Physics Education Research Among University Students

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Some Relevant Personal History

1959  Ph.D.  Experimental Nuclear Physics  (Columbia U.)

1962 – Moved to Seattle, Washington

Nepotism rules in Washington State precluded faculty position at University of Washington (UW).

Taught in temporary part-time positions and as volunteer at UW and at Seattle University
1969 – 1972 Insights from teaching experience at UW in laboratory-based courses for teachers that Arnold Arons and I taught.

- inadequacy of teaching by telling
- value of listening (instead of talking) in assessing intellectual state of students
- role of qualitative questions in eliciting student thinking
- failure of standard introductory courses to help teachers develop a functional understanding* of basic concepts
- Began to write worksheets to help students learn by laboratory-based experience, not by lectures → *Physics by Inquiry*

* Interpret a concept properly, distinguish it from related concepts, and do the reasoning to apply it correctly to real objects and events.
1962–1972 Additional insights from teaching experience at UW, Seattle University, and City College of NY

- Qualitative questions that revealed conceptual and reasoning difficulties elicited similar responses from students with weak & strong backgrounds.

  *Math/science skills often ‘masked’ underlying problems.*

- Intellectual difficulties were often similar among different populations.

- Instructional strategies that proved effective in helping one population often proved effective with other populations.

- Instruction that focuses either on concepts alone or reasoning alone is inadequate. Concepts and reasoning must be addressed together.
Concern about lack of impact on physics faculty

Anecdotal evidence by Arnold Arons (based on informal conversations with a few students) had little effect.

Would documentation of student learning by pretest/post-test comparisons make a difference?
1973: Became Assistant Professor and began research in physics education at UW

Three (very strong) graduate students in physics (David Trowbridge, Mark Rosenquist, James Evans) asked me to be their advisor (to my surprise)

Suggested to David that he administer Piaget’s motion tasks to university students. When these proved too easy (even for underprepared students), I asked him to develop more suitable tasks,

David designed more challenging tasks that he administered to better prepared university students during *individual demonstration interviews*
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

Research guides development and assessment of curriculum
1973: Physics Education Research Began at UW

Individual demonstration interviews before and after instruction to assess student ability to distinguish kinematical concepts from one another in comparing observed motions of two balls.

Administered to:
- Preservice elementary school teachers
- Underprepared EOP students
- Introductory students in algebra-based course
- Introductory students in calculus-based course

Speed comparison tasks:
“Do the balls ever have the same speed?”

Balls pass twice

Results were poor (tendency to say speeds are equal at two passing points). Only small improvement after instruction.
Recognized need to communicate results from such research to physics faculty

• provide evidence of serious (and persistent) conceptual and reasoning difficulties in physics

• use language familiar to physicists

• publish in journals readily accessible to (and respected by) university physics faculty (e.g., AJP)
First *PER* papers in *AJP* by the UW Physics Education Group


Research drives curriculum

Suggested to Mark Rosenquist (then a TA in EOP course) that he design instructional strategies to promote meaningful learning of kinematical concepts (explicitly addressing conceptual and reasoning difficulties identified by Dave).


Physics Education Research can help improve student learning from the elementary to the graduate level.

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

- focuses on student understanding of physics content (discipline-based)

- is an important field for investigation by physics university faculty, graduate students, & physics teachers (need deep understanding of physics & access to students)
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.*
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 (pre-tests/post-tests)

* ability to do the reasoning necessary to apply concepts to physical phenomena
Systematic investigations of student learning
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  – for ascertaining prevalence of specific difficulties
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• descriptive studies during instruction
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Traditional approach to instruction in introductory physics

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
Evidence from research indicates a gap

Gap greater than most instructors realize
Application of research to development of curriculum

Research

Curriculum Development

Instruction at UW

Instruction at pilot sites
Research-based curriculum development

Preparing precollege teachers to teach physics and physical science

- *Physics by Inquiry* -
  (John Wiley & Sons, Inc., 1996)

Improving student learning in introductory physics

- *Tutorials in Introductory Physics* -
  (Prentice Hall, 2002)
Research as a guide to instruction to help close gap

Physics by Inquiry
and
Tutorials in Introductory Physics
Physics by Inquiry

Laboratory-based, self-contained curriculum designed primarily for teachers but also suitable for other students
Tutorials in Introductory Physics
(and others on more advanced topics)
Investigation of student understanding of physical optics

• *Interference and diffraction*


• *Representations of light*

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.

<table>
<thead>
<tr>
<th>Introductory students</th>
<th>Graduate students</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantitative question (N ~ 130)</td>
<td>Qualitative question (N ~ 510)</td>
</tr>
<tr>
<td>70% correct with angle</td>
<td>10% correct with explanation</td>
</tr>
</tbody>
</table>
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.
Written question: double-slit interference of light

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

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:

<table>
<thead>
<tr>
<th></th>
<th>Introductory calculus-based physics (N ~ 600)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
<td>40%</td>
</tr>
<tr>
<td>Incorrect:</td>
<td>45%</td>
</tr>
<tr>
<td>Interference pattern remains</td>
<td></td>
</tr>
</tbody>
</table>

Results essentially the same before and after lecture instruction.
Examples of Incorrect Responses

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
Interview task: single-slit diffraction
(30 modern physics students, 16 introductory students)

Situation: Distant monochromatic 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
Specific difficulties with interference and diffraction indicated

Basic underlying difficulty
failure to relate interference and diffraction effects to differences in path length (or phase)

lack of a conceptual wave model for light
On certain types of qualitative questions, student performance is essentially the same:

- before and after instruction
- in calculus-based and algebra-based course
- 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.
Application of research and teaching experience to large introductory course

Challenge

to improve student learning within constraints of 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?
Development of tutorials is guided by research-based generalizations on learning and teaching.

Tutorial sequence consists of:

**Pretest**
(class or web-based)

**Worksheet**
(collaborative small groups)

**Homework**
(individual)

**Post-test**
(course examinations)
Emphasis in tutorials is on

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

not on

• solving standard quantitative problems
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 assessment of student learning through pretesting and post-testing
Pretest

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

A third slit is added $d$ to the right:

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.
Post-test

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

A third slit is added $d/2$ to the right:

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?*

<table>
<thead>
<tr>
<th></th>
<th>Undergraduate students</th>
<th>Graduate TA’s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pretest (d)</td>
<td>Post-test (d / 2)</td>
</tr>
<tr>
<td></td>
<td>N ~ 560</td>
<td>N ~ 405</td>
</tr>
<tr>
<td>Correct <em>without</em> regard to reasoning</td>
<td>30%</td>
<td>80%</td>
</tr>
<tr>
<td>Correct <em>with</em> correct reasoning</td>
<td>&lt; 5%</td>
<td>40%</td>
</tr>
</tbody>
</table>
Practical criterion for effectiveness of a tutorial:

Post-test performance of introductory students matches (or surpasses) pretest performance of graduate students.
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
Research in physics education is an important field for investigation by physics university faculty and teachers

- Understanding of physics in depth
- Access to students who take physics
- Influence on instruction in department
- Credibility among other physicists
- Publication in language physicists understand and in journals they read
- Avoidance of frequent reference to educational theories and psychology