Taking a scientific approach to Science and Eng. Education

Presented March 20, 2012
Wisconsin Institutes for Discovery
Madison, WI

Carl Wieman
Assoc. Director for Science
OSTP

*Based on the research of many people, some from my science education research group (most examples college physics, but results general)
Why need better STEM education?

Scientifically literate public

Modern economy built on S & T

Requires large “STEM competent” workforce

Need all students to think about and use science and engineering more like scientists and engineers
Major advances past 1-2 decades
Consistent picture ⇒ Achieving learning

College science classroom studies

brain research

cognitive psychology

opportunity
Science education Model 1 (I used for many years)

- **think hard, figure out subject**
  - **tell students how to understand it**
    - **give problem to solve**
      - **done**
      - **students lazy or poorly prepared**
        - **no**
          - **tell again Louder**
        - **yes**
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 and apply underlying principles.
Research on learning—college science context

A. What is “thinking like a scientist”?  
B. How is it learned?  
C. Evidence from the classroom
Expert competence research*
historians, scientists, chess players, doctors,…

Expert competence =
• factual knowledge
• Mental organizational framework \(\Rightarrow\) retrieval and application

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
  • 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.”
Teacher is “cognitive coach”.

* “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)

Jane Smith chose a.

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!
3. Evidence from the Science Classroom

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

- “active learning”
- “formative assessment”
- “context rich” or “real world” problems,
- much of “collaborative learning”
- ...

Many with same cost as traditional & better results

~ 1000 research studies!
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**

Hoellwarth and Moelter, Am. J. Physics May ‘11
Giant intro biology course.
University of Washington--
Similar instruction--
all students improved, underrepresented students improved more (+1/3 letter grade on average)
## Perceptions about science

<table>
<thead>
<tr>
<th><strong>Novice</strong></th>
<th><strong>Expert</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Content:</strong> isolated pieces of information to be memorized.</td>
<td><strong>Content:</strong> coherent structure of concepts.</td>
</tr>
<tr>
<td>Handed down by an authority. Unrelated to world.</td>
<td>Describes nature, established by experiment.</td>
</tr>
</tbody>
</table>

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

*adapted from D. Hammer*
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
What (research) every teacher should know
Components 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.
Experiment -- inexperienced teacher trained to use “expert-thinking practice” approach.
Control -- standard lecture class-- highly experienced Prof with good student ratings.

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

Clear improvement for entire student population. Engagement also much higher.

Standard lecture

Histogram of exam scores

ave 41 ± 1 %

74 ± 1 %

experiment

R.G.
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. ...
Vision - STEM teaching & Learning

-- like astronomy, not astrology

⇒ dramatic improvements for all students.

copies of slides (+30 extras) available

Good Refs.:
S. Ambrose et. al. “How Learning works”
NAS Press “How people learn”
Colvin, “Talent is over-rated”
Wieman, Change Magazine-Oct. 07
at www.carnegiefoundation.org/change/
cwsei.ubc.ca-- resources, references, effective clicker use booklet and videos
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!**
~ 30 extras below
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.
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
Vision— STEM teaching & Learning
teaching— like astronomy, not astrology

• Rigorous research, routine rapid application of research findings
• Professional standards linked to ed research
• Routinely sharing materials, practices, results

Learning—
• routine instructor-independent assessment
• x 2+ meaningful learning and long-term retention
Student Perceptions/Beliefs

Kathy Perkins, M. Gratny

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

Percent of Students

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

Expert

Novice
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
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.
<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>
Common claim “But students resent new active learning methods that make them pay attention and think in class.”

or do they...
Survey of student opinions--transformed section

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

```
Number of students

63 57 12 0

strongly agree Agree Neutral Disagree Strongly disagree
```

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

```
Number of students

67 36 21 8 2

Strongly agree Agree Neutral Disagree Strongly disagree
```

Not unusual for SEI transformed courses
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
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.
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.
Comparison of teaching methods: identical sections (270 each), intro physics. (Deslauriers, Schewleew, 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>
</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) (Agreement with physicist)</td>
<td>63±1%</td>
<td>65±1%</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
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)
Nearly all intro classes average shifts to be 5-10% less like scientist.

Explicit connection with real life $\rightarrow \sim 0\%$ change

+Emphasize process (modeling) $\rightarrow +10\%$ !!
Concept Survey Score (%)

Retention interval (Months after course over)

transformed $\Delta = -3.4 \pm 2.2\%$

award-winning

traditional $\Delta = -2.3 \pm 2.7\%$

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

Average Number

Number of Solutions

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.
• End of 2nd yr Modern physics course (very selective and demanding, N=67)

bottom 1/4 **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:

- **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.

- 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><strong>10% after 15 minutes</strong> ⇒ &gt;90 % after 2 days</td>
<td></td>
</tr>
<tr>
<td>Fraction of concepts mastered in course</td>
<td></td>
</tr>
<tr>
<td>15-25% ⇒ 50-70% with retention</td>
<td></td>
</tr>
<tr>
<td>Perceptions of science—what it is, how to learn,</td>
<td></td>
</tr>
<tr>
<td><strong>significantly less</strong> (5-10%) <em>like physicist</em> ⇒5-10% more like physicist</td>
<td></td>
</tr>
</tbody>
</table>
**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](http://www.cwsei.ubc.ca)
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