# *Physics Education Research: the key to improving student learning*

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# Physics Education Group

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# Discipline-based research on learning and teaching

- differs from traditional education research (in which emphasis is on educational theory and methodology)

- focuses on student understanding of science content

- is an important field for scholarly inquiry by science faculty (need deep understanding of content and access to students)

***Discipline-based education research can be a useful guide for improving student learning from the elementary to the graduate level.***

# Physics Education Group

**Perspective:** ***Teaching is a science*** *(as well as an art).*

**Procedures:**

- conduct systematic investigations
- apply results (*e.g.*, develop instructional strategies)
- assess effectiveness of curriculum
- document methods and results so that they can be replicated
- report results at meetings and in papers

***These are characteristics of an empirical applied science.***

# Physics Education Group

## Research

- **Focus:** Intellectual issues related to content
  (not psychological/social issues nor educational theory/methodology)
- **Emphasis:** Concepts and ability to do reasoning to apply concepts
  (not on skill in using formulas to solve quantitative problems)
- **Perspective:** Evidence-based
  - (not hypothesis-driven)
- **Scope:** University Level
  (introductory to advanced)

**Application of research ——> development of curriculum**

research-based and research-validated

# Context for research and curriculum development

**Student populations** (at UW and at pilot sites)

- Introductory students (physics, engineering, other sciences)
- Underprepared students
- K-12 teachers (preservice and inservice)
- Engineering students beyond introductory level
- Advanced undergraduates and graduate students

# Focus of research

## *is not* on teaching by instructors

## but

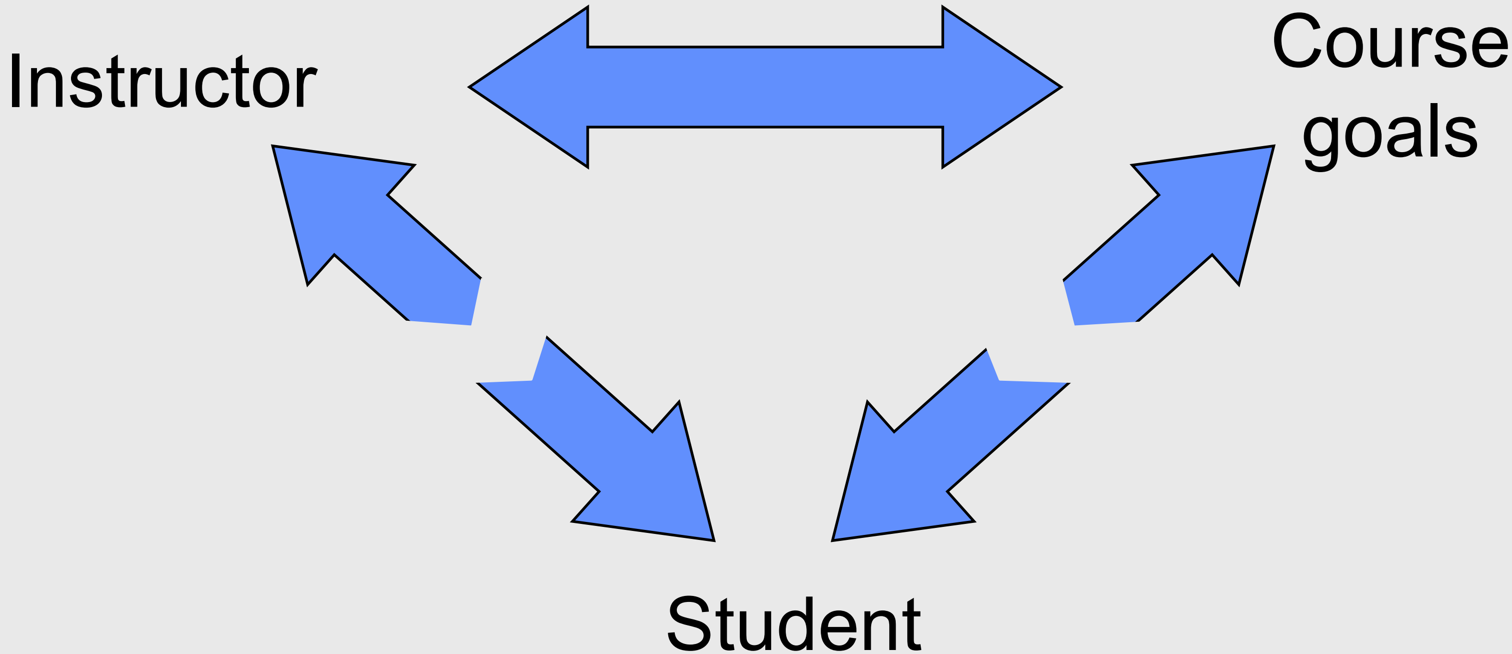
## *is* on learning by students

---

- **identifying what students *can* and *cannot* do**
- **designing instruction to develop functional understanding***
- **assessing effect on student learning**

* *ability to do the reasoning necessary to construct and apply conceptual models to the interpretation of physical phenomena*

# Evidence from research indicates a gap




***Gap is greater than most instructors realize.***

# ***Traditional approach***

***is based on:***

- instructor's present understanding of subject
- instructor's belief that he or she can transmit "knowledge" to students
- instructor's personal perception of student

***ignores differences between physicist and student:***

- small for future physicists (<5% of introductory course)
- large for most students

# ***Alternative approach***

***is based on:***

- research that focuses on student learning

# Systematic investigations of student learning

(at the beginning, during, and after instruction)

- **individual demonstration interviews**
  - for probing student understanding in depth
- **written questions** (pretests and post-tests)
  - for ascertaining prevalence of specific difficulties
  - for assessing effectiveness of instruction
- **descriptive studies during instruction**
  - for providing insights to guide curriculum development

***What are students thinking?***

**Students with similar background tend to:**

– have similar ideas at same stage of instruction

– respond in similar ways to same instructional strategy

**Need for control groups is minimized when:**

– student populations are large

– goal of an instructional strategy is a large change

# Identifying and addressing student difficulties with conceptual models for light

- **Physical Optics**

"An investigation of student understanding of single-slit diffraction and double-slit interference," B.S. Ambrose, P.S. Shaffer, R.N. Steinberg, and L.C. McDermott, *Am. J. Phys.* **67** (2), 1999.

"Addressing student difficulties in applying a wave model to the interference and diffraction of light," K. Wosilait, P.R.L. Heron, P.S. Shaffer, and L.C. McDermott, *Physics Education Research:* A Supplement to the *American Journal of Physics* **67** (7), 1999.

- **Geometrical Optics**

"An investigation of student understanding of the real image formed by a converging lens or concave mirror," F. M. Goldberg and L.C. McDermott, *Am. J. Phys.* **55** (1987).

"Development and assessment of a research-based tutorial on light and shadow," K. Wosilait, P.R.L. Heron, P.S. Shaffer, and L.C. McDermott, *Am. J. Phys.* **66** (1998).

"Bridging the gap between teaching and learning in geometrical optics: The role of research," P.R.L. Heron and L.C. McDermott, *Opt. & Phot.* News **9** (1998).

# Physical Optics

## Interpreting and applying a wave model for light

Examples of conceptual difficulties from written examinations and individual demonstration interviews

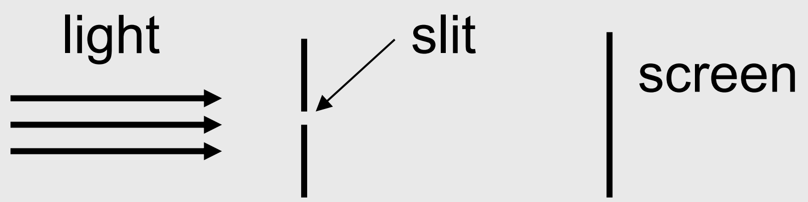
# Determining what students *can* and *cannot* do

# Questions on single-slit diffraction

Given after standard instruction in
introductory calculus-based course

## Quantitative question (N ~130)

**Light of wavelength $\lambda$ is incident on a slit of width $a = 4\lambda$.**



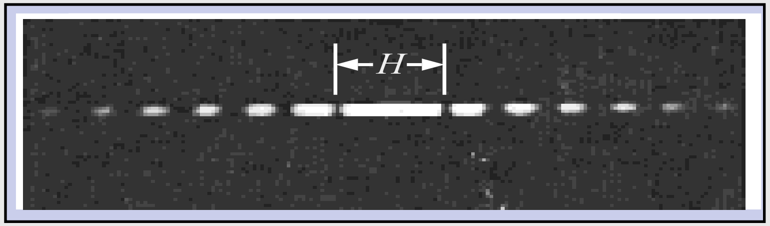

**Would minima appear on a distant screen? If so, find the angle to the first minimum.**

$$a \sin\theta = \lambda$$

Since $a > \lambda$ --> there are minima

## Qualitative question (N ~510)

**The pattern below results when a mask with a narrow slit is placed between a laser and a screen.**




**Is the slit width *greater than, less than,* or *equal to* the wavelength? Explain.**

$$a \sin\theta = \lambda$$

Since there are minima --> $a > \lambda$

# What students *can* and *cannot* do

## Comparison of performance on quantitative and qualitative questions.

| Introductory students | | Graduate students |
|---|---|---|
| **Quantitative question** (N ~ 130) | **Qualitative question** (N ~ 510) | **Qualitative question** (N ~ 95) |
| **70%** correct with angle | **10%** correct with explanation | **55%** correct with explanation |

## Interview task: single-slit diffraction

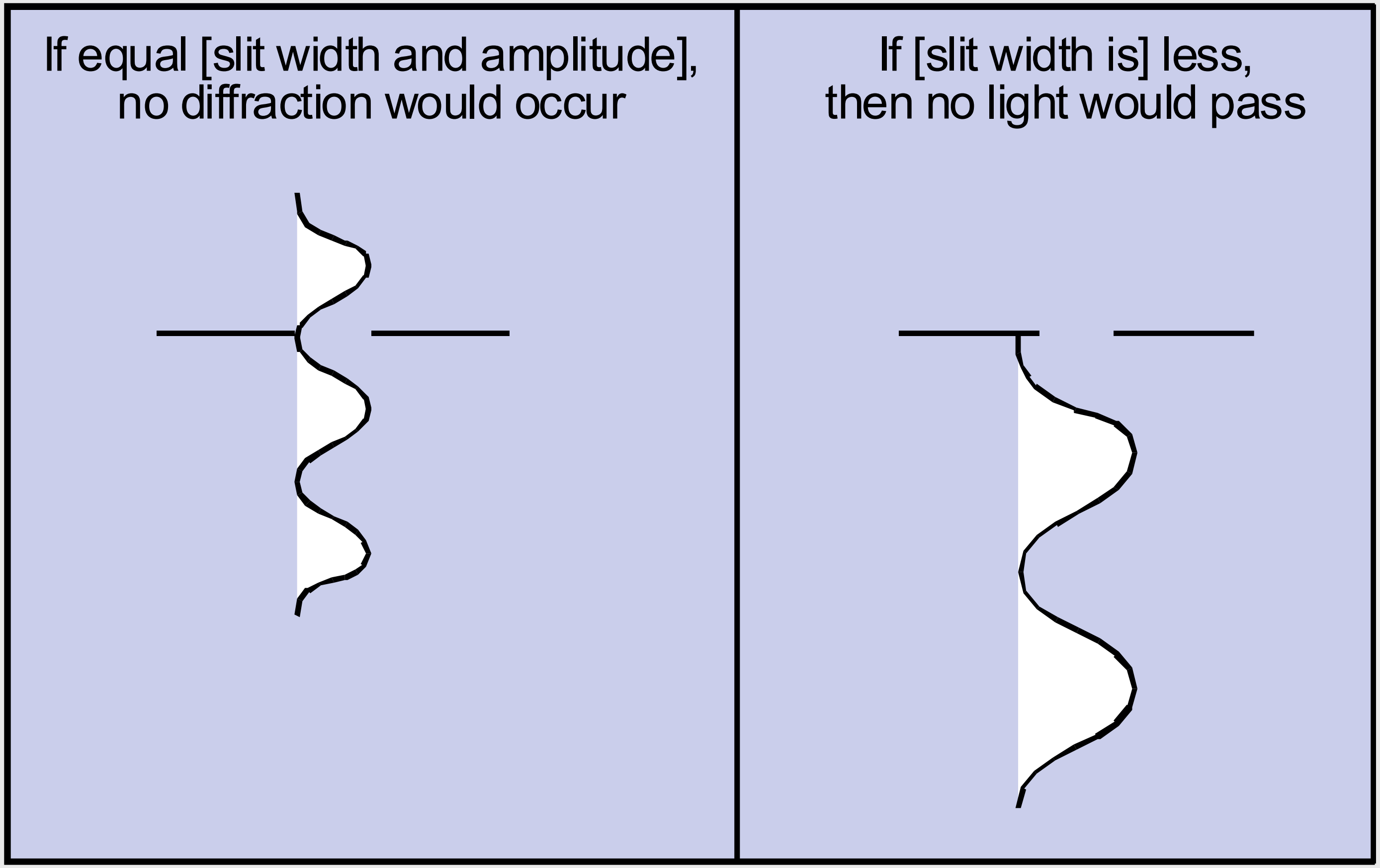
(30 modern physics students, 16 introductory students)

**Situation:** **Distant light source, mask with slit, and screen**

**Task:** **What would be observed on the screen as slit is narrowed? Explain.**

*Many serious difficulties emerged during the interviews.*

# Diagrams drawn by student

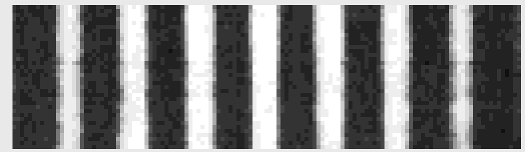



***student explanation:*** ***light must "fit" through slit***

***mistaken belief:*** ***the amplitude of a light wave has a spatial extent***

# Written exam question: double-slit interference

The pattern shown appears on a screen when light from a laser passes through two very narrow slits.



pattern on screen **with both slits uncovered**

**Sketch what would appear on the screen when the left slit is covered. Explain.**

## Correct response:

Interference minima disappear and the entire screen becomes (nearly) uniformly bright.

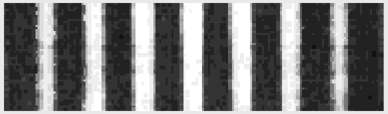
## Results:

| | Introductory calculus-based physics (N ~ 600) |
|---|---|
| **Correct** | 40% |
| **Incorrect:** Interference pattern remains | 45% |

***Results essentially the same before and after standard instruction (lecture, lab, textbook, homework problems).***

# Responses reminiscent of geometrical optics

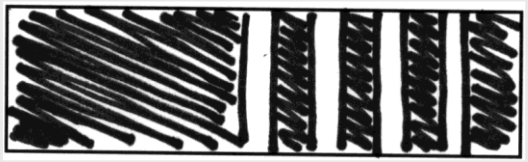
pattern with
both slits uncovered



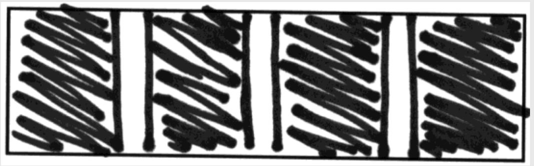
## When one slit is covered:

- *pattern stays the same or gets dimmer*

- *maxima on one side vanish*



- *every other maximum vanishes*



***tendency to associate each bright region with a particular slit***
***(use of a hybrid model:  geometrical and physical optics)***

# Illustration of research and curriculum development: geometrical optics

(simpler context than physical optics)

# What students *could* do
## (after standard instruction):

***Solve problems algebraically and with ray diagrams***

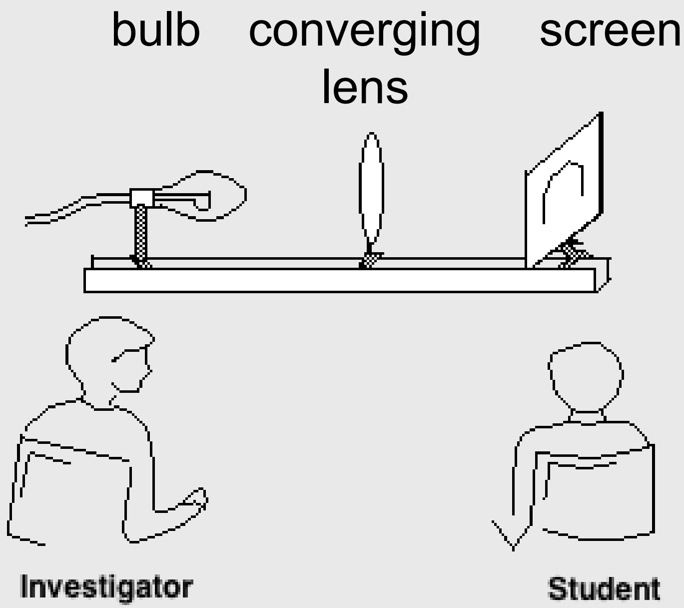
*Example:*

An arrow, 2 cm long, is 25 cm in front of a lens whose focal length is 17.3 cm.

Predict where the image would be located.

$$\frac{1}{S} + \frac{1}{S'} = \frac{1}{F}$$

# What students could *not* do:




| **Predict effect on screen** | **Correct** |
|---|---|
| (1) if the lens is removed | 50% |
| (2) if the top half of the lens is covered | 35% |
| (3) if the screen is moved toward the lens | 40% |

**Individual Demonstration Interviews: both <u>before</u> and <u>after</u> instruction**

**Generalizations on learning and *teaching***

**inferred and validated from research**

**have helped guide the**

**development of curriculum.**

◊ **Facility in solving standard quantitative problems is not an adequate criterion for functional understanding.**

***Questions that require qualitative reasoning and verbal explanations are essential for assessing student learning***

***and are an effective strategy for helping students learn.***

◊ **Connections among concepts, formal representations** (diagrammatic, graphical, etc.) **and the real world are often lacking after traditional instruction.**

***Students need repeated practice in interpreting physics formalism and relating it to the real world.***

## Students could all state that light travels in a straight line but did not recognize that:

- Principal rays locate image but are not necessary to form it.
- Area of lens affects only brightness, not extent, of image.
- For every point on an object, there is a corresponding point on the image.

**Question for research: What happens if there is no lens?**

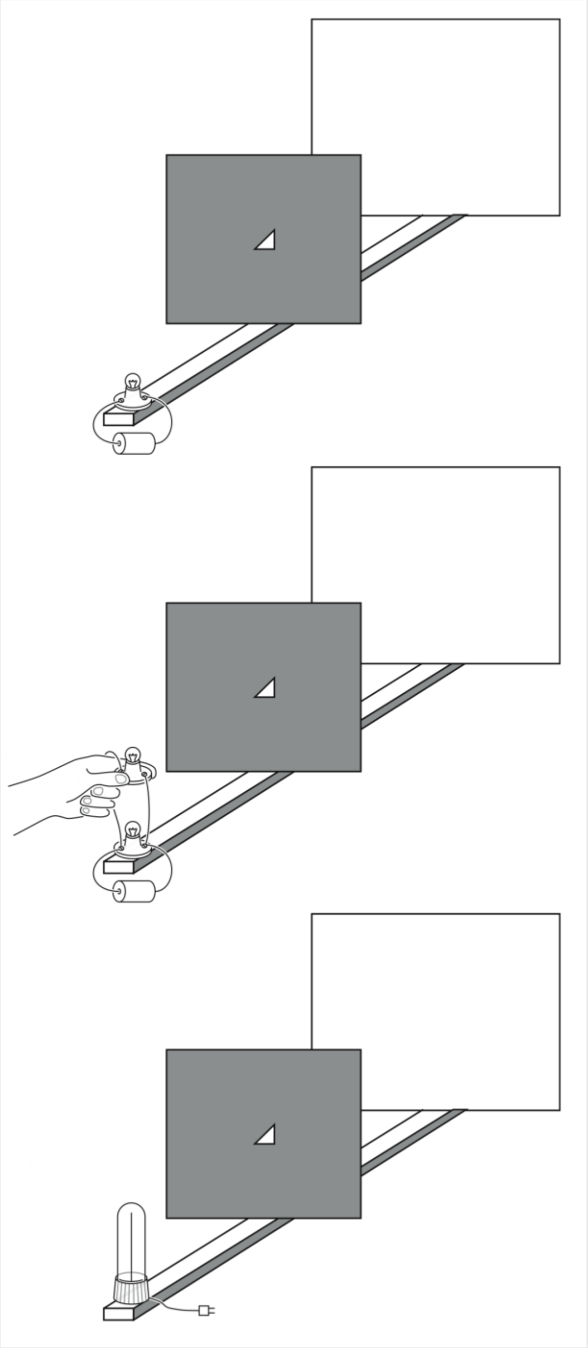
**Research led to identification of a more basic difficulty.**

# What students *could not* do:

(either before or after standard instruction in introductory university calculus-based physics)

**Sketch what you would see on the screen.**

**Explain your reasoning.**

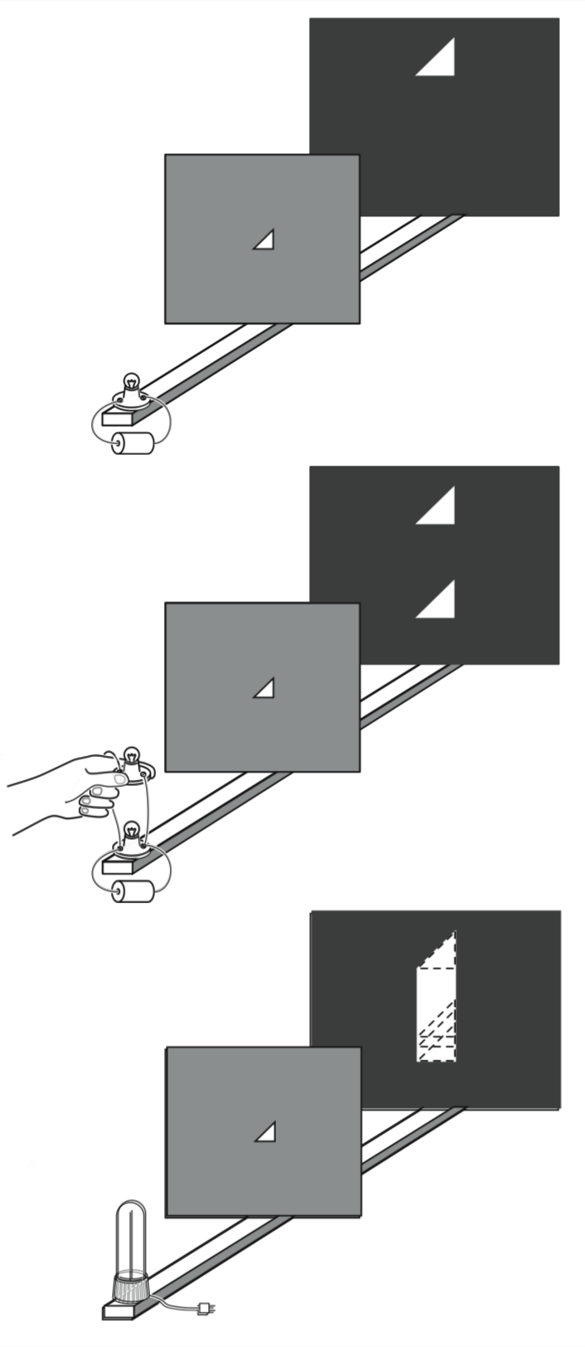


**Pretest** (N >> 1000 students)

Sketch what you would see on the screen.
Explain.

Correct responses

| | |
|---|---|
| Single bulb | 90% |
| Two bulbs | 60% |
| Long-filament bulb | 20% |



***Most common incorrect response: image mimics shape of aperture***

# Fundamental difficulty:

# Lack of a functional understanding of a basic ray model for light

- Light travels in a straight line.
- Every point on an object acts like a source of an infinite number of rays emitted in all directions.

◊ **A coherent conceptual framework is not typically an outcome of traditional instruction.**

***Students need to go through the process of constructing models and applying them to predict and explain real-world phenomena.***

## *On certain types of qualitative questions, student performance is essentially the same:*

- *before and after instruction*
- *in calculus-based, algebra-based, and “conceptual” courses*
- ***whether topics seem ‘complex’ or ‘simple’***
- *with and without demonstrations*
- *with and without standard laboratory*
- *in large and small classes*
- *regardless of popularity of the instructor*

*Hearing lectures, reading textbooks, seeing demonstrations, doing homework, and performing laboratory experiments often have little effect on student learning.*

◊ **Teaching by telling is an ineffective mode of instruction for most students.**

***Students must be intellectually active to develop a functional understanding.***

# Need for a different instructional approach
## (“guided inquiry”)

## *Physics by Inquiry*

Laboratory-based, self-contained curriculum designed primarily for K-12 teachers, but suitable for other students

## *Tutorials in Introductory Physics*

Supplementary curriculum designed for use in standard introductory physics courses

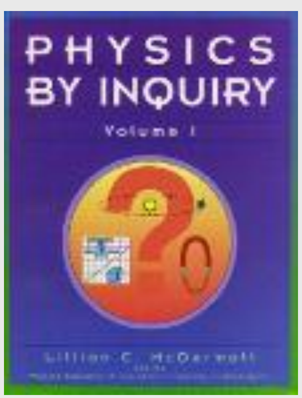
# Iterative cycle for development of curriculum

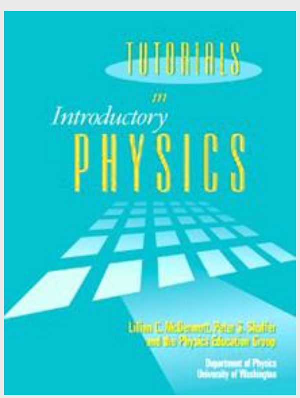
**Research**

**Curriculum Development**

**Instruction**
at UW

**Instruction**
at pilot sites



# Emphasis in *Pbl* and in *Tutorials* is on:

- constructing concepts and models
- developing reasoning ability
- addressing known difficulties
- relating physics formalism to real world

<u>not</u> on

- solving standard quantitative problems

## ***Physics by Inquiry***

## Instruction on Geometrical Optics

- Students are guided in constructing a basic ray model from their direct experience with light sources and apertures of different shapes.

- Questions that require qualitative reasoning and verbal explanations help students develop a functional understanding through their own intellectual effort.

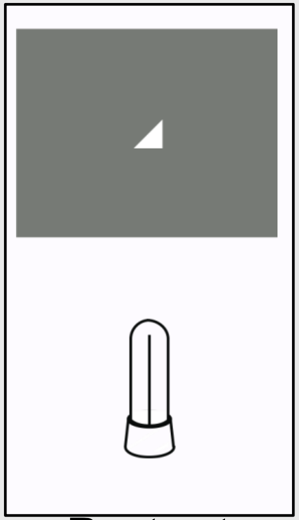
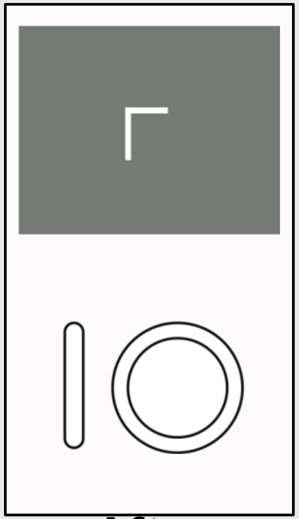
- Curriculum explicitly addresses conceptual and reasoning difficulties identified through research.

*This type of laboratory-based instruction is especially important for pre-university teachers.*

# Inspiration for development of *Tutorials in Introductory Physics*

*We found that elementary school teachers who had learned from **Physics by Inquiry** could do better on certain types of questions than engineering and physics majors.*

## Results with *Physics by Inquiry* module.

| | In-service K-12 teachers | |
|---|---|---|
| |  **Pretest** *N* = 22 |  **After PbI** *N* = 22 |
| **correct or nearly correct for all bulbs** | **5%** | **90%** |
| **image(s) mimic hole in mask** | **75%** | **5%** |

# Application in 9th-grade

**Success rate of 9th-grade students with:**

- under-prepared inservice teacher < *20%*
- well-prepared *(PbI)* preservice teacher ~ 45%
- well-prepared *(PbI)* inservice teacher ~ 85%

*With under-prepared inservice teacher ~ introductory university students*
*With well-prepared (PbI) inservice teacher > graduate students (~65%)*

## Challenge

to improve student learning in introductory course
(constraints:  large class size, breadth of coverage, and fast pace)

## Need

to secure mental engagement of students at deep level

## Requirement

to develop a practical, flexible, sustainable approach

# Response

to improve instruction in introductory physics through cumulative, incremental change

(evolution not revolution)

- by recognizing the constraints imposed by lecture-based courses
- by developing research-based tutorials that supplement standard instruction with a modified version of the intellectual experience provided by *Physics by Inquiry*

⬇

*Tutorials in Introductory Physics*

# Tutorials respond to the research question:

**Is standard presentation of a basic topic in textbook or lecture adequate to develop a functional understanding?**

(i.e. the ability to do the reasoning necessary to apply relevant concepts and principles in situations not explicitly studied)

**If not,**

**what needs to be done?**

# Tutorial sequence consists of:

Pretest

(paper or web-based)

Worksheet

(collaborative small groups)

Homework

(individual)

Post-test

(course examinations)

Note that ***research-based*** is <u>not</u> the same as ***research-validated.***

*Pretests are not enough.*
*Post-tests are necessary.*

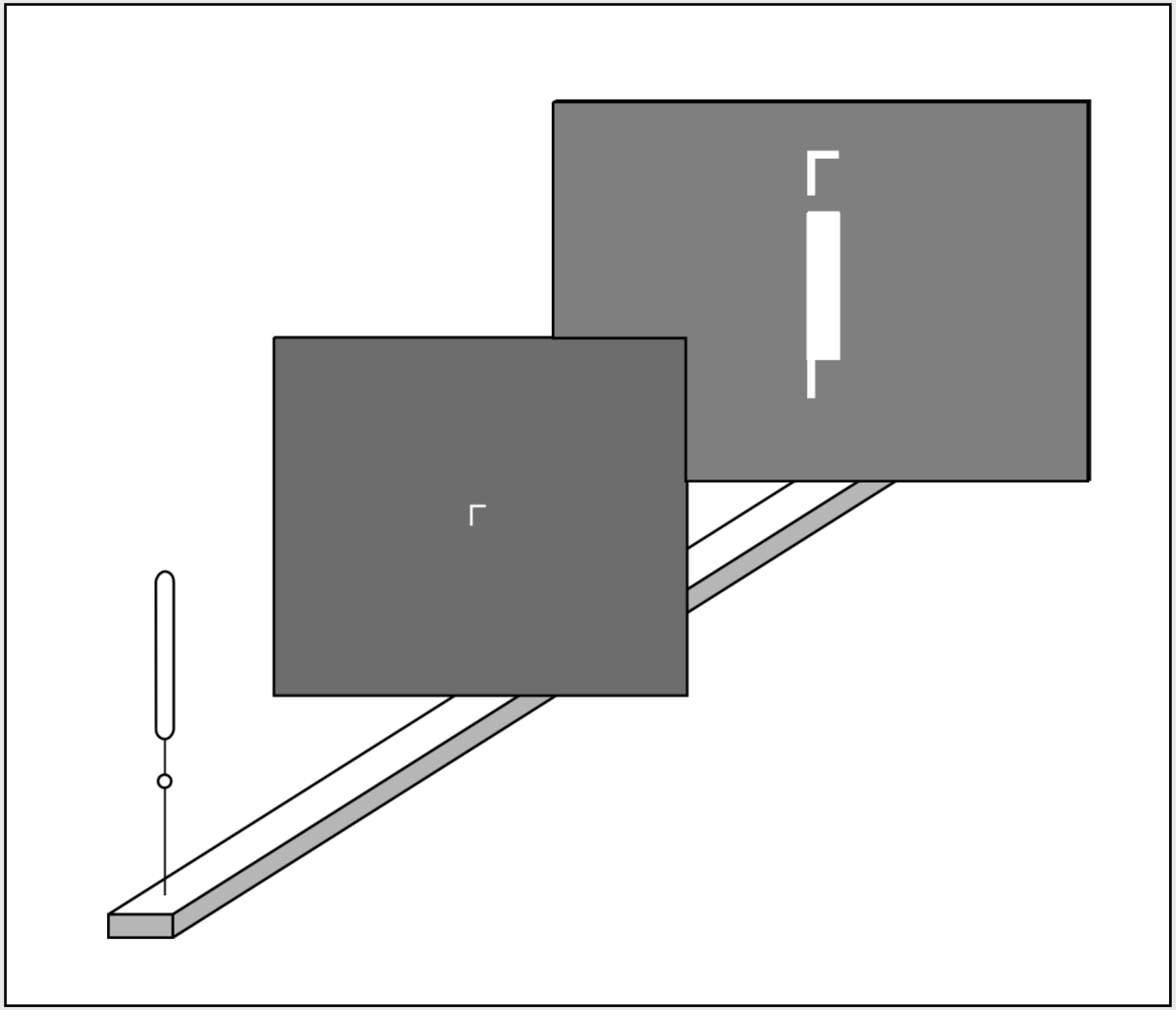
# Tutorial: *Light and Shadow*

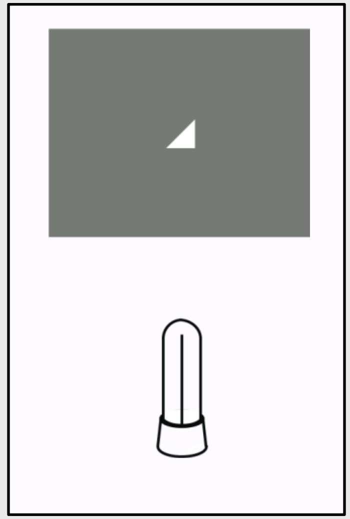
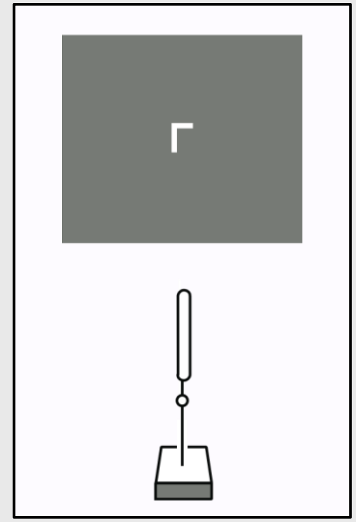
**Carefully sequenced questions guide students in investigating geometric images produced by various combinations of apertures and light sources.**

# Post-test 1

**administered after tutorial *Light and shadow***

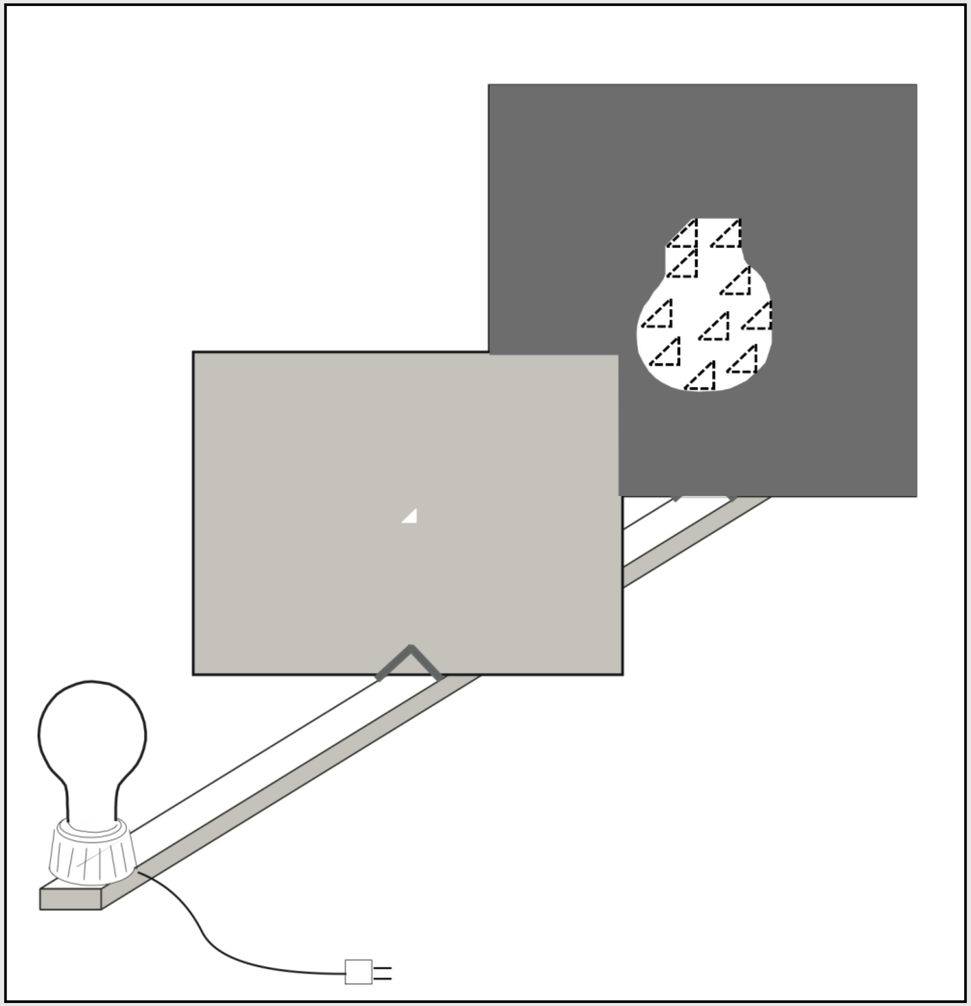
**Sketch what you would see on the screen when the bulbs are turned on.**



| | <br>**Pretest**<br>before and after traditional instruction<br>$N > 2100$ | <br>**Post-test 1**<br>after tutorial<br>$N = 415$ |
|---|---|---|
| correct or nearly correct | **20%** | **60%** |
| image mimics hole in mask | **70%** | **25%** |

# Revision to tutorial (and to *Physics by Inquiry*)

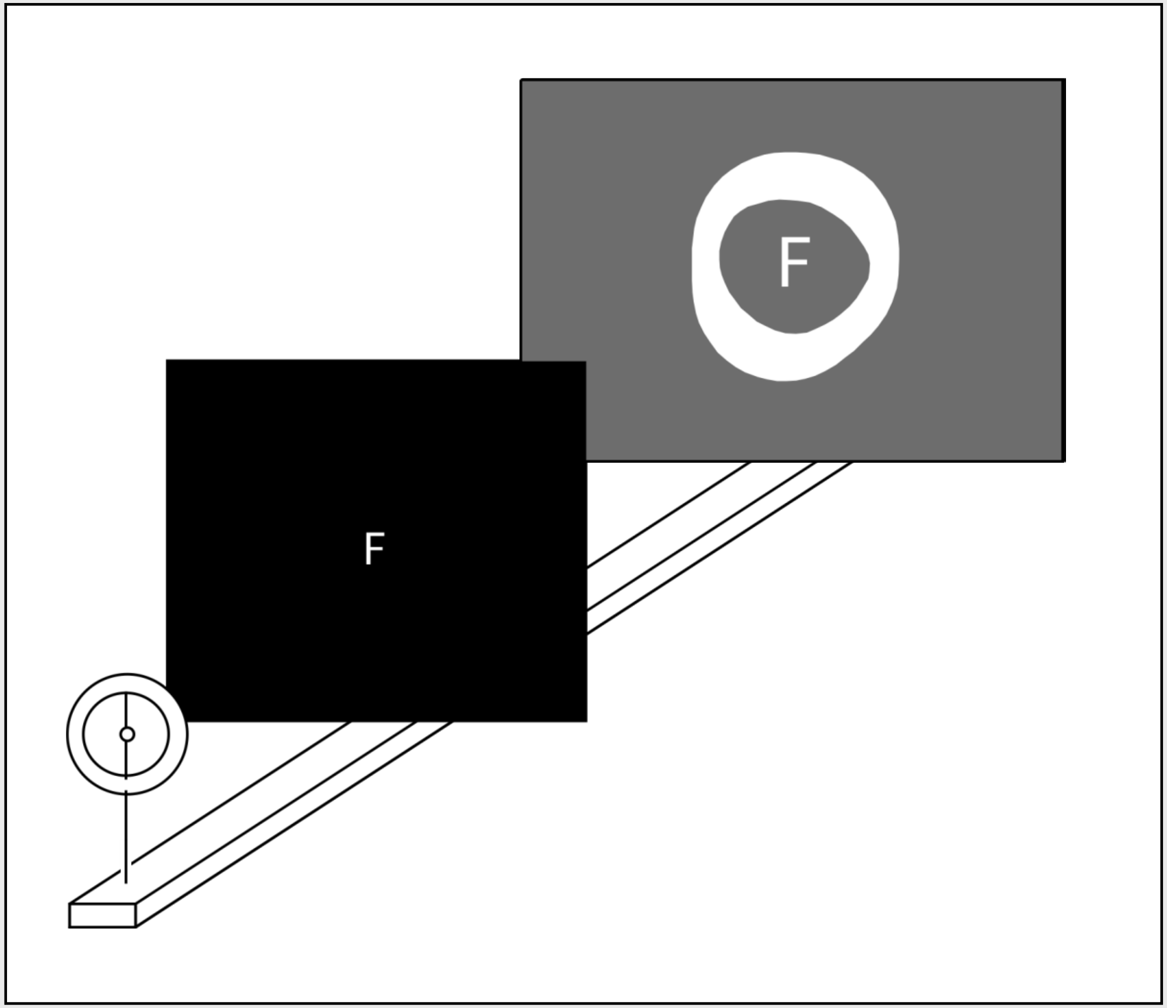
**Students consider a true extended source (frosted light bulb).**

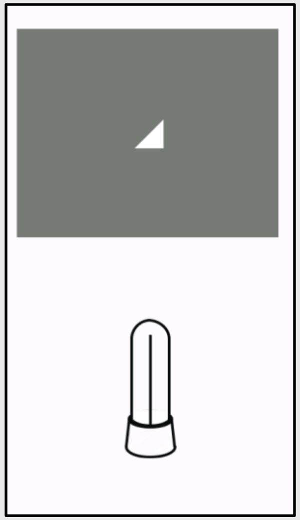
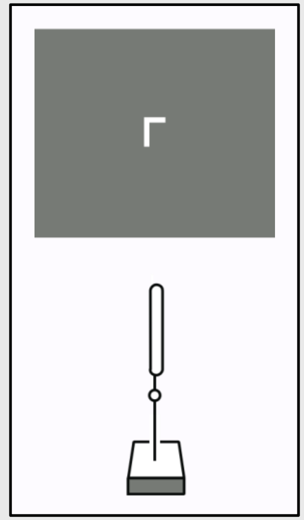
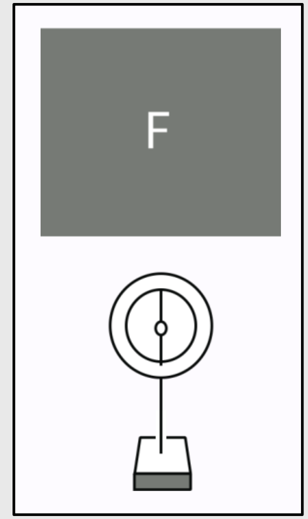


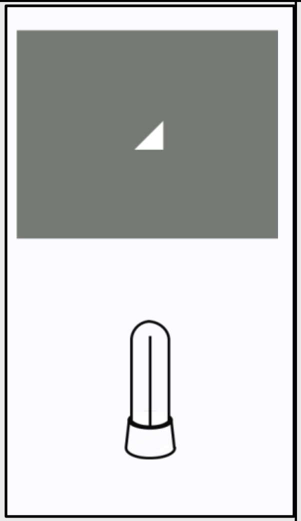
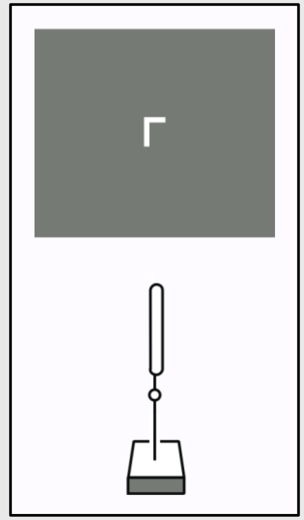
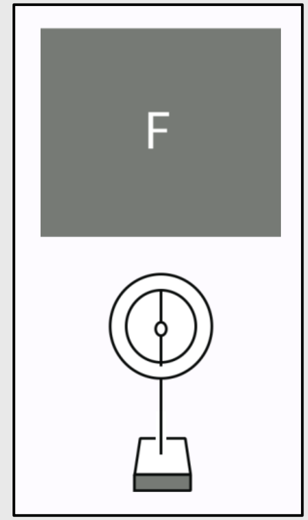
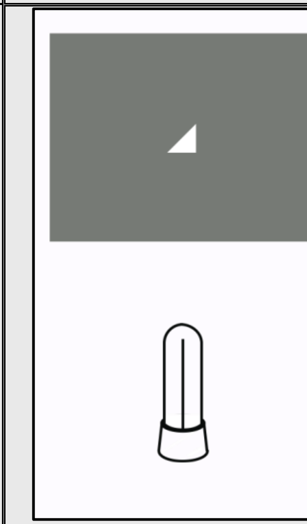
# Post-test 2

## administered after revised tutorial

**Sketch what you would see on the screen when the bulbs are turned on.**



| | Undergraduates | | |
|---|---|---|---|
| |  **Pretest** with “hint” *N* > 2100 |  **After original tutorial** *N* = 415 |  **After revised tutorial** *N* = 175 |
| **correct or nearly correct** | **20%** | **60%** | **75%** |
| **image mimics hole in mask** | **70%** | **25%** | **10%** |

| | Undergraduates | | | Graduate TAs |
|---|---|---|---|---|
| |  |  |  |  |
| | **Pretest** with “hint” *N* > 2100 | **After original tutorial** *N* = 415 | **After revised tutorial** *N* = 175 | **Pretest (before tutorial)** *N* = 110 |
| **correct or nearly correct** | **20%** | **60%** | **75%** | **65%** |
| **image mimics hole in mask** | **70%** | **25%** | **10%** | **30%** |

Note: Results not as good as with *Physics by Inquiry* (75% *vs* 90%) but less time spent.

**Practical criterion**
**for effectiveness of a tutorial:**

*Post-test performance of introductory students*

*matches (or surpasses)*

*pretest performance of graduate students.*

(75% *vs.* 65%)

- ◊ **Certain conceptual difficulties are not overcome by traditional instruction. (Advanced study may not increase student understanding of basic concepts.)**

  ***Persistent conceptual difficulties must be explicitly addressed.***

Can explanations by lecturer substitute for direct experience of students??

Two professors at UW tried to save time through demonstrations and homework

Results were much poorer,

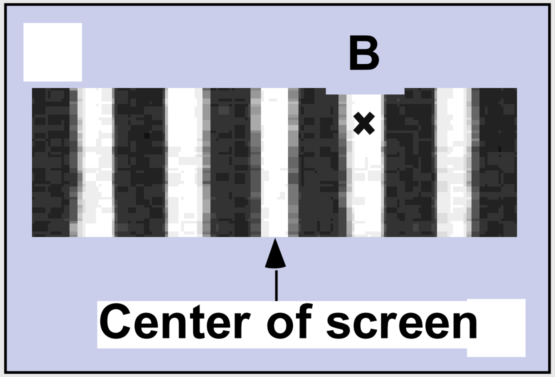
even for honors students .

(< 45% correct *vs* 75%)

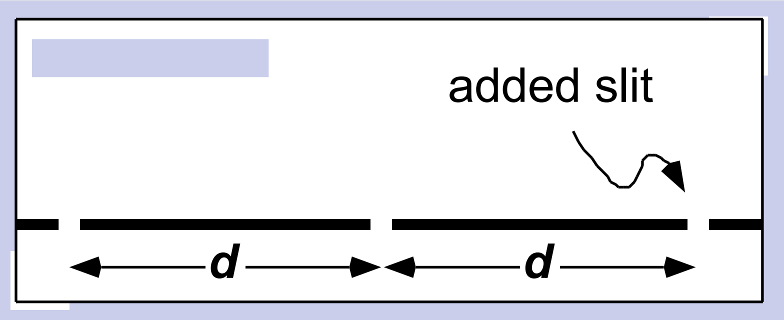
# Example of assessment of student learning through pretesting and post-testing in physical optics

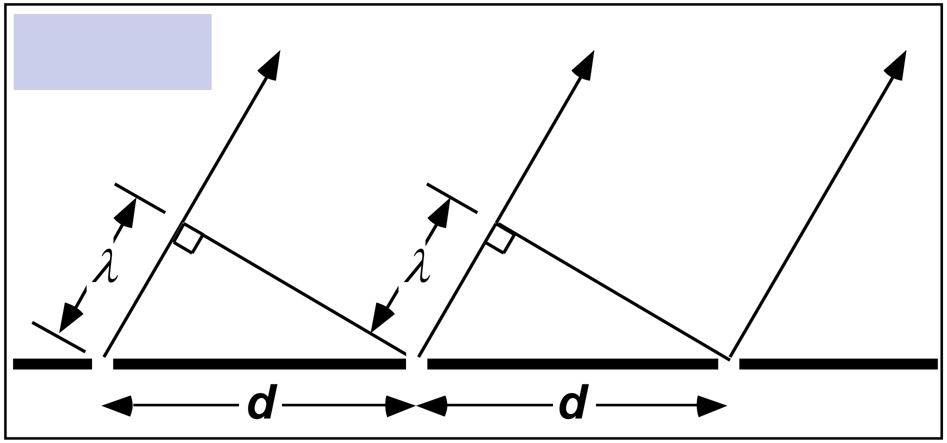
# Example of pretest on multiple-slit interference

The pattern at right appears on a distant screen when coherent red light passes through two very narrow slits separated by a distance *d.*




**Suppose that a third slit is added as shown:**




***Would the intensity at point B increase, decrease, or remain the same?***

Point *B* is a maximum for the first two slits, so the light from all three slits is in phase at point *B.* Therefore, the intensity at point *B* **increases.**

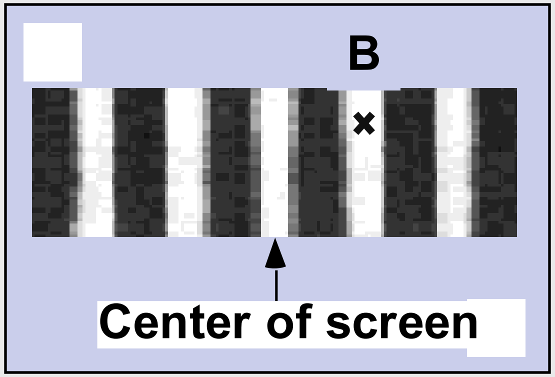
# Tutorials guide students in constructing and applying a basic wave model for light.

## Worksheets and homework help students:

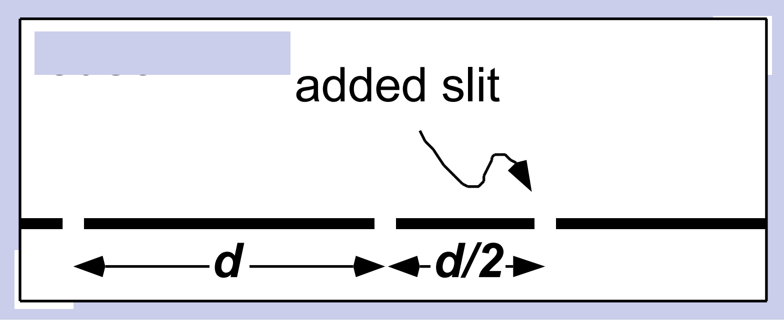
- **Develop basic interference concepts in context of water waves**
  - path length (and phase) difference
  - superposition
  - mathematical formalism
- **Make appropriate analogies between water and light waves**
- **Extend model for two-slit interference**
  - to more than two slits
  - to single-slit diffraction
  - to combined interference and diffraction
- **Resolve specific difficulties through their own intellectual effort**
- **Extend and apply model in different situations**

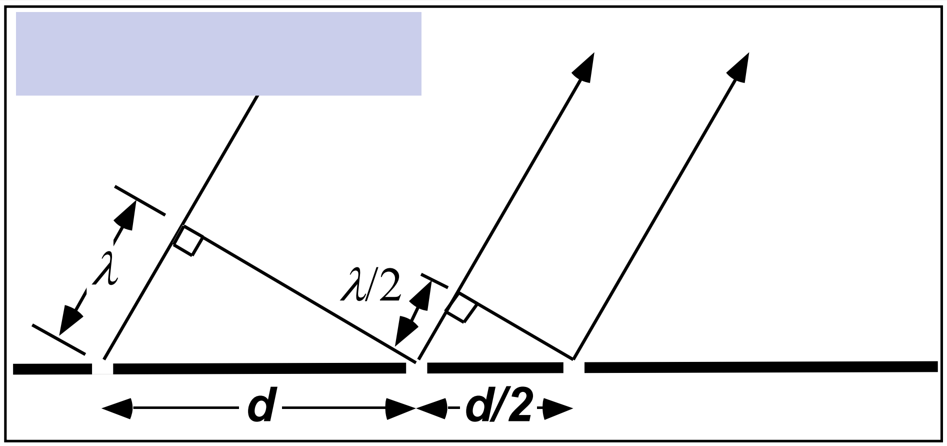
# Example of post-test on multiple-slit interference

The pattern at right appears on a distant screen when coherent red light passes through two very narrow slits separated by a distance *d.*




**Suppose that a third slit is added as shown:**

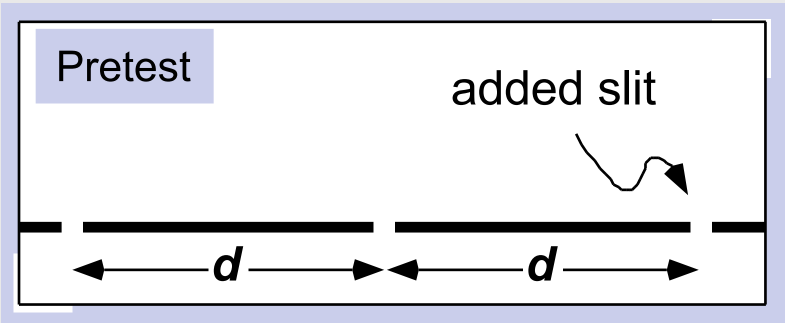


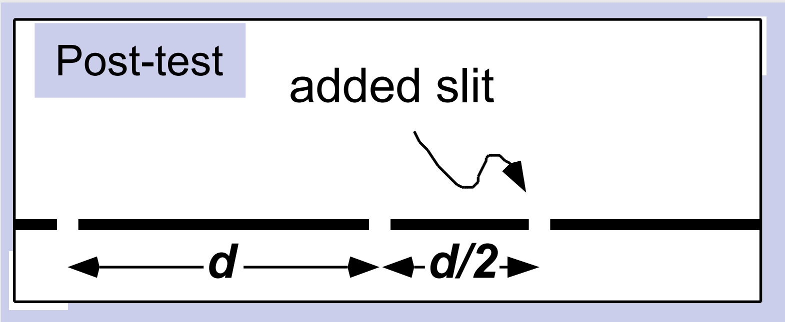




**Would the intensity at point *B* increase, decrease, or remain the same?**

Light from the third slit is not in phase with that from the original two slits and thus there is some cancellation. Therefore the intensity at point *P* **decreases.**

# Results from pretest and post-test on multiple-slit interference




Does the intensity at point *B* (a maximum) *increase, decrease,* or *remain the same?*

| | **Undergraduate students** | | **Graduate TA's** |
|---|---|---|---|
| | **Pretest** **(*d*)** **N ~ 560** | **Post-test** **(*d* / 2)** **N ~ 405** | **Pretest** **(*d*)** **N ~ 55** |
| **Correct** *without* regard to reasoning | **30%** | **80%** | **60%** |
| **Correct** *with* correct reasoning | **< 5%** | **40%** | **25%** |

# Assessment of student learning

## Effect of tutorials on student performance

***On qualitative problems:***

– *much better*

***On quantitative problems:***

– *typically somewhat better*

– *sometimes much better*

***On retention:***

– *sometimes much better*

***despite less time devoted to solving standard problems (Emphasis is on reasoning.)***

- **Growth in reasoning ability does not result from traditional instruction.**

***Scientific reasoning skills must be expressly cultivated.***

***Concepts and reasoning are inseparably linked and must be taught together.***

# Reflection on some important features of

# *Tutorials in Introductory Physics*

- Students do the reasoning needed for the development and application of concepts and construction of models.
- Conceptual and reasoning difficulties that have been identified by research are explicitly addressed.
- Students work in small groups (collaborative learning and peer instruction).
- Instructors teach by questioning, not by lecturing.

- **Examinations require application of concepts from tutorials.**
- **Weekly teaching seminar is required for TA's and other tutorial instructors (content and instructional method).**

***Emphasis on explanations of reasoning***

# Results from research

**indicate:**

- many students encounter same conceptual and reasoning difficulties
- same instructional strategies are effective for many students

**are:**

- generalizable beyond a particular course, instructor, or institution
- reproducible

**become:**

- publicly shared knowledge that provides a basis for acquisition of new knowledge and for cumulative improvement of instruction

∴ **constitute:**

- a rich resource for improving instruction

***Discipline-based education research can be an effective guide for improving the learning of science from elementary school to the graduate level.***

***Such research at the university level is best conducted in science departments because it requires:***

- Deep understanding of the subject.
- Ready access to students while they are learning.

These conditions are not usually found outside of science departments.