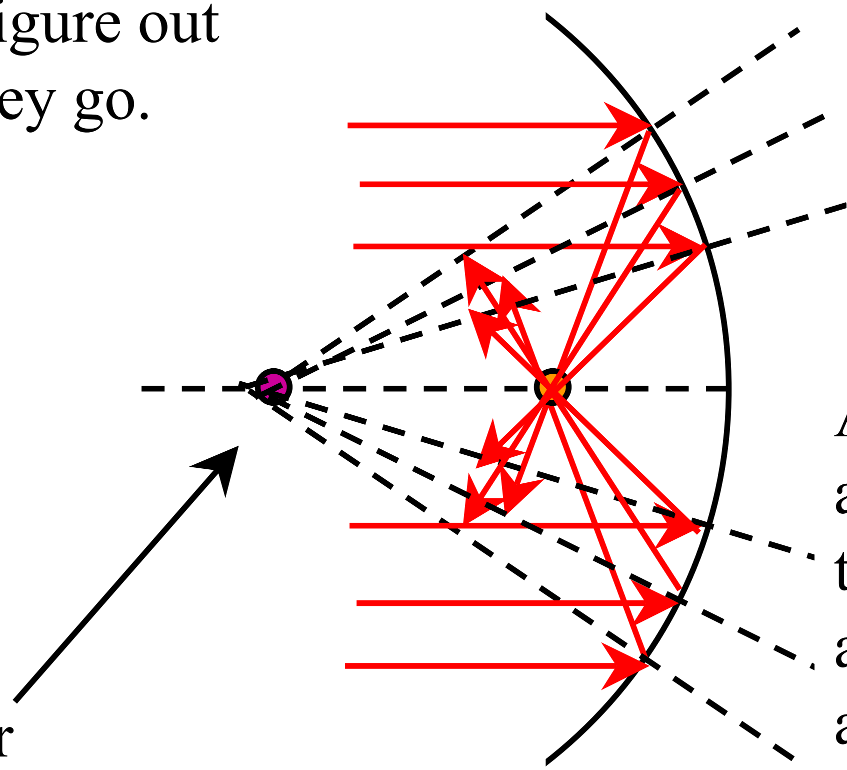


The ray hitting the central line of the diagram is particularly simple.

center of sphere

A Spherical Mirror: Parallel Rays

A few rays are easy to figure out where they go.



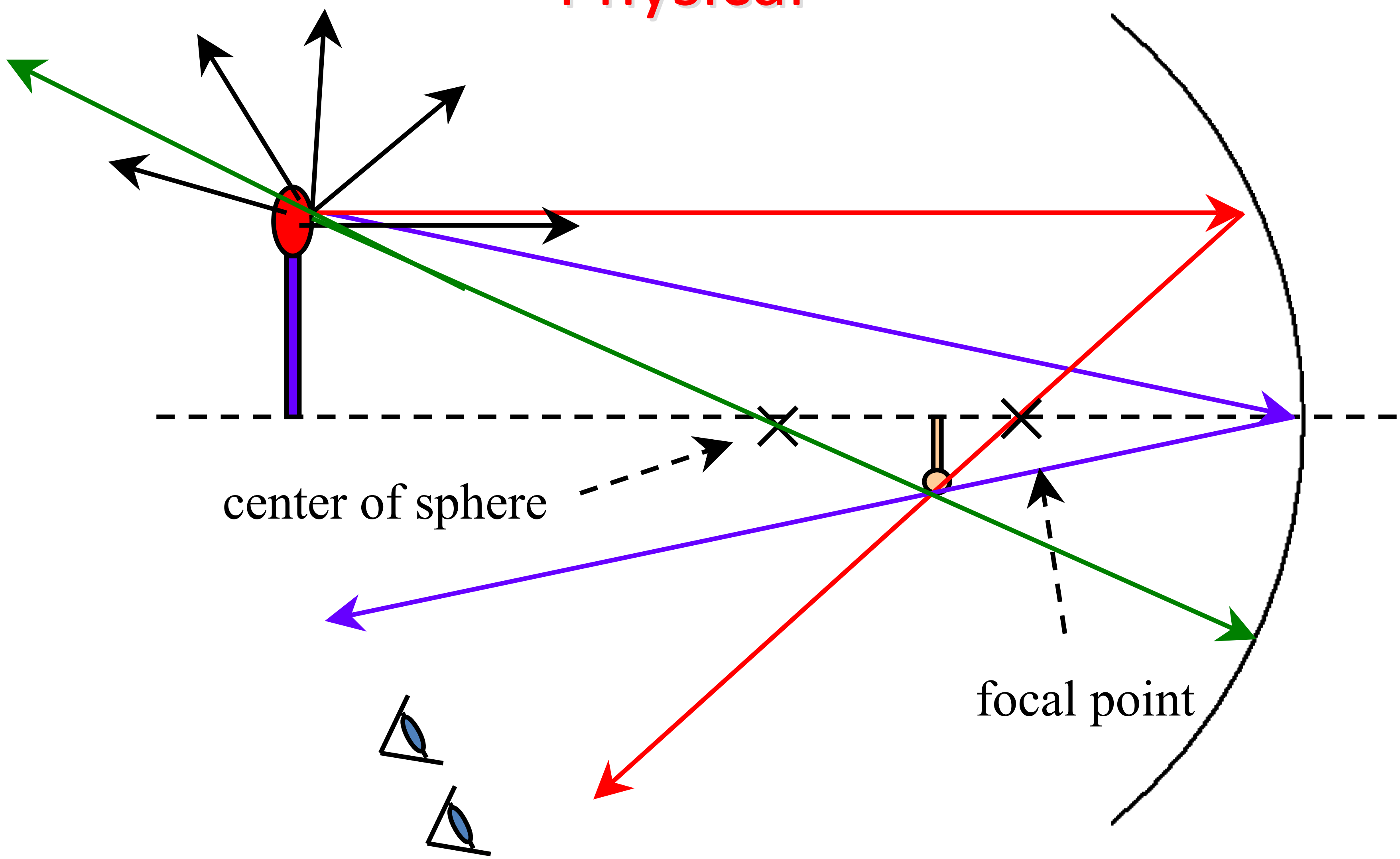
All rays satisfy the "angle of incidence = angle of reflection" measured to the normal to the surface

All rays parallel to and near an axis of the sphere reflect through a single point on the axis (the focal point)

center of sphere

Images in a Spherical Mirror: 1

Physical



Kinds of Images: Real

- In the case of the previous slide, the rays seen by the eye do in fact converge at a point.
- When the rays seen by the eye do meet, the image is called *real*.
- If a screen is put at the real image, the rays will scatter in all directions and an image can be seen on the screen, just as if it were a real object.

Light – many questions in lab

- How do the various filters change the spectrum produced by the hydrogen lamp?
- How is the sun's spectrum different from or similar to those produced by the lamps (H, Na, and Hg)? Is the sun's spectrum still 'quantized'? Why or why not?
- Is the sun's spectrum the same outside the window as it is when the sun has travelled through the window's glass? (Does the glass absorb any light? If so, which frequencies or bands of frequencies are most affected?)
- How do the UV (ultra-violet) and LED light sources compare to the solar spectrum or to the incandescent spectrum? How do the filters change the spectra observed from these sources?
- Does water act as a filter? If so, which frequencies or bands of frequencies are most affected?
- What factors affect the observed color of different reflective surfaces (like your t-shirts or you notebook covers)?
- What frequencies or bands of frequencies are affected by using your sunglasses as a filter? Are all sunglasses the same?

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