

Diffraction I

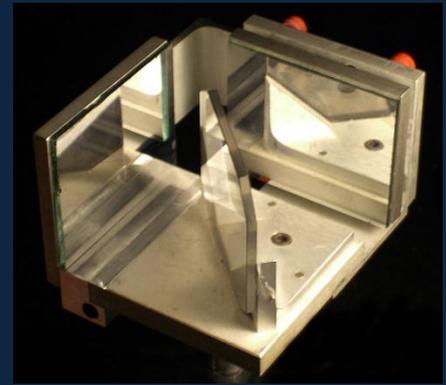
Physics 2415 Lecture 37

Michael Fowler, UVa

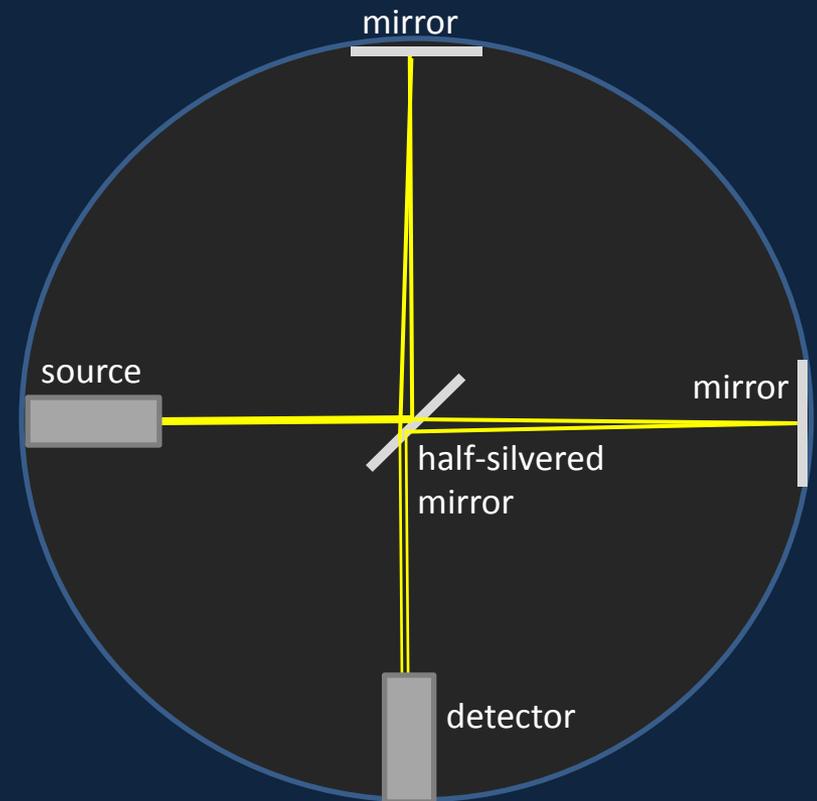
Today's Topics

- Michelson's interferometer
- The Michelson Morley experiment
- Single-slit diffraction
- Eye of a fly
- Angular resolution

Michelson Interferometer

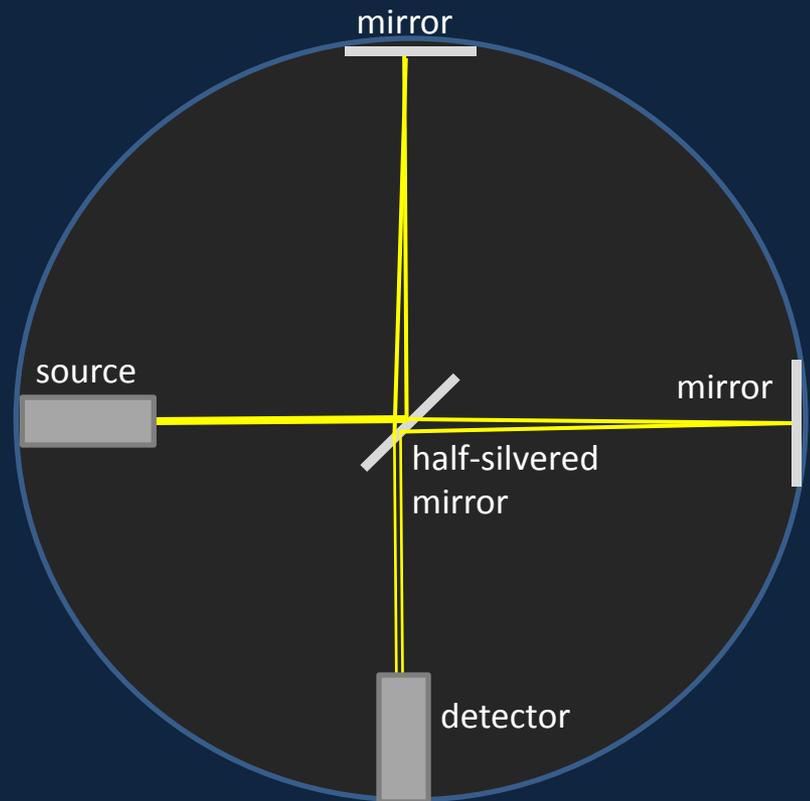


- A narrow beam of light is split in two by a half silvered mirror as shown, the two halves are reflected back by two different mirrors, they partially pass through the half silvered mirror to be recombined and then detected.



Michelson Interferometer

- The two beams entering the detector will interfere constructively or destructively depending on the difference in path lengths.
- A series of light and dark bands (fringes) are observed in the detector.
- Moving one mirror one quarter of a wavelength exchanges the dark and light fringes.
- Small distances can be measured by counting fringe shifts as the mirror is moved.

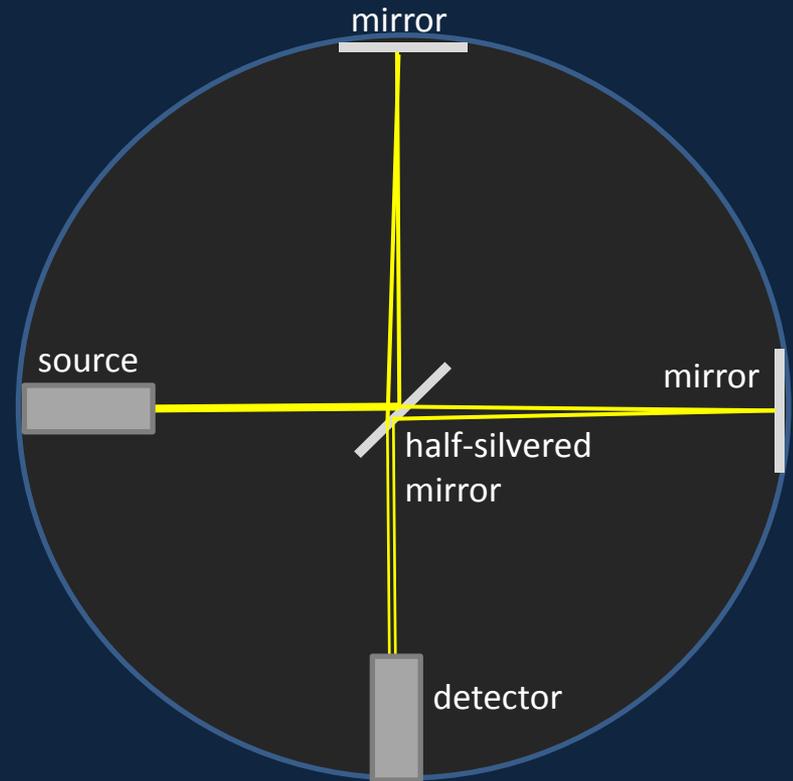


Detecting the Aether

- The velocity of light was measured by Michelson, and agreed well with that predicted by Maxwell: we now define it as 299,792,458 m/sec.
- But **relative to what?**
- Sound speed is relative to the medium, air.
- Presumably electromagnetic waves are in some medium—the term used is aether.
- How can it be detected?

Michelson's Aether Detector

- Michelson and Morley used his interferometer **to look for the aether!**
- The idea was that as the Earth moves in orbit at 30 km/sec, the aether “wind speed” through the lab would vary.
- The relative phases of the two beams of light would be affected by whether they were upstream and back or cross stream relative to the aether flow.
- The difference is small, but detectable.



Flashlet

River Race (Clicker question)

- The river is 100m wide, and flowing steadily at 3 m/sec.
- The race: **A** swims **directly across** the river and back to the same point (by somewhat angling up stream so that relative to the bank, **A's** direction was perpendicularly across).
- **B** swims **parallel to the bank**, 100 m upstream then back.
- Both swim at 5 m/sec. Who wins?
- **Answer: A, B, or C = draw.**

River Race (Clicker answer)

- The river is 100m wide, and flowing steadily at 3 m/sec.
- The race: **A** swims **directly across** the river and back to the same point: speed 5 m/sec, must be 3m/sec upstream so 4 m/sec across, so 25 secs each way: 50 secs round trip.
- **B** swims parallel to the bank, 100 m upstream then back. 2 m/sec upstream—already 50 secs!
- Both swim at 5 m/sec. Who wins?
- • **Answer: A.**

Michelson and Morley's Result: Nothing!

- Despite years of trying, and improvements in measurement that should have detected the “aether breeze” caused by the earth's rotation as well as earth's orbital speed, no trace of the aether was ever found...

The Speed of Light could be relative to:

- A. The aether, they just missed it somehow.
- B. Absolute space
- C. The object emitting the light
- D. The observer (note the observer could be moving)

One Idea: The Emitter Theory

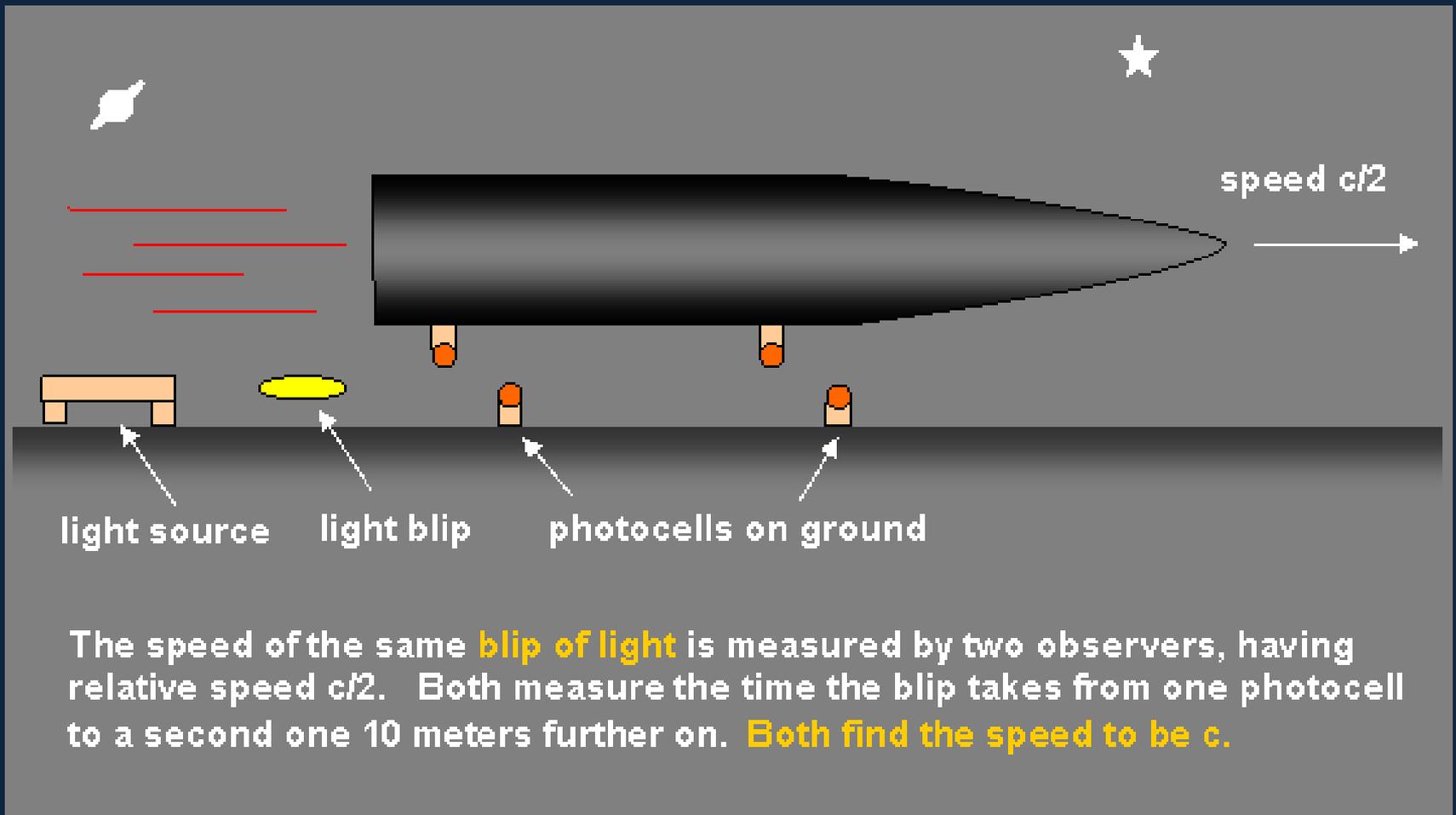
- Suppose a train has a cannon on board, the train is going at 50 m/sec, it shoots a cannonball forwards at 200 m/sec.
- The cannonball is going at 250 m/sec relative to the ground.
- The emitter theory suggests that light going forward from the train's lamp is going at $c + 50$ m/sec, where c is the usual velocity of light.
- **What's wrong with this argument?**

Seeing Double Stars Double

- A double star is two stars circling their common center of mass.
- With the emitter theory, if one of them is coming towards us, its light gets an extra boost in our direction.
- So we would see it coming towards us perhaps years later than we see it going away—in fact, we'd likely see it in two places at once.
- This just doesn't happen—the **emitter theory is wrong** (more recently checked with X-rays from a pulsar, which reach us with little absorption).

The Speed of Light: Einstein's Answer

- So, what *is* the speed of light relative to?
- D. The *observer*—even if the observer's moving!

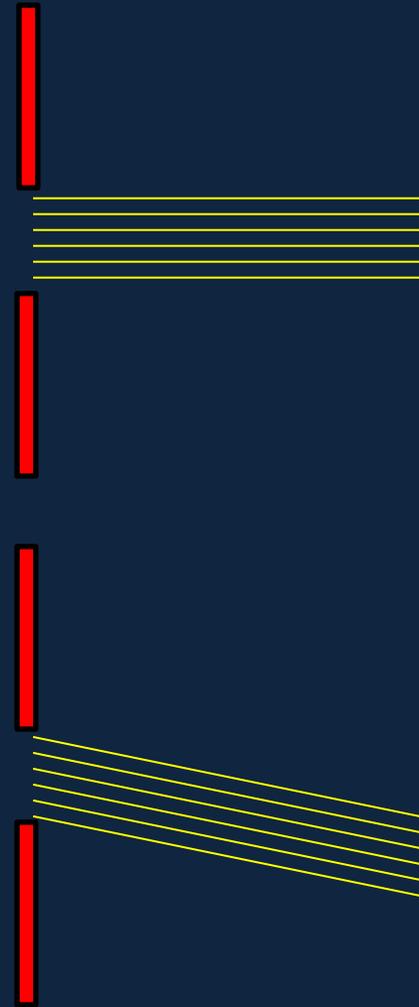


Interference and Diffraction

- Interference is usually of just **two** waves, like those from the two slits, although **more could be added**.
- Diffraction is the same addition of waves, but now from many or even an infinite number (a continuum) of sources.
- **Example: single slit of finite width.**

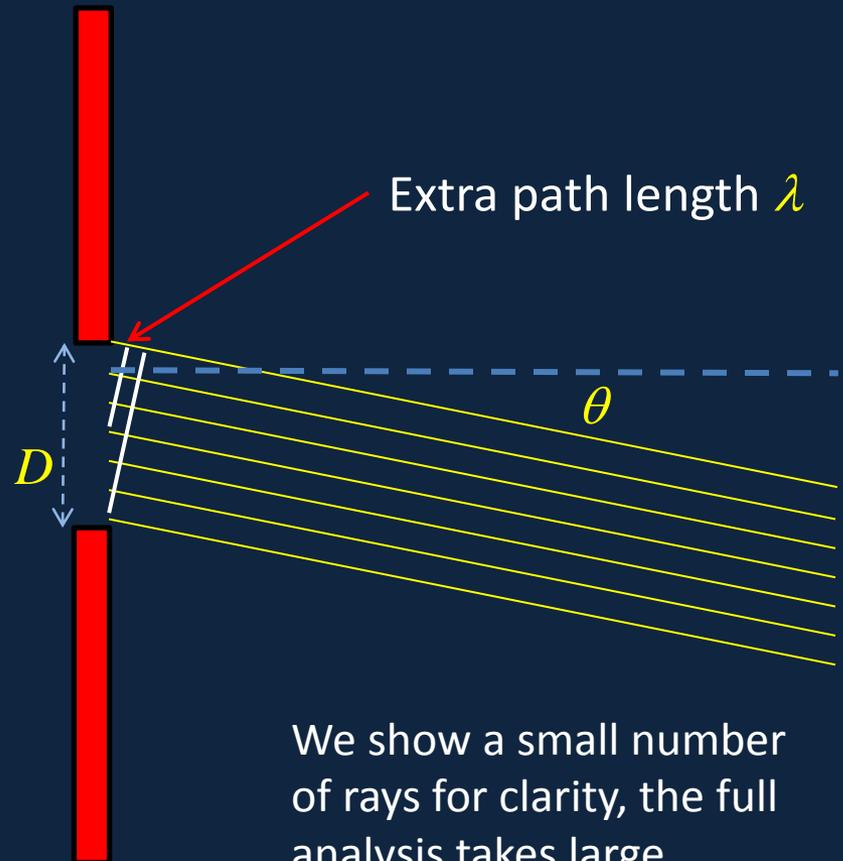
Fresnel's Single Slit Analysis

- Fresnel suggested that the light through a **single slit** be regarded as made up of many rays, or wavelets.
- Going forward, they will all be in phase—but what light intensity will be detected at an angle?



Dark Spot

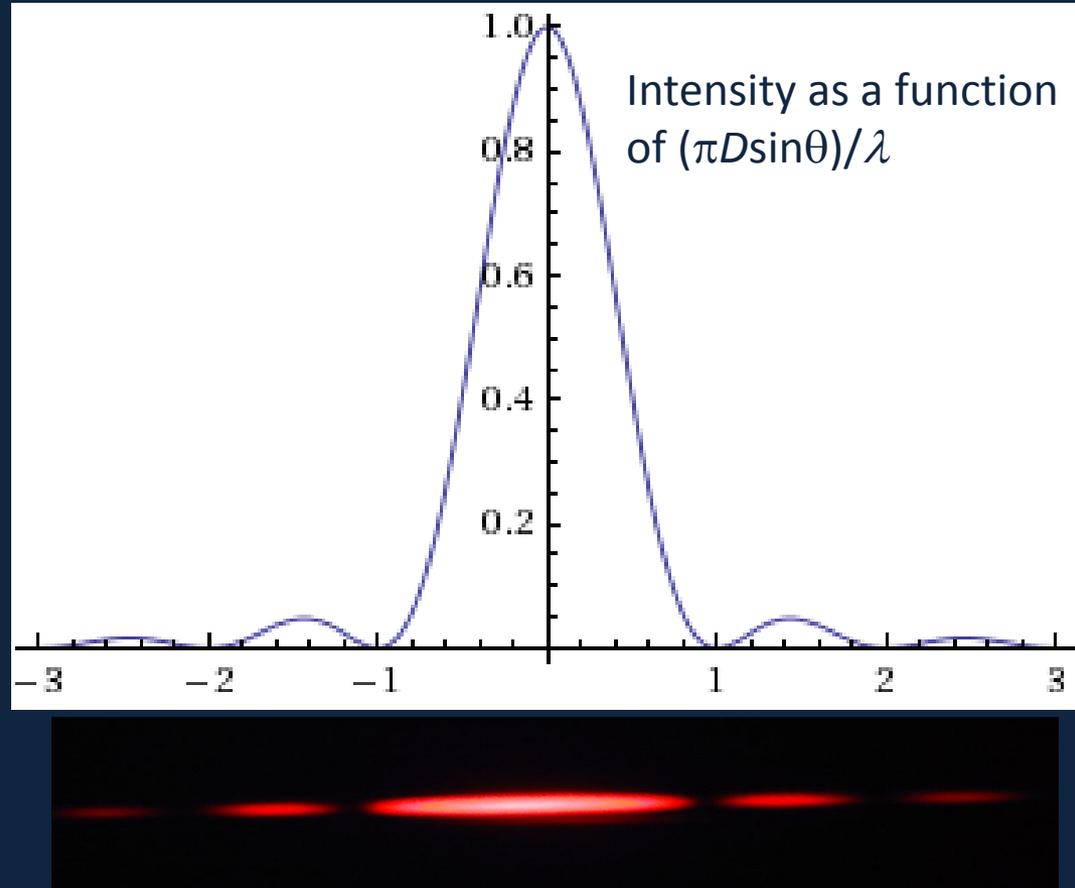
- If the ray from the top of the slit is λ longer than that from the bottom, the middle ray is exactly out of phase with the top ray, and **these two will cancel**.
- Then the next ray down from the top cancels the next down from the middle—*all* the rays cancel!
- **Dark spot: $D\sin\theta = \lambda$**



We show a small number of rays for clarity, the full analysis takes large numbers of tiny rays, and integrates over them.

More Dark Spots...

- The single slit diffraction pattern is dark wherever
$$D\sin\theta = n\lambda, n = 1, 2, \dots$$
- The intensity maxima between these dark spots are far less than the central spot, because of the many differing phases of the rays.



Poisson Spot

- Ten years after Young's double slit experiment, French mathematician Simeon Poisson *still* didn't believe light was a wave.
- He pointed out that the **shadow** of a ball illuminated by a point source of light should have a **bright spot** in the middle—the waves from all around the edge should all be in phase there, and nowhere else.
- **This sounded very unlikely...**

Poisson Spot

- ...but **turned out to be true!**
- His colleague Arago, a physicist who was convinced of the wave nature of light did the experiment.
- The **light source must be very small** to see this, otherwise light from different parts of the source will cancel.

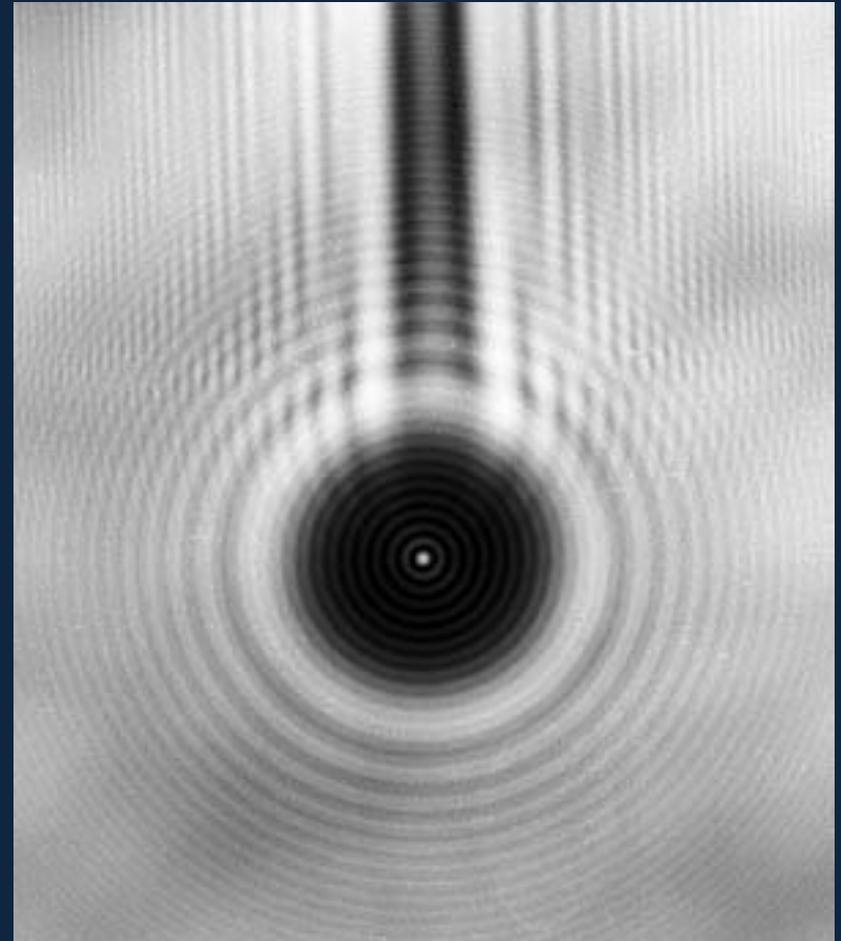


Photo by [C.C.Jones](#)

Edge Diffraction

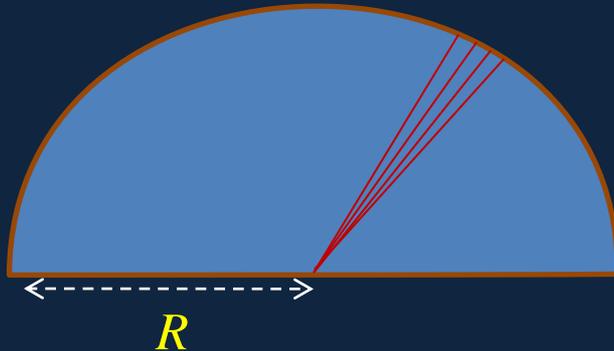
- This is the shadow of a knife edge using laser light. It agrees very well with Fresnel's mathematical analysis.
- A classical particle type picture would give black above the red line, uniform light below.
- The light penetrates into the classical shadow region, dying away as it does.
- The fringes are all in the classically allowed region. Fresnel explained them by dividing the wavefront into zones which partly cancelled each other, as in the single slit work above.



Fly's Eye



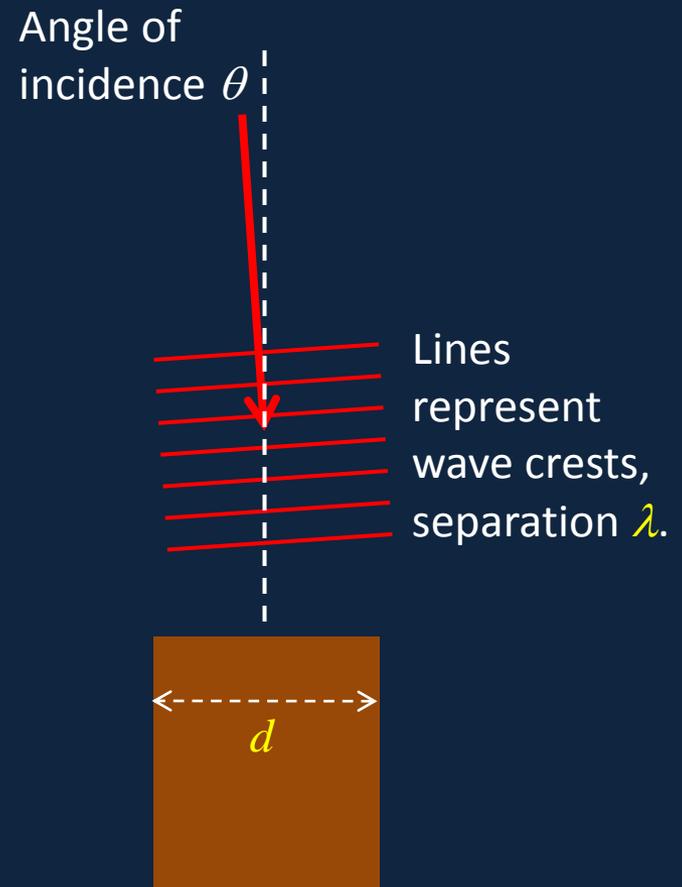
Fly's Eye



- There is **no lens**—just a hemisphere made up of narrow tubes, each tube receiving light from one direction.
- If the hemisphere has radius $R \sim 1\text{mm}$, and the tubes have end diameter d , the angular resolution is d/R .
- BUT **these tubes are small**: an individual tube has angular resolution $\sim \lambda/d$ from diffraction.
- OPTIMAL TUBE SIZE: $d/R \sim \lambda/d$, $d^2 \sim \lambda R$, $d \sim 30\mu\text{m}$.

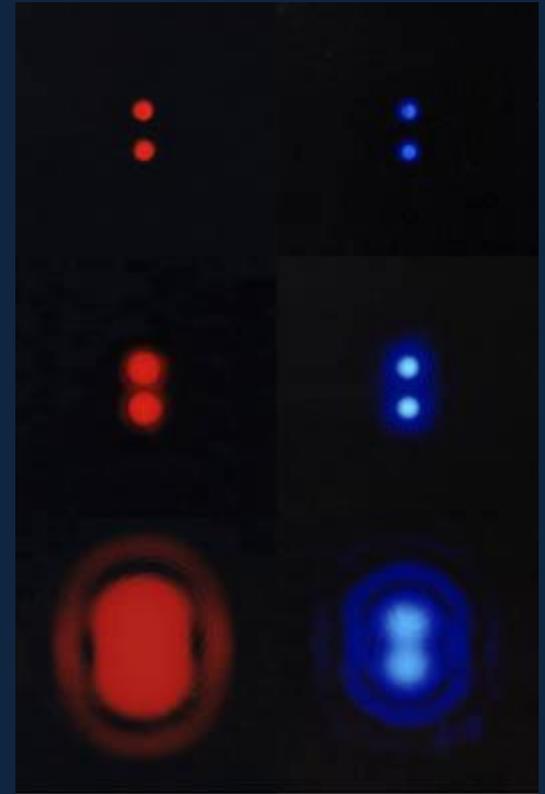
Angular Resolution of a Fly's Eye Tube

- As long as θ is smaller than λ/d , the whole end of the tube will detect a crest at the same time. For larger angles, crests and troughs will enter the tube at the same time, cancelling.
- The tube cannot pin down direction of origin better than an angle $\sim \lambda/d$.



Angular Resolution of a Lens

- The argument for the fly's optic tube also works for a lens—stars can only be resolved through a telescope if their angular separation is $\sim \lambda/D$ or more (D lens diameter).
- This is also the angular limitation on **how well a lens can focus the image of a small object**. A microscope with focal length $f \sim D$ (object lens diameter) can just separate objects λ apart.

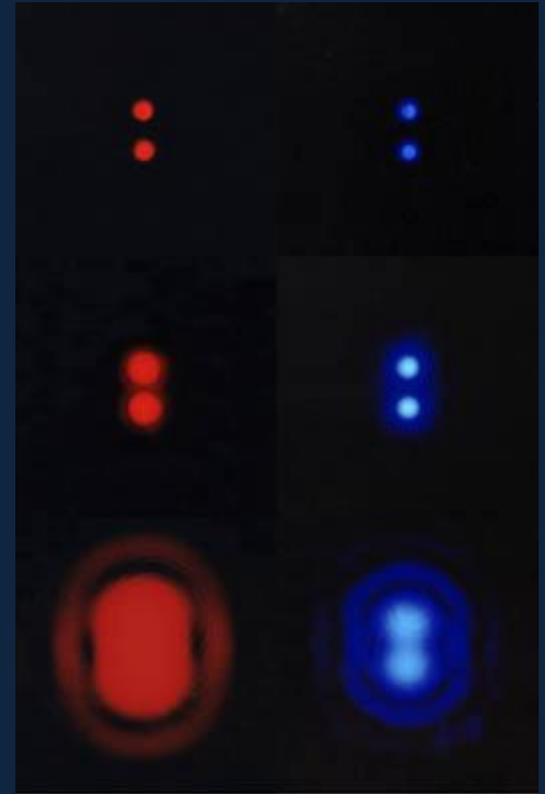


Two objects viewed with smaller and smaller lens size D , red and blue light. From [C.C.Jones](#)

Angular Resolution of a Lens

- The argument for the fly's optic tube also works for a lens—stars can only be resolved through a telescope if their angular separation is $\sim \lambda/D$ or more (D lens diameter).
- Lord Rayleigh gave a precise criterion that is now standard: for the first dark ring of one diffracted star image to be at the center of the other one, the angular separation

$$\theta = 1.22\lambda/D$$



Two objects viewed with smaller and smaller lens size D , red and blue light. From [C.C.Jones](#)