Science Education for the 21st Century

Using the insights of science to teach/learn science

and most other subjects

Carl Wieman  UBC & CU

Nobel Prize

Data!!

Colorado physics & chem education research group:
The Vision

Guided by research on learning All students much better educated. ⇒ many benefits to society.

Scientifically literate public

Modern economy

Teaching more effective and more efficient and rewarding for the teacher.
How to achieve?

I. 2 models for teaching.

II. Research on science learning
   a. Components of scientific expertise
   b. Measuring development of expertise
   c. Effective teaching and learning
Science teaching Model 1  (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
Model 1 (*figure out and tell*) Strengths & Weaknesses
Works well for basic knowledge, prepared brain:

- **bad, avoid**
- **good, seek**

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

See problems if learning:
- involves complex analysis or judgment
- organize large amount of information
- ability to learn new information and apply

*Complex learning-- different.*
Significantly changing the brain, not just adding bits of knowledge.

Growing neurons & building proteins ⇒ enhance neuron connections, ...

How to teach and measure this complex learning?
Science teaching Model 2.

Goals. What students will be able to do.
(solve, design, analyze, capacity to learn,...)

Create activities and feedback targeting desired expertise.

Use, and measure results.

Prior research

Prior research

yes

no

why?

goals unrealistic

wrong treatment

modify

done
Is model for **doing** science

**Goals. Question to be answered. What data will answer it.**

**Design and build experiment.**

**Run and measure results.**

- yes: done
- no:
  - goals unrealistic
  - why?
  - wrong experiment
  - modify

prior research
Model 2 -- scientific approach to science education

- Goals. What students will be able to do. (solve, design, analyze, learn,...)
- Create activities and feedback targeting desired expertise.
- Run and measure results.

Prior research

- yes → done
- no
  - why?
  - goals unrealistic
  - wrong treatment

⇒ New opportunities for improving teaching.
Major advances past 1-2 decades
Consistent picture \(\Rightarrow\) Achieving learning
### Some Data (science from classrooms):

<table>
<thead>
<tr>
<th>Model 1 (telling)</th>
<th>scientific teaching</th>
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<td>traditional lecture method</td>
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- Retention of information from lecture
  - **10% after 15 minutes** ⇒ **>90% after 2 days**
- Fraction of concepts mastered in course
  - **15-25%** ⇒ **50-70% with retention**
- Perceptions of science—what it is, how to learn, **significantly less** (5-10%) like scientist ⇒ more like scientist

improves for future nonscientists and scientists
Model 2-- scientific approach

What has been learned?

1. Identifying components of expertise, and how expertise developed.

2. How to measure components of science expertise. *(and what traditional exams have been missing)*

3. Components of effective teaching and learning.
Developing expertise-- transforming brain

Think about and use science like a scientist.

What does that mean? How is it accomplished?
Expert competence research*

historians, scientists, chess players, doctors,...

Expert competence =
• factual knowledge

• **Organizational framework** ⇒ effective retrieval and application

or ?

• Ability to monitor own thinking and learning
(“Do I understand this? How can I check?”)

New ways of thinking—require **MANY** hours of intense practice with guidance/reflection. Change brain “wiring”

*Cambridge Handbook on Expertise and Expert Performance*
Measuring conceptual mastery

- Force Concept Inventory - basic concepts of force and motion 1st semester physics

Ask at start and end of semester -- What % learned? (100's of courses)

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).
• Experts in science also have unique “belief” systems

<table>
<thead>
<tr>
<th><strong>Novice</strong></th>
<th><strong>Expert</strong></th>
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<tr>
<td><strong>Content:</strong> isolated pieces of information to be memorized.</td>
<td><strong>Content:</strong> coherent structure of concepts.</td>
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<td>Handed down by an authority. Unrelated to world.</td>
<td>Describes nature, established by experiment.</td>
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*adapted from D. Hammer
Measuring student beliefs about science

Novice  Expert

Survey instruments--
MPEX--1st yr physics, CLASS--physics, chem, bio tests

~40 statements, strongly agree to strongly disagree--

*adapted from D. Hammer

Understanding physics basically means being able to recall something you've read or been shown.

I do not expect physics equations to help my understanding of the ideas; they are just for doing calculations.

5-10% shift?

intro physics ⇒ more novice

ref.s Redish et al, CU work--Adams, Perkins, MD, NF, SP, CW

Intro Chemistry and biology just as bad!

*adapted from D. Hammer
Model 2-- scientific approach

What has been learned?

1. Identifying components of expertise, and how expertise developed.

2. How to measure components of science expertise. *(and what traditional exams have been missing)*

⇒ 3. Components of effective teaching and learning.
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

4. Explicit authentic practice of expert thinking. Extended & strenuous
   *(brain development like muscle development)*
Motivation-- essential
(complex- depends on previous experiences, ...)
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)

4. Explicit authentic practice of expert thinking. Extended & strenuous
   (brain development like muscle development)
Mr Anderson, May I be excused? My brain is full.

**Limits on working memory**—best established, most ignored result from cognitive science

Working memory capacity **VERY LIMITED!**

*(remember & process <7 distinct new items)*

**MUCH less than in typical science lecture**
⇒ processing and retention from lecture tiny
(for novice)

...many examples from research:

**Wieman and Perkins** - test 15 minutes after told
nonobvious fact in lecture.
10% remember

*Also true in technical talks!*
Reducing unnecessary demands on working memory improves learning.

- jargon, use figures, analogies
“Curse of knowledge” common teaching mistake

step 1-- teach all the pieces of background knowledge and math procedures.
step 2-- give problem and show how pieces are put together to solve.

Makes sense only if already know subject! For student, pieces are disconnected facts to memorize. Requires lots of working memory and is boring.

Better Approach:
step 1-- present interesting problem
step 2-- bring in facts and procedures as steps to solve. Builds expert connections and mental framework. Reduces working memory & more motivating.
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

4. **Explicit authentic practice of expert thinking. Extended & strenuous**
   *brain development like muscle development*
Practicing expert-like thinking--

**Challenging but doable tasks/questions**

Explicit focus on expert-like thinking
- concepts and mental models
- recognizing relevant & irrelevant information
- self-checking, sense making, & reflection

Teacher provide effective feedback (timely and specific)

Research shows time and effort not enough-- need to know what and how to practice.
Do not know if not expert.
Good teacher is “cognitive coach”. Like sports coach.
How to actually do in class?
Hundreds of students???

a) proven practices from research

b) use technology to help

Example from a class--practicing expert thinking with effective guidance/feedback

1. Assignment--Read chapter on electric current. Learn basic facts and terminology. Short quiz to check/reward.

2. Class built around series of questions.
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!)
Do “experiment.”-- simulation.
Follow up instructor discussion--
review correct and incorrect thinking, extend ideas.
Respond to student questions & suggestions.

*(additional student learning)*
How practicing expert thinking--

Challenging but doable question
(*difficult concept, prior thinking*)

Explicit focus on expert-like thinking
  • actively developing concepts and mental models
  • recognizing relevant & irrelevant information
  • self-checking, sense making, & reflection

Getting timely and specific feedback
(peers, clicker histogram, instructor)

Highly engaged-- “exercising” brain in optimum way
good start, but not enough time in class!

further practice-- well designed homework
Require expert thinking & feedback,

⇒ long term retention

Same approach and improved results
physics for poets..... science graduate students

same learning principles apply
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improves for future nonscientists and scientists
How to get into every classroom?
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
**Summary:**
Scientific model for science education

Much more effective. (and more fun)

**Good Refs.:**
NAS Press “How people learn”
Handelsman, et al. “Scientific Teaching”
Wieman, Change Magazine-Oct. 07
at [www.carnegiefoundation.org/change/](http://www.carnegiefoundation.org/change/)

CLASS belief survey: CLASS.colorado.edu
phet simulations: phet.colorado.edu
cwsei.ubc.ca-- resources,   *Guide to effective use of clickers*
extra unused slides below
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
IV. Institutionalizing improved research-based teaching practices. *(From bloodletting to antibiotics)*

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
Electricity & Magnetism concepts

Consumer behavior class

~1/2 1/4 yr later, below 0.2 after 2 yrs

1.5 yrs later
Highly Interactive educational simulations--
phet.colorado.edu  ~80 simulations physics & chem
FREE, Run through regular browser

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

balloons and sweater  laser
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
Implications for instruction

Student beliefs about science and science problem solving important!

- Beliefs ↔ content learning
- Beliefs -- powerful filter → choice of major & retention
- Teaching practices → students’ beliefs
  typical significant decline (phys and chem)
  (and less interest)

Avoid decline if explicitly address beliefs.

Why is this worth learning?
How does it connect to real world?
How connects to things student knows/makes sense?
Data 2. Conceptual understanding in traditional course

**electricity**

Eric Mazur (Harvard Univ.)

End of course. 70% can calculate currents and voltages in this circuit.

only 40% correctly predict change in brightness of bulbs when switch closed!