Taking a scientific approach to Science Education*

...and many other subjects

Carl Wieman

*based on the research of many people, some from my science ed research group (most examples college physics, but results general)
Why need better science, engineering, and mathematics education?

Scientifically literate public

Modern economy built on S & T

Need **all** students to think about and understand science more like scientists (and engineers, ...
Major advances past 1-2 decades
Consistent picture ⇒ Achieving learning

College science classroom studies

brain research

cognitive psychology

opportunity
Education Model 1  (I used for many years)

think hard, figure out subject

tell students how to understand it

give problem to solve

yes

done

no

students lazy or poorly prepared

tell again Louder
Figure out, tell students

my enlightenment

grad students
17 yrs of success in classes.
Come into lab clueless about physics?

2-4 years later ⇒ expert physicists!

--approach teaching as science.
Research on how people learn, particularly science.
Obtain, use, and test basic principles. ~ 10 years

explained puzzle, different way to think about learning, showed how to greatly improve classes
Research on learning—college science context

A. What is “thinking like a scientist”?

B. How is it learned?

C. Evidence from the classroom, sample of methods, results.  
   (all different from 2008 talk)

A. General research-based principles for effective teaching.

B. A final test
Implicit assumptions of university science teaching

If you don't tell it to them, they won't learn it.
If you do tell it to them, they will learn it.

The data completely refute.
Expert competence research*

historians, scientists, chess players, doctors,...

Expert competence =
• factual knowledge
• **Mental organizational framework** \(\Rightarrow\) retrieval and application patterns, relationships, scientific concepts

• Ability to monitor own thinking and learning
  "Do I understand this? How can I check?"

New ways of thinking-- everyone requires MANY hours of intense practice to develop.
Brain changed

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

Challenging but doable tasks/questions

Explicit focus on expert-like thinking
  • concepts and mental models + selection criteria
  • recognizing relevant & irrelevant information
  • self-checking, sense making

Feedback and reflection (teacher)

10,000 hours later—world-class level expertise
very different brain

Requires brain “exercise.”
Effective teacher is “cognitive coach”.

Innate talent relatively minor. (but beliefs matter)

* “Deliberate Practice”, A. Ericsson research
accurate, readable summary in “Talent is over-rated”, by Colvin
How to apply in classroom?

**Example from teaching about current & voltage--**

1. **Preclass assignment**--Read pages on electric current. Learn basic facts and terminology. Short online quiz to check/reward (and retain).

2. **Class built around series of questions & tasks.**
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, primed to learn)

4. Discuss with “consensus group”, revote. (prof listen in!)

How practicing thinking like a scientist?
• forming, testing, applying conceptual mental models
• testing one’s reasoning
+ getting multiple forms of feedback to refine thinking

Lots of instructor talking, but reactive.

Requires much more subject expertise. Fun!
3. Evidence from the Science Classroom

“Deliberate practice” learning of expertise embodied in many innovative teaching practices.

• “active learning”
• “formative assessment”
• much of “collaborative learning”
• ...

Better results than traditional, many with same cost
(see NRC discipline-based education research report, ~ 1000 STEM research studies!)
Measuring conceptual mastery

- Carefully developed tests (“concept inventories”)—measure if students understand and use concepts like expert. Questions on simple real world situations. Multiple choice—wrong answers are known student thinking.

~8 in physics, several in biology, geology, chemistry, calculus, ...

Give at start and end of the semester--
What % learned? (“learning gain”) (100’s of courses/yr)

For many of these tests, average student learns <30% of concepts did not already know. Lecturer quality, class size, institution,...doesn't matter!
average trad. Cal Poly instruction
1st year mechanics

Hoellwarth and Moelter, Am. J. Physics May ’11

9 instructors, 8 terms, 40 students/section.
Same prescribed set of student activities.
Mental activities of the students dominate
Giant intro biology course.
University of Washington--
Similar types of instruction--
all students improved, underrepresented students improved more (+1/3 letter grade on average)
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
What (research) every teacher should know
Principles of effective teaching/learning apply to all levels, all settings

1. Motivation (*lots of research*)
2. Connect with prior thinking
3. Apply what is known about memory
   a. short term limitations
   b. achieving long term retention

List of specific strategies for how to incorporate these in instruction in materials to Peter and Theresa.
Testing in classroom*

Comparing the learning in two identical sections of 1st year college physics. 270 students each.

**Control**--standard lecture class– highly experienced Prof with good student ratings.

**Experiment**-- inexperienced teacher (postdoc) trained to use these principles of effective teaching.

Same learning objectives, same class time, same exam (jointly prepared)

Clear improvement for entire student population.
Engagement 85% vs 45%.
Survey of student opinions-- transformed section

“Q1. I really enjoyed the interactive teaching technique during the three lectures on E&M waves.”

“Q2. I feel I would have learned more if the whole phys153 course would have been taught in this highly interactive style.”

Not unusual for SEI transformed courses
Vision–Science and Eng. teaching & Learning
-- like astronomy, not astrology
⇒dramatic improvements for all students.
copies of slides (+30 extras) available

Good References:
S. Ambrose et. al. “How Learning works”
Colvin, “Talent is over-rated”
cwsei.ubc.ca-- resources, references, effective clicker
use booklet and videos

NAS Press, “Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering”, and “How people learn”

PHET.colorado.edu Interactive simulations for sci. & math
~ 30 extras below
Measuring conceptual mastery

- Force Concept Inventory - basic concepts of force and motion 1st semester university physics. Simple real world applications.

Ask at start and end of the semester --
What % learned? (“value added”) (100’s of courses/yr)

On average learn <30% of concepts did not already know. Lecturer quality, class size, institution,...doesn't matter! Similar data for conceptual learning in other courses.

R. Hake, "...A six-thousand-student survey…” AJP 66, 64-74 (‘98).
a. Limits on working memory -- best established, most ignored result from cognitive science

Working memory capacity VERY LIMITED!
(remember & process ~ 5 distinct new items)

MUCH less than in typical lecture

slides to be provided

Mr Anderson, May I be excused? My brain is full.
Components of effective teaching/learning apply to all levels, all settings

1. Motivation

2. Connect with and build on prior thinking

3. Apply what is known about memory
   a. short term limitations
   b. achieving long term retention (Bjork)
      retrieval and application -- repeated & spaced in time (test early and often, cumulative)

4. Explicit authentic practice of expert thinking. Extended & strenuous
Motivation-- essential
(complex- depends on previous experiences, ...)

Enhancing motivation to learn

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

b. Sense that can master subject and how to master

c. Sense of personal control/choice
Use of Educational Technology

Danger!
Far too often used for its own sake! *(electronic lecture)*
Evidence shows little value.

Opportunity
Valuable tool *if* used to supporting principles of effective teaching and learning.

Extend instructor capabilities.
Examples shown.

- Assessment (pre-class reading, online HW, clickers)
- Feedback (more informed and useful using above, enhanced communication tools)
- Novel instructional capabilities (PHET simulations)
- Novel student activities (simulation based problems)
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.
Perceptions about science

**Novice**

Content: isolated pieces of information to be memorized.

Handed down by an authority. Unrelated to world.

Problem solving: pattern matching to memorized recipes.

**Expert**

Content: coherent structure of concepts.

Describes nature, established by experiment.


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measure student perceptions, 7 min. surveys. Pre-post intro physics course ⇒ more novice than before chem. & bio as bad

*adapted from D. Hammer*
Student Perceptions/Beliefs

Kathy Perkins, M. Gratny

Percent of Students (measured at start of 1st term of college physics)

- All Students (N=2800)
- Intended Majors (N=180)
- Survived (3-4 yrs) as Majors (N=52)

Novice

Expert

CLASS Overall Score

(measured at start of 1st term of college physics)
Student Beliefs

- Actual Majors who were originally intended phys majors
- Survived as Majors who were **NOT** originally intended phys majors

Percent of Students

CLASS Overall Score (measured at start of 1st term of college physics)

Novice

Expert
Perceptions survey results—Highly relevant to scientific literacy/liberal ed. Correlate with everything important

Who will end up physics major 4 years later?

7 minute first day survey better predictor than first year physics course grades

recent research⇒ changes in instruction that achieve positive impacts on perceptions
How to make perceptions significantly more like physicist (very recent)--

• process of science much more explicit (model development, testing, revision)

• real world connections up front & explicit
Highly Interactive educational simulations--
phet.colorado.edu  >100 simulations
FREE, Run through regular browser. Download
Build-in & test that develop expert-like thinking and learning (& fun)

balloons and sweater
laser
cl|ik|ers*--

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
Why **so hard** to give up lecturing? *(speculation)*

1. tradition
2. Brain has no perspective to detect changes in self. *“Same, just more knowledge”*
3. Incentives not to change—research is closely tracked, educational outcomes and teaching practices not.

Psychology research and our physics ed studies

**Learners/experts cannot remember or believe previously held misunderstandings!**
What is the role of the teacher?

“Cognitive coach”
• Designs tasks that practice the specific components, of “expert thinking”.
• Motivate learner to put in LOTS of effort
• Evaluates performance, provides timely specific feedback. Recognize and address particular difficulties (inappropriate mental models, ...)
• repeat, repeat, ...-- always appropriate challenge

Implies what is needed to teach well: expertise, understanding how develops in people, common difficulties, effective tasks and feedback, effective motivation.
long term retention

Transformed \( \Delta = -3.4 \pm 2.2\% \)

Award-winning

Traditional \( \Delta = -2.3 \pm 2.7\% \)

Retention curves measured in Bus’s School course.

UBC physics data on factual material, also rapid drop but pedagogy dependent. (in prog.)
Comparison of teaching methods: identical sections (270 each), intro physics. (Deslauriers, Schewlew, submitted for pub)

I

Experienced highly rated instructor--trad. lecture

wk 1-11

very well measured--identical

II

Very experienced highly rated instructor--trad. lecture

wk 1-11

Wk 12-- experiment
Two sections the same before experiment. (different personalities, same teaching method)

<table>
<thead>
<tr>
<th></th>
<th>Control Section</th>
<th>Experiment Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Students enrolled</td>
<td>267</td>
<td>271</td>
</tr>
<tr>
<td>Conceptual mastery (wk 10)</td>
<td>47± 1 %</td>
<td>47 ± 1%</td>
</tr>
<tr>
<td>Mean CLASS (start of term)</td>
<td>63±1%</td>
<td>65±1%</td>
</tr>
<tr>
<td>(Agreement with physicist)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Midterm 1 score</td>
<td>59± 1 %</td>
<td>59 ± 1%</td>
</tr>
<tr>
<td>Mean Midterm 2 score</td>
<td>51± 1 %</td>
<td>53 ± 1%</td>
</tr>
<tr>
<td>Attendance before</td>
<td>55±3%</td>
<td>57±2%</td>
</tr>
<tr>
<td>Engagement before</td>
<td>45±5 %</td>
<td>45±5 %</td>
</tr>
</tbody>
</table>
Comparison of teaching methods: identical sections (270 each), intro physics. (Deslauriers, Schewlew, submitted for pub)

I
Experienced highly rated instructor-- trad. lecture

wk 1-11

identical on everything diagnostics, midterms, attendance, engagement

Wk 12-- competition

elect-mag waves
inexperienced instructor
research based teaching

II
Very experienced highly rated instructor-- trad. lecture

wk 1-11

elect-mag waves
regular instructor
intently prepared lecture

wk 13 common exam on EM waves
<table>
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<tr>
<th></th>
<th>control</th>
<th>experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Attendance</td>
<td>53(3) %</td>
<td>75(5)%</td>
</tr>
<tr>
<td>3. Engagement</td>
<td>45(5) %</td>
<td>85(5)%</td>
</tr>
</tbody>
</table>
Measuring student (dis)engagement. Erin Lane
Watch random sample group (10-15 students). Check
against list of disengagement behaviors each 2 min.

example of data from earth science course
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.
What about learning to think more innovatively?
Learning to solve challenging novel problems

Jared Taylor and George Spiegelman

“Invention activities”— practice coming up with mechanisms to solve a complex novel problem. Analogous to mechanism in cell.

2008-9-- randomly chosen groups of 30, 8 hours of invention activities. This year, run in lecture with 300 students. 8 times per term. (video clip)
Plausible mechanisms for biological process student never encountered before

<table>
<thead>
<tr>
<th>Number of Solutions</th>
<th>Control</th>
<th>Structured Problems (tutorial)</th>
<th>Inventions (Outside of Lecture)</th>
<th>Inventions (During Lecture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Number</td>
<td>0.0</td>
<td>1.0</td>
<td>6.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Bringing up the bottom of the distribution

“What do I do with the weakest students? Are they just hopeless from the beginning, or is there anything I can do to make a difference?”

many papers showing things that do not work

Here-- Demonstration of how to transform lowest performing students into medium and high.

Intervened with bottom 20-25% of students after midterm 1.
a. very selective physics program 2nd yr course
b. general interest intro climate science course
What did the intervention look like?

Email after M1-- “Concerned about your performance. 1) Want to meet and discuss”; or 2) 4 specific pieces of advice on studying. [on syllabus]

Meetings-- “How did you study for midterm 1?” “mostly just looked over stuff, tried to memorize book & notes”

Give **small number** of **specific** things to do:
1. **test** yourself as review the homework problems and solutions.
2. **test** yourself as study the learning goals for the course given with the syllabus.
3. **actively** *(explain to other)* the assigned reading for the course.
4. Phys only. Go to weekly (optional) problem solving sessions.
No intervention

Email only

Email & Meeting

intervention

no intervention
• End of 2\textsuperscript{nd} yr Modern physics course (very selective and demanding, N=67)

• Intro climate science course. Very broad range of students. (N=185)

bottom 1/4 \textbf{averaged} +19\% improvement on midterm 2 !

\[ \text{Averaged } +30\% \text{ improvement on midterm 2 !} \]
Bunch of survey and interview analysis end of term.

⇒ students changed how they studied

(but did not think this would work in most courses, ⇒ doing well on exams more about figuring out instructor than understanding the material)

Instructor can make a dramatic difference in the performance of low performing students with small but appropriately targeted intervention to improve study habits.
(lecture teaching) Strengths & Weaknesses

Works well for basic knowledge, prepared brain:

- **Bad, avoid**
- **Good, seek**

Easy to test. ⇒ Effective feedback on results.
Information needed to survive ⇒ intuition on teaching

But problems with approach if learning:
- involves complex analysis or judgment
- organize large amount of information
- ability to learn new information and apply

Complex learning-- different.
Reducing unnecessary demands on working memory improves learning.

\[ \text{X} \quad \text{jargon, use figures, analogies, pre-class reading} \]
### Some Data (from science classrooms):

<table>
<thead>
<tr>
<th>Model 1 (telling)</th>
<th>scientific teaching</th>
</tr>
</thead>
<tbody>
<tr>
<td>retention of information from lecture</td>
<td></td>
</tr>
<tr>
<td>10% after 15 minutes</td>
<td>&gt;90% after 2 days</td>
</tr>
<tr>
<td>fraction of concepts mastered in course</td>
<td>50-70% with retention</td>
</tr>
<tr>
<td>perceptions of science -- what it is, how to learn, significantly less (5-10%) like physicist</td>
<td>5-10% more like physicist</td>
</tr>
</tbody>
</table>
Characteristics of expert tutors* (Which can be duplicated in classroom?)

Motivation major focus (context, pique curiosity,…) Never praise person-- limited praise, all for process

Understands what students do and do not know. ⇒ timely, specific, interactive feedback

Almost never tell students anything-- pose questions.

Mostly students answering questions and explaining.

Asking right questions so students challenged but can figure out. Systematic progression.

Let students make mistakes, then discover and fix.

Require reflection: how solved, explain, generalize, etc.

*Lepper and Woolverton pg 135 in Improving Academic Performance
Changing educational culture in major research university science departments necessary first step for science education overall

• Departmental level
  ⇒ scientific approach to teaching, all undergrad courses = learning goals, measures, tested best practices
  Dissemination and duplication.

All materials, assessment tools, etc to be available on web
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
Fixing the system
but...need higher content mastery, new model for science & teaching

Higher ed

K-12 teachers

everyone

STEM teaching & teacher preparation

STEM higher Ed
Largely ignored, first step
Lose half intended STEM majors
Prof Societies have important role.
Many new efforts to improve undergrad STEM education (partial list)

1. College and Univ association initiatives (AAU, APLU) + many individual universities

2. Science professional societies

3. Philanthropic Foundations

4. New reports — PCAST, NRC (~April)


6. Government — NSF, Ed $$, and more

7. ...