Taking a scientific approach to science education

Carl Wieman  
Stanford University  
Department of Physics and Grad School of Education

need all students, future scientists or not, to be able to think about science more like scientists

results & implications, not practice of DBER

*based on the research of many people, some from my science ed research group
Learning in class. Two nearly identical 250 student sections—same learning objectives, same class time, same test.

Experienced highly rated traditional lecturer versus Postdoc trained in principles of effective teaching
Learning in class. Two nearly identical 250 student sections—same learning objectives, same class time, same test.
Major advances past 1-2 decades ⇒ Guiding principles for achieving learning

- College sci classroom studies
- brain research
- cognitive psychology
Education approach 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!

Research on how people learn, particularly physics

- explained puzzle
- different way to think about learning
- how to improve classes
New paradigm on learning complex tasks (e.g. science, math, & engineering)

old view, current teaching

knowledge soaks in, variable

new view

transform via suitable “exercise”
I. What is it that we want students to learn? ("thinking more like scientist"?)

II. How is it learned?

III. Data from the classroom
Expertise research*
historians, scientists, chess players, doctors,…

Expert competence =
• factual knowledge
• Mental organizational framework ⇒ retrieval and application

or ?

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

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

Challenging but doable tasks/questions

Explicitly practicing expert thinking
Guiding feedback

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

Effective teacher is “cognitive coach”
• Designing good practice activities
• Giving useful feedback
• Motivating

requires expertise!

* “Deliberate Practice”, A. Ericsson research accurate, readable summary in “Talent is over-rated”, by Colvin
3. Evidence from the Classroom

~ 1000 research studies undergrad science
  • consistently show greater learning
  • lower failure rates

a few examples
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).
9 instructors, 8 terms, 40 students/section. 
Same prescribed set of student activities. 
Mental activities of the students dominate

average trad. Cal Poly instruction

1st year mechanics

Hoellwarth and Moelter, 
Am. J. Physics May ‘11
U. Cal. San Diego, Computer Science
Failure & drop rates—*Beth Simon et al., 2012*

<table>
<thead>
<tr>
<th>Course</th>
<th>Standard Instruction</th>
<th>Peer Instruction</th>
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<tbody>
<tr>
<td>CS1*</td>
<td>24%</td>
<td>10%</td>
</tr>
<tr>
<td>CS1.5</td>
<td>14%</td>
<td>11%</td>
</tr>
<tr>
<td>Theory*</td>
<td>25%</td>
<td>6%</td>
</tr>
<tr>
<td>Arch*</td>
<td>16%</td>
<td>3%</td>
</tr>
<tr>
<td>Average*</td>
<td>20%</td>
<td>7%</td>
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Learning *in the in classroom*^

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

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

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

- Same learning objectives
- Same class time (3 hours, 1 week)
- Same exam (jointly prepared)- start of next class

*Deslauriers, Schewlew, Wieman, Sci. Mag. May 13, '11*
Applying all the important principles of effective teaching/learning apply to all levels, all settings

1. Motivation (*lots of research*)

2. Connect with and build on prior thinking & knowledge

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

4. Explicit strenuous practice of expert thinking. Timely & specific feedback.
Clear improvement for entire student population. Engagement 85% vs 45%.
3 simple immediately applicable findings from research on learning. Every course.

1. expertise and homework design

2. limitations on how brain remembers

3. priming learner and knowing how to help
1. Compare with typical HW & exam problems that provide practice and assessment
   • 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.)
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**

- reduce jargon & nonessential info.
- Explicitly connect.

---

Mr Anderson, May I be excused? My brain is full.
3. Benefits to interrupting lecture with challenging conceptual question with student-student discussion

Not that important whether or not they can answer it, just have to engage.

Reduces WM demands—consolidates and organizes. Simple immediate feedback ("what was mitosis?")

Practice expert thinking. Primes them to learn.

**Instructor listen in on discussion. Can understand and guide much better.**
Vision—Science and Eng. teaching & Learning

research--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”

PHET.colorado.edu Interactive simulations for sci. & math
cwsei.ubc.ca-- resources, references, effective clicker
use booklet and videos

How to apply cog. psych. principles in classroom? *(practicing expert thinking, with feedback)*

**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!)
5. Elicit student reasoning, discuss. Show responses.
Do “experiment.” -- cck simulation. Many questions.

Jane Smith chose a.
How practicing thinking like a scientist?
• forming, testing, applying conceptual mental models, identifying relevant & irrelevant information, ...
• testing reasoning
+ getting multiple forms of feedback to refine thinking

Still instructor talking (~ 50%), but reactive.

Requires much more subject expertise. Fun!
~ 30 extras below
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.
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)
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
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 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
Survey of student opinions-- transformed section

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

- **Strongly agree**: 63 students
- **Agree**: 57 students
- **Neutral**: 12 students
- **Disagree**: 2 students
- **Strongly disagree**: 0 students

Not unusual for SEI transformed courses
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.


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

*adapted from D. Hammer*
Student Beliefs

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

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

Percent of Students

- 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](http://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
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.
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
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!
Retention curves measured in Bus’s Sch’l course.
UBC physics data on factual material, also rapid drop but pedagogy dependent. (in prog.)

award-winning
Δ = -3.4 ± 2.2%

traditional
Δ = -2.3 ± 2.7%

long term retention
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

Wk 12-- experiment

II
Very experienced highly rated instructor--trad. lecture

wk 1-11
Two sections the same before experiment. (different personalities, same teaching method)

<table>
<thead>
<tr>
<th></th>
<th>Control Section</th>
<th>Experiment Section</th>
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</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>
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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

II

Very experienced highly rated instructor--trad. lecture

wk 1-11

elect-mag waves

inexperienced instructor

research based teaching

wk 13 common exam on EM waves

elect-mag waves

regular instructor

intently prepared lecture
<table>
<thead>
<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

time (minutes)
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)
Average Number

Plausible mechanisms for biological process student never encountered before

<table>
<thead>
<tr>
<th></th>
<th>Number of Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>~1.0</td>
</tr>
<tr>
<td>Structured Problems</td>
<td>~1.5</td>
</tr>
<tr>
<td>(tutorial)</td>
<td></td>
</tr>
<tr>
<td>Inventions (Outside</td>
<td>~5.0</td>
</tr>
<tr>
<td>of Lecture)</td>
<td></td>
</tr>
<tr>
<td>Inventions (During</td>
<td>~4.0</td>
</tr>
<tr>
<td>Lecture)</td>
<td></td>
</tr>
</tbody>
</table>

Graph showing average number of solutions across different conditions.
Average Time to First Solution Thread

- Control
- SPSA (Outside of Lecture)
- IA (Outside of Lecture)
- IA (During Lecture)

Time (min)
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.
Intro climate Science course (S. Harris and E. Lane)

The scatter plot shows the relationship between Midterm 1 Score and Midterm 2 Score. The data is categorized into three groups:

- **No intervention** (diamonds)
- **Email only** (black dots)
- **Email & Meeting** (black squares)

The plot highlights the intervention and no intervention groups:

- **Intervention**: The area where the data points are more clustered, indicated by the black squares.
- **No intervention**: The area where the data points are more spread out, indicated by the diamonds.

The line represents the trend, with the diamond line indicating no intervention and the solid line indicating potential intervention effects.
• End of 2\textsuperscript{nd} yr Modern physics course (very selective and demanding, N=67)

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

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

Averaged +30\% 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:

\[ \text{bad, avoid} \quad \text{good, seek} \]

Easy to test. \( \Rightarrow \) Effective feedback on results.
Information needed to survive \( \Rightarrow \) 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.

- jargon, use figures, analogies, pre-class reading
### Some Data (from science classrooms):

<table>
<thead>
<tr>
<th>Model 1 (telling) traditional lecture method</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></td>
</tr>
<tr>
<td>15-25%</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](http://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

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. ...
The problem with education—
Everyone is an expert--
countless opinions, all considered equally valid

Value of a scientific approach—
separate out reality from opinions

**Scientific Approach**
- theories
- experiments
- results
- revised theories more experiments
- finally reproducible and right

Nobel Prize

Data!!