Research in physics education: A resource for improving student learning

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Physics Education Group

Research · Curriculum · Instruction

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Physics Education Group at the University of Washington

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Goals of UW Physics Education Group

- Conduct research on learning and teaching of physics concepts and reasoning (differs from traditional education research)

- Develop instructional procedures that:
  - are effective at helping students learn (concepts and reasoning)
  - yield similar results when used by faculty at other institutions

- Document impact and procedures in journals that are read by physics faculty (written in language accessible to physicists)

To help all faculty improve the effectiveness of instruction whether or not they are engaged in physics education research.

- Strengthen the preparation of K-12 teachers to teach physics and astronomy by inquiry

- **Promote development of reasoning ability within and beyond physics**

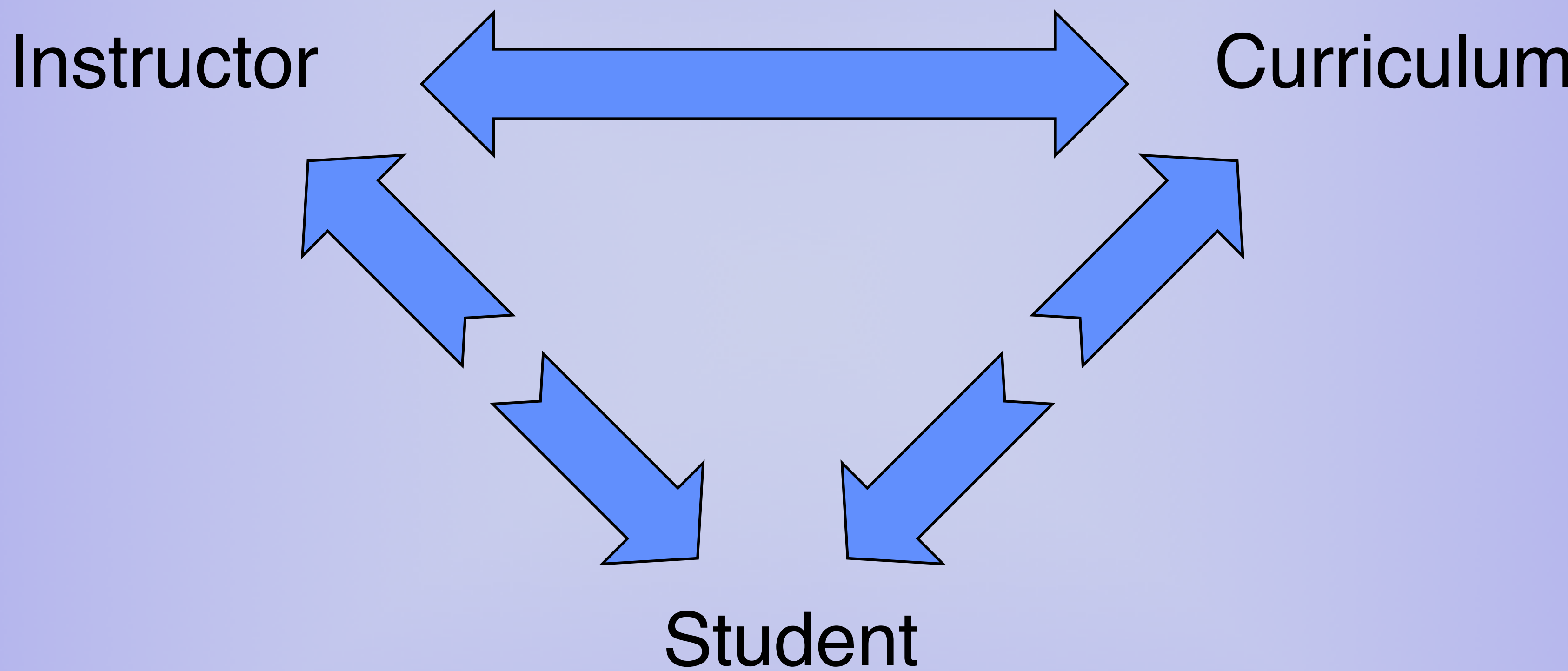
In working toward these goals, we have come to an important generalization:

On certain types of qualitative questions, student performance is essentially the same over a wide range of student ability:

- *before and after standard instruction*
- *in calculus-based and algebra-based courses*
- *with and without standard 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.

Evidence from research indicates a gap



Gap greater than most instructors realize

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

Teaching by questioning can be more effective.

Students must be intellectually active to develop a functional understanding.

(i.e., the ability to apply concepts and reasoning to situations that have not been memorized.)

Caution: "active learning" does not always lead to "intellectual engagement" at a deep level

- ***Documented research is necessary to determine the depth of understanding.***
- ***Conceptual inventories (e.g. FCI , MBT) are helpful, but inadequate to assess understanding.***

Quantitative questions alone are inadequate.

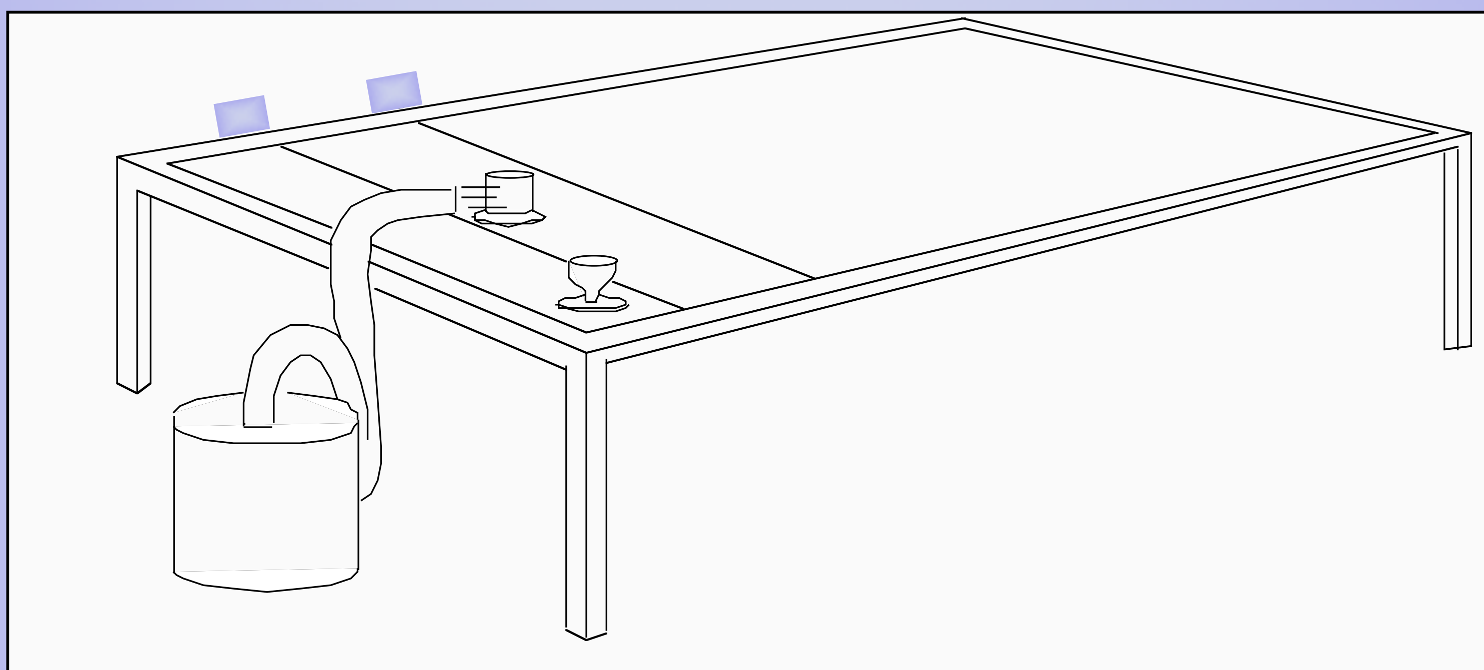
Qualitative questions are necessary.

Systematic investigations of student learning (at the beginning, during, and after instruction)

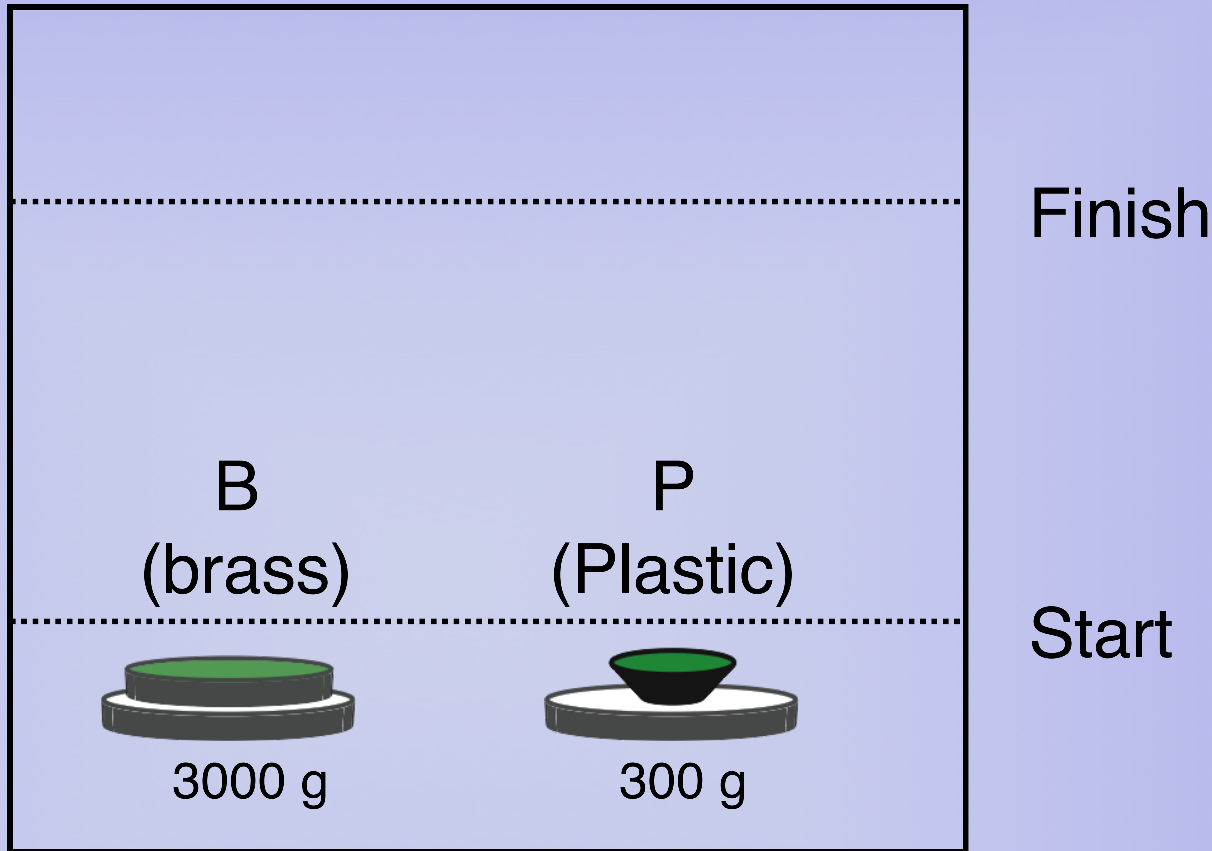
- **individual demonstration interviews**
  - for probing student understanding in depth
- **written questions with explanations**
  (pretests and post-tests)
  - for ascertaining prevalence of specific difficulties
  - for assessing effectiveness of instruction
- **descriptive studies during instruction**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

Apparatus used in Individual Demonstration Interviews

Pucks are pushed with constant force between starting and finishing lines by steady stream of air.



Comparison tasks



Tasks **After crossing the finish line, do the brass (B) and plastic (P) pucks have the same or different:**

- **kinetic energy?**
- **momentum?**

Criterion for understanding

Ability to apply work-energy and impulse-momentum theorems to a simple real motion

Correct Response:

$K_B = K_P$ *because* $\Delta K = F\Delta x$

$p_B > p_P$ *because* $\Delta p = F\Delta t$

Results from interview tasks and written questions -- given after instruction

Correct explanation required
for responses to be counted as correct.

Correct comparison of:	Interviews Algebra-based physics (N = 16)	Written questions Calculus-based physics (N = 965)
kinetic energy	**0%**	**15%**
momentum	**0%**	**5%**

Example of intervention during interview

I: ...What ideas do you have about the term work?

S: Well, the definition that they give you is that it is the amount of force applied times the distance.

I: Okay. Is that related at all to what we've seen here? How would you apply that to what we've seen here?

S: Well, you do a certain amount of work on it for the distance between the two green lines: you are applying a force for that distance, and after that point it's going at a constant velocity with no forces acting on it.

I: Okay, so do we do the same amount of work on the two pucks or different?

S: We do the same amount.

I: Does that help us decide about the kinetic energy or the momentum?

S: Well, work equals the change in kinetic energy, so you are going from zero kinetic energy to a certain amount afterwards ... so work is done on each one …
... but the velocities and masses are different so they (the kinetic energies) are not necessarily the same.

Incomplete causal reasoning

Results from pretests

	Interviews	Written questions	
Correct comparison of:	Algebra-based physics (N = 16)	Calculus-based physics (N = 965)	Physics Teaching Assistants (N = 74)
kinetic energy	0%	15%	65%
momentum	0%	5%	70%

Topic for Workshop: *Light and Shadow*

- **Motivation for topic**
  - Illustrates the difficulties that apparently ‘simple’ topics can present to students
  - Provides opportunity for participants to gain experience with how curriculum can guide students in the development a conceptual model (*e.g.,* a ray model for light)

***Constraint**: Can be done in a limited amount of time*

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).

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

Solve problems algebraically or with ray diagrams

Example:

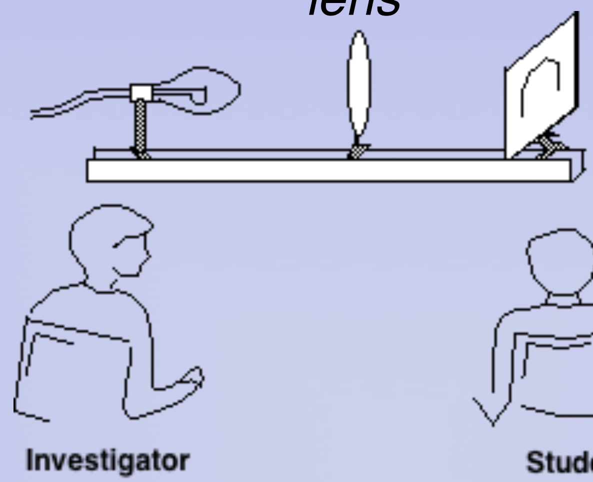
An arrow, 2 cm long, is 25 cm in front of a lens whose focal length is 17.3 cm.

Predict where the image would be located.

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

What students could *not* do:

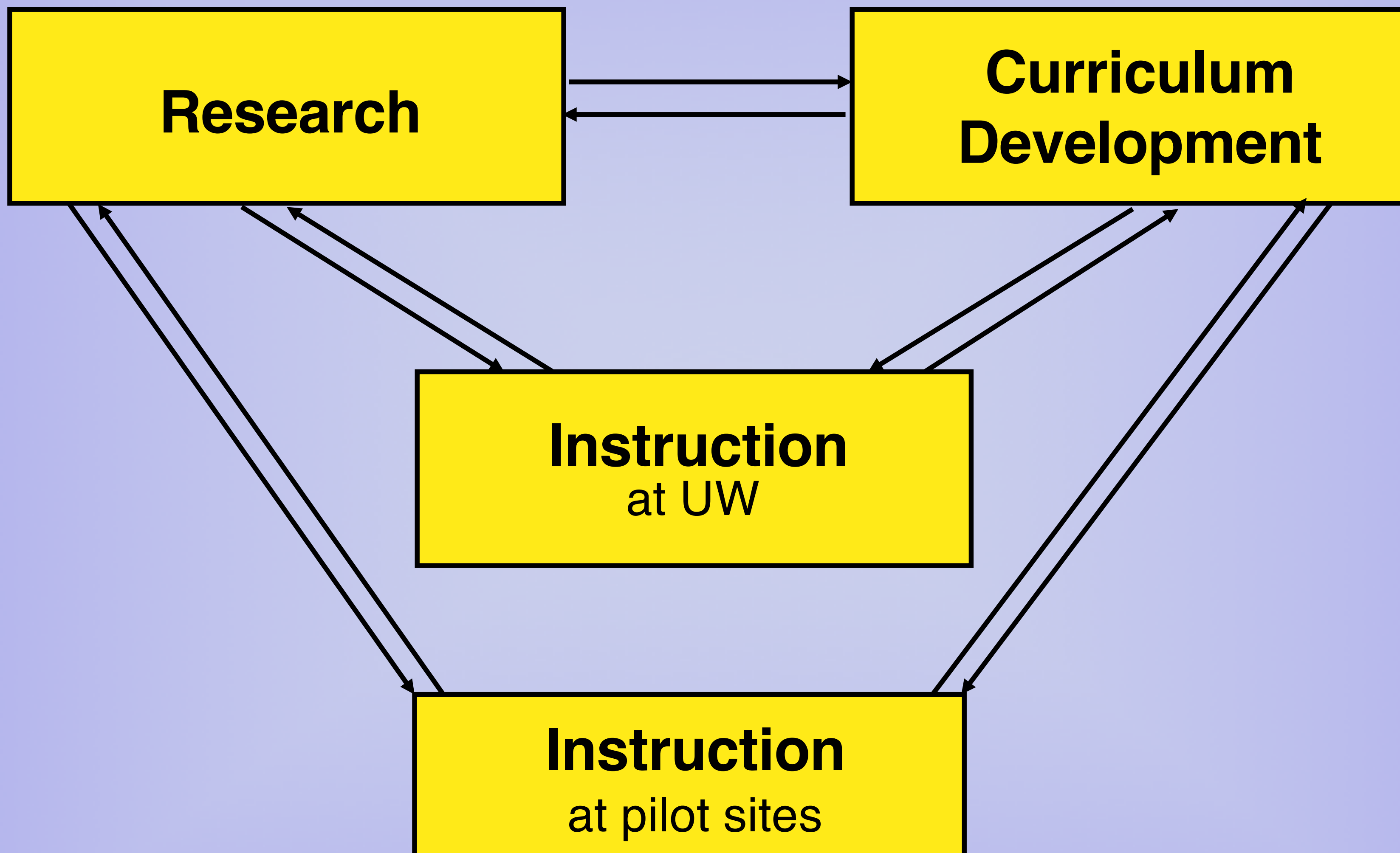
bulb *converging lens* *screen*



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: before/after instruction

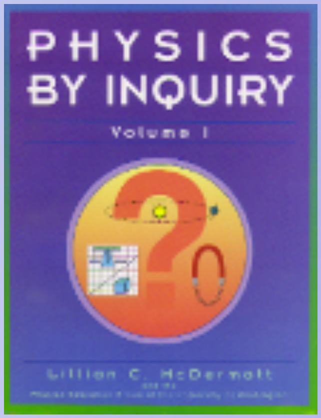
Application of research to development of curriculum



Research-based ≠ Research-validated

Research-based curriculum development

Preparing precollege teachers to teach physics and physical science

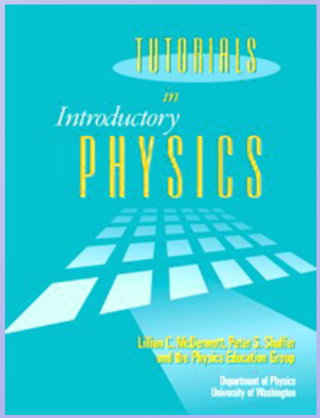


– Physics by Inquiry –

(John Wiley & Sons, Inc., 1996)

Self-contained, laboratory-based, no lectures

Improving student learning in introductory physics



– Tutorials in Introductory Physics –

(Prentice Hall, 2002)

Supplementary to lecture-based course

Choice of the term *tutorial*

- At the time (< 1990), small group sessions in the U.S. were primarily known as quiz, recitation, problem-solving sections.

- We chose the term *tutorial* both to distinguish them from TA or instructor-led sessions and also to convey a more active intellectual experience.

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?

Emphasis in tutorials is

on

- constructing concepts
- developing reasoning ability
- relating physics formalism to real world

<u>not</u> on

- solving standard quantitative problems

Brief overview of tutorial structure
before ‘hands-on’ tutorial experience

Primary context for tutorials

Each week:

- 3 lectures (50 minutes)
- 1 laboratory (2-3 hours)
- 1 tutorial (50 minutes)

Use at UW and elsewhere can vary (in lectures, labs, etc.), depending on constraints. (class size, room availability, number of lecturers, number of TAs or peer-instructors, etc.)

Tutorial Components

- **weekly pretests**
  - *given usually after lecture on relevant material but before tutorial*
- **tutorial sessions or interactive tutorial lectures**
  - *small groups (3-4) work through carefully structured **worksheets***
  - *tutorial instructors question students in semi-socratic manner*
- **tutorial homework**
- **examination questions**
  - *all examinations include questions as **post-tests** on tutorial topics*
- ***required weekly seminar for tutorial instructors***
  - *TA's, peer instructors, etc.*
  - *preparation in content and instructional method*
  - *TAs take the pretest, work through the tutorial, and discuss student responses.*

Tutorials are <u>one way</u>:

- to get students intellectually engaged in thinking about physics

and

- to arrive at a *functional understanding* of important concepts and principles.

Timing of tutorials

- Most tutorials are intended for use *after* lecture instruction (supplement to lectures and text)

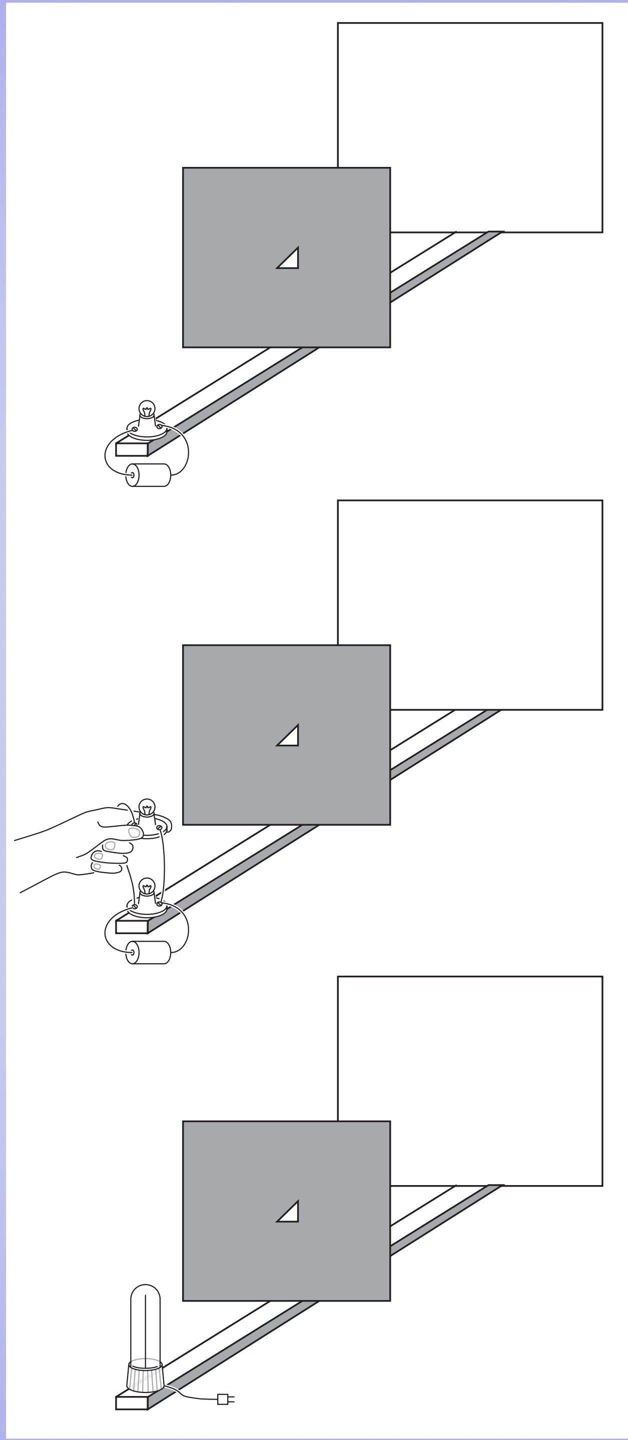
- Some tutorials do not depend on lecture and can come before or after tutorial instruction.

Light and Shadow is an example

Pretest

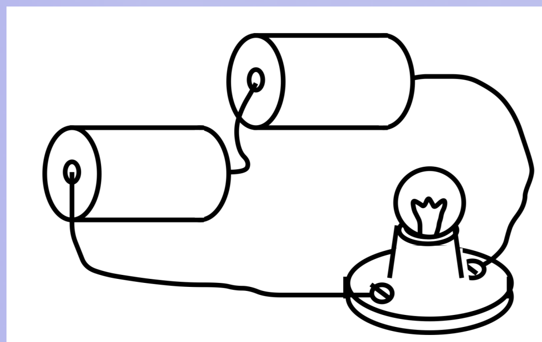
Sketch what you would see on the screen.

Explain your reasoning.

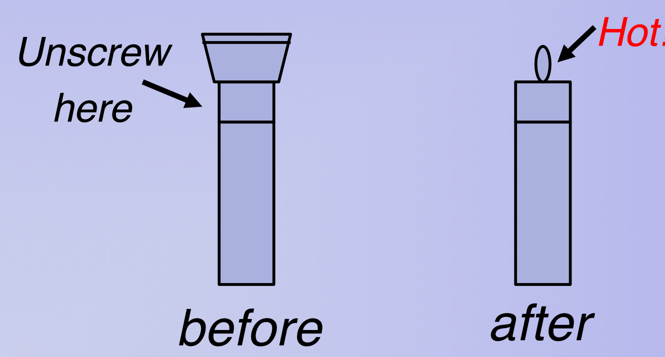


Notes on equipment

Small bulbs with batteries

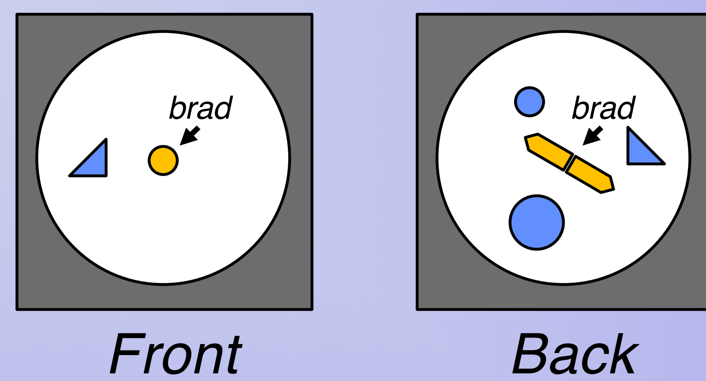


Maglights with top removed.



Masks with circular and triangular holes

'Dial-a-hole"



The tutorial asks for *predictions*.

Please COMMIT to an answer BEFORE making observations.

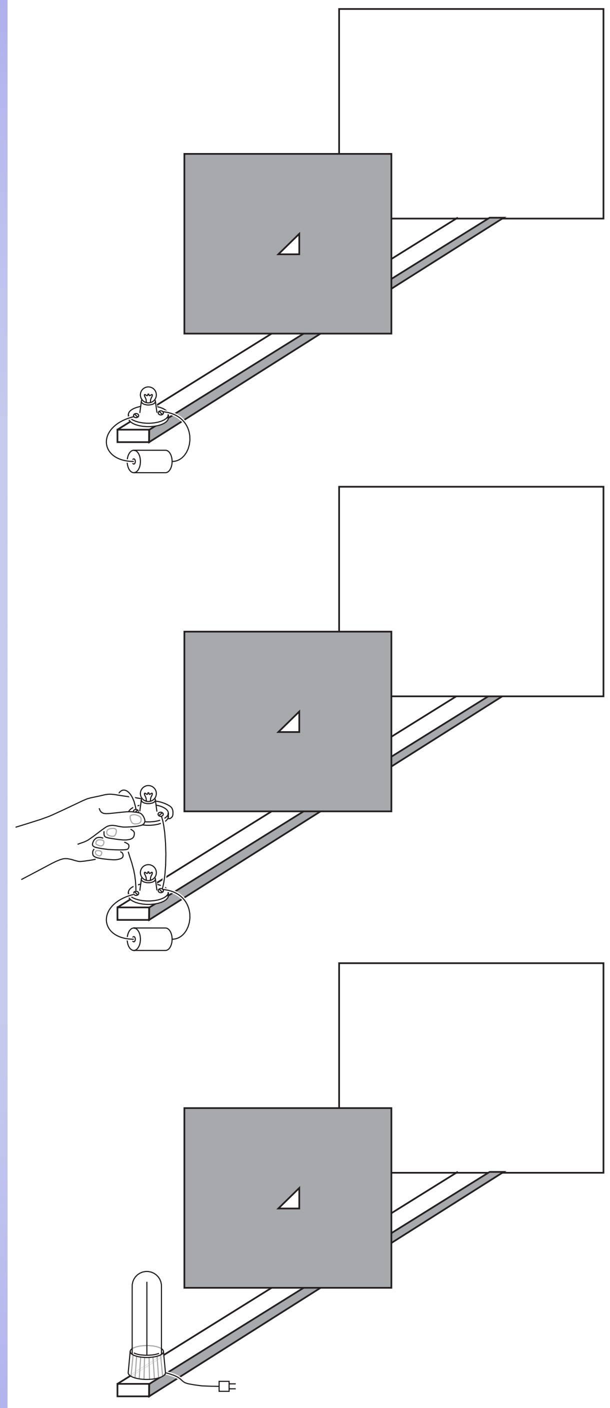
Individuals within groups do not need to agree, but everyone should have a prediction.

Page 2: After making your first prediction (Part E), ask for handouts showing what students would observer when performing experiments.

Results from student pretests

Sketch what you would see on the screen.

Explain your reasoning.



Administered before, during, and after lectures and labs on geometrical optics, including lenses

Sketch what you would see on the screen.

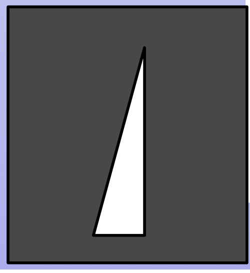
Correct responses

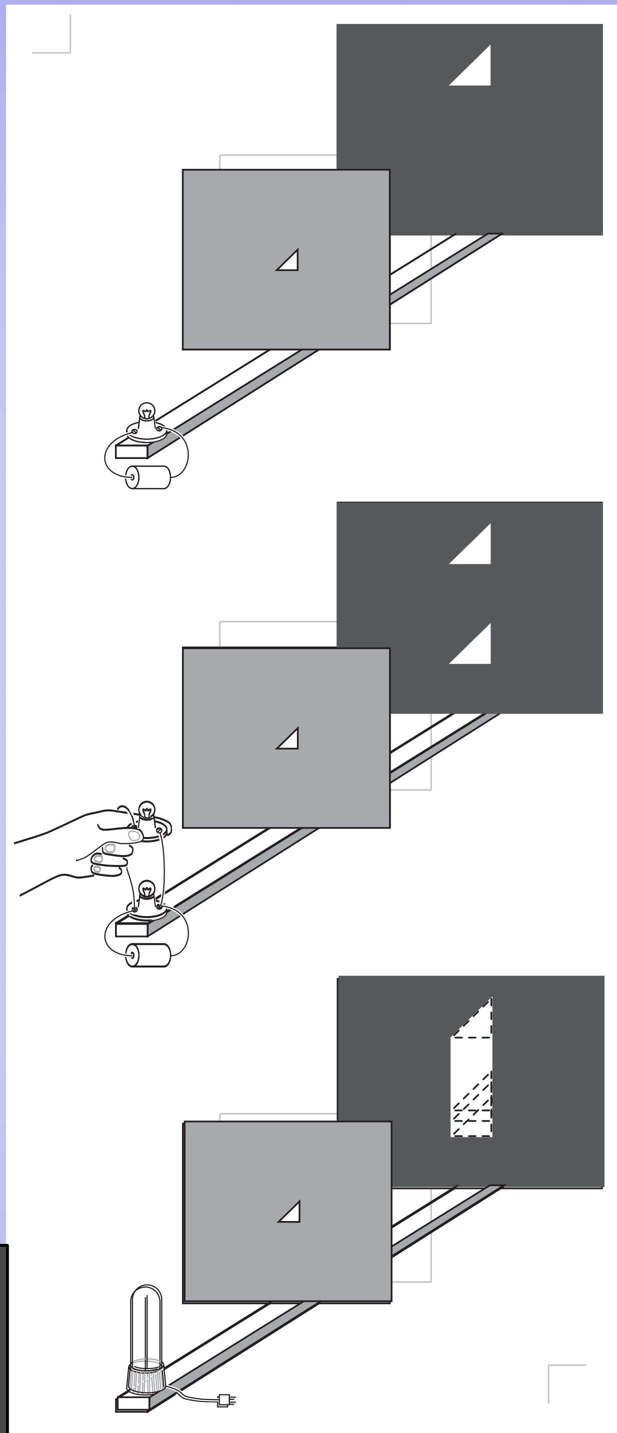
Single bulb *90%*

Two bulbs *60%*

Long-filament bulb *20%*

Most common incorrect response: 'Stretching model'





Pretest summary:

- Few students modeled a long-filament bulb as a collection of point sources.

- Many students thought that the image shape mimics the hole in the mask -- *independent of the shape of the light source.*

Lack of a functional understanding of two fundamental ideas:

- *Light travels in straight lines*

- *Each point on an object acts like a point source of light*

Ideas that are covered very quickly in a typical course

Need for tutorial: *Light and shadow*

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

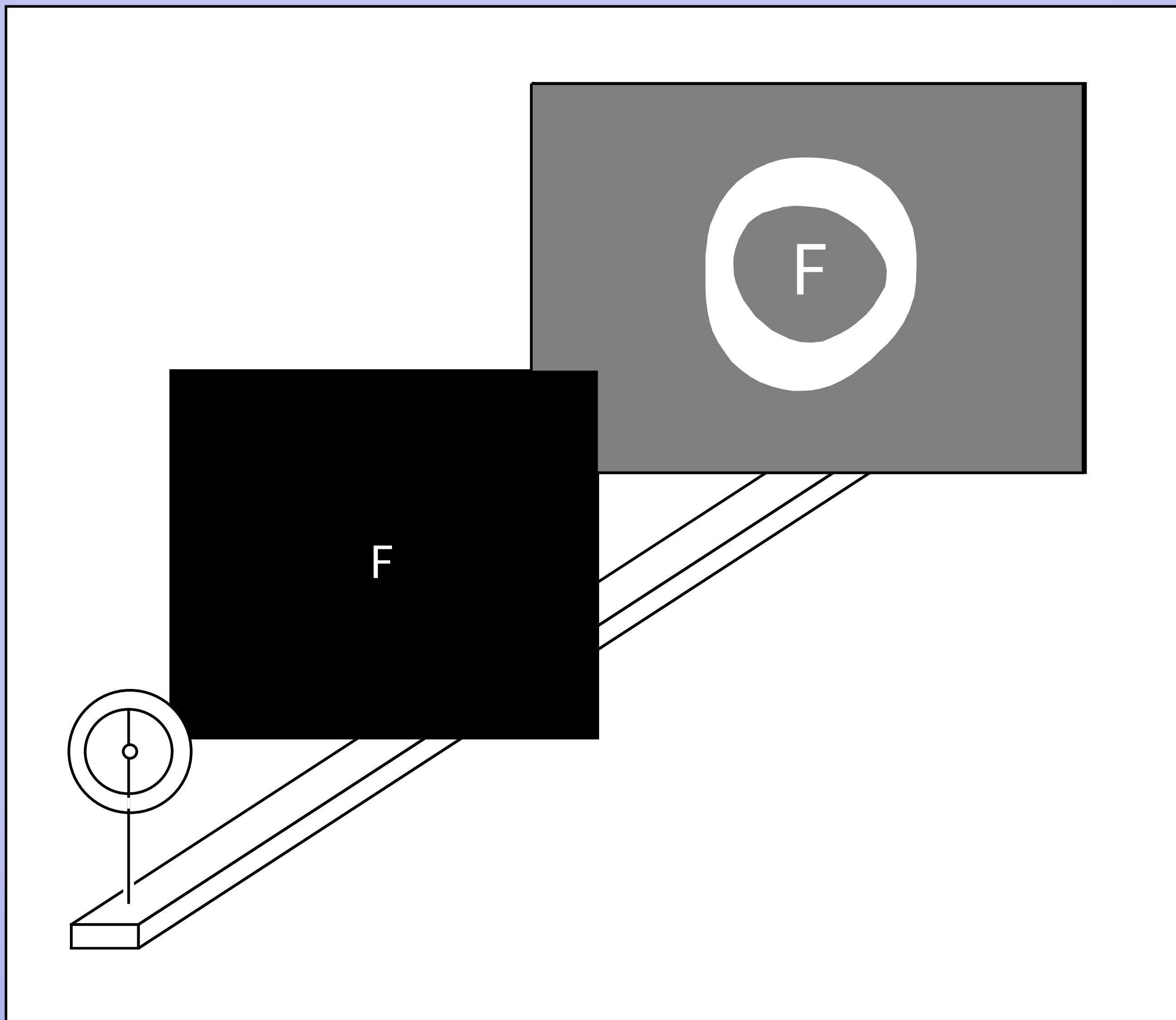
Primary goal: Students construct a model for light.

Provides basis for thinking about image formation more generally (e.g., with lenses and mirrors).

(Other tutorials on geometrical optics cover these topics.)

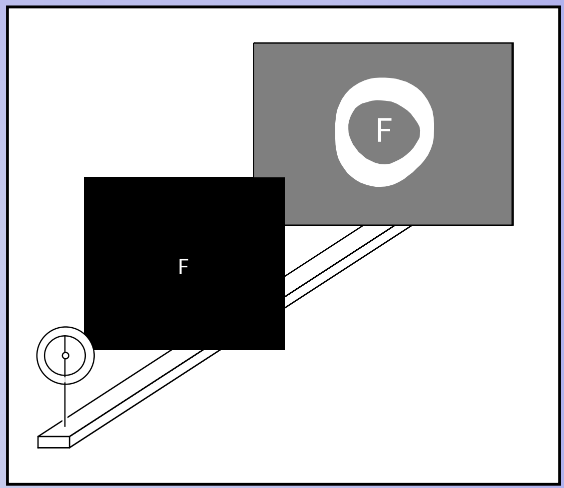
Results

- **After initial versions of tutorial:**



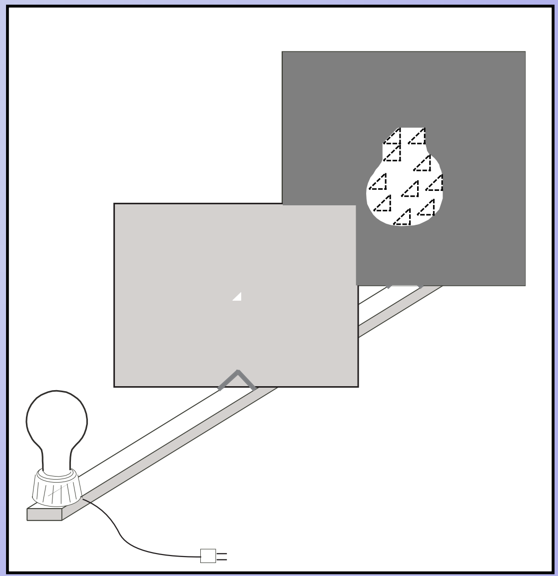
Results

- **After initial versions of tutorial:**
- ~ 60% correct on post-tests using various combinations of point and extended sources.
  - Results demonstrate that:
    - basic ideas may be surprisingly hard
    - ***knowledge of student problems*** is not sufficient for designing effective instructional materials



- ***Critical modification:***
  Use of frosted bulb as light source.

- ***Subsequent results after tutorial:***
  > 75% correct
  (Note: Graduate TAs ~ 65% correct on pretest)



Practical criterion
for effectiveness of a tutorial:

Post-test performance of introductory students
matches (or surpasses)
pretest performance of graduate students.

Commentary: It is tempting for instructors to adapt instructional strategies to their own teaching.

To what extent are such adaptations effective?

Two faculty at UW replaced the Light and Shadow tutorial with a lecture and homework problems with solutions.

Both faculty were:

- ***Experienced***
- ***Popular***
- ***Appreciative of the tutorials***
- ***Informed about student difficulties***

Results: *Post-test performance of students in both courses (~40%) was well below that of students who had worked through the tutorial.*

Generalization based on findings from research on geometrical optics and other research:

It is insufficient for the instructor to

- give clear explanations
- show demonstrations
- assign problems and provide solutions
- be informed about student difficulties

Active mental engagement by the students, themselves, is necessary.

Choice of tutorial *Light and Shadow* for workshop

- Relatively simple topic to illustrate instructional approach

- Illustrates that even for simple topics many students may not develop a coherent conceptual framework

Approach has proved effective on a wide variety of topics: e.g., mechanics, introductory and advanced electricity and magnetism, waves, physical optics, and quantum mechanics.

Assessments of student learning at UW and beyond on many topics

Effect of tutorials on student performance

On qualitative problems:

– *much better*

On quantitative problems (e.g., end of chapter):

– *typically somewhat better*

– *sometimes much better*

On retention:

– *sometimes much better*

despite less time devoted to solving standard problems

The tutorials are <u>one</u> example of how, with a small time allotment, a research-based curriculum can help:

- make physics meaningful to students
- provide a foundation for quantitative problem solving
- develop scientific reasoning ability

even under constraints of large class size,
breadth of coverage, fast pace, limited time

The perspective that teaching is a science, as well as an art, is an effective approach for:

- setting high (yet realistic) standards
- assessing the extent to which meaningful learning takes place
- helping students meet expectations