Seeing the Light:
What's so hard about teaching optics?

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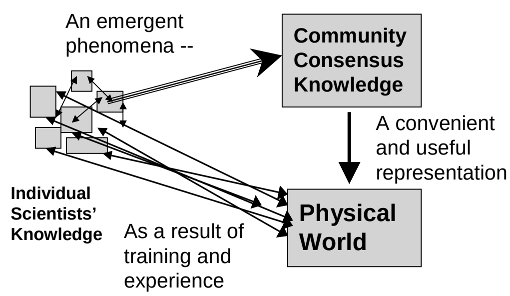
Outline

- Physics Education Research (PER)
  - Building a community knowledge
  - Modeling the student
- Problems learning about light
  - Overview
  - The basics
  - Waves
  - Photons
- What can we do about it?

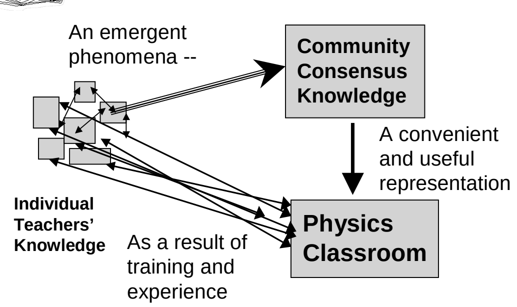
Introduction

- Optics in one of the most interesting and challenging areas of physics to teach.
  - It relates directly to everyday experience.
  - It relates to topics of much interest to many students such as photography, movies, astronomy, and biology.
  - It's a class of phenomena where physics has developed a number of different models of increasing sophistication — rays, waves, photons.
  - It's an area where it has been demonstrated that students are strongly resistant to learning scientific reasoning.

How does science learn?
Builng a community consensus



How can we learn to teach effectively?
Building a community consensus



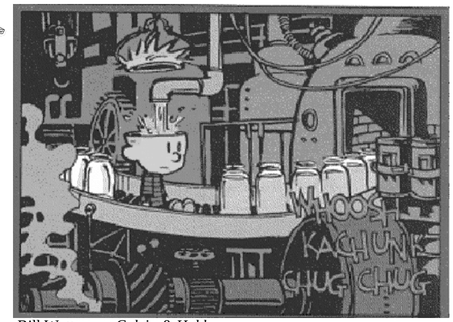
Learning About Student Learning

- Physics Education Research (PER) is the subject in which we study how students understand (and fail to understand) physics in order to
  - help individual students get over their difficulties in learning physics
  - develop curriculum and materials that are more effective for many students.

The PER frame

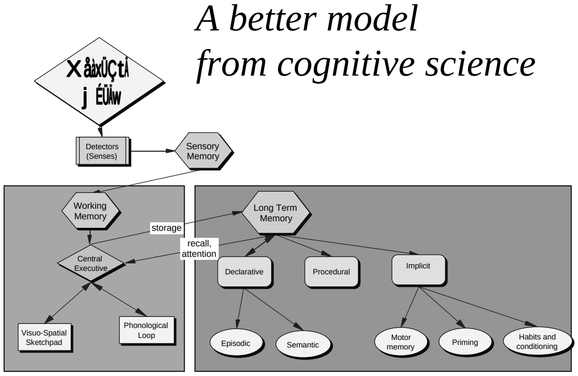
- Observe students carefully using
  - interviews
  - open-ended exam questions (explain…, show…)
- Interpret student errors in terms of a model of learning.
- Apply our understanding of student starting points to
  - not gloss over points which are difficult for students
  - use what students know as resources for their learning
  - focus our evaluations on the basic building blocks instead of on superficial manipulations

A model of student learning from a noted expert



Bill Watterson, *Calvin & Hobbes*

A better model from cognitive science



Adapted from A. Baddeley, *Human Memory: Theory and Practice* (Allyn & Bacon, 1998). and L. R. Squire and E. R. Kandel, *Memory: From Mind to Molecules* (Scientific American Library, 1999).

Learning is about building long-term memory

- Long-term memory
  - contains data, procedures, and rules about when to use them
  - is productive / generative
  - is associative
  - is structured
- The key structures are patterns of association
  - links may be weak or strong
  - both connections and reasoning are context dependent

Key implications

- **<u>1. Learning is productive / constructive.</u>**
  - The brain tries to make sense of new input in terms of existing mental structures.
  - ➢ *We learn by analogy / metaphor*
  - -- *New constructions tend to be based on the model of existing structures.*
- **<u>2. Cognitive response is context dependent</u>.**
  - The productive response depends on the context in which new input is presented, including the student's mental state (expectations).
  - ➢ *Students can use multiple models*
  - -- *Confusion about appropriate context can make it appear as if students hold contradictory ideas at the same time*

The trouble with light

- Physicists ideas about light are difficult to teach to novices for two reasons.
  - Sighted people have lots of experience with light. As a result, they have strong associations and interpretations that create barriers to learning.
  - Physicists' use a variety of models (rays, waves, photons), sometimes hybridizing them in ways that are difficult for students to make sense of.
- There has been a lot of PER concerning learning about light at a variety of levels.

Major contributors

- Most of the work I will talk about has been done by physicists, in particular, Lillian McDermott, her collaborators, students, and postdocs.

- There has also been a lot of important work by education specialists around the world including Driver (England), Treagust (Australia), and Anderson (Sweden).

Some difficult items learning about light

- The ray model
  - how we see
  - colors
  - straight line propagation
  - images made by mirrors and lenses
- The wave model
  - superposition
  - Huygen's principle
  - interference and diffraction
- The Maxwell model
  - plane wave
  - fields
- The photon model
  - photoelectric effect
  - wave-particle duality (hybridizing the models)
  - entangled states
  - meaning of quantum numbers

Why can't we just tell them? show them?

- When a student has a strong association with or interpretation of a phenomena, telling them — even showing them — often has little effect.
  - Students often re-interpret what they hear so that it makes sense in their personal scheme of things.
  - Even when shown a phenomenon explicitly, students will often fail to interpret things in the way we want them to.

How we see

- Children's view of how we see has been studied in depth.
  - Piaget found that young children often made no connection between the eye and the object.
  - Many studies of high school students show that only about 1/3 of students know we see an object by light coming to our eye from it.
  - About 1/3 of high school students have no explanation for vision: "We see with our eyes" suffices.

- The results stated on the previous slide lead to problems with mirrors and lenses, even at the university level.
- In this case, the critical interpretive fact is that the image is determined by what light comes to our eyes.

Images: Mirrors

- Many students at the university level do not understand basic issues with mirrors. They think:
  - The image in a mirror lies on the surface of the mirror. (~30% pre instruction)
  - That the position of a mirror image changes when the observer moves. (~30% post instruction)
  - If a mirror is too small to see all of yourself, you can step back and see more. (~70% post instruction)

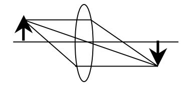
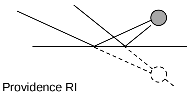
** F. Goldberg and L.C. McDermott, The Physics Teacher. 24, 472 (1986).*

Images: Lenses

- Many students at the university level do not understand basic issues with lenses. If a lens is positioned to create a real image of a bulb on a screen they think:
  - removing the lens will make the image right-side up (~45% post instruction)
  - the image does not lie on the screen (~75% post instruction)
  - covering half a lens will block half of the real image it creates (~75% post instruction)

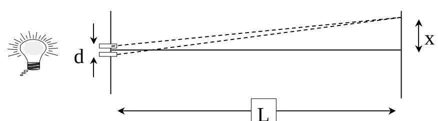
Sherwood's Theorem

- "Glass attracts light."
- We often show only the relevant "critical rays", ignoring the fact that many students do not understand
  - that light scatters from every point on an object in all directions and that image formation arises from what rays make it into our eyes (and how our eyes interpret them)

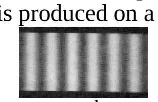
Wave Optics

- Waves are particularly confusing for students.
  - They have trouble with functions of many variables.
  - They get deeply confused about superposition.
  - We carry out calculations of interference and diffraction using a hybrid wave / ray model.



Interference: A sample problem

- When monochromatic laser light is shone on a pair of double slits, the pattern shown below is produced on a distant screen.



- What would happen to the pattern if one of the slits were covered?
  (Since the interference arises from the waves from the two slits interfering with each other, the pattern would go away and be replaced by an almost uniform brightness.)

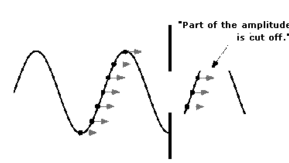
Results

- This question was posed to a class of engineering physics students before and after instruction.
- More than half of the students expected part of the pattern would remain.
  - Some said the left half of the lines would remain.
  - Some said every other line would remain.

** K. Wosilait, P. Heron, P.S. Shaffer, and L.C. McDermott, PERS to Am. J. Phys. 67, S5-S15 (1999).*

Photons

- When students are asked to incorporate the photon idea into their previous observations they construct some bizarre models.



  - Some students suggest that photons move in oscillatory paths "along the sine wave."
  - Some students suggest that diffraction occurs because "the photons bounce off the edge of the slit."
  - Some suggest diffraction occurs because "the E-field vector won't fit through the slit and gets cut off."

** B. Ambrose, P.S. Shaffer, R. Steinberg, and L.C. McDermott, Am. J. Phys. 67, 146-155 (1999).*

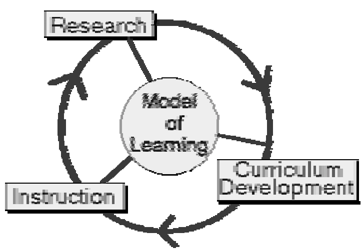
Why do they do this?

- Many of the problems arise from the fact that students use common sense rather than reason using the physical principles they have learned.
  - Students use their natural and spontaneous responses based on experience and overly simplistic reasoning. ("I know how light [or motion {or electricity}] works. I don't need to go through that confusing physics stuff to get the answers.")
  - Most students do not spontaneously seek to build the tight consistency and coherence required by a scientific approach. It needs to be learned (and taught).

How can we help them?

- In the past decade, it has been demonstrated that instructional environments can be constructed that are much more effective than traditional instruction.
- They need to be built
  - with an awareness of students' natural responses
  - with an understanding of what instructional techniques have a significant impact.

The PER instructional development process



The UW Tutorial Model

- Tutorials replace recitations:
  - training session for TAs
  - group-learning sessions with research-based worksheets and facilitators
  - tutorial homework
  - exams have a tutorial question
- Lectures (and labs) as usual.

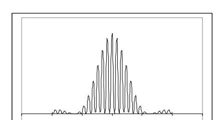
** L. C. McDermott, et al., Tutorials In Introductory Physics (Prentice Hall, NY, 1998)*

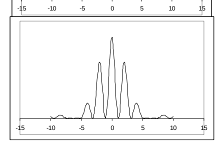
Tutorials on interference and diffraction

- A series of 4 one-hour tutorials on interference and diffraction
  - focus on qualitative reasoning
  - concentrate on difficulties know to exist from PER
  - use a cognitive conflict model to engage student interest (predict / observe / resolve)
  - stress logical coherence

Results

Shown many graphs of the type shown at the right, rank the relative slit width and spacing.



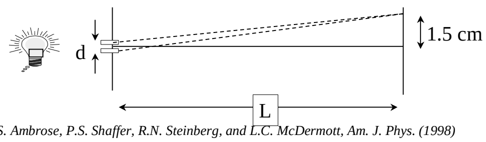


	After traditional instruction (N=365)	*After tutorial (N=330)*
Ranking by slit width	~55%	~85%
Ranking by slit spacing	~45%	~80%

** K. Wosilait, P. Heron, P.S. Shaffer, and L.C. McDermott, PERS to Am. J. Phys. 67, S5-S15 (1999).*

What about problem solving?

- *Example:*
  - Light with λ = 500 nm is incident on two narrow slits separated by d = 30 µm. An interference pattern is observed on a screen a distance L away from the slits. The first dark fringe is found to be 1.5 cm from the central maximum. Find L.



B.S. Ambrose, P.S. Shaffer, R.N. Steinberg, and L.C. McDermott, Am. J. Phys. (1998)

Results at UMd

	Example	recitation (N=165)	tutorial (N=117)
correct (L=1.8 m)	$\Delta D = d\sin\theta = \frac{\lambda}{2}$, $\sin\theta \approx \frac{y}{L}$	16%	60%
L=0.9 m	$y = \frac{m\lambda L}{d}$	40%	9%
other incorrect	$L = 5.0\times10^{-7}\,m$	44%	31%

Conclusions

- After mechanics, optics is that area of physics where the most is known about what difficulties students have learning it.
- Modern research-based instructional methods have proven effective in substantially increasing the fraction of students who “get it.”
- If we want to introduce modern topics by cutting out introductory ones, we might do so more efficiently by making careful observations of student responses and learning.

For more information

- For more information about PER in general check our our website at
  - *http://www.physics.umd.edu/perg/*
- For references to the articles in PER on optics check out the AJP resource letter on PER by McDermott and Redish (Oct. ’99)
  - *http://www.physics.umd.edu/rgroups/ripe/papers/rlpre.pdf*