Taking a scientific approach to Science and Engineering Education

Carl Wieman

relevant to both teachers and learners

*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 & eng. 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

students lazy or poorly prepared

no

done

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 sci. & eng. context

A. What is “thinking like a scientist/engineer”?

B. How is it learned?

C. Evidence from the classroom, sample of methods, results.

D. General research-based principles for effective teaching & a final test. Doubling learning.
Expert competence research*

historians, scientists, chess players, doctors,…

Expert competence =
• factual knowledge
• **Mental organizational framework** ⇒ retrieval and application
  patterns, relationships, scientific concepts

or ?

• **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

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.”

Innate talent unimportant. (but beliefs matter)

* “Deliberate Practice”, A. Ericsson research
accurate, readable summary in “Talent is over-rated”, by Colvin
Learning expertise*--

What is involved in good teaching?
What is involved in good learning?

Effective teacher is “cognitive coach”.

• Analyzing what makes up expertise in subject
• Designing tasks that explicitly practice. Hard but doable (*collaborative learning broadens range*)
• Motivate learner to work long and hard
• Provide timely feedback to guide thinking, encourage reflection
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.
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!
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
    - relevant context— why worthwhile
    - requires time
    - offers feedback
3. Evidence from Sci. & Eng. courses

2012 NRC Discipline-Based Education Research study (NAS press, free download)

~ 1000 STEM research studies showing several methods with consistently better results than traditional lecture.

Many with same cost.
Measuring conceptual mastery

• Carefully developed tests ("concept inventories")—measure if students understand and use concepts like expert.

Multiple choice—wrong answers are known student thinking.

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

Give at beginning and end of the semester--
What % learned? ("learning gain")
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
It doesn’t just work in physics--

1. Giant intro biology course. Univ. of Wash. All students improved, underrepresented students improved more (+1/3 letter grade on average)

2. UCSD Computer Sci. (Beth Simon) Fail rates down by average of 67% for same instructors when switched from standard lectures to research-based methods. Biggest drop—87%!

*Science Magazine June 3, 2011 (Haak et al)*
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

*4. Explicit authentic practice of expert thinking.
   Extended & strenuous. Timely & specific feedback.
Testing in classroom*

Comparing the learning in two identical sections of 1st year physics for engineers. 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)

*Deslauriers, Schewlew, Wieman, Sci. Mag. May 13, ‘11*
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.”

Not unusual for SEI transformed courses

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

Intro courses, can cover the same amount. But typically cut back by ~20%, as faculty understand better what is reasonable to learn.
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.
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 Perceptions/Beliefs

Kathy Perkins, M. Gratny

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**CLASS Overall Score**

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

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**Percent of Students**

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

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**Expert**

**Novice**
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 >100 simulations
FREE, Run through regular browser. Download

Build-in & test that develop expert-like thinking and learning (& fun)

balloons and sweater

laser
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!
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.
Retention curves measured in Bus’s Sch’l course. UBC physics data on factual material, also rapid drop but pedagogy dependent.

(Deslauriers & Wieman, PRST-PER)
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>
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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>
</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>
<thead>
<tr>
<th></th>
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<th>experiment</th>
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<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 \textit{(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
What about learning to think more innovatively? Learning to solve challenging novel problems

Jared Taylor and George Spiegelman
*Cell Biology Education (notable paper of 2011)*

“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

Average Number

Control
Structured Problems (tutorial)
Inventions (Outside of Lecture)
Inventions (During Lecture)
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)

- No intervention
- Email only
- Email & Meeting

![Scatter plot showing midterm scores]

- Intervention
- No intervention
• End of 2nd yr Modern physics course (very selective and demanding, N=67)

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

bottom 1/4 averaged +19% improvement on midterm 2!

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:

- bad, avoid
- 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)</th>
<th>scientific teaching</th>
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<tbody>
<tr>
<td>traditional lecture method</td>
<td></td>
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<tr>
<td>• Retention of information from lecture</td>
<td></td>
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<tr>
<td>10% after 15 minutes $\Rightarrow$ &gt;90 % after 2 days</td>
<td></td>
</tr>
<tr>
<td>• Fraction of concepts mastered in course</td>
<td></td>
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<tr>
<td>15-25% $\Rightarrow$ 50-70% with retention</td>
<td></td>
</tr>
<tr>
<td>• Perceptions of science-- what it is, how to learn, significantly less (5-10%) like physicist</td>
<td></td>
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<tr>
<td></td>
<td>5-10% more like physicist</td>
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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

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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)
5. **Industry**— WH Jobs Council, Business Higher Ed Forum
6. **Government**— NSF, Ed $$, and more
7. ...