Taking a scientific approach to Science & Math education*

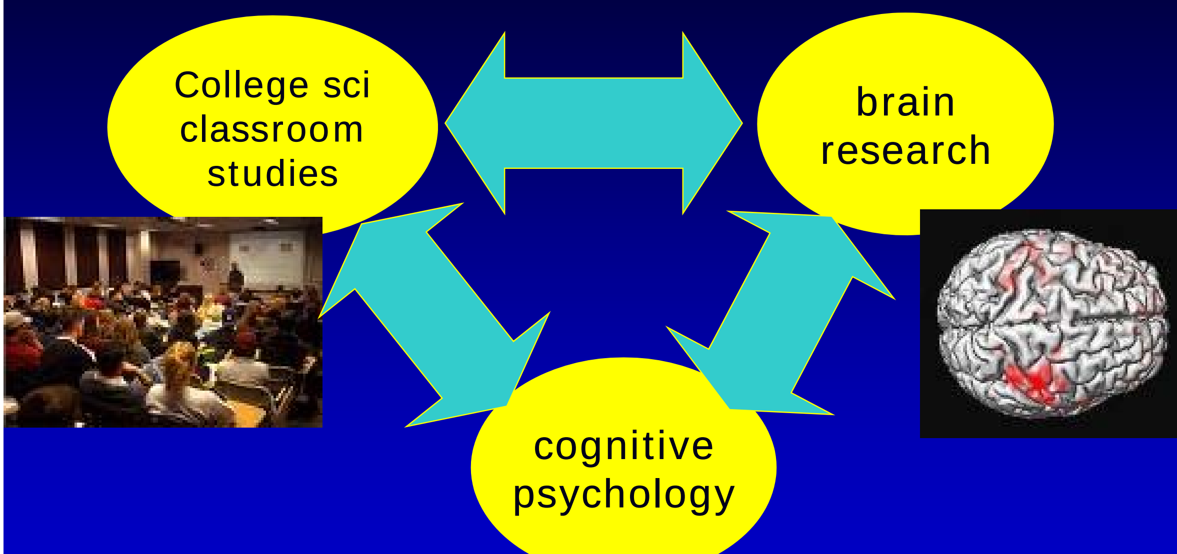
Carl Wieman
Stanford University
Department of Physics and Grad School of Education

Need all students, future scientists or not, to be able to think about science more like scientists.
Successful economy, successful democracy.

What does this mean & how to get there…

*based on the research of many people, some from my science ed research group

Major advances past 1-2 decades
⇒ Guiding principles for achieving learning



Medicine ~150 years ago–
standard treatments-- still tradition & superstition, but biology & scientific treatments known.

example of what is achievable with scientific approach

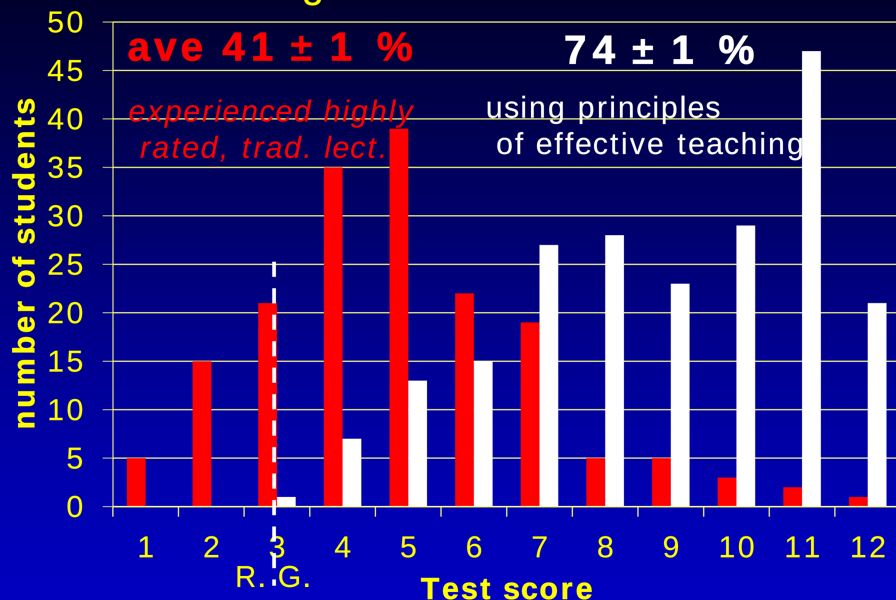
Learning in class. Two nearly identical 250 student sections intro physics—**same learning objectives, same class time, same test** (right after 3 lectures).

Experienced highly rated traditional lecturer (good teacher by current measures)

versus

Postdoc trained in principles and methods of effective teaching

Histogram of test scores



highly rated teacher, same populations, same class time, same test.

What is going on?

I. Exactly what is *"thinking like scientist" (or mathematician)--our educational goal.*

II. How is it learned?

III. Examples from college classroom research

IV. Making effective science teaching and learning the norm

Education approach I used for many years

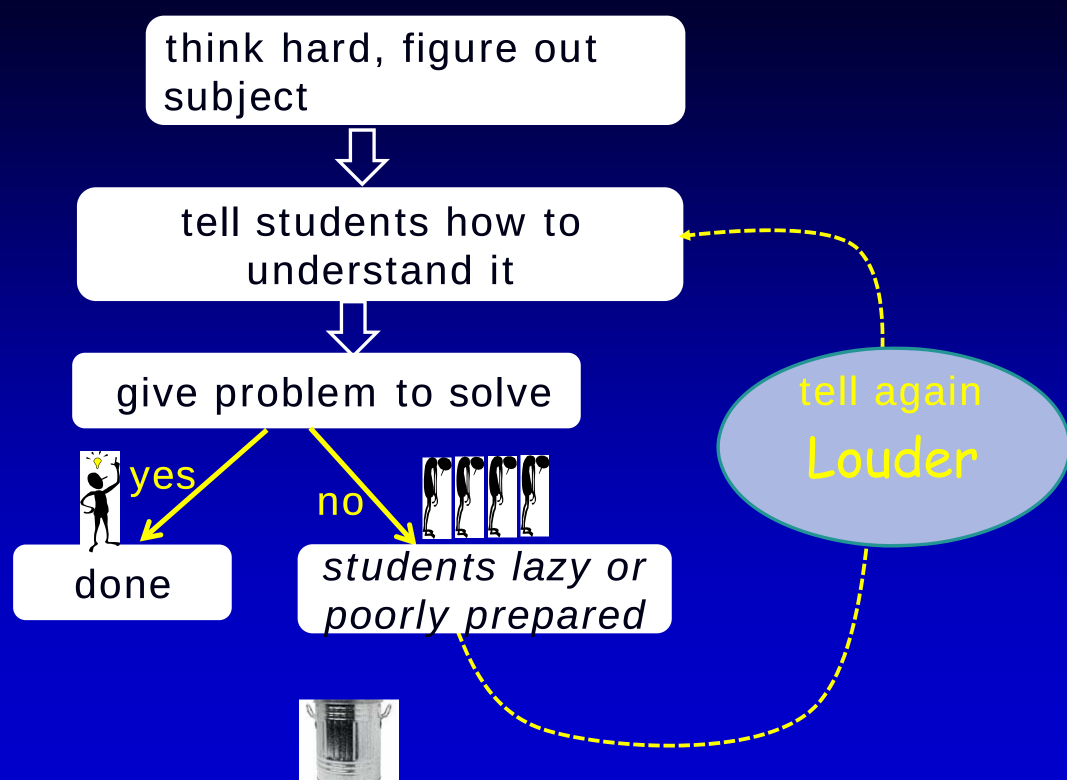
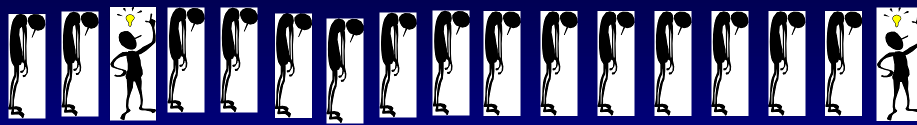


Figure out, then tell students



??

my enlightenment

grad students

Why good in physics classes, not in physics?
Why improve rapidly in lab?

I. Expertise research*

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

Expert competence =

- factual knowledge
- **Mental organizational framework** ⇒ retrieval and application

or ?

patterns, relationships, scientific concepts

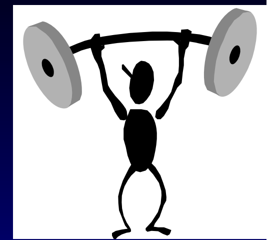
- **Ability to monitor own thinking and learning**
("Do I understand this? How can I check?")

New ways of thinking-- everyone requires MANY hours of intense practice to develop.
Brain changed

*Cambridge Handbook on Expertise and Expert Performance

II. Learning expertise*--

Challenging but doable tasks/questions
Practicing all the elements of expertise with feedback and reflection. Motivation critical!



Requires brain "exercise"

Subject expertise of instructor essential—

- designing practice tasks
  (what is expertise, how to practice, proper level)
- feedback/guidance on learner performance
- why worth learning

* "Deliberate Practice", A. Ericsson research
accurate, readable summary in "Talent is over-rated", by Colvin

Some components of science expertise

- concepts and mental models + selection criteria
- recognizing what information is needed to solve, what irrelevant
- does answer/conclusion make sense- ways to test
- moving between specialized representations
  (graphs, equations, physical motions, etc.)
- ...

Knowledge important, but only as integrated part with how to use.

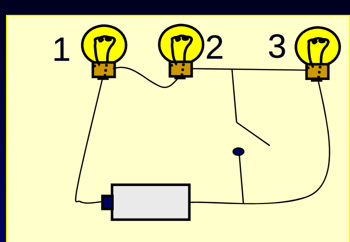
III. How to apply in classroom?
(best opportunity for feedback & student-student learning)
"Expertise-centered classroom"

example– large intro physics class

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.

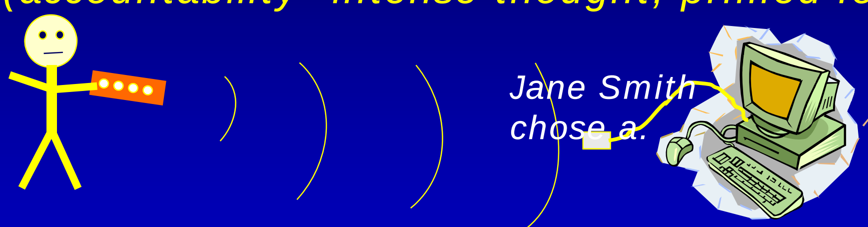
2. Class starts with question:



When switch is closed,
bulb 2 will
a. stay same brightness,
b. get brighter
c. get dimmer,
d. go out.

answer & reasoning

3. Individual answer with clicker
(accountability=intense thought, primed for learning)



4. Discuss with "consensus group", revote.
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 physicist thinking—

feedback that guides thinking—other students, informed instructor, demo

Class just the beginning. Building the same elements into homework and exams equally important.

3. Evidence from the Classroom

~ 1000 research studies from undergrad science
- consistently show greater learning
- lower failure rates
- benefits all, but at-risk most

a few examples—
- learning from course
- failure and drop rates
- learning in classroom

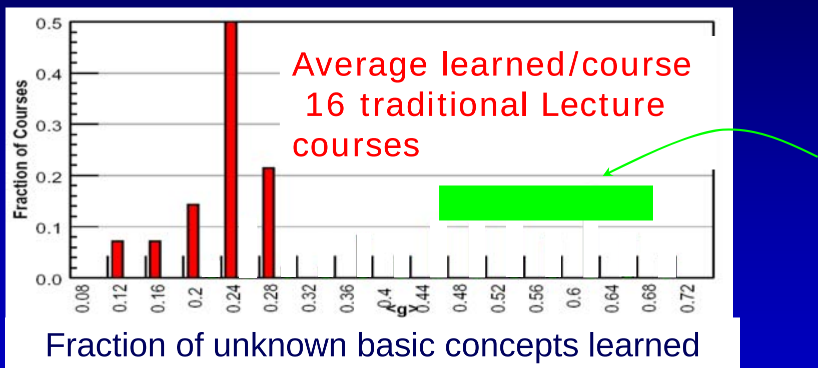
all sciences & eng. similar.
PNAS Freeman, et. al. 2014 massive meta-analysis

Measuring conceptual mastery

• Force Concept Inventory- basic concepts of force and motion

Apply like physicist in simple real world applications?

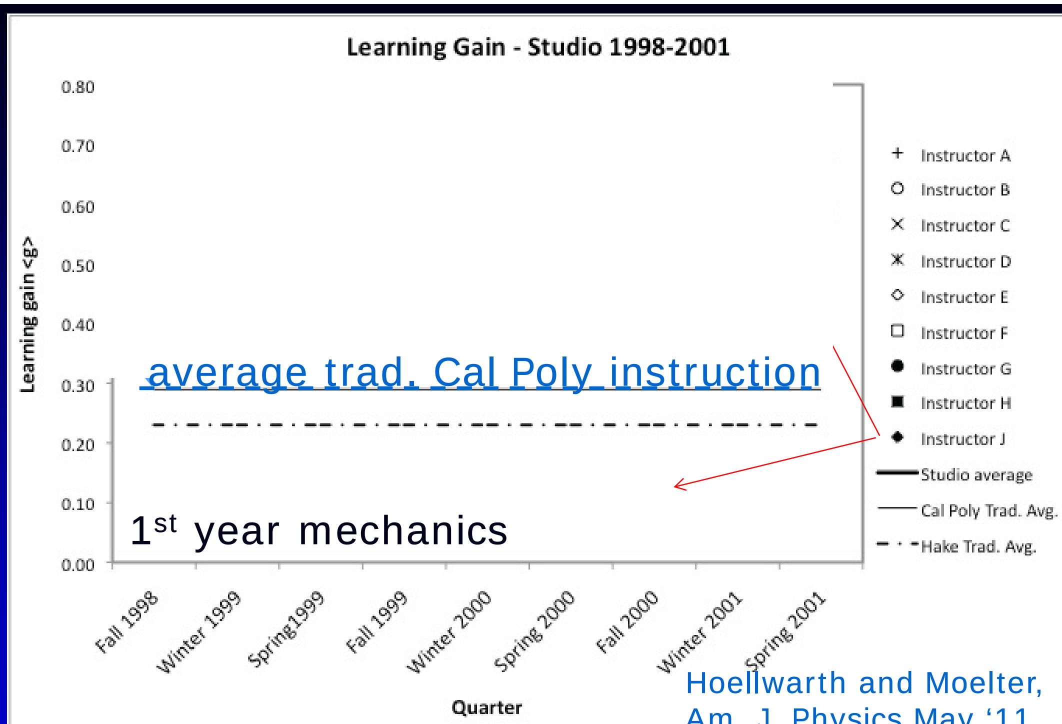
Test at start and end of the semester--
What % learned? (*100's of courses/yr*)



improved methods

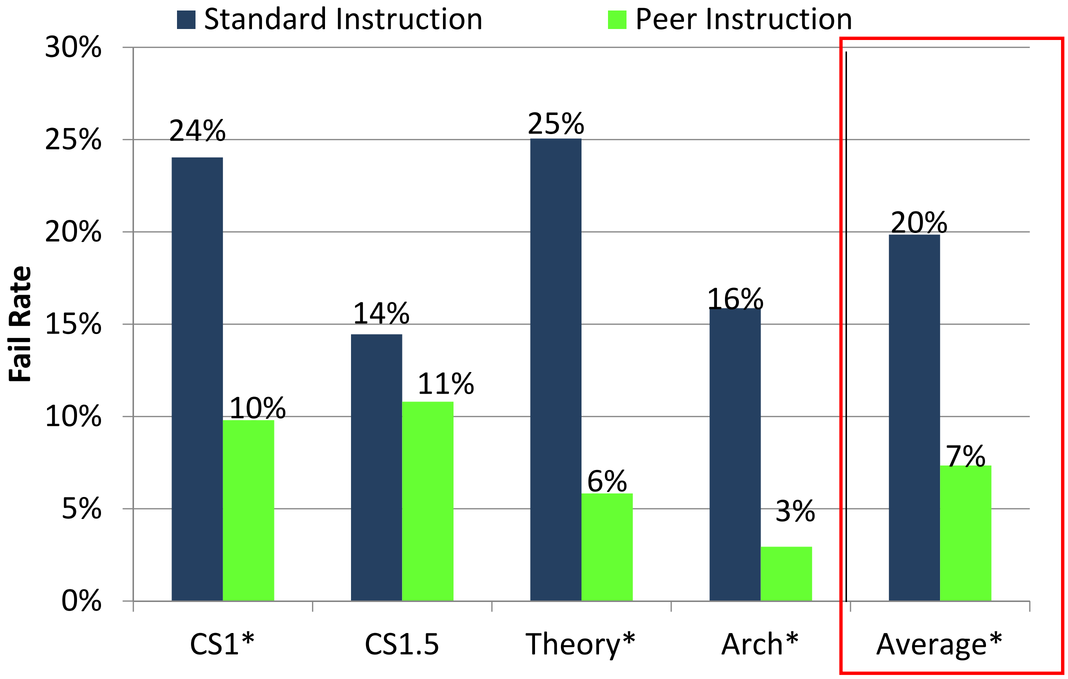
On average learn <30% of concepts did not already know.
Lecturer quality, class size, institution,...doesn't matter!

R. Hake, "…A six-thousand-student survey…" AJP 66, 64-74 ('98).



9 instructors, 8 terms, 40 students/section.
Same instructors, better learning!

U. Cal. San Diego, Computer Science
Failure & drop rates– *Beth Simon et al., 2012*



Learning **in the in classroom***

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

Control--standard lecture class– highly experienced Prof with good student ratings.
Experiment–- physics postdoc trained in principles & methods of effective teaching.

They agreed on:

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

**Deslauriers, Schewlew, Wieman, Sci. Mag. May 13, '11*

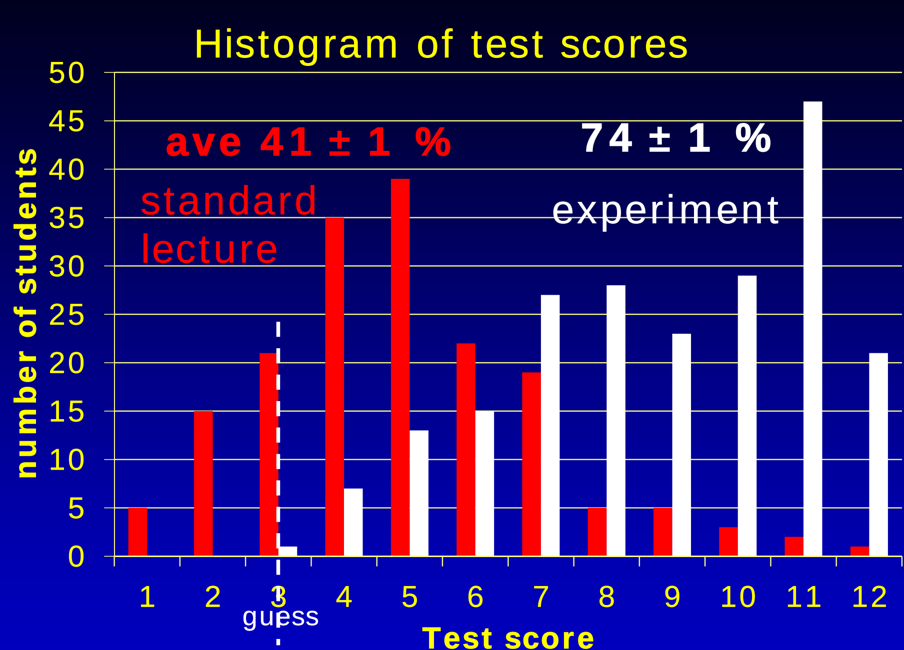
Class design

1. Targeted pre-class readings

2. Questions to solve, respond with clickers or on worksheets, discuss with neighbors

3. Discussion by instructor follows, not precedes. (but still talking ~50% of time)

4. Activities address motivation (relevance) and prior knowledge.



Clear improvement for <u>entire</u> student population.
Engagement 85% vs 45%.

IV. Making effective research-based teaching the norm *(What this university should do.)*

Why demonstrably more effective teaching methods not being widely adopted in Higher Ed. STEM?

Incentives are against at all levels– fac., dept, admin. *Research productivity only thing measured and rewarded. Diverting even small amount of time is bad.*

Necessary (and probably sufficient) 1st step- have good way to evaluate teaching quality

> **"A better way to evaluate undergraduate science teaching"**
> Change Magazine, Jan-Feb. 2015
> Carl Wieman

Discusses criteria for "good", how student evaluations fail

> 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

Tool to fully characterize teaching practices
~10 min or less to complete

CBE—Life Sciences Education
Vol. 13, 552–569, Fall 2014

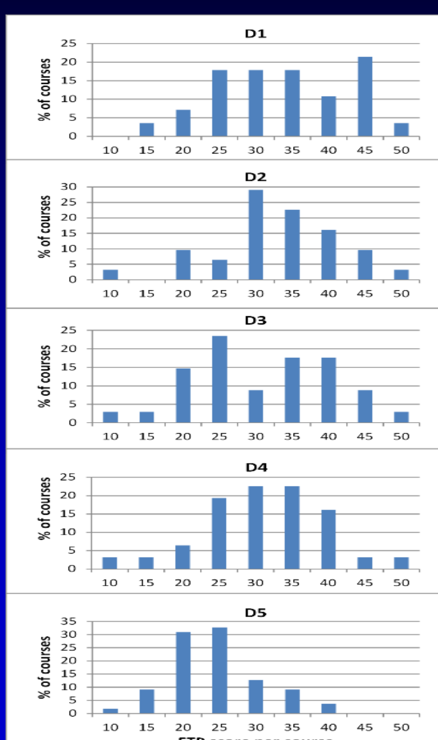
The Teaching Practices Inventory: A New Tool for Characterizing College and University Teaching in Mathematics and Science

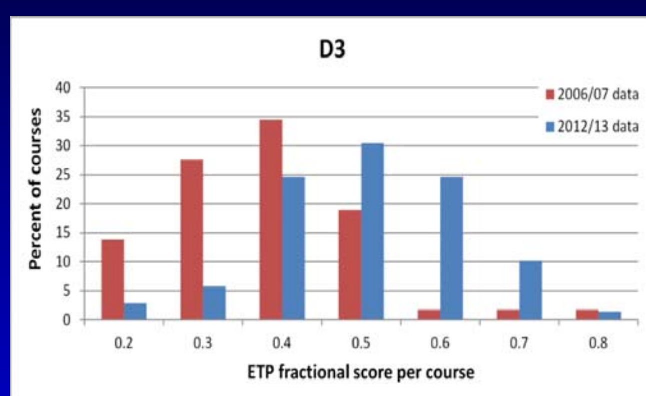
Carl Wieman* and Sarah Gilbert†

Fill out for your course, see how you compare, maybe get some ideas for how to improve

http://www.cwsei.ubc.ca/resources/TeachingPracticesInventory.htm

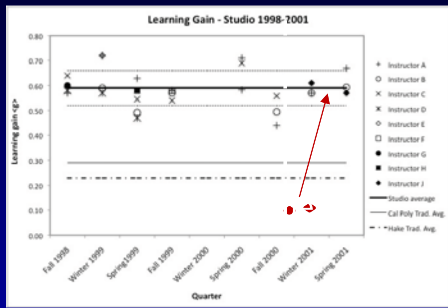
Effective teaching practices, ETP, scores
various math and science departments at UBC

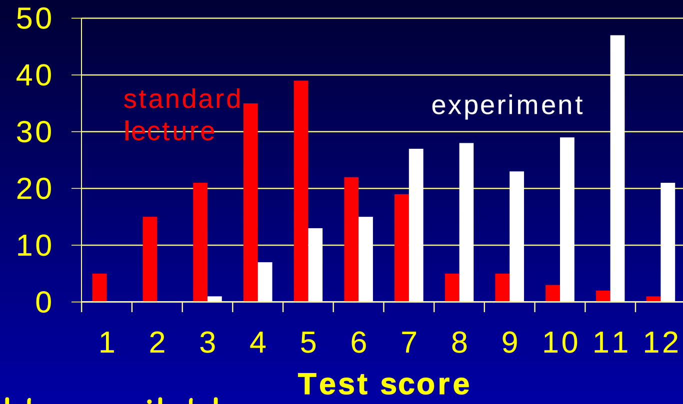




before and after for dept that made serious effort to improve teaching

A scientific approach to Science (Eng) teaching





slides (+30 extras) will be available

Good References:
S. Ambrose et. al. "How Learning works"
Colvin, "Talent is over-rated"

cwsei.ubc.ca-- many resources, references, effective clicker use booklet and videos

~ 30 extras below

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

1. 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

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

Working memory capacity
VERY LIMITED!
(remember & process 5-7 distinct new items)

MUCH less than in typical lecture

slides to be provided

Reducing demands on working memory in class

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

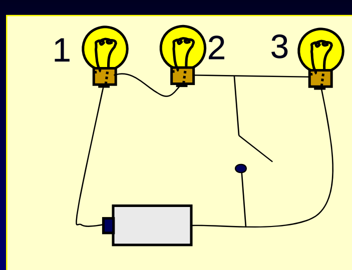
"Concepts first, jargon second improves understanding"
L. Macdonnell, M. Baker, C. Wieman
Biochemistry and Molecular biology Education (in press)

How to apply cog. psych. principles in classroom? *(practicing expert thinking, with feedback)*

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.



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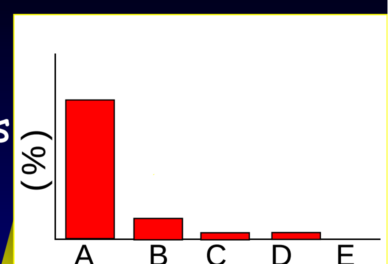
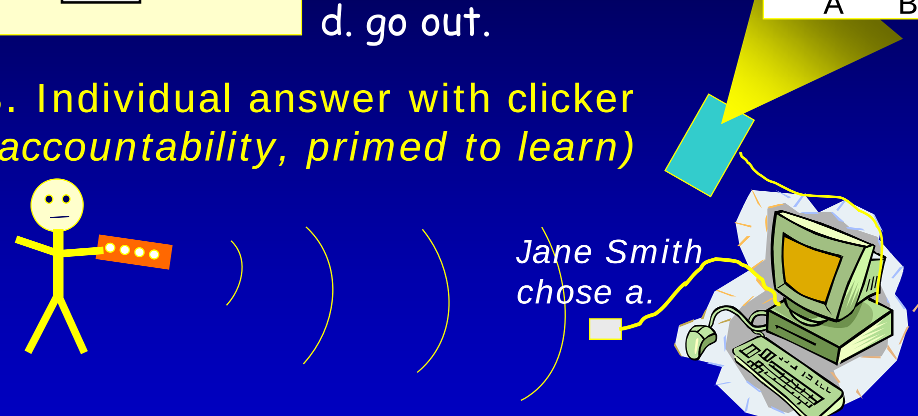


3. Individual answer with clicker *(accountability, primed to learn)*



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, identifying relevant & irrelevant information, ...
- testing reasoning

+getting multiple forms of feedback to refine thinking

Still instructor talking (~ 50%), but **reactive.**

Requires much more subject expertise. Fun!

Perceptions about science

Novice	**Expert**
Content: isolated pieces of information to be memorized.	**Content: coherent structure of concepts.**
Handed down by an authority. Unrelated to world.	**Describes nature, established by experiment.**
Problem solving: following memorized recipes.	**Prob. Solving: Systematic concept-based strategies.**

measure student perceptions, 7 min. survey. Pre-post

best predictor of physics major

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

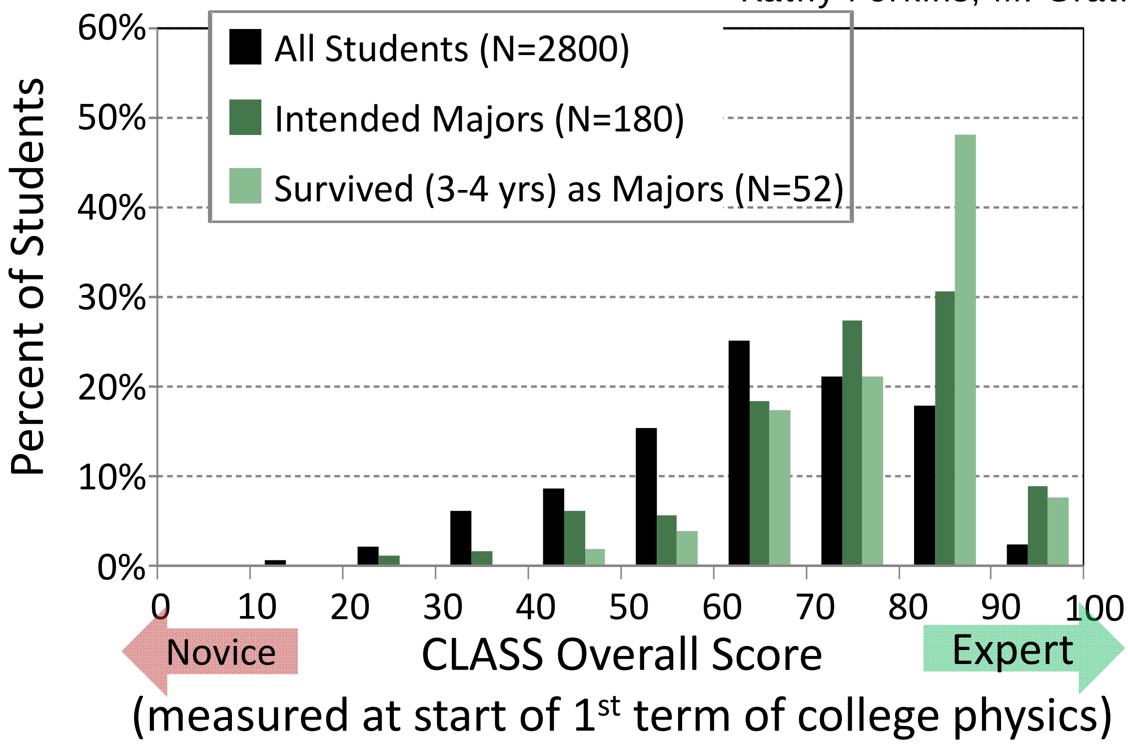
recent research⇒ changes in instruction that achieve positive impacts on perceptions

How to make perceptions significantly more like physicist (very recent)--

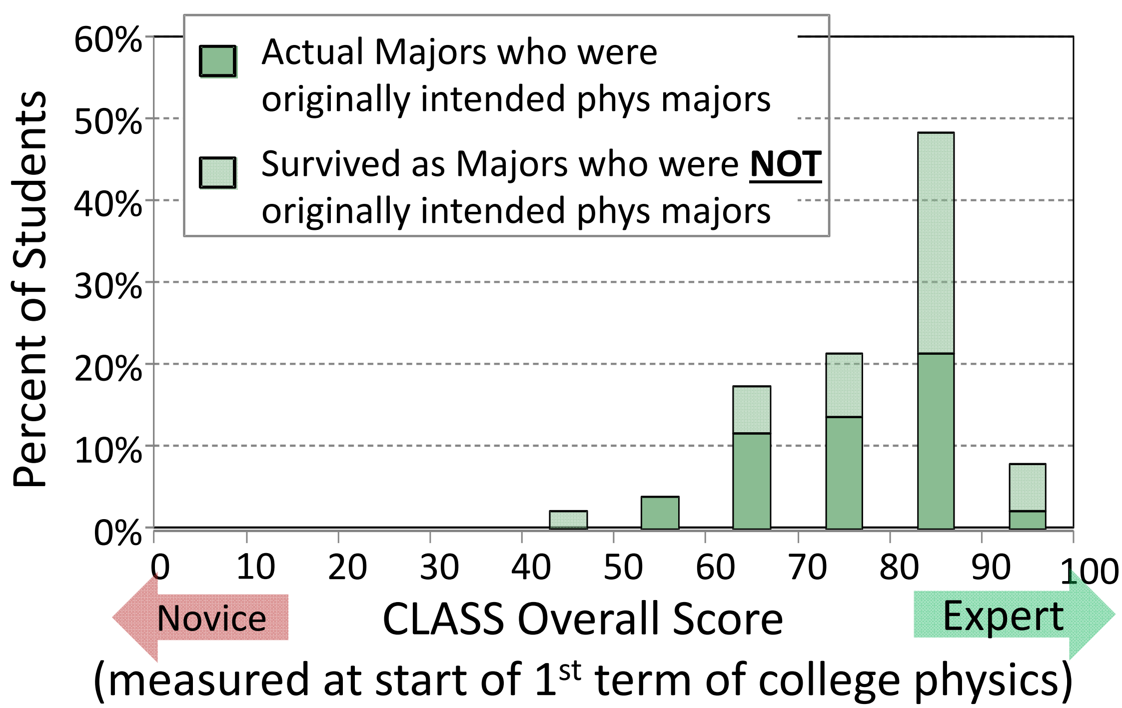
- process of science much more explicit (model development, testing, revision)
- real world connections up front & explicit

Student Perceptions/Beliefs

Kathy Perkins, M. Gratny



Student Beliefs



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)

New paradigm on learning complex tasks
(e.g. science, math, & engineering)

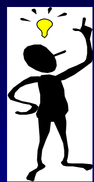
old view, current teaching

knowledge
soaks in, variable

new view

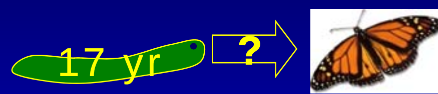
transform via
suitable "exercise"

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
- how to improve classes

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--
  o builds on class
  o explicit practice of all aspects of expertise
  o requires reasonable time
  o reasonable feedback

Components of effective teaching/learning

apply to all levels, all settings

1. Motivation

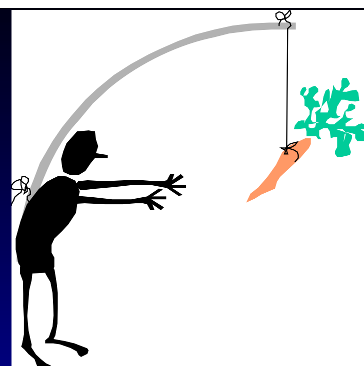
2. Connect with and build on prior thinking

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

Motivation-- essential

(complex- depends on background)



Enhancing motivation to learn

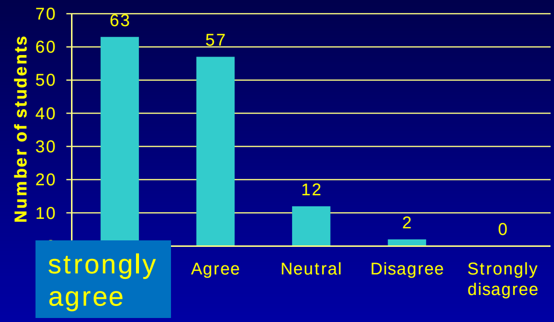
a. Relevant/useful/interesting to learner (**meaningful context-- connect to what they know and value)**
requires expertise in subject

b. Sense that **can** master subject and how to master, recognize they are improving/accomplishing

c. Sense of personal control/choice

Survey of student opinions-- transformed section

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



Not unusual for SEI transformed courses

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 <u>more</u>

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.

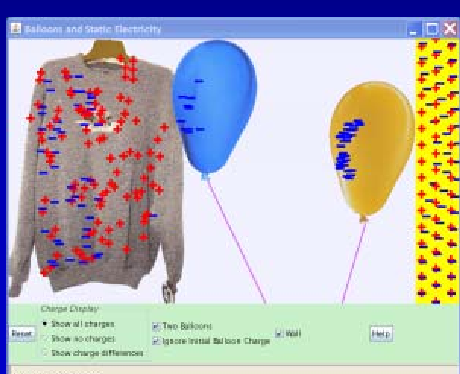
Reduces WM demands– consolidates and organizes. Simple immediate feedback (“what was mitosis?”)

Practice expert thinking. Primes them to learn.

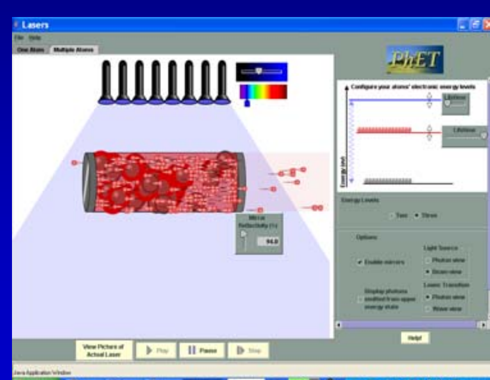
Instructor listen in on discussion. Can understand and guide much better.

<u>Highly Interactive educational simulations</u>--
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

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.

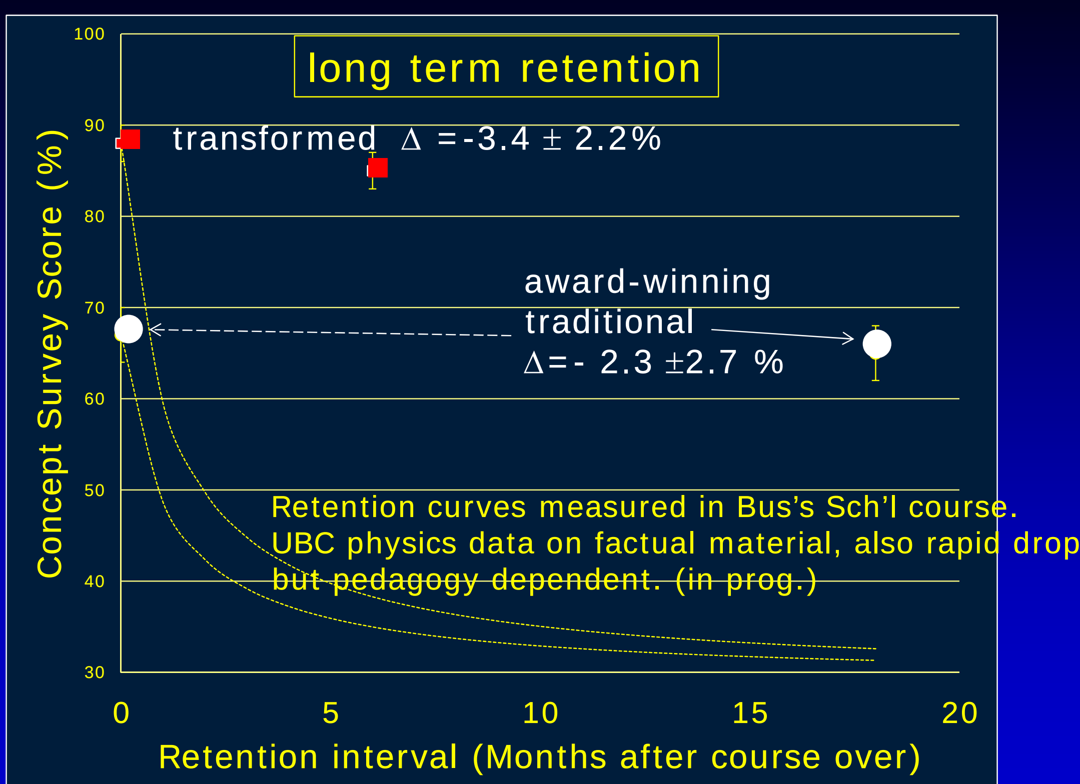
Why **so hard** to give up lecturing?

(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!



Comparison of teaching methods: identical sections (270 each), intro physics. (Deslauriers, Schewlew, submitted for pub)

I
Experienced highly rated instructor-- trad. lecture

II
Very experienced highly rated instructor--trad. lecture

wk 1-11

very well measured--
identical

wk 1-11

Wk 12-- experiment

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

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

Comparison of teaching methods: identical sections (270 each), intro physics. (Deslauriers, Schewlew, submitted for pub)

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

identical on everything diagnostics, midterms, attendance, engagement

Wk 12-- **competition**

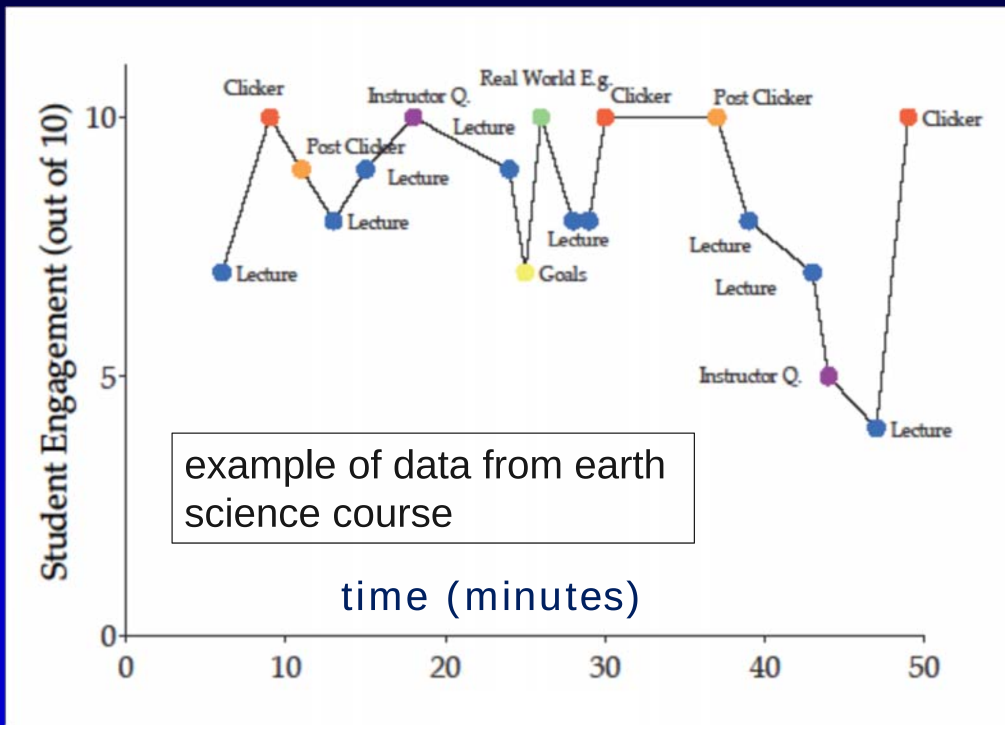
elect-mag waves inexperienced instructor research based teaching	elect-mag waves regular instructor intently prepared lecture

wk 13 common exam on EM waves

	control	experiment
2. Attendance	53(3) %	**75(5)%**
3. Engagement	45(5) %	**85(5)%**

Measuring student (*dis*)engagement. *Erin Lane*

Watch random sample group (10-15 students). Check against list of disengagement behaviors each 2 min.



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.

DP

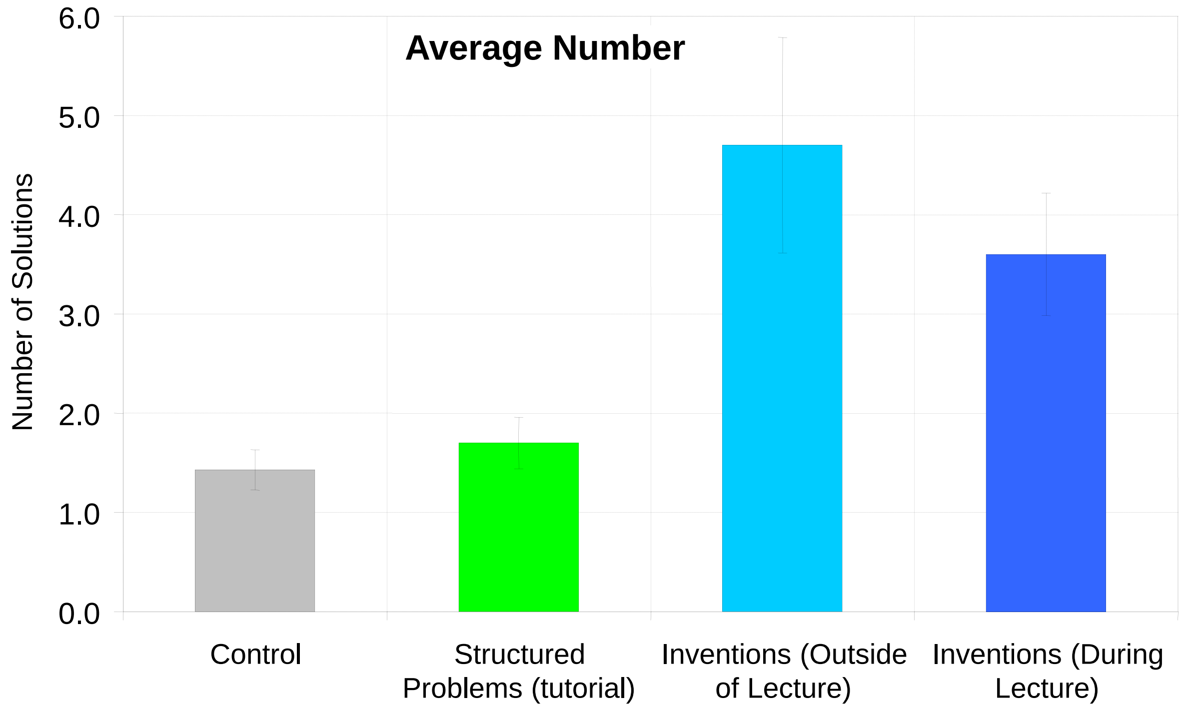
What about learning to think more innovatively?
Learning to solve challenging novel problems

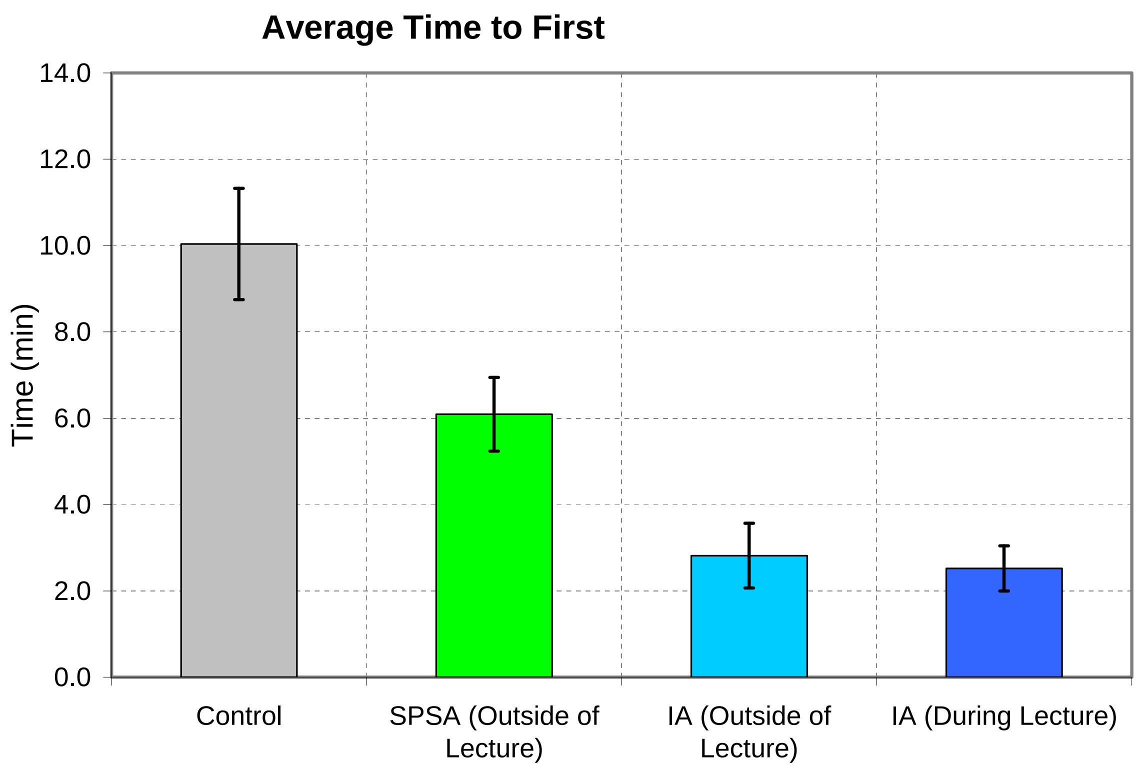
Jared Taylor and George Spiegelman

"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 nev
encountered before





Deslauriers, Lane, Harris, Wieman

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.

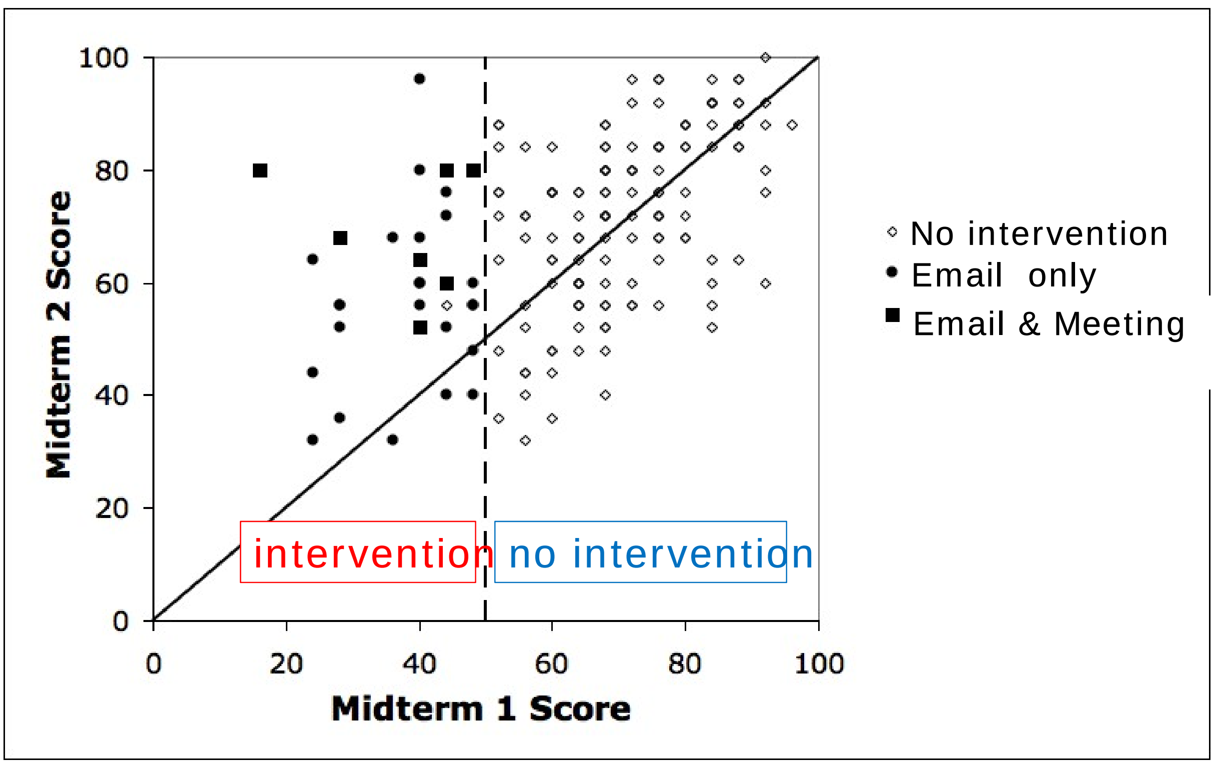
a. very selective physics program 2nd yr course
b. general interest intro climate science course

What did the intervention look like?

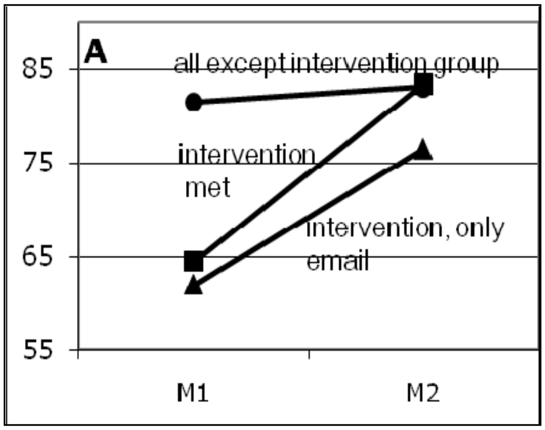
Email after M1-- "Concerned about your performance. 1) Want to meet and discuss";
or 2) 4 specific pieces of advice on studying. **[on syllabus]**

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.

Intro climate Science course (S. Harris and E. Lane)

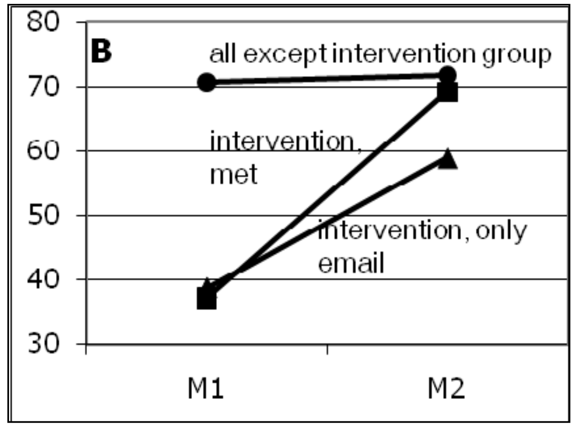


- End of 2nd yr Modern physics course (very selective and demanding, N=67)



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 <u>how</u> 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 <u>but appropriately targeted</u> 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:

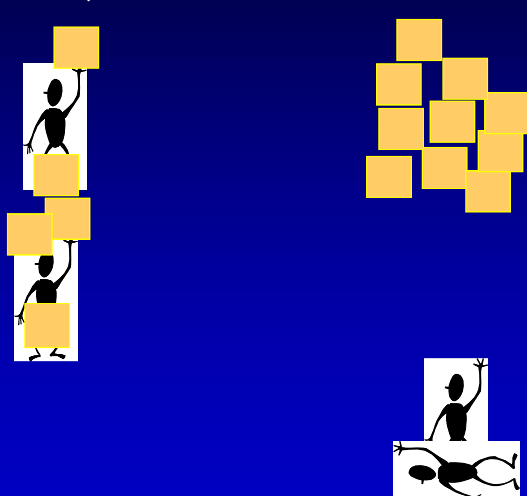
- involves complex analysis or judgment
- organize large amount of information
- ability to learn new information and apply

scientific thinking

Complex learning-- different.

Reducing unnecessary demands on working memory improves learning.

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



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 Perfomance

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UBC CW Science Education Initiative and U. Col. SEI

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)*

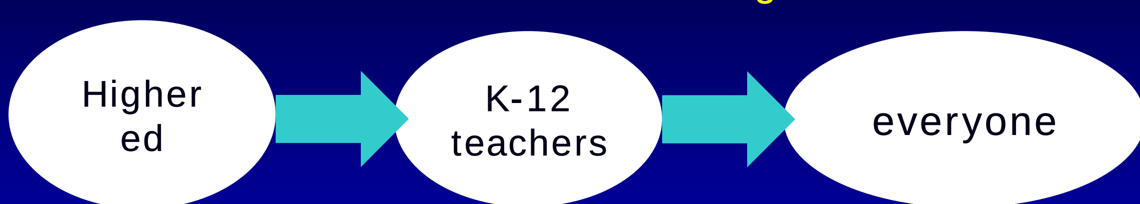
Goal of Univ. of Brit. Col. CW Science Education Initiative *(CWSEI.ubc.ca)* & Univ. of Col. Sci. Ed. Init.

- 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



STEM teaching &
teacher preparation

STEM higher Ed
Largely ignored, first step
Lose half intended STEM majors
Prof Societies have important role.

<u>Many new efforts to improve undergrad stem education</u> (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. …

The problem with education—

<u>Everyone</u> is an expert--
countless opinions, all considered equally valid

Value of a scientific approach—
separate out reality from opinions

<u>Scientific Approach</u>

- theories
- experiments
- results
- revised theories more experiments
- <u>finally reproducible and right</u>