Taking a scientific approach to Science and engineering education*

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

and most other subjects

copies of slides to be available

*based on the research of many people, some from my science ed research group
How I used to teach.
Figure out subject, then tell students

????????????????????????????????????????

my enlightenment
(~ 30 years ago)

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 and teaching
• got me started doing physics/sci education research--not tradition & opinion, controlled experiments & data!
Learning in class. Two nearly identical UBC 250 student sections intro physics—same test (right after 3 lectures).

Experienced highly rated traditional lecturer versus

Recent physics Ph.D. trained in “scientific teaching”

example of what is achievable with scientific approach
Histogram of test scores

- **ave 41 ± 1 %**
- **74 ± 1 %**

experienced highly rated, trad. lect.
using scientific teaching

**experienced highly rated teacher, much less learning??**
Major advances past 1-2 decades ⇒ Bringing together research fields

- University science classroom studies
- Brain research
- Cognitive psychology

Strong arguments for why apply to most fields
I. Exactly what is “thinking like a scientist/expert?”
   Not all become scientists!

Science education goal—
Learn to make better decisions/choices.
Not just memorize facts, procedures, and vocabulary.

II. How is it learned?

III. Examples from applying in university science classrooms and measuring results.

IV. Institutional change.
   How move from folk art to science.
Expert thinking/competence =
- factual knowledge
- **Mental organizational framework** \(\Rightarrow\) retrieval and application

or？

scientific concepts, (& criteria for when apply)

- Ability to monitor own thinking and learning
  
  *(subject specific criteria for checking if result makes sense)*

New ways of thinking—everyone requires MANY hours of intense practice to develop.

Brain changed—rewired, not filled!

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

Challenging but doable tasks/questions

• Practicing specific thinking skills
• Feedback on how to improve

Sci. & Eng. thinking to practice & learn

• concepts and mental models + selection criteria
• does answer/conclusion make sense - ways to test
• moving between specialized representations (graphs, equations, physical motions, etc.)

Knowledge/topics important but only as integrated part with how and when to use.

* “Deliberate Practice”, A. Ericsson research accurate, readable summary in “Talent is over-rated”, by Colvin
Effective teacher—
• Designing suitable practice tasks
• Providing timely guiding feedback
• Motivating
  (“cognitive coach”)

III. How to apply in classroom? *practicing scientist thinking with feedback*

*Example— large intro physics class (similar chem, bio, comp sci, …)*

**Teaching about electric current & voltage**

1. Preclass assignment--Read pages on electric current. Learn basic facts and terminology without wasting class time. Short online quiz to check/reward.

2. Class starts with question:
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=intense thought, primed for learning)

Jane Smith chose a.

4. Discuss with “consensus group”, revote.
Instructor listening in! What aspects of student thinking like physicist, what not?
5. Demonstrate/show result

6. Instructor follow up summary— feedback on which models & which reasoning was correct, & **which incorrect and why**. Many student questions.

Students practicing thinking like physicists-- (applying, testing conceptual models, critiquing reasoning...)

Feedback that improves thinking—other students, informed instructor, demo
Evidence from the Classroom

~ 1000 research studies from undergrad science and engineering comparing traditional lecture with “scientific teaching”.

• consistently show greater learning
• lower failure rates
• benefit all, but at-risk most
• recent results- improves wider participation

a few examples—
various class sizes and subjects
Apply concepts of force & motion like physicist to make predictions in real-world context?

**average trad. Cal Poly instruction**

1\textsuperscript{st} year mechanics

---

Cal Poly, Hoellwarth and Moelter, Am. J. Physics May ‘11

9 instructors, 8 terms, 40 students/section.
Same instructors, better methods = more learning!
same 4 instructors, better methods = 1/3 fail rate
Learning *in the in classroom* *

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

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

**Experiment**-- new physics Ph. D. trained in principles & methods of research-based teaching.

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

*Deslauriers, Schelew, Wieman, Sci. Mag.  May 13, ’11*
Experimental class design

1. Short targeted pre-class readings

2. During class--Questions to solve, respond with clickers or on worksheets, discuss with neighbors. Instructor circulates, listens.

3. Discussion by instructor follows, not precedes. (but still talking ~50% of time)
Clear improvement for entire student population. Engagement 85% vs 45%. Attendance increased.
Biology

Concepts first, jargon second improves understanding

L. Macdonnell, M. Baker, C. Wieman, *Biochemistry and Molecular biology Education*

Biol. jargon, barrier to learning?
“excess cognitive load”

Small change, big effect!

“Concepts first, jargon second improves understanding”

L. Macdonnell, M. Baker, C. Wieman, *Biochemistry and Molecular biology Education*
Recent--Applying same principles and methods to more advanced topics and students—
Advanced courses 2nd - 4th Yr physics
Univ. British Columbia & Stanford

Final Exam Scores (UBC) nearly identical ("isomorphic") problems (highly quantitative and involving transfer)

- practice & feedback 2nd instructor
- practice & feedback, 1st instructor
- 1 standard deviation improvement
- taught by lecture, 1st instructor, 3rd time teaching course

Stanford Outcomes

8 physics courses 2\textsuperscript{nd}-4\textsuperscript{th} year, 7 faculty, ‘15-‘16

- Attendance up from 50-60\% to \sim 95\% for all.
- Covered as much or more content
- Student anonymous comments:
  90\% positive (mostly VERY positive, “All physics courses should be taught this way!”)
  only 4\% negative
- All the faculty greatly preferred to lecturing.

Typical response across \sim 200 faculty at UBC & U. Col.
New way of teaching much more rewarding, never go back.
IV. Institutional change.

Better for students & faculty prefer *(when try)*

*Why these methods not being used universally?*
What universities and departments should do.

Sci. Ed. Init.—UBC & U. Colorado, changed teaching of 200+ sci. courses & faculty. 20,000 cred hrs/yr

Competitive grant program to departments. Supported Science Education Specialists Work with faculty to transform courses and teaching. Provide labor and expertise—

New on Amazon Books
Primary barrier to change—takes \( \sim 50 \) hours to learn to teach in new, better, more enjoyable way

**University incentive system**—Poor evaluation of teaching, does not recognize expertise

\[ \implies \text{Punishes all time away from research} \]
A better way to evaluate undergraduate science teaching
Change Magazine, Jan-Feb. 2015
Carl Wieman

“The Teaching Practices Inventory: A New Tool for Characterizing College and University Teaching in Mathematics and Science”
Carl Wieman* and Sarah Gilbert

(and now engineering & social sciences)

Try yourself. ~ 10 minutes to complete.
http://www.cwsei.ubc.ca/resources/TeachingPracticesInventory.htm

Provides detailed characterization of how course is taught
Extent of use of practices research shows are effective
### Conclusion:

Meaningful science education—
Learn to make decisions/choices, not memorize.

Research providing new insights & data on effective teaching and learning

A scientific approach to teaching greatly improves student learning & faculty enjoyment.

**Good References:**

- S. Ambrose et. al. “How Learning works”
- D. Schwartz et. al. “The ABCs of how we learn”
- Colvin, “Talent is over-rated”
- “Reaching Students” NAS Press (free pdf download)

**cwsei.ubc.ca-- resources** (implementing best teaching methods), references, effective clicker use booklet and videos
~ 30 extras below
Research on Learning

Components of effective teaching/learning—

1. Motivation
   - relevant/useful/interesting to learner
   - sense that can master subject

2. Connect with prior thinking

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

4. Explicit authentic practice of expert thinking

5. Timely & specific feedback on thinking
“Practice-with-feedback/Research-based/ Active learning”

What it is not:
“hands-on”
“experiential”
“flipped classroom”

These may contain the necessary mental practice activities and structure, but frequently do not.
Necessary (and probably sufficient) 1st step - have good way to evaluate teaching quality

Requirements:
• measures what leads to most learning
• equally valid/fair for use in all courses
• actionable-- how to improve, & measures when do
• is practical to use routinely

Student course evaluations fail on all but #4

Better way– thoroughly characterize all the practices and decisions used in teaching a course. Determine extent of use of research-based methods (ones shown to improve learning).

Better proxy for what matters

“A better way to evaluate undergraduate science teaching”
Change Magazine, Jan-Feb. 2015, Carl Wieman
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)
2 simple immediately applicable findings from research on learning. Apply in every course.

1. expertise and homework design

2. reducing demands on short term memory
Expertise practiced and assessed with typical HW & exam problems.

- 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

Mr Anderson, May I be excused? My brain is full.

slides to be provided
A scientific approach to teaching

Improve student learning & faculty enjoyment of teaching

**My ongoing research:**
1. Bringing “invention activities” into courses—students try to solve problem first. **Cannot** but prepares them to learn.

2. Making intro physics labs more effective. (our studies show they are not. Holmes & Wieman, Amer. J. Physics)

Lesson from these Stanford courses—

**Not hard for typical instructor to switch to active learning and get good results**

- read some references & background material (like research!)
- fine to do incrementally, start with pieces
No Prepared Lecture

**Actions**

### Preparation
- **Students**: Complete targeted reading
- **Instructors**: Formulate/review activities

### Introduction (2-3 min)
- **Students**: Listen/ask questions on reading
- **Instructors**: Introduce goals of the day

### Activity (10-15 min)
- **Students**: Group work on activities
- **Instructors**: Circulate in class, answer questions & assess students

### Feedback (5-10 min)
- **Students**: Listen/ask questions, provide solutions & reasoning when called on
- **Instructors**: Facilitate class discussion, provide feedback to class
Lecture Notes Converted to Activities

3) Consider this optical setup

Laser with tunable frequency

3a) Explain what this second expression means:
3b) What is the meaning of the terms $U_n$ and $U_{n+1}$?
3c) What is $U_0$ in terms of $r_1$, $r_2$, $t_1$, and $U_{\text{laser}}$?
3d) What is $r$ in terms of $r_1$ and $r_2$?
3e) Suppose there was a loss inducing optical element inside the cavity with a field transmission coefficient of $t_{\text{loss}}$. What would $r$ be in terms of $t_{\text{loss}}$, $r_1$, and $r_2$? What if $t_{\text{loss}}$ were complex?
3f) What is the effect of changing the index of refraction of the material between the mirrors? Is this equivalent to changing the distance between the mirrors? Why or why not?
3g) Evaluate the infinite sum for the field and derive an expression for the intensity.

Often added bonus activity to keep advanced students engaged
Pre-class Reading

Purpose: Prepare students for in-class activities; move learning of less complex material out of classroom
Spend class time on more challenging material, with Prof giving guidance & feedback

Can get >80% of students to do pre-reading if:
• Online or quick in-class quizzes for marks (tangible reward)
• Must be targeted and specific: students have limited time
• DO NOT repeat material in class!

Stanford Active Learning Physics courses (all new in 2015-16)

### 2nd-4th year physics courses, 6 Profs

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Instructor</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYS 70</td>
<td>Modern Physics</td>
<td>Wieman</td>
<td>Aut 2015</td>
</tr>
<tr>
<td>PHYS 120</td>
<td>E&amp;M I</td>
<td>Church</td>
<td>Win 2016</td>
</tr>
<tr>
<td>PHYS 121</td>
<td>E&amp;M II</td>
<td>Hogan</td>
<td>Spr 2016</td>
</tr>
<tr>
<td>PHYS 130</td>
<td>Quantum I</td>
<td>Burchat</td>
<td>Win 2016</td>
</tr>
<tr>
<td>PHYS 131</td>
<td>Quantum II</td>
<td>Hartnoll</td>
<td>Spr 2016</td>
</tr>
<tr>
<td>PHYS 110</td>
<td>Adv Mechanics</td>
<td>Hartnoll</td>
<td>Aut 2015</td>
</tr>
<tr>
<td>PHYS 170</td>
<td>Stat Mech</td>
<td>Schleier-Smith</td>
<td>Aut 2015</td>
</tr>
</tbody>
</table>
Math classes—similar design

Other types of questions---
• What is next (or missing) step(s) in proof?
• What is justification for (or fallacy in) this step?
• Which type of proof is likely to be best, and why?
• Is there a shorter/simpler/better solution? Criteria?
Reducing demands on working memory in class

- Targeted pre-class reading with short online quiz
- Eliminate non-essential jargon and information
- Explicitly connect
- Make lecture organization explicit.
Perceptions about science

**Novice**

Content: isolated pieces of information to be memorized.

Handed down by an authority. Unrelated to world.

Problem solving: following memorized recipes.

**Expert**

Content: coherent structure of concepts.

Describes nature, established by experiment.


*adapted from D. Hammer

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

best predictor of physics major

*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
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
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)

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
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
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
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.
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.
Measuring conceptual mastery

- Force Concept Inventory - basic concepts of force and motion

Apply like physicist in simple real world applications?

Test at start and end of the semester --
What % learned? (100’s of courses/yr)

On average learn <30% of concepts did not already know.
Lecturer quality, class size, institution,...doesn't matter!

R. Hake, "...A six-thousand-student survey…” AJP 66, 64-74 (‘98).
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*
Retention curves measured in Bus’s Sch’l course. UBC physics data on factual material, also rapid drop but pedagogy dependent. (in prog.)

- **transformed**: $\Delta = -3.4 \pm 2.2\%$
- **award-winning**: $\Delta = -2.3 \pm 2.7\%$
- **traditional**: $\Delta = -2.3 \pm 2.7\%$

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

II
Very experienced highly rated instructor--trad. lecture
wk 1-11

very well measured--identical

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, Schewlewe, submitted for pub)

I

Experienced highly rated instructor -- trad. lecture

wk 1-11

identical on everything diagnostics, midterms, attendance, engagement

Wk 12 -- competition

I

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>
<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>
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)
Reducing unnecessary demands on working memory improves learning.

jargon, use figures, analogies, pre-class reading
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. ...
Deliberate Practice of desired expert thinking

Learning goals: including metacog knowledge org

Practice Tasks: expert decision making prob solving processes and procedures, knowledge organization, planning and checking

Guiding Feedback: Important features: timely, specific, why incorrect wrong, ...

Enablers of D. P.
- Motivation
  - Self efficacy
    - belief can learn subject
    - know how to learn it
    - see are learning interest & value
  - sense of belonging & supportive ed environ
- Prior Knowledge and Experiences
  - expert-novice differences difficult ideaa
- Brain science
  - working memory
    - cognitive load
    - optimizing use
  - long term memory
    - connecting with
    - spaced, interleaved, repeated practice

Time (on task)
- optimize use
- essential & guides design

Metacognition
- guides design
- connects with & builds on

Group work/ collab learning
- supports
- provider