May 10, 2017 Physics 132 Prof. E. F. Redish

- **Theme Music:** **Count Basie**
  ***The Party's Over***
- **Cartoon:** **Mike Peters**
  ***Mother Goose and Grimm***


# Outline

- Makeup exam
- Closing things out and advice for the final.
- Diffraction examples
- Reconciling the photon, particle, and wave models of light.

# Makeup Exam 2

| #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|
| 51% | 33% | 20% | 65% | 64% |




# The Equation Game

- What physical system are we talking about?
- What variables and parameters do we use to describe the system?
- What physical principles are relevant?
  Do they lead to any equations? (Check dims.)
- What models are relevant?
  Do they lead to any equations? (Check dims.)
- What do we know and what are we supposed to find?
- Work with symbols to solve.
  Don't put in numbers until the end!

## ne Equation

- at symbols am I given
- o I remember any e ations with th e ymbols in them?
- o any of the mbers I'm given fit my uations? so, put them in.
- D O check for physical relev e.
- Do N check for units or di sions.



## Suggestions for how to study for the final?

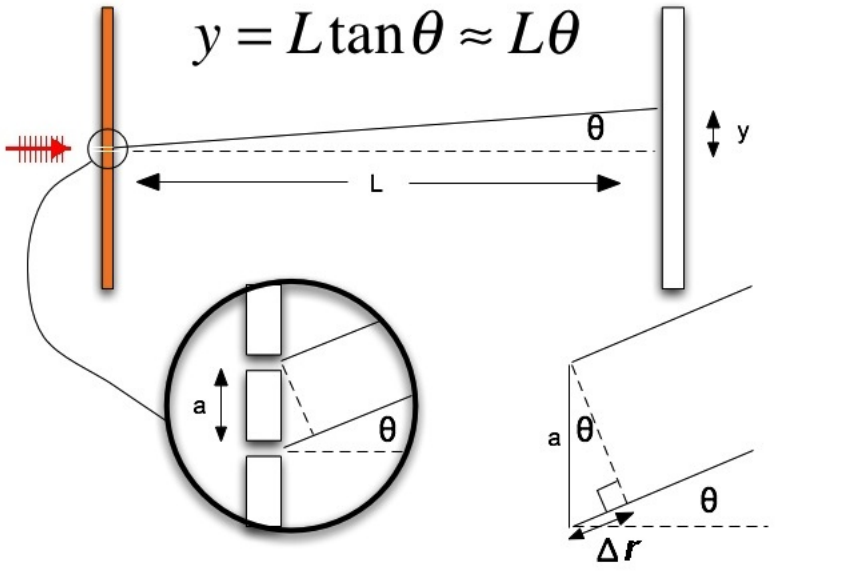
- Break semester into sections.
- For each section, identify core principles (foothold slides for the 3 exams) and boil them down.
- Review the toolbelt entries.
- Go over exam, quiz, clicker, and HW probs. Identify − not answers − but how principles and tools let you solve them.
  - Pay particular attention to problems the class had trouble with!

# Some applications of diffraction

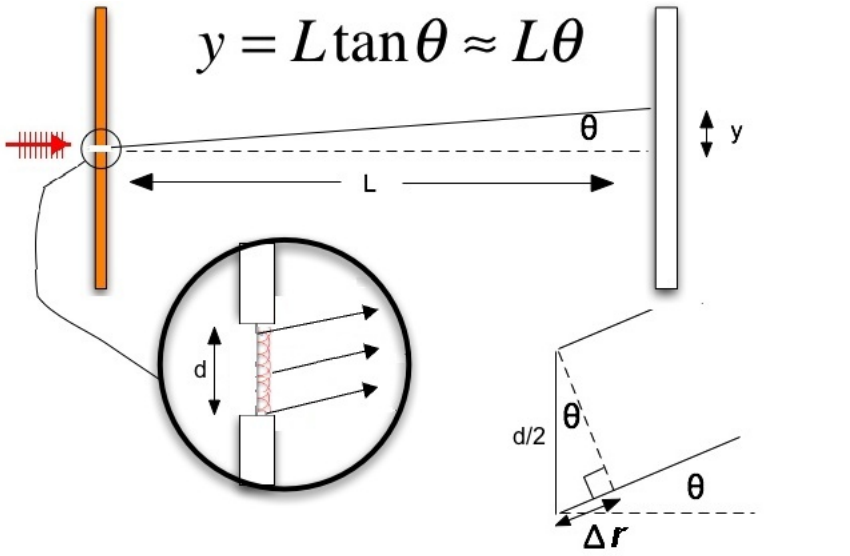
- X-ray diffraction (structure of crystals)
- Holography
- Higher resolution microscopy
  - Diffraction limits resolution of standard microscopy. Understanding it helps get around this.
- Diffraction enhanced x-ray imaging (DEI)
- Diffraction-based multi-focal intra-optical lenses

*https://www.youtube.com/watch?v=jWz_MxaKAWM*



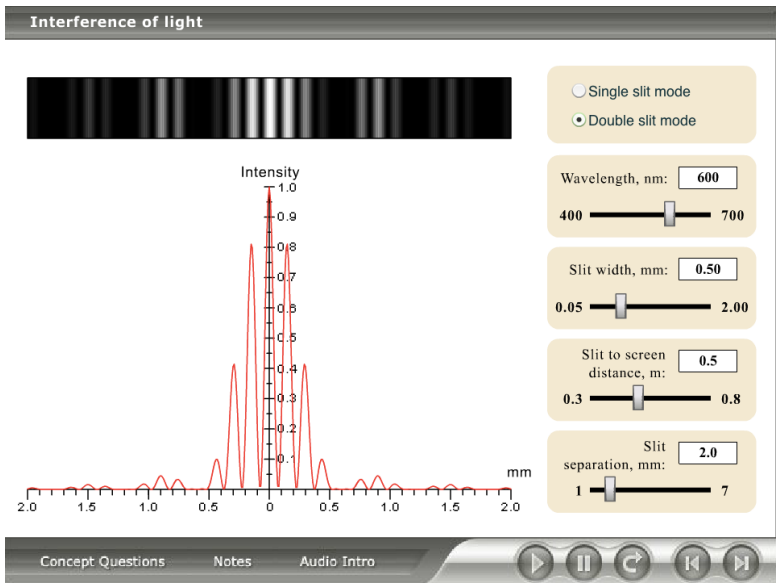



$$\Delta r = a\sin\theta \approx a\theta$$




$$y = L\tan\theta \approx L\theta$$

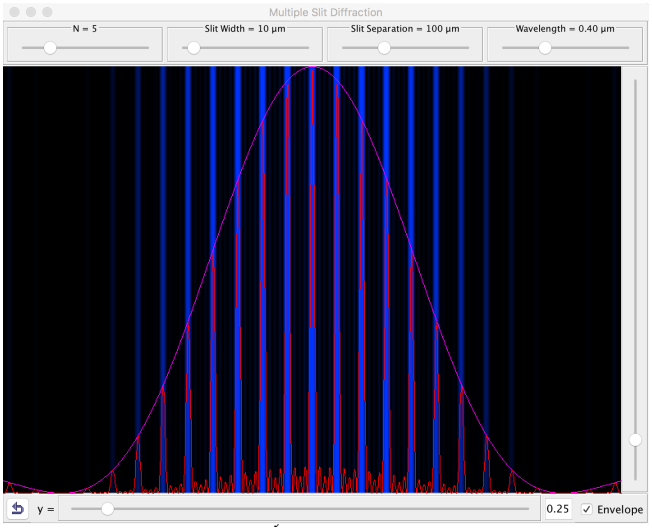
$$\Delta r = \frac{d}{2}\sin\theta \approx \frac{d}{2}\theta$$




http://www.wiley.com/college/halliday/0470469080/simulations/sim48/sim48.html

5/10/17

# What happens if there are more than 2 slits?




5/10/17 **21**

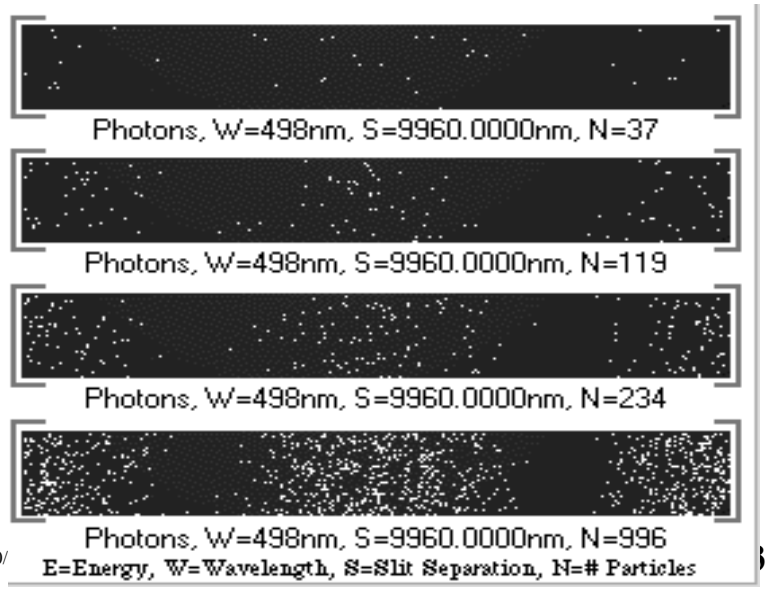
# Reconciling Photons and the Wave Model: Starting Quantum Physics

- The photon picture seems to contradict the wave model − but relies on it.
- What if we pass photons through a double-slit but with a low enough energy density that we expect only one photon in the system at a time.
- What would the pattern look like?

5/10/17 Physics 132 **22**

http://phys.educ.ksu.edu/vqm/html/doubleslit/

# Results




5/10/

# Both Particle and Wave Properties are Displayed

- Individual photons strike the target individually and are detected as tiny spots.
- Individual photons still follow an interference pattern – but at random.
- The intensity of an EM wave only tells us the *probability* of finding a photon at a particular place.


24

# Foothold Ideas: The Probability Framework

- It's clear that both the wave model and the photon have an element of truth. Here's the way we reconcile it:
  - *Maxwell's equations and the wave theory of light yield a function – the electric field – whose square (the intensity of the light) is proportional to the probability of finding a photon.*
  - *No theory of the exact propagation of individual photons exist. This is the best we can do: a theory of the probability function for photons.*



# Reading questions

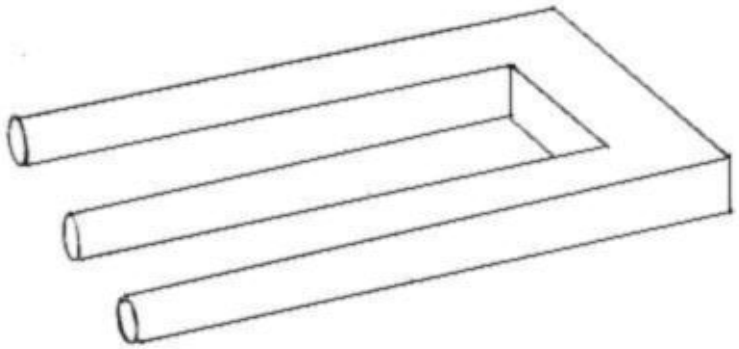
- I don't understand how photons are able to "interfere with themselves". What property of the photon allows it to even have an interference pattern?
- Is there a way to explain how it is that photons interfere with themselves even though it should technically be impossible?
- I thought that the intensity of light was a quantitative measure of the magnitude of almost the brightness of light at a particular point? How can we relate this to the position of a photon? Lastly, for any single wave, wouldn't the probability that you can find a photon anywhere along that wave or oscillation be the same?
- I am confused on what it means by the photons interfere with themselves to create the interference pattern. How can one photon compete with itself for a position on the screen?
- How does a photon interfere with itself?

# So are they waves? Or particles?

- Alice laughed. "There's no use trying," she said: "one *can't* believe impossible things."
- "I daresay you haven't had much practice," said the Queen. "When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."
  - *Through the Looking Glass*
    *Lewis Carroll*



# A Quantum Model of Light



Single photons are directed, one by one, toward a double slit. The distribution pattern of impacts that make it through to a detector behind the slits is identical to an interference pattern. We now repeat this experiment, but block slit 1 for the first half of the experiment and slit 2 for the second half. The distribution of impacts in the second experiment is

A. the same as in the first experiment.
B. the sum of the distributions one gets for each slit separately.
C. neither of the above.



# Foothold Ideas: The Nature of Matter

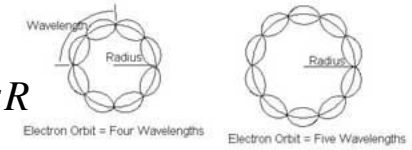
- Atoms and molecules naturally exist in states having specified energies. EM radiation can be absorbed or emitted by these atoms and molecules.
- When light interacts with matter, both energy and momentum are conserved.
- The energy of radiation either emitted or absorbed therefore corresponds to the difference of the energies of states.
- DeBroglie suggested that the discreteness property of atomic state might be explained if electrons had wave properties like photons.

# DeBroglie's matter waves

- Assume that Einstein's photon equations hold for free electrons:

$$E = hf \qquad p = h/\lambda$$
$$E = \tfrac{1}{2}mv^2 \qquad p = mv$$
$$E = p^2/2m = h^2/2m\lambda^2$$

- This would suggest that you would only be allowed to have discrete electron orbits (standing waves) when the wavelengths fit into the orbit. $n\lambda = 2\pi R$






# Foothold Ideas: The Probability Framework

- DeBroglie's waves have to be generalized to 3D and potential energy included. The result is the Schrödinger equation.
  - *Schrödinger's equation is the wave theory of matter. It's solution yields the wave function whose square is proportional to the probability of finding an electron.*
  - *No theory of the exact propagation of individual electrons exist. This is the best we can do now: a theory of the probability function for electrons.*