Taking a scientific approach to Physics education*

and most other subjects

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copies of slides to be available

*based on the research of many people, some from my science ed research group
17 yrs of success in classes. Come into lab clueless about physics?

2-4 years later ⇒ expert physicists!

??????? ~ 25 years ago

Research on how people learn, particularly physics

- explained puzzle
- different way to think about learning and teaching
- got me started doing physics/sci ed research--controlled experiments & data!
Major advances past 1-2 decades ⇒ Bringing together research fields

- University science & eng. classroom studies
- Cognitive psychology
- Brain research

Today

Strong arguments for why apply to most fields
Physics/Science education goal—
*Not all become physicists, ...*
All learn to make better decisions/choices.
“Thinking like a physicist”

I. What is “thinking like a physicist/expert?”

II. How is it learned?
(curriculum determines what topics students see, pedagogy determines what thinking they learn)

III. Examples from applying learning principles in university science classrooms and measuring results

IV. A bit on institutional change if time

V. Something instructors can use in next class.
I. Research on expert thinking*
historians, scientists, chess players, doctors,...

Expert thinking/competence =
• factual knowledge

• Mental organizational framework $\Rightarrow$ retrieval and application

*Cambridge Handbook on Expertise and Expert Performance

or ?

scientific concepts, mental models
(& criteria for when apply)
Expert has rich array of predictive mental models, analogous to set of tools for different functions. Labelled by basic features and where to use.
Expert thinking/competence =
- factual knowledge
- **Mental organizational framework** \(\Rightarrow\) retrieval and application

or?

- **Ability to monitor own thinking and learning**

New ways of thinking-- everyone requires MANY hours of intense practice to develop.
Brain changed—rewired, not filled!

*I. Research on expert thinking*  
historians, scientists, chess players, doctors,...

*Cambridge Handbook on Expertise and Expert Performance*
II. Learning expertise*--

Challenging but doable tasks/questions

• Practicing specific thinking skills
• Feedback on how to improve

Physics thinking skills–

1 minute to ponder:
List of decisions you make when solving problems in your research?

* “Deliberate Practice”, A. Ericsson research. See “Peak;...” by Ericsson for accurate, readable summary
II. Learning expertise*--
Challenging but doable tasks/questions
• Practicing specific thinking skills
• Feedback on how to improve

Physics/Science & eng. thinking skills
• Decide: what concepts/models relevant (selection criteria), what information is needed, what irrelevant,
• Decide: what approximations are appropriate.
• ” : potential solution method(s) to pursue.
• ” : best representations of info & result (field specific).
• ....
• ” : if solution/conclusion make sense- criteria for tests.

Knowledge/topics important but only as integrated part with how and when to use.

* “Deliberate Practice”, A. Ericsson research. See “Peak;...” by Ericsson for accurate, readable summary
Teaching about electric current & voltage

1. Preclass assignment--Read pages on electric current. Learn basic facts and terminology without wasting class time. Short online quiz to check/reward.

2. Class starts with question:

III. How to apply in classroom?
practicing thinking with feedback

Example– large intro physics class (similar chem, bio, comp sci, ...)

Teaching about electric current & voltage

1. Preclass assignment--Read pages on electric current. Learn basic facts and terminology without wasting class time. Short online quiz to check/reward.

2. Class starts with question:
When switch is closed, bulb 2 will
a. stay same brightness,
b. get brighter
c. get dimmer,
d. go out.

3. Individual answer with clicker
   *(accountability=intense thought, primed for learning)*

4. Discuss with “consensus group”, revote.
   *Instructor listening in!* What aspects of student thinking
   like physicist, what not?

Jane Smith chose a.
5. Demonstrate/show result

6. Instructor follow up summary—feedback on which models & which reasoning was correct, & **which incorrect and why**. Many student questions.

**Students practicing thinking like physicists**—(applying, testing conceptual models, critiquing reasoning...)

**Feedback that improves thinking**—other students, informed instructor, demo

**Homework extends & builds upon**
Research on effective teaching & learning

Students learn the thinking/decision-making they practice with good feedback (*timely, specific, guides improvement*).
Research on effective teaching & learning

but must have enablers & still learning how to do most effectively

Address prior knowledge and experience

Motivation

Cognitive demand/brain limitations

diversity

Students learn the thinking/decision-making they practice with good feedback *(timely, specific, guides improvement).*

Requires expertise in the discipline & expertise in teaching it.

disciplinary expertise knowledge & thinking of science
3. Evidence from the Classroom

~ 1000 research studies from undergrad science and engineering comparing traditional lecture with “scientific teaching”.

• consistently show greater learning
• lower failure rates
• benefit all, but usually at-risk more

A few examples—
various class sizes and subjects

Massive meta-analysis all sciences & eng. similar.
PNAS Freeman, et. al. 2014
Apply concepts of force & motion like physicist to make predictions in real-world context?

**average trad. Cal Poly instruction**

**1st year mechanics**

9 instructors, 8 terms, 40 students/section. Same instructors, better methods = more learning!
U. Cal. San Diego, Computer Science  
Failure & drop rates—Beth Simon et al., 2012

same 4 instructors, better methods = 1/3 fail rate
Comparing the learning in two identical sections
UBC 1st year college physics.
270 students each.

Control--standard lecture class– highly experienced Prof with good student ratings.
Experiment-- new physics Ph. D. trained in principles & methods of research-based teaching.

They agreed on:
• Same learning objectives
• Same class time (3 hours, 1 week)
• Same exam (jointly prepared)- start of next class

mix of conceptual and quantitative problems

*Deslauriers, Schelew, Wieman, Sci. Mag.  May 13, ‘11
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)
Clear improvement for entire student population. Engagement 85% vs 45%.
Advanced courses 2nd - 4th Yr physics

Univ. British Columbia & Stanford

No Prepared Lecture

**Actions**

**Preparation**
- Complete targeted reading
- Formulate/review activities

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

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

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

1 standard deviation improvement

practice & feedback, 1st instructor
practice & feedback 2nd instructor

taught by lecture, 1st instructor, 3rd time teaching course

Stanford Outcomes

7 physics courses 2\textsuperscript{nd}-4\textsuperscript{th} year, seven faculty, ‘15-’16

- Attendance up from 50-60\% to \sim 95\% for all.
- Covered as much or more content
- Student anonymous comments:
  90\% positive (mostly VERY positive, “\textit{All physics courses should be taught this way!”})
  only 4\% negative

- All the faculty greatly preferred to lecturing.
Typical response across \sim 250 science faculty at UBC \& U. Col. New way of teaching much more rewarding, would never go back.
Institutional Change

Better for students & faculty prefer \textit{(when try)}

\textit{How to make universal?}
What universities and departments can do. Experiment demonstrating teaching transformation process.

Transformed the teaching of ~200 science faculty and ~150,000 credit hours/year at UBC.

*Factors that help and hinder.*
Necessary $1^{st}$ step-
better evaluation of teaching quality

“A better way to evaluate undergraduate science teaching”
Change Magazine, Jan-Feb. 2015, Carl Wieman

Requirements:
1) measures what leads to most learning
2) equally valid/fair for use in all courses
3) actionable-- how to improve, & measures when do
4) is practical to use routinely

Better way–characterize the practices used in teaching a course, extent of use of research-based methods.
“Teaching Practices Inventory”
http://www.cwsei.ubc.ca/resources/TeachingPracticesInventory.htm
Final note—learning research you can use tomorrow

Very standard teaching approach: Give formalism, definitions, equations, and then move on to apply to solve problems.

What could possibly be wrong with this? Nothing, if learner has an expert brain. Expert organizes this knowledge as tools to use, along with criteria for when & how to use.

1) Novice does not have this system for organizing knowledge. Can only learn as disconnected facts, not linked to problem solving.
2) Much higher demands on working memory ("cognitive load")= less capacity for processing.
3) Unmotivating—no value.
A better way to present material—
“Here is a meaningful problem we want to solve.”
“Try to solve” (and in process notice key features of context & concepts—basic organizational structure).

Now that they are prepared to learn--“Here are tools (formalism and procedures) to help you solve.”

More motivating, better mental organization & links, less cognitive demand = more learning.

“A time for telling” Schwartz & Bransford (UW), Cog. and Inst. (1998), Telling after preparation ⇒ x10 learning of telling before, and better transfer to new problems.
Conclusion:

Meaningful science education—
Learn to make decisions/choices, not memorize.

Research providing new insights on—establishes expertise of teaching.

Improves student learning & faculty enjoyment.

Good References:
• S. Ambrose et. al. “How Learning works”
• D. Schwartz et. al. “The ABCs of how we learn”
• Ericsson & Pool, “Peak:….”
• Wieman, “Improving How Universities Teach Science”

• cwsei.ubc.ca-- resources (implementing best teaching methods), references, effective clicker use booklet and videos
~ 30 extras below
Expertise practiced and assessed with typical HW & exam problems.

- Provide all information needed, and only that information, to solve the problem
- Say what to neglect
- Not ask for argument for why answer reasonable
- Only call for use of one representation
- *Possible* to solve quickly and easily by plugging into equation/procedure

- concepts and mental models + selection criteria
- recognizing relevant & irrelevant information
- what information is needed to solve
- How I know this conclusion correct (or not)
- **model** development, testing, and use
- moving between specialized representations (graphs, equations, physical motions, etc.)
Effective teacher—
• Designing suitable practice tasks
• Providing timely guiding feedback
• Motivating
(“cognitive coach”)

Requires disciplinary expertise
Learning from peer discussion.
Questions on concepts covered in class. Intro QM. (clickers last term)
“Practice-with-feedback/Research-based/Active learning”

What it is not:
“experiential”
“flipped classroom”
“student centered”

These may contain the necessary mental practice activities and structure, but frequently do not.

Is centered on thinking to be learned.
Lots of “instructor” -- Design of task, feedback and elaboration to “prepared” students*.

* (“A time for telling”, Schwartz & Bransford)
3) Consider this optical setup

Steck writes the right moving wave amplitude in the cavity as

\[ U = U_0 + U_1 + U_2 + \ldots \]

where \[ U_{n+1} = re^{i2kd}U_n \]

3a) Explain what this second expression means:
3b) What is the meaning of the terms \( U_n \) and \( U_{n+1} \)?
3c) What is \( U_0 \) in terms of \( r_1, r_2, t_1, \) and \( U_{\text{laser}} \)?
3d) What is \( r \) in terms of \( r_1 \) and \( r_2 \)?
3e) Suppose there was a loss inducing optical element inside the cavity with a field transmission coefficient of \( t_{\text{loss}} \). What would \( r \) be in terms of \( t_{\text{loss}}, r_1, \) and \( r_2 \)? What if \( t_{\text{loss}} \) were complex?
3f) What is the effect of changing the index of refraction of the material between the mirrors? Is this equivalent to changing the distance between the mirrors? Why or why not?
3g) What is the effect of changing the wavelength of the input laser field? Is this equivalent to changing the distance between the mirrors? Why or why not?

Often added bonus activity to keep advanced students engaged
Research on Learning

Components of effective teaching/learning—expertise required.

1. Motivation
   - relevant/useful/interesting to learner
   - sense that can master subject

2. Connect with prior thinking

3. Apply what is known about memory
   - short term limitations
   - achieving long term retention

4. Explicit authentic practice of expert thinking

5. Timely & specific feedback on thinking
A better way to evaluate undergraduate science teaching
Change Magazine, Jan-Feb. 2015
Carl Wieman

“The Teaching Practices Inventory: A New Tool for Characterizing College and University Teaching in Mathematics and Science”
Carl Wieman* and Sarah Gilbert
(and now engineering & social sciences)

Try yourself. ~ 10 minutes to complete.
http://www.cwsei.ubc.ca/resources/TeachingPracticesInventory.htm

Provides detailed characterization of how course is taught
People learn from telling, but only if well-prepared to learn. Activities that develop knowledge organization structure. Students analyzed contrasting cases ⇒ recognize key features.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Noted in Study Work</th>
<th>Missed in Study Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analyze + lecture</td>
<td>.60</td>
<td>.26</td>
</tr>
<tr>
<td>Analyze + analyze</td>
<td>.18</td>
<td>.15</td>
</tr>
<tr>
<td>Summarize + lecture</td>
<td>.23</td>
<td>.06</td>
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</table>
Emphasis on motivating students
Providing engaging activities and talking in class
Failing half as many
“Student-centered” instruction

Aren't you just coddling the students?

Like coddling basketball players by having them run up and down court, instead of sitting listening?

Serious learning is inherently hard work
Solving hard problems, justifying answers—much harder, much more effort than just listening.

But also more rewarding (if understand value & what accomplished)—motivation
A few final thoughts—

1. Lots of data for college level, does it apply to K-12?

There is some data and it matches. Harder to get good data, but cognitive psych says principles are the same.

2. Isn’t this just “hands-on”/experiential/inquiry learning?

No. Is practicing thinking like scientist with feedback. Hands-on may involve those same cognitive processes, but often does not.
2. **Limits on short-term working memory** -- best established, most ignored result from cog. science

Working memory capacity **VERY LIMITED!**

(remember & process 5-7 distinct new items)

**MUCH less than in typical lecture**

Mr Anderson, May I be excused? My brain is full.

slides to be provided
Lesson from these Stanford courses—

**Not hard for typical instructor to switch to active learning and get good results**

- read some references & background material (like research!)
- fine to do incrementally, start with pieces
Pre-class Reading

Purpose: Prepare students for in-class activities; move learning of less complex material out of classroom

Spend class time on more challenging material, with Prof giving guidance & feedback

Can get >80% of students to do pre-reading if:

• Online or quick in-class quizzes for marks (tangible reward)
• Must be targeted and specific: students have limited time
• DO NOT repeat material in class!

Stanford Active Learning Physics courses (all new in 2015-16)

2nd-4th year physics courses, 6 Profs

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Instructor</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYS 70</td>
<td>Modern Physics</td>
<td>Wieman</td>
<td>Aut 2015</td>
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<tr>
<td>PHYS 120</td>
<td>E&amp;M I</td>
<td>Church</td>
<td>Win 2016</td>
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<tr>
<td>PHYS 121</td>
<td>E&amp;M II</td>
<td>Hogan</td>
<td>Spr 2016</td>
</tr>
<tr>
<td>PHYS 130</td>
<td>Quantum I</td>
<td>Burchat</td>
<td>Win 2016</td>
</tr>
<tr>
<td>PHYS 131</td>
<td>Quantum II</td>
<td>Hartnoll</td>
<td>Spr 2016</td>
</tr>
<tr>
<td>PHYS 110</td>
<td>Adv Mechanics</td>
<td>Hartnoll</td>
<td>Aut 2015</td>
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<tr>
<td>PHYS 170</td>
<td>Stat Mech</td>
<td>Schleier-Smith</td>
<td>Aut 2015</td>
</tr>
</tbody>
</table>
Math classes—similar design

Other types of questions---

• What is next (or missing) step(s) in proof?
• What is justification for (or fallacy in) this step?
• Which type of proof is likely to be best, and why?
• Is there a shorter/simpler/better solution? Criteria?
Reducing demands on working memory in class

- Targeted pre-class reading with short online quiz
- Eliminate non-essential jargon and information
- Explicitly connect
- Make lecture organization explicit.
Perfection in class is not enough!

*Not enough hours*

- Activities that prepare them to learn from class
  (targeted pre-class readings and quizzes)

- Activities to learn much more after class
  **good homework**—
  - builds on class
  - explicit practice of all aspects of expertise
  - requires reasonable time
  - reasonable feedback
Motivation-- essential (complex- depends on background)

Enhancing motivation to learn

a. Relevant/useful/interesting to learner (meaningful context-- connect to what they know and value) requires expertise in subject

b. Sense that can master subject and how to master, recognize they are improving/accomplishing

c. Sense of personal control/choice
How it is possible to cover as much material? 
(if worrying about covering material not developing students expert thinking skills, focusing on wrong thing, but...)

• transfers information gathering outside of class, 
• avoids wasting time covering material that students already know

Advanced courses-- often cover more

Intro courses, can cover the same amount. But typically cut back by ~20%, as faculty understand better what is reasonable to learn.
On average learn <30% of concepts did not already know.

Lecturer quality, class size, institution,...doesn't matter!

R. Hake, "…A six-thousand-student survey…” AJP 66, 64-74 (‘98).

Measuring conceptual mastery

- Force Concept Inventory- basic concepts of force and motion

Apply like physicist in simple real world applications?

Test at start and end of the semester--

What % learned? (100’s of courses/yr)

![Graph showing fraction of unknown basic concepts learned](image)

On average learn <30% of concepts did not already know. Lecturer quality, class size, institution,…doesn't matter!

improved methods
clickers*--

Not automatically helpful--
  give accountability, anonymity, fast response

Used/perceived as expensive attendance and testing device⇒ little benefit, student resentment.

Used/perceived to enhance engagement, communication, and learning ⇒ transformative

- challenging questions-- concepts
- student-student discussion ("peer instruction") & responses (learning and feedback)
- follow up instructor discussion- timely specific feedback
- minimal but nonzero grade impact

*An instructor's guide to the effective use of personal response systems ("clickers") in teaching-- www.cwsei.ubc.ca
Retention curves measured in Bus’s Sch’l course. UBC physics data on factual material, also rapid drop but pedagogy dependent. (in prog.)
Design principles for classroom instruction

1. Move simple information transfer out of class. Save class time for active thinking and feedback.

2. “Cognitive task analysis”—how does expert think about problems?

3. Class time filled with problems and questions that call for explicit expert thinking, address novice difficulties, challenging but doable, and are motivating.

4. Frequent specific feedback to guide thinking.
Institutionalizing improved research-based teaching practices. *(From bloodletting to antibiotics)*

Goal of Univ. of Brit. Col. CW Science Education Initiative *(CWSEI.ubc.ca)* & Univ. of Col. Sci. Ed. Init.

- Departmental level, widespread sustained change at major research universities
  ⇒ scientific approach to teaching, all undergrad courses
- Departments selected competitively
- Substantial one-time $$$ and guidance

Extensive development of educational materials, assessment tools, data, etc. Available on web. Visitors program