Using research to improve university science teaching

and most other subjects

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25 years ago—"Why grad students can do well in courses but not do physics?"

=> my doing research on science teaching

*based on the research of many people, some from my science ed research group
Major advances past few decades ⇒ Bringing together research fields

University science & eng. classroom studies —— cognitive psychology —— brain research

today

Strong arguments for why apply to most fields
Science education goal—
Learn to make better decisions (like scientist)

I. What is “thinking like a scientist?”

II. How is it learned?

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

IV. Institutional change (widespread adoption of evidence-based teaching—expertise)
Expert thinking/competence =
• factual knowledge
• **Mental organizational framework** $\Rightarrow$ retrieval and application

or ?

• **Ability to monitor own thinking and learning**

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
- evaluation of result- 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")
“Practice-with-feedback/evidence-based/Active learning”

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

These may contain the necessary mental activities and structure, but frequently do not.
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:

Example-- large intro physics class (similar chem, bio, comp sci, ...)

III. How to apply in classroom? practicing thinking with feedback
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
3. 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 more

A few examples—
various class sizes and subjects

Massive meta-analysis all sciences & eng. similar.
PNAS Freeman, et. al. 2014
Apply concepts of force & motion like physicist to make predictions in real-world context?

average trad. Cal Poly instruction

1st 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
UBC 1st year college physics.
270 students each.

**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
mix of conceptual and quantitative problems

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

1. Targeted pre-class readings

2. 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%. 
Advanced courses 2nd -4th Yr physics
Univ. British Columbia & Stanford

Final Exam Scores

nearly identical (“isomorphic”) problems
(highly quantitative and involving transfer)

practice & feedback 2\textsuperscript{nd} instructor

practice & feedback, 1\textsuperscript{st} instructor

1 standard deviation improvement

taught by lecture, 1\textsuperscript{st} instructor, 3rd time teaching course

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Stanford Outcomes

7 physics courses 2nd-4th year, seven faculty, ‘15-’16

- Attendance up from 50-60% to ~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 ~ 250 faculty at UBC & U. Col. New way of teaching much more rewarding, would never go back.
Better for students & faculty prefer \textit{(when try)}

\textbf{How to get widespread adoption?}

\section*{IV. Institutional Change}
\textit{train is starting to move—get on it or be left behind}

\textbf{Calls for changes in university STEM teaching}
\begin{itemize}
\item NAS – DBER report 2012
\item PCAST report 2012
\item Program funding shifts– NSF, HHMI
\item Amer. Assoc. of Univ. (AAU) 2012--
\item Council of Ind. Coll. & Univ. 2017
\item Amer. Acad. Arts & Sci. 2017
\end{itemize}

talking about teaching & need for members to improve !?
A Message from the President (2017)
Mary Sue Coleman, Association of American Universities
“... AAU continues its commitment to achieving widespread systemic change in this area and to promoting excellence in undergraduate education at major research universities.

... We cannot condone poor teaching of introductory STEM courses ... simply because a professor, department and/or institution fails to recognize and accept that there are, in fact, more effective ways to teach. Failing to implement evidence-based teaching practices in the classroom must be viewed as irresponsible, an abrogation of fulfilling our collective mission to ensure that all students who are interested in learning and enrolled in a STEM course. ...."
What universities and departments can do.

Science Education Initiative--Experiment in widespread change in teaching at large research Univ.

Transformed the teaching of ~ 200 science faculty and ~ 150,000 credit hours/year at UBC.
Main lessons from SEI
• Widespread change in teaching at major research universities is possible
• Major barriers to overcome

Many challenges—top 3
1. **Recognize teaching as expertise**...
   *Alchemy to chemistry,*
   *Bloodletting to modern medicine*

2. **University incentive system**
   ("expert" teaching not measured or rewarded)

3. **Departmental organization**
   (needs to be set up to improve, not preserve status quo)
What worked well?

• Competitive large grant program to depts.  
  Generated dept-wide conversations on ed./teaching  
  Groundwork for serious change

• Sci. Ed Specialist in dept.– provide expertise and labor  
  (but need training and support)

• Faculty seeing/experiencing interactive class. Engaged interested students—teaching more fun!
Critical step--
Better evaluation of teaching quality

“A better way to evaluate undergraduate science teaching”
Change Magazine, Jan-Feb. 2015, Carl Wieman

Characterize the practices used in teaching a course, extent of use of research-based methods.
“Teaching Practices Inventory” (5-10 minutes to complete)
http://www.cwsei.ubc.ca/resources/TeachingPracticesInventory.htm

Insensitive to many variables outside instructor’s control
Shows how to improve & measures when do.
(unlike student course evaluations)
Conclusion:

Research providing new insights & data on effective teaching and learning

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

Major changes are starting. Will redefine what it means to be a “good university”.

Good References: slides will be available
S. Ambrose et. al. “How Learning works”
D. Schwartz et. al. “The ABCs of how we learn”
C. Wieman, “Improving how universities teach science”

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—expertise required.

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
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
Transform faculty by supporting them in transforming courses

1st: Decide on learning goals. (what should students be able to do?)

2nd: Better assessment

3rd: Add research-based teaching methods to improve student learning. (technology to improve effectiveness & save time)

faculty supported by departmental educational specialists, expertise both in teaching and in the subject
Impact on teaching by Department - UBC 2016

- % cred hrs changed
- % faculty changed

- EOAS
- PHY-AS
- BIO*
- STATS
- CS
- Math

Lots of success, lots of variation - lessons therein
Jargon bogs down working memory, reduces learning?

Control
preread: textbook

<table>
<thead>
<tr>
<th>DNA structure</th>
<th>Control</th>
<th>jargon-free</th>
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<tbody>
<tr>
<td>Genomes</td>
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Experiment
jargon-free

active learning class

common post-test

“Concepts first, jargon second improves understanding”
L. Macdonnell, M. Baker, C. Wieman, *Biochemistry and Molecular biology Education*

Small change, big effect!
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
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
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
Creating better homework problems--

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.
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.
Reducing unnecessary demands on working memory improves learning.

- jargon, use figures, analogies, pre-class reading
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
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!

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
3) Consider this optical setup

Laser with tunable frequency

\[ U_{\text{laser}} \]

\[ d \]

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) What is the effect of changing the wavelength of the input laser field? Is this equivalent to changing the distance between the mirrors? Why or why not?

Often added bonus activity to keep advanced students engaged
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.


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

*adapted from D. Hammer
Student Perceptions/Beliefs

Kathy Perkins, M. Gratny

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

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

- Actual Majors who were originally intended physics majors
- Survived as Majors who were not originally intended physics majors

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

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

Award-winning
Δ = -3.4 ± 2.2%

Traditional
Δ = -2.3 ± 2.7%

Long term retention
Two sections the same before experiment. (different personalities, same teaching method)

<table>
<thead>
<tr>
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<th>Control Section</th>
<th>Experiment Section</th>
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<tbody>
<tr>
<td><strong>Number of Students enrolled</strong></td>
<td>267</td>
<td>271</td>
</tr>
<tr>
<td><strong>Conceptual mastery (wk 10)</strong></td>
<td>47±1%</td>
<td>47±1%</td>
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<tr>
<td><strong>Mean CLASS (start of term)</strong></td>
<td>63±1%</td>
<td>65±1%</td>
</tr>
<tr>
<td><strong>(Agreement with physicist)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mean Midterm 1 score</strong></td>
<td>59±1%</td>
<td>59±1%</td>
</tr>
<tr>
<td><strong>Mean Midterm 2 score</strong></td>
<td>51±1%</td>
<td>53±1%</td>
</tr>
<tr>
<td><strong>Attendance before</strong></td>
<td>55±3%</td>
<td>57±2%</td>
</tr>
<tr>
<td><strong>Engagement before</strong></td>
<td>45±5%</td>
<td>45±5%</td>
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</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

wk 13 common exam on EM waves

II

Very experienced highly rated instructor--trad. lecture

wk 1-11

elect-mag waves
regular instructor
intently prepared lecture
<table>
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<tr>
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<th>control</th>
<th>experiment</th>
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<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>
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</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”—practicing 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)
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.
“A time for telling” Schwartz and Bransford, Cognition and Instruction (1998)

People learn from telling, but only if well-prepared to learn. Activities that develop knowledge organization structure.

Students analyzed contrasting cases ⇒ recognize key features

<table>
<thead>
<tr>
<th>Condition</th>
<th>Noted in Study Work</th>
<th>Missed in Study Work</th>
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</thead>
<tbody>
<tr>
<td>Analyze + lecture</td>
<td>.60</td>
<td>.26</td>
</tr>
<tr>
<td>Analyze + analyze</td>
<td>.18</td>
<td>.15</td>
</tr>
<tr>
<td>Summarize + lecture</td>
<td>.23</td>
<td>.06</td>
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Predicting results of novel experiment