A scientific approach to learning and teaching

Carl Wieman
Assoc. Director for Science
OSTP

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

Scientifically literate public

Modern economy built on S & T

Future scientists and engineers

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

College science classroom studies

brain research

Cognitive psychology
Research on learning complex tasks 
(e.g. expertise in math, science, ...)

old view, current teaching
knowledge
soaks in, variable

new view
brain plastic
transform via suitable “exercise”
Outline

I. What is the learning we want? ("thinking like a scientist/expert")
   How to measure? How to learn?

II. Data from classrooms-- comparisons of instructional approaches, examples of data.

III. What every teacher should know.

IIII. Example of classroom implementation of effective science teaching. Useful technology.
Expert competence research*
historians, scientists, chess players, doctors,...

Expert competence =
• factual knowledge
• **Mental organizational framework** ⇒ 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

*Cambridge Handbook on Expertise and Expert Performance
Significantly changing the brain, not just adding bits of knowledge.

Building proteins, growing neurons ⇒ enhance neuron connections, ...
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
Connecting with the Science Classroom

Learning to think like expert-- conceptual mastery
Measuring conceptual mastery

- Force Concept Inventory- basic concepts of force and motion in 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

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

**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)  
*predictions?*
Histogram of exam scores

Average: 41 ± 1% for standard lecture
Average: 74 ± 1% for experiment

Clear improvement for entire student population.
Effect size = 2.5

differences in failure rates...
<table>
<thead>
<tr>
<th>Results</th>
<th>control</th>
<th>experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Attendance</td>
<td>53(3)%</td>
<td>75(5)%</td>
</tr>
<tr>
<td>2. Engagement</td>
<td>45(5)%</td>
<td>85(5)%</td>
</tr>
</tbody>
</table>
"noncognitive" expert thinking

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.


Widely applicable.

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—best predictor of who will end up physics major 4 years later
What 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.
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.
Implementation of all these principles in the science classroom (aided by technology).

As in Deslauriers, Schewlew, Wieman, Science paper.
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!)
6. Small group tasks. *Explain, test, find analogy, solve, give criteria for choosing solution technique, ...*
Each student write down, hand 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 to guide thinking.
Responding to (many!) student questions.

Requires much more subject expertise. Fun!
Summary:
Many aspects not new.
New-- the quality of the data, and understanding why.

Implementing research-based principles and practices ⇒ dramatic improvements in learning for all students.

copies of slides (+30 extras) available

Good Refs.:
NAS Press “How people learn”
Colvin, “Talent is over-rated”
Redish, “Teaching Physics”
Wieman, Change Magazine-Oct. 07
at www.carnegiefoundation.org/change/
simulations at phet.colorado.edu
cwsei.ubc.ca-- resources, references, effective clicker use booklet and videos
~ 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.
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.”

“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
Student Perceptions/Beliefs

Kathy Perkins, M. Gratny

Percent of Students

CLASS Overall Score

(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)
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
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
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, 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>
</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>
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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

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

new $+$ Emphasize process (modeling) $\rightarrow$ $+10\%$ !!
Retention curves measured in Bus’s Sch’l course. UBC physics data on factual material, also rapid drop but pedagogy dependent. (in prog.)

<table>
<thead>
<tr>
<th>Retention interval (Months after course over)</th>
<th>Concept Survey Score (%)</th>
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<tbody>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
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<tr>
<td>10</td>
<td>80</td>
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<tr>
<td>15</td>
<td>70</td>
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<tr>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>30</td>
<td>50</td>
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**transformed** $\Delta = -3.4 \pm 2.2\%$

**award-winning** $\Delta = -2.3 \pm 2.7\%$

**traditional** $\Delta = -3.4 \pm 2.2\%$
Highly Interactive educational simulations--
phet.colorado.edu ~85 simulations physics + 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

<table>
<thead>
<tr>
<th></th>
<th>Number of Solutions</th>
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<tbody>
<tr>
<td>Control</td>
<td></td>
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<tr>
<td>Structured Problems (tutorial)</td>
<td></td>
</tr>
<tr>
<td>Inventions (Outside of Lecture)</td>
<td></td>
</tr>
<tr>
<td>Inventions (During Lecture)</td>
<td></td>
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Average Time to First Solution Thread

![Bar chart showing average time to first solution thread for different conditions: Control, SPSA (Outside of Lecture), IA (Outside of Lecture), and IA (During Lecture). The chart indicates that Control had the longest average time, followed by SPSA (Outside of Lecture), IA (Outside of Lecture), and finally IA (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.
The figure shows a scatter plot comparing Midterm 1 scores to Midterm 2 scores. The data points are categorized into three groups based on intervention type:

- Diamonds represent students with no intervention.
- Black dots represent students who received email only.
- Black squares represent students who received email and a meeting.

The plot indicates a trend where students who received interventions (email only or email & meeting) tended to have higher scores on both midterms compared to those without intervention. The trend line suggests a positive correlation between the two scores.
• 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:

- **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>
</tr>
</thead>
<tbody>
<tr>
<td>traditional lecture method</td>
<td></td>
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<tr>
<td>Retention of information from lecture</td>
<td></td>
</tr>
<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>
</tr>
<tr>
<td>15-25% $\Rightarrow$ 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>significantly less (5-10%) like physicist</td>
<td>5-10% more like physicist</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*
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