Research on the teaching and learning of physics

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25 years ago— "Why can my grad students do so well in many years of physics courses, but come into my lab and cannot do physics? And why do the students who do great in courses never turn out to be great in doing physics?"

Led to my learning about and carrying out physics education research
Not just opinions—is a science of the teaching of physics

Doing controlled experiments. Measuring learning results.

DATA and fundamental principles

Started in physics, now similar research & results from all undergrad sciences and engineering (me ~ 25 yrs, ~ 100 papers)
Brings together multiple areas of research

University classroom studies

social psych

cognitive psychology

brain research
example #1

Experiment: Learning from lecture
Two nearly identical 250 student sections
intro physics (same attendance, exam scores
precourse backgrounds, ...)—
**same learning objectives, same class time,**
**same test** (given right after 3 lectures).

Experienced highly rated traditional lecturer
(*good teacher by current standards*)

*versus*

Postdoc in physics, trained in scientific teaching methods
Experimental class design

1. Targeted pre-class readings

2. Questions to solve, respond with clickers or on worksheets, discuss with neighbors.
Instructor circulates, listens.

3. Discussion by instructor follows, not precedes.
   (but still talking ~50% of time)
   Targets thinking—flagging incorrect thinking & how to fix.
Distribution of test scores

- Experienced highly rated, trad. lecture
- New Ph.D. scientific teaching

**Average:**
- Experienced highly rated, trad. lecture: $41 \pm 1\%$
- New Ph.D. scientific teaching: $75 \pm 1\%$

Entire distribution shifted up.
Learning from traditional, “good” lecture 41-25 = tiny 16% !!
Intro Physics Lab courses; Do they help students learn physics content?

Example # 2

Understanding of scientific concepts

Interest and motivation

Scientific practical skills and problem solving abilities

Scientific habits of mind

Understanding of the nature of science

Does it work?
Two first year lab courses where explicit target is only to teach the physics content of lecture course + recitations.
1 term mechanics, 1 term E &M

~ half the students in courses take lab, half do not. (N~ 200 each)

Compare:

Students who take the lab vs. Students who do not take the lab on learning the physics content from lecture

Use the final exam

BUT…
BUT…

Different majors, courses, …

*How to account for selection effects?*

Not all (~½) exam questions are about concepts covered in lab!

- Score on lab-related questions
- Score on non-lab-related questions

Students who take the lab ≠ Students who do not take the lab
Score on lab-related questions

Score on non-lab-related questions

No difference?!

Maybe better for E & M?
Mean lab benefit

\[
\begin{bmatrix}
\frac{1}{N_{Lab}} \sum_{i=1}^{N_{Lab}} (LR_i, NLR_i) \\
\frac{1}{N_{NoLab}} \sum_{j=1}^{N_{NoLab}} (LR_j, NLR_j)
\end{bmatrix}
\]

Physics 1: 0.6%±1.2%  
Physics 2: 0.5%±2%  

Other Wieman group physics lab research;
Natasha Holmes

3 related areas of research studies
*a. Value of traditional introductory lab courses for teaching physics content
*b. Cognitive tasks carried out by students doing undergraduate research
*c. Creating a good diagnostic tool for measuring (pre—post) quantitative critical thinking. *Isabella, Adam
ex #3 Undergraduate research experiences—if good, why?

2. (some of you last summer)
End of examples
Physics education research as a discipline

how students think about & learn physics

American Physical Society- official area of physics research

Physical Review journal PER

Done by: faculty & grad students in physics departments
(Natasha new Prof at Cornell)

• Better ways to measure learning (Isabella, Adam, Ruqayya)
• Controlled experiments on different ways of teaching
  small scale lab/interview studies
  large classroom studies (all phys41 sections)
Fundamental Research

Understanding learning in university STEM courses

How do students reason and solve problems?

How do students learn with computer simulations?

Who?
- Graduate students in Education
- Postdocs in physics & biology
- Undergraduate students in science & engineering

Wieman Group

Applied Research

Incorporating cognitive science principles in instruction

Improving learning in university STEM courses

Critical thinking in lab courses

Scientific teaching in lecture

Who?

Graduate students in Education

Postdocs in physics & biology

Undergraduate students in science & engineering

Collaboration with D. Schwartz group
Wieman physics/science education research approach

1. Students do physics problem-solving task
2. Read their minds while doing (& verify)
3. Identify important elements of thinking - novice expert differences

   How do expert physicists think/make decisions?
   How well are students learning that thinking?

4. Create better/more efficient ways to measure
5. Teach better(?) (use cognitive psych often)
6. Measure result
Some other recent/ongoing research *(using you?*)

1. Mechanistic reasoning (Engin Bumbacher) *(what is it good for? who uses? how to teach?)*

2. What and how do students learn from interactive simulations? (Argenta Price) Insights to teach wider range of learners?

*3. Problem solving strategies* *(Shima Salehi, Ruqayya, Isabella, and Adam)*
goal: teaching better problem solving
tool: black box CCK
PhET Circuit Construction Kit (CCK): Simulation

- Set up circuits
- Measure and/or observe effects
- ‘See’ motion of electrons in wires
black box CCK

Circuit Construction Kit Black box:
- Elements of the circuit are hidden
- Students need to figure out the hidden circuit – *solve the problem*
- Increasingly difficult - *everyone* is challenged
Probing general problem solving strategies

*Impossible to measure & teach with traditional paper diagrams/activities*

What strategies do they use to figure out?

- What questions do they ask?
- What information do they seek?
- How do they interpret and act upon evidence/data?
Participants

- 41 participants with a broad range of content-knowledge and backgrounds

- physics profs to community college intro psychology students

- Individual cognitive interviews with think-aloud protocol. Record audio and video, notes, computer actions.
1. Identify the primary elements of strategies.

2. See detailed differences between good and bad strategies. Interplay with content knowledge.
See consistent quantifiable differences in strategies of ‘experts’ (e.g. physics profs) to ‘novices’ (e.g. 1st year non-science students). Detailed coding of 40+ interviews.
Emergent Coding Scheme
(details ask R, I, & A)

Experimentation Practices

- Breaking Down the Problem
- Data Collection
- Data Representation
- Data Interpretation

Reflective Practices

- Verification
- Reflection on Knowledge
- Reflection on Strategy
- Reflection on Assumptions

(details ask R, I, & A)
“Does this make sense?”

- Solution verification is a highly beneficial practice
- Even participants with high content knowledge frequently failed to verify their solution

“Let me step back and see if I am making any unjustified assumptions.”

- Jumping to erroneous assumptions and continuing to use them is major time waste and a source of error for all level of participants!

Future- target and teach
A new study just starting *(volunteers to help?)*—
How can we better help struggling Stanford physics students?

**Physics 41a**—companion course to physics 41
Pre and post test on concepts and attitudes

a fraction scores much lower on conceptual mastery
Study just starting (volunteers to help?)—How can we better help struggling Stanford physics students? Physics 41a—companion course to physics 41

Pre and post test on concepts and attitudes

a fraction scores much lower on conceptual mastery

Instruction failed for these students! Why? How can we fix? Identify, interview, intervene (this year). Test if works.
Questions?

1. Physics education research as a discipline or career
2. Methods used in the research
3. Specific studies
   a. learning in lecture
   b. learning physics content from intro labs
   c. cognitive activities in good undergrad research experience (that courses do not provide)
   d. problem solving strategies using black box circuit construction kit
   e. figuring out how to help students struggling in phys41
   f. bunch of research I did not have time to discuss
1. Transforming 2nd - 4th Yr physics courses

UBC to Stanford

No Prepared Lecture!

**Actions**

**Preparation**
- **Students**: Complete targeted reading
- **Instructors**: Formulate/review activities

**Introduction (2-3 min)**
- **Students**: Listen/ask questions on reading
- **Instructors**: Introduce goals of the day

**Activity (10-15 min)**
- **Students**: Group work on activities
- **Instructors**: Circulate in class, answer questions & assess students

**Feedback (5-10 min)**
- **Students**: Listen/ask questions, provide solutions & reasoning when called on
- **Instructors**: Facilitate class discussion, provide feedback to class
Final Exam Scores
nearly identical ("isomorphic") problems

- practice & feedback 2\textsuperscript{nd} instructor

- practice & feedback, 1\textsuperscript{st} instructor

- 1 standard deviation improvement

- taught by lecture, 1\textsuperscript{st} instructor, 3rd time teaching course

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• Less discussion (URE not there yet)
• Structured labs: “Massaging data” to get expected values
S1: “When you break a machine in the one way that the professor said, ‘Do not break the machine because they don’t make spare parts for this thing anymore.’ But then you manage to fix it anyways and then the thing starts working again, that’s good... Overcoming obstacles.”

S2: “I completely agree with that. Yesterday I was struggling all day long with how to fit this one graph a certain way and I was so upset and this morning I came in early and then it magically worked and I got it to work and I was so happy and it’s carried me through the whole day.”
EVALUATING RESULTS & IMPLICATIONS

[URE] “...having the sort of, basically the amount of freedom that research does give you, having the time and the space to step back a bit and say, ‘What can we actually learn from this?’ instead of just trying to blindly get a result.”

[Structured labs] “And then sometimes when those labs, when you don’t get the results you want, you’re tempted – because you know exactly what result you want - so it’s tempting to just massage what you’ve gotten until it looks like something like a distant relative of what you want.”
Students are practicing far more complete set of cognitive tasks in URE than in structured lab courses.

Critical differences between research and structured lab courses that were repeatedly noted:

• autonomy (own decisions)
• opportunity and time for iteration and reflection/troubleshooting. (is when the learning happens!)
• “pursuing new knowledge” was not mentioned!
But not total autonomy

Student learning

“Cookbook”

Student autonomy

Disorganized chaos
Does engagement in the cognitive tasks relate to benefits of UREs?

• Especially related to affect and identity development?

How might engagement in tasks in coursework (ie better preparation with the tasks) impact:

• Affect + identity?
• Quality of URE-overall (for students and mentors)?
3. Research with PHET interactive simulations  
(used 100 M times last year, grades 6-16)

1. (Shima Salehi, with Engin Bumbacher, Eric Kuo,) Using sim to study problem solving strategies. Diagnose and teach better.

2. Not discuss (Argenta Price) how are they used and what is learned? How depends on age, background, task, ??? Method– LOTS of cognitive interviews observing use and learning. Very diverse set of students
The end --- Questions?

1. Transforming 2\textsuperscript{nd}-4\textsuperscript{th} year physics courses at Stanford.
2. What is good active learning? --creating instructional Design Principles.
3. Studying learning in labs, both courses and research. Physics concepts, and thinking like experimental physicists.
Fundamental Research

- Understanding learning in university STEM courses
- How do students reason and solve problems?
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Collaboration with D. Schwartz group

Critical thinking in lab courses
Scientific teaching in lecture
Experimental physics cognitive task analysis


Most apply broadly
Establish research goals
- Decide if goal is interesting
- Predict if goal is ahead of current knowledge
- Evaluate whether RQ is feasible
- What would be convincing?
- What variables are important and how to measure/control?
- What types of controls and checks are needed
- Predict if it's realistic + analyze needed resources
- Analyze contingency options

Define criteria for suitable evidence
- Explore many feasible preliminary designs
- Analyze relevant variables leading to systematic errors
- Finalize design
- Develop data acquisition strategy
- Who should build
- Develop criteria and test procedures for apparatus
- Collect data on performance of components and apparatus
- Develop procedures for tracking source of malfunction
- Figure out how to modify apparatus as needed
- Reiterate data acquisition strategies

Experimental design
- Collect data [student cognitive tasks in red]
- Model data, deciding justified approximations
- Decide on statistical analysis methods
- Calculate statistical uncertainty
- Calculate systematic uncertainties
- Check results when different than expected
- Test data that come out as expected
- Identify plausible interpretations, directions
- Data display procedures
- Explain work, appropriate to audience

Construction & testing of apparatus/code

Analyzing data

Evaluating results & analyzing implications

Presenting the work
Results explained:
The thinking students are doing in intro lab courses, not what needed to learn content. So they don’t!
What student sees

What instructor sees
3. b. How can students get practice thinking like experimental physicists?

Lecture courses?
Instructional lab courses?
Undergraduate research experiences (URE)?

(N. Holmes and C. Wieman, just published in Phys. Rev. PER)
METHODS: FOCUS GROUP INTERVIEWS
PHYSICS STUDENTS IN SUMMER UNDERGRADUATE RESEARCH PROGRAM

8 interviews

2-8 students per interview

Semi-structured

• questions about URE with comparisons to coursework elicited

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<thead>
<tr>
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<tbody>
<tr>
<td>Rising sophomores</td>
<td>16/19</td>
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<tr>
<td>Rising juniors</td>
<td>10/19</td>
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<tr>
<td>Rising seniors</td>
<td>4/12</td>
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METHODS: FOCUS GROUP INTERVIEWS

Analyzing: not looking at # of statements

- If something does not come up, we cannot claim it does not happen
- If students explicitly say they do not do it, we can claim it does not happen
- Mentions in repeated interviews provide strength to claim
WHERE DO THEY SAY THEY DO WHAT?

1. Goals
2. Criteria
3. Feasibility
4. Design
5. Testing
6. Analyzing
7. Evaluating
8. Presenting

Section

No  Mixed  Yes
WHERE DO THEY SAY THEY DO WHAT?

URE

Design labs

Structured labs


Section Number of interviews

No Mixed Yes
Lab courses

Structured labs
- Goals and protocol laid out
- Students follow steps to obtain an expected result
- New experiment every week

Design labs
- Students choose research question and design experiment
- Two experiments over 10 weeks
1. Goals
2. Criteria
3. Feasibility
4. Design
5. Testing
6. Analyzing
7. Evaluating
8. Presenting

Section

Number of interviews

Overall (student perceptions)
- URE doing most of the things
- Structured labs explicitly not doing the things
- Design labs unclear – consistent “yes” but rarely discussed