

# *Teaching students to think like scientists\**

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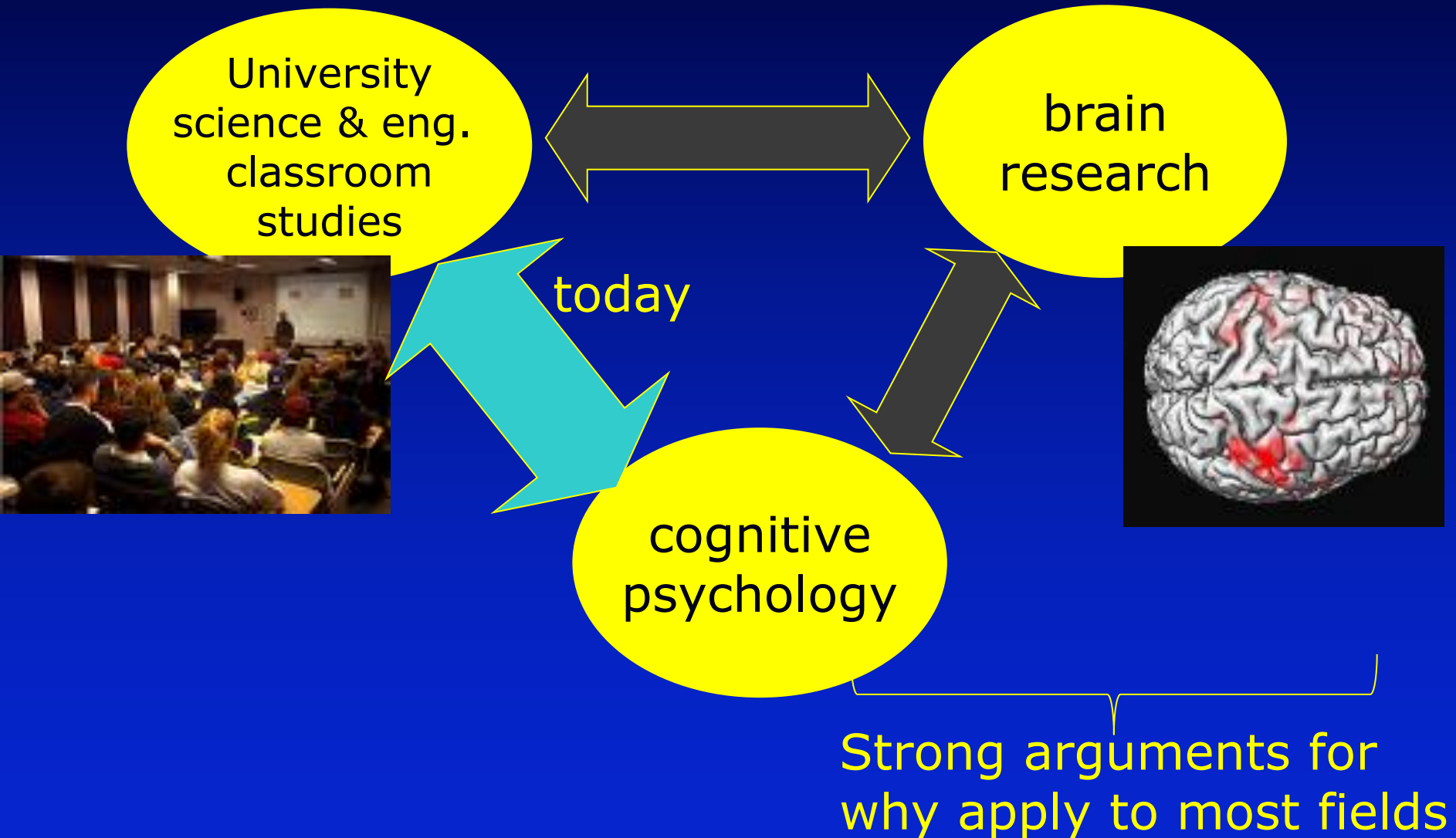
How expert (phd+ level) brain different from novice (undergrad). How learn differently, best way to turn novice brains into expert.

Copies of  
slides to be  
available

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

# Major advances past 1-2 decades

⇒ New insights on how to learn & teach complex thinking



I. What is "*thinking like a scientist?*"

II. How is it learned?

(curriculum determines what topics students see,  
pedagogy determines what thinking they learn)

III. Examples of common teaching practices  
encountered in sci. & eng. classes.

How research shows they are poor at teaching to  
think like scientist. How to do better.

*(for students, what you can do to learn anyway)*

IV. A few examples of data from courses backing up  
my claims.

V. A bit on institutional change– better evaluation of  
teaching

# I. Research on expert thinking\*

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

Expert thinking/competence =

- factual knowledge

- **Mental organizational framework**  $\Rightarrow$  retrieval and application



or ?



scientific concepts,  
predictive models  
(& criteria for when apply)

- 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



### Science thinking skills-

#### **1 minute to ponder:**

*List of decisions you make when solving problems in your research?*

\* "Deliberate Practice", A. Ericsson research. See "Peak;..." by Ericsson for accurate, readable summary

## II. Learning expertise\* -- **Challenging but doable tasks/questions**

- Practicing specific thinking skills
- Feedback on how to improve



### Science & eng. thinking skills

- Decide: what concepts/models relevant (*selection criteria*), what information is needed, what irrelevant,
- Decide: what approximations are appropriate.
- " : potential solution method(s) to pursue
- ....
- " : if solution/conclusion make sense- criteria for tests

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

\* "Deliberate Practice", A. Ericsson research. See "Peak;..." by Ericsson for accurate, readable summary

# effective teaching & learning

but must have  
enablers

Address prior  
knowledge and  
experience

Motivation

Cognitive demand/  
brain limitations

diversity

Students learn the thinking/decision-making  
they practice with good feedback (*timely,  
specific, guides improvement*).

disciplinary expertise  
knowledge & thinking  
of science

**Requires expertise in discipline &  
expertise in teaching it.**

### III. Examples of teaching practices common in sci. & eng. classes that learning research shows are bad:

1. Organization of how topics are presented
2. Structure of courses and exams
3. What information given on problems
4. Feedback on answers
5. When instructor is talking—



**1. Very** standard teaching approach:

Give formalism, definitions, equa's, and then move on to apply to solve problems.

*What could possibly be wrong with this?*

*Nothing, **if** learner has an expert brain.*

Expert organizes this knowledge as tools to use, along with criteria for when & how to use.

- 1) Novice does not have this system for organizing knowledge. Can only learn as disconnected facts, not linked to problem solving.
- 2) Much higher demands on working memory ("cognitive load")= less capacity for processing.
- 3) Unmotivating—no value.

A better way to present material—

*"Here is a meaningful problem we want to solve."*

*"Try to solve" (and in process notice key features of context & concepts & goal—basic organizational structure).*

**Now that they are prepared to learn--***"Here are tools (formalism and procedures) to help you solve."*

*More motivating, better mental organization & links, less cognitive demand = more learning.*

*"A time for telling" Schwartz & Bransford (UW), Cog. and Inst. (1998),  
Telling after preparation ⇒ x10 learning of telling before,  
and better transfer to new problems.*

# 1.b. Importance of limitations on working memory, and minimizing unnecessary "cognitive load".

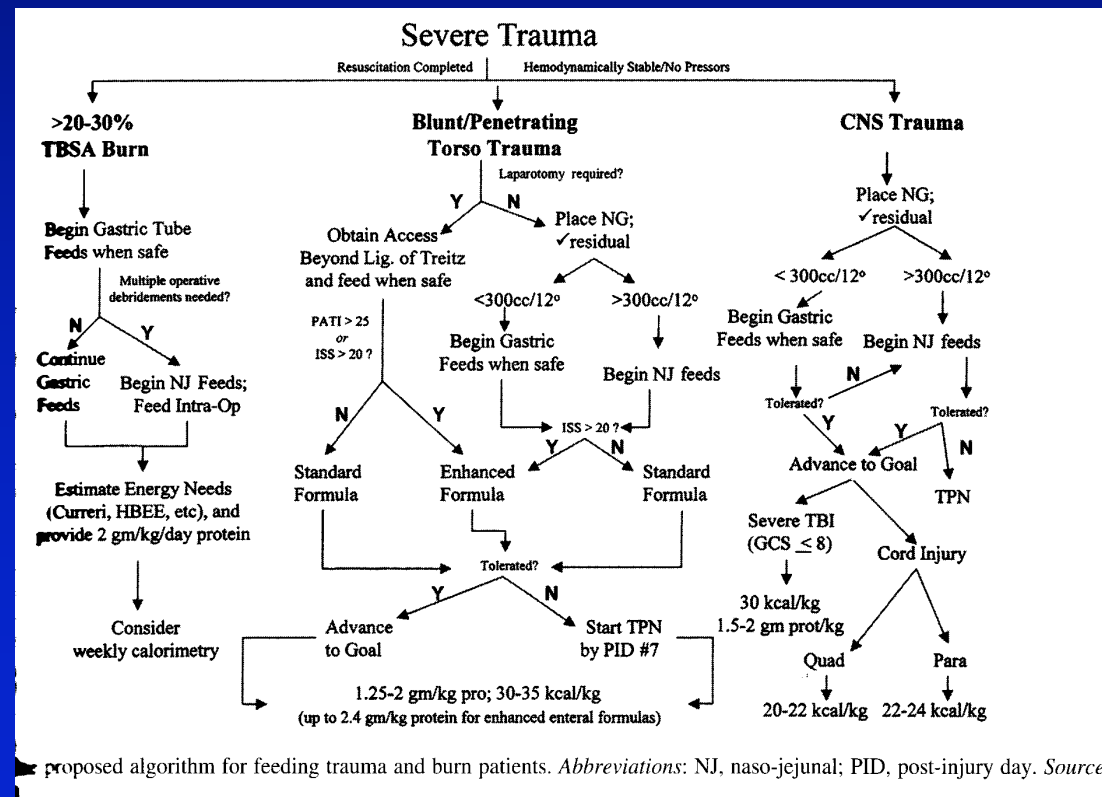
"short term working memory" – amount of new things brain can remember/pay attention to on short time scales (1 hr class)

Extremely limited capacity (5-7 items)!

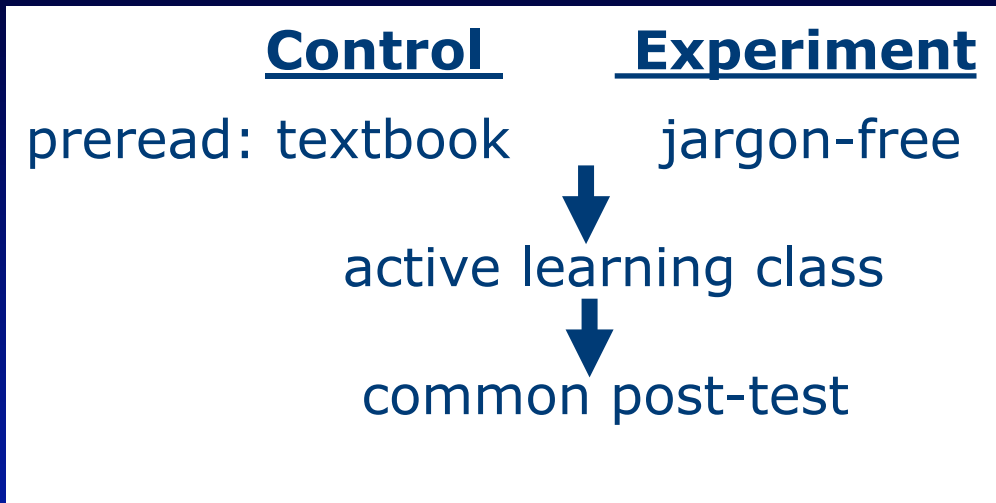
Anything extra hurts learning!

All disciplines are bad but bio probably worst with jargon.

*physiology class slide*

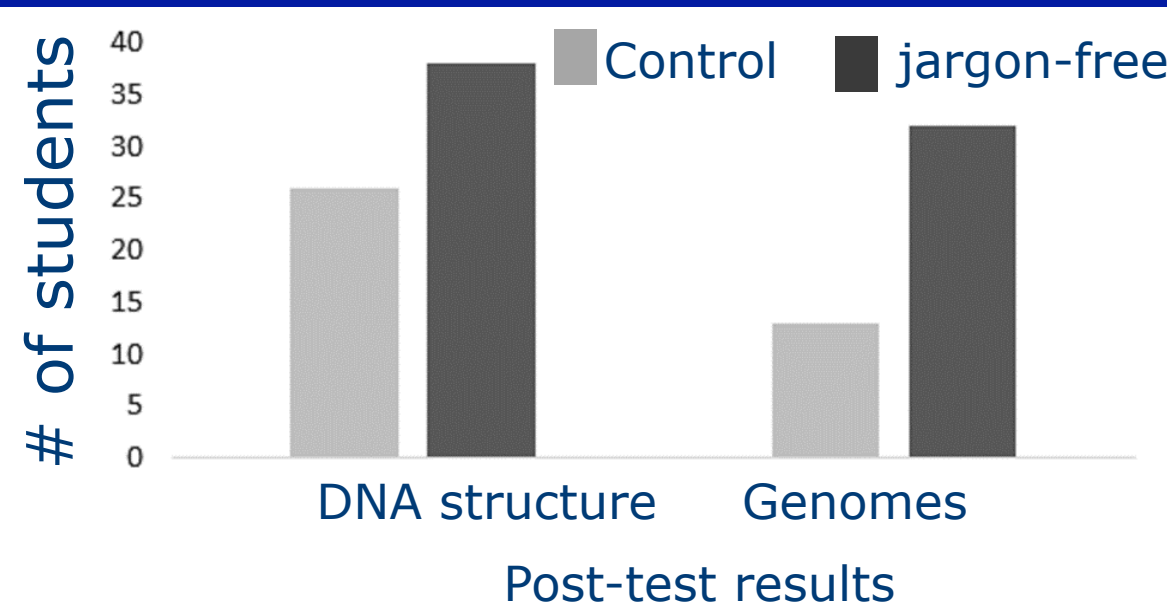


# Biology Jargon bogs down working memory, reduces learning?



“Concepts first, jargon second improves understanding”

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



Small change, big effect!

## 2. Structure of courses and exams.

Standard teaching practice--chap. 3 material--  
Lectures, HW, exam ch. 3, done.

chap. 4 ditto, done.

Material organized in brain chronologically by chap.

But real problems not labelled with chap. #!

Expertise— *decide when and how to use which material!*

*Better--How material in all chapters related & different?*

*What aspects of a problem mean which concepts and models useful? Which don't apply & why?*

### B. T. 3. What information given on problems

Standard practice– on HW problems and exams

Give all the information needed to solve and only that information (nothing extraneous)

What simplifications and approximations to use--  
“Neglect air resistance.”, ...

Major element of expertise--recognizing what information is relevant and what irrelevant, what approximations and simplifications to use.

*Better– challenge students to find criteria to use to justify any simplifications or approximations given. Find another example where would apply, and one where would not.*

*Pick realistic problem, find criteria for deciding what information relevant to solve, what is not.*

## B. T. 4. Feedback on answers

Standard practice— you get wrong.

Feedback—“That is wrong, here is correct solution.”

Why bad? Research on feedback—simple right-wrong with correct answer very limited benefit.

Learning happens when feedback **timely and specific on what thinking was incorrect and why**, and how to improve.

*Students—when incorrect, make sure know why and what to change.*

*Faculty—incentives to students to do.*

*option-part credit for wrong answers if then explain what was wrong with thinking. How to fix.*

...

## B. T. 35. When instructor is talking.

Standard teaching practice— instructor spends 90+% talking while students listen passively, maybe take notes, ask very occasional question.

Why bad—student brain is not doing processing.  
Practicing expert thinking that provides necessary brain exercise and rewiring.

Learning from expert feedback and telling highly effective, but only if brain is prepared first.

*(knowledge org., recognizes need, and how to use)*

Requires mental preparation activity.

Schwartz & Bransford "A time for Telling", x 10 learning if prepared



## Evidence from the Classroom

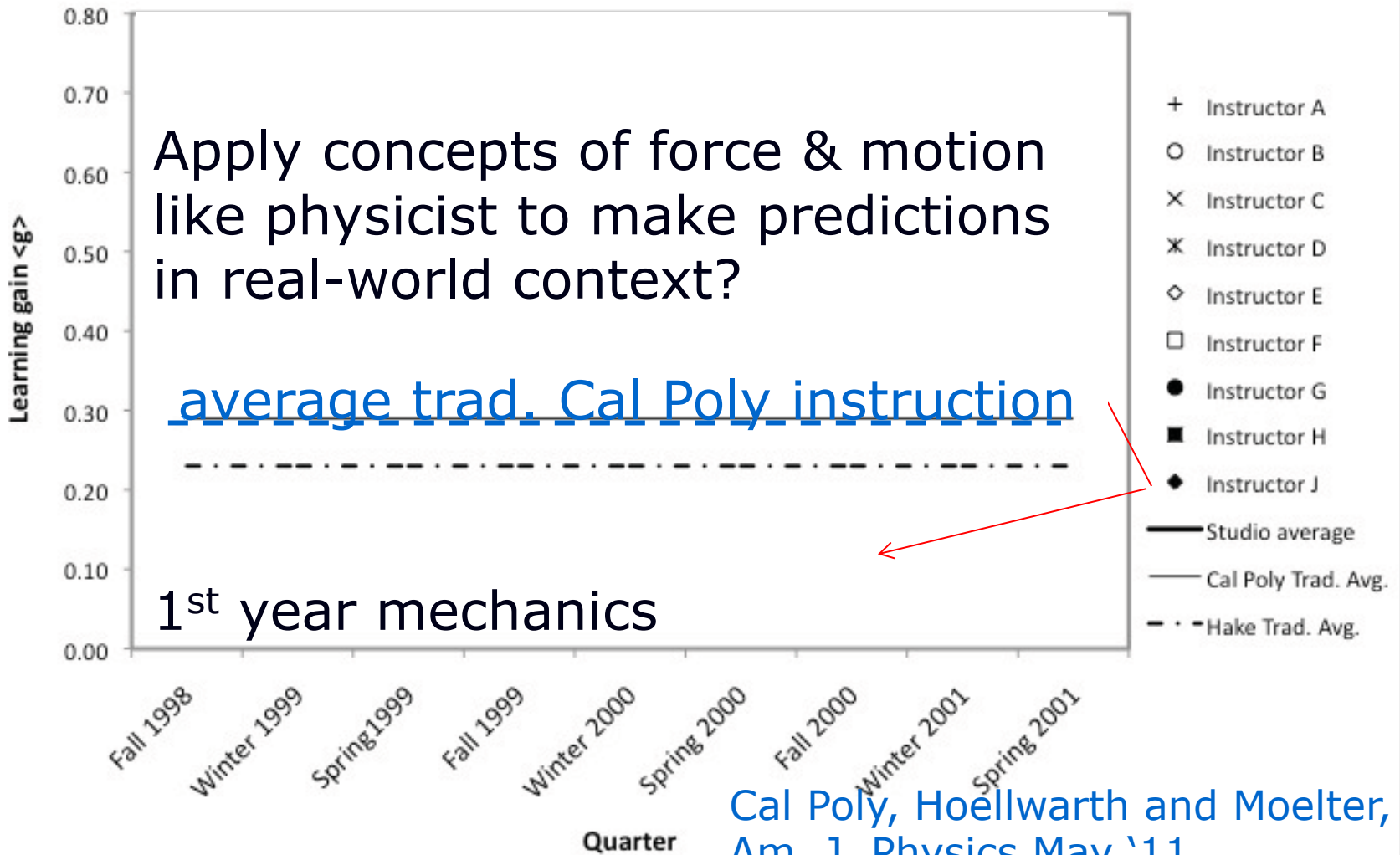
~ 1000 research studies from undergrad science and engineering comparing traditional lecture with “active learning”.

- consistently show greater learning, biggest effects are when measure expert-like decision making
- lower failure rates
- benefit all, but at-risk more

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

a few examples

## Learning Gain - Studio 1998-2001



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

# Learning in the in classroom\*



Comparing the learning in two  
~identical sections  
UBC 1<sup>st</sup> 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*

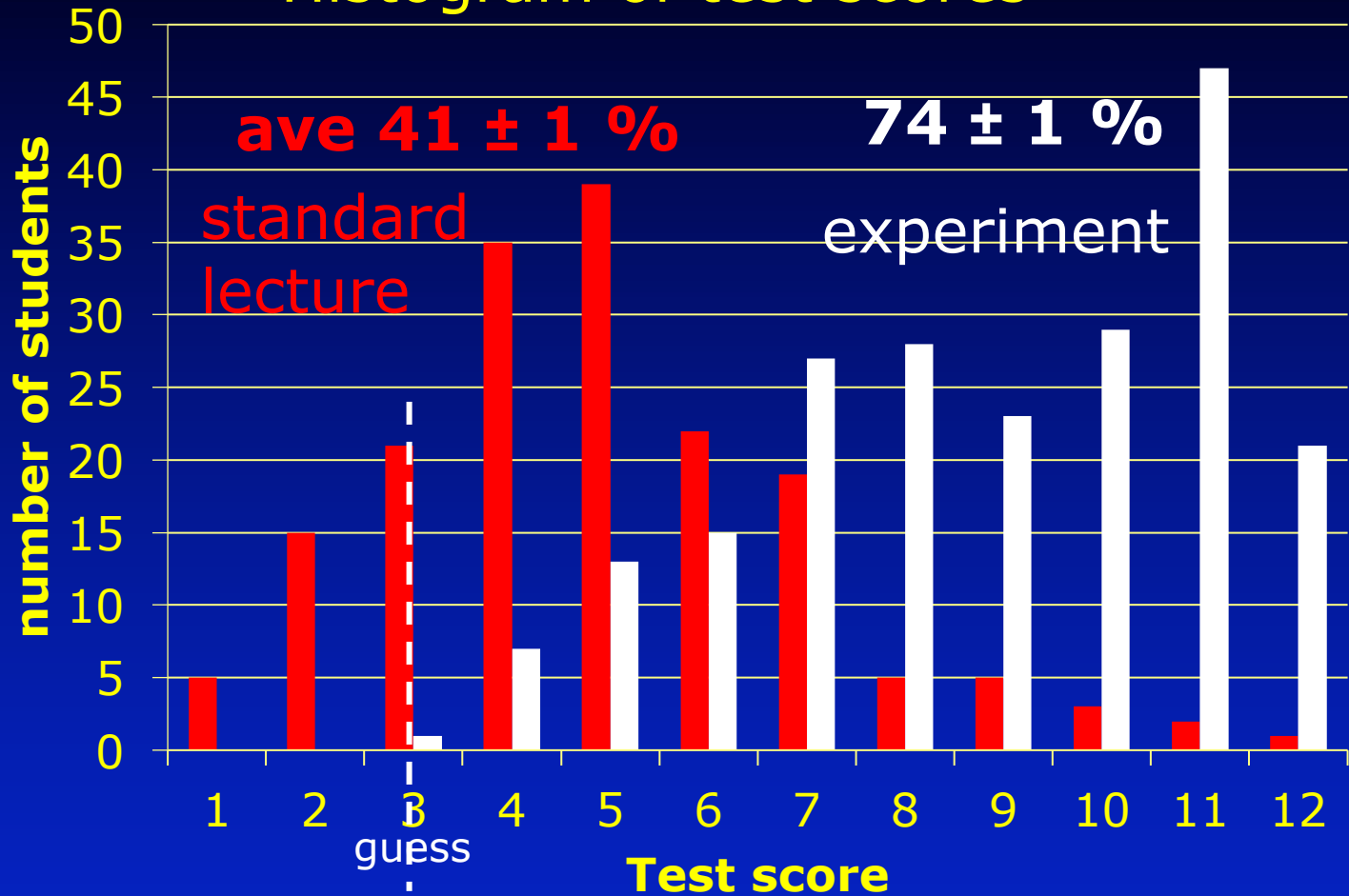
\*Deslauriers, Schelew, Wieman, *Sci. Mag.* May 13, '11

## Experimental class design

1. Targeted pre-class readings—basic information
2. Questions to solve, respond with clickers or on worksheets, discuss with neighbors.  
Instructor circulates, listens.
3. Discussion by instructor follows, not precedes.  
Targeted feedback to prepared students.  
Answering questions.  
(but still talking ~50% of time)

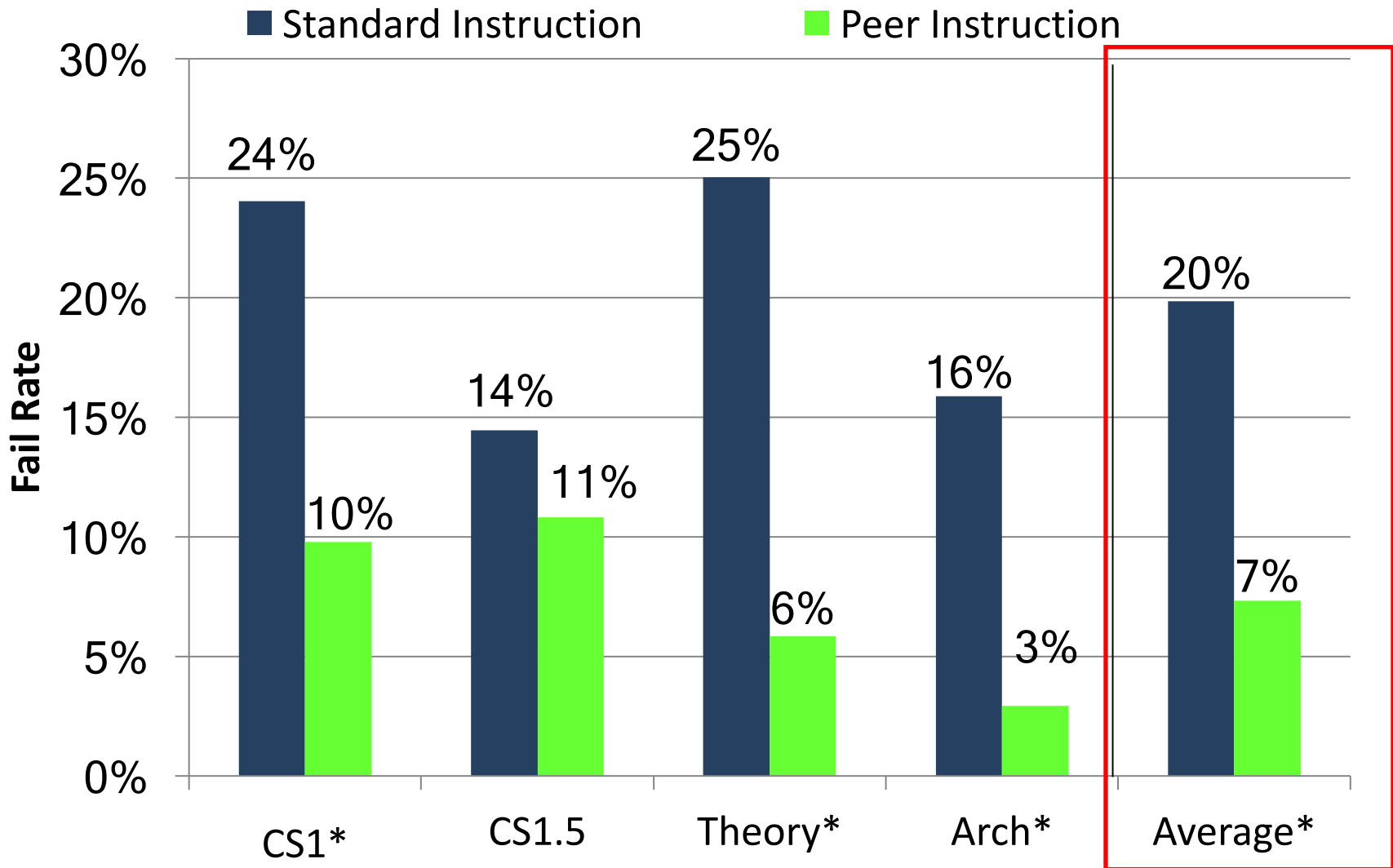
Practicing thinking like physicists  
+ multiple forms of timely specific feedback.

# Histogram of test scores



Clear improvement for entire student population.  
Engagement 85% vs 45%.

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



same 4 instructors, better methods = 1/3 fail rate

# Also works for advanced courses

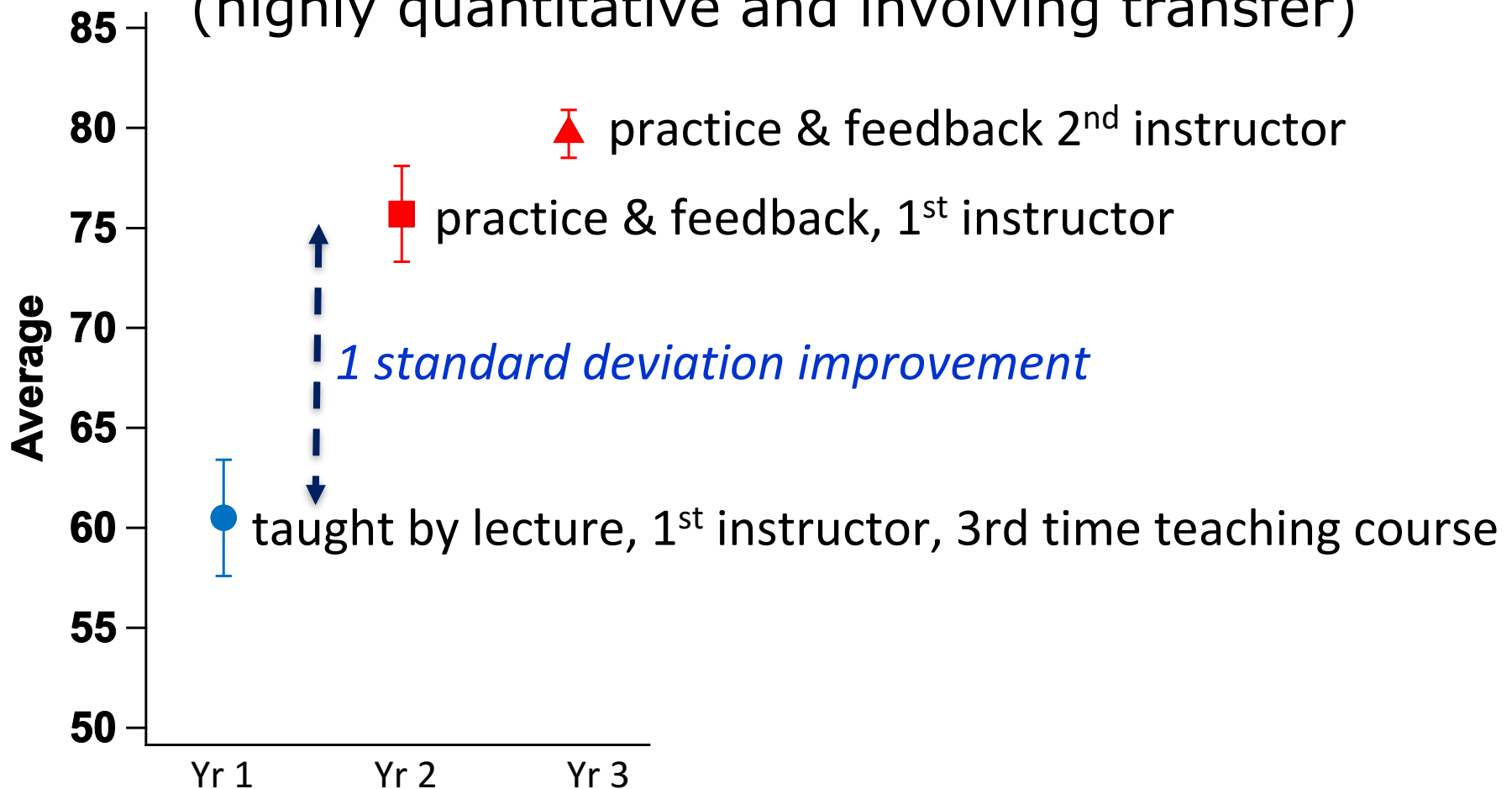
2<sup>nd</sup> -4<sup>th</sup> Yr physics



*Design and implementation: Jones, Madison, Wieman, Transforming a fourth year modern optics course using a deliberate practice framework, Phys Rev ST – Phys Ed Res, V. 11(2), 020108-1-16 (2015)*

# Final Exam Scores

nearly identical ("isomorphic") problems  
(highly quantitative and involving transfer)



*Jones, Madison, Wieman, Transforming a fourth year modern optics course using a deliberate practice framework, Phys Rev ST – Phys Ed Res, V. 11(2), 020108-1-16 (2015)*



# Stanford Outcomes

*7 physics courses 2<sup>nd</sup>-4<sup>th</sup> 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. Once learned the necessary expertise of teaching, much more rewarding, would never go back to old methods.**

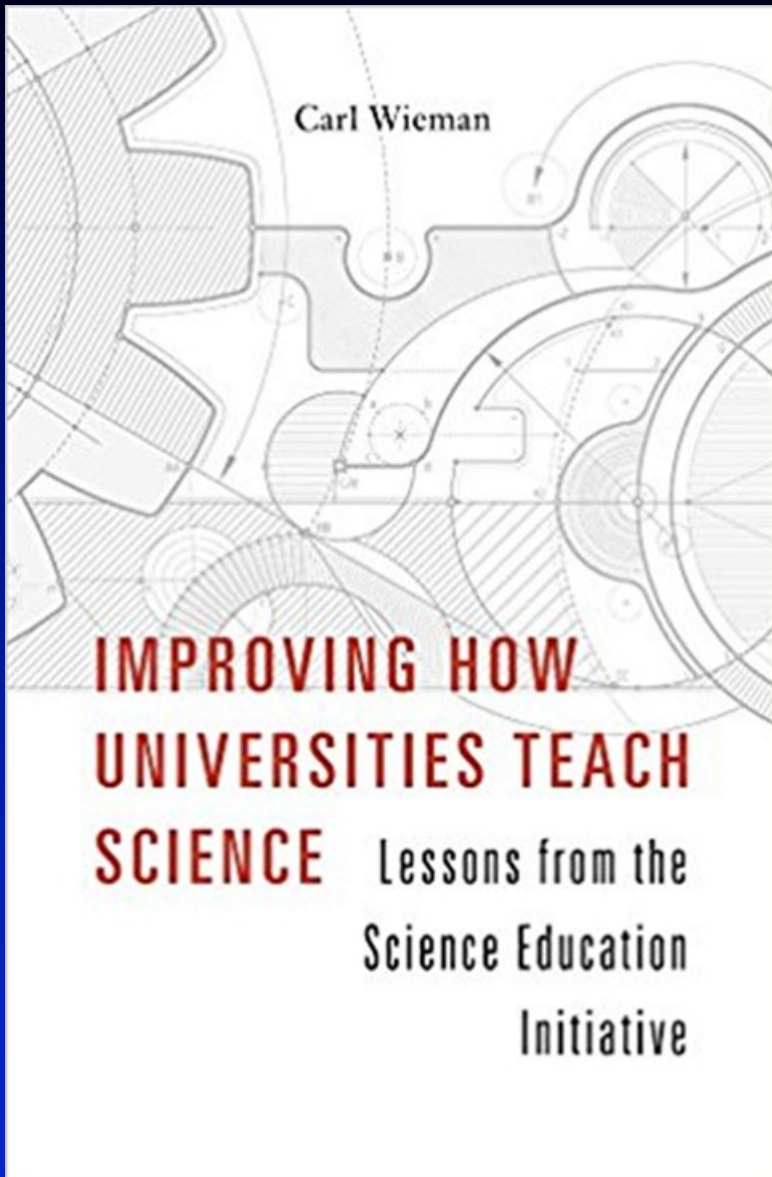
## Type of evidence led to message from the President (2017) Mary Sue Coleman, AAU

<https://www.aau.edu/sites/default/files/AAU-Files/STEM-Education-Initiative/STEM-Status-Report.pdf>

*"... 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. ...."***



For faculty and administrators...

What universities and departments can do to make large scale changes in teaching.

Transformed the teaching of  
~ 250 science faculty and  
~ 200,000 credit hours/year  
at UBC & CU.

What factors help and hinder

# Necessary 1<sup>st</sup> step- better evaluation of teaching quality

**“A better way to evaluate undergraduate science teaching”**

Change Magazine, Jan-Feb. 2015, Carl Wieman

## Requirements:

- 1) measures what leads to most learning
- 2) equally valid/fair for use in all courses
- 3) actionable-- how to improve, & measures when do
- 4) is practical to use routinely

student course evaluations fail on all but #4

Better way—characterize the practices used in teaching a course, extent of use of research-based methods.

**“Teaching Practices Inventory”**

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

better proxy for what matters

## Conclusion:

Meaningful science education—  
Learn to make decisions like scientists.

Research providing new insights on how to achieve;  
establishes expertise of teaching.

Improves student learning & faculty enjoyment.

## Good References:

- S. Ambrose et. al. *"How Learning works"*
- D. Schwartz et. al. *"The ABCs of how we learn"*
- Ericsson & Pool, *"Peak:..."*
- Wieman, *"Improving How Universities Teach Science"*
- **[cwsei.ubc.ca](http://cwsei.ubc.ca)-- resources** (implementing best teaching methods), references, effective clicker use booklet and videos

*slides will be available*

~ 30 extras below

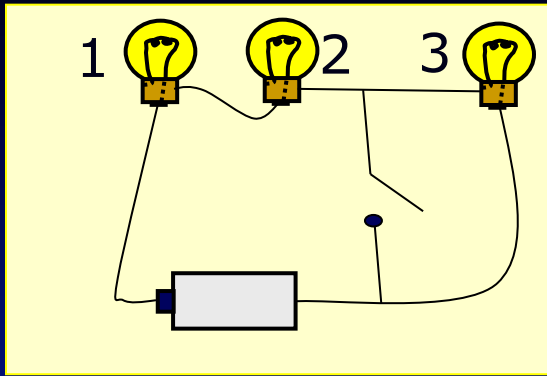
### III. How to apply in classroom? *practicing thinking with feedback*

*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:

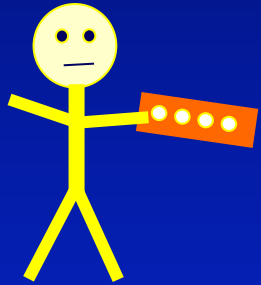


When switch is closed, bulb 2 will

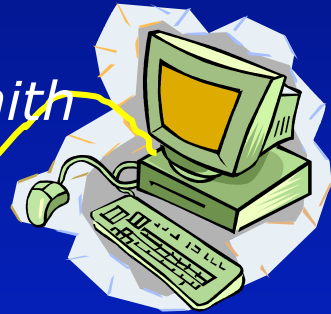
- a. stay same brightness,
- b. get brighter
- c. get dimmer,
- d. go out.

answer & reasoning

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...)

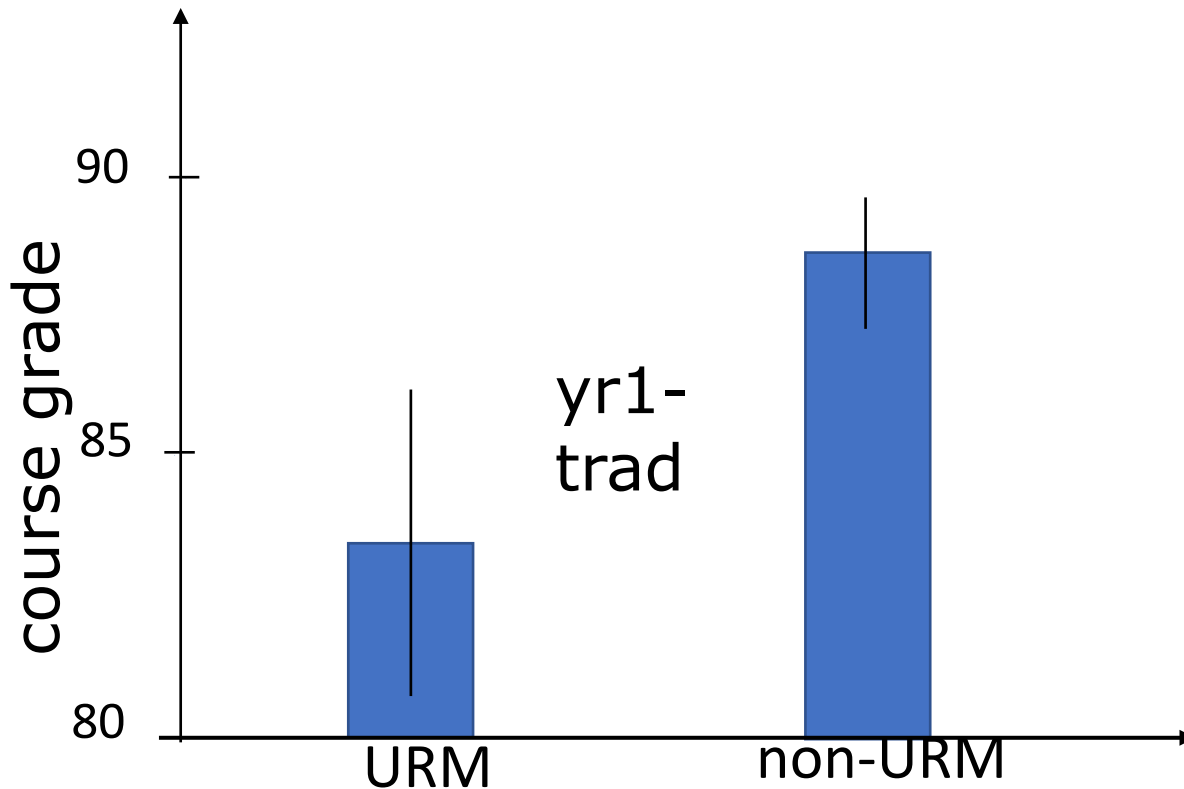
Feedback that improves thinking—other students,  
informed instructor, demo

# Enhancing Diversity in Undergraduate Science: Self-Efficacy Drives Performance Gains with Active Learning, CBE-LSE. 16

*Cissy Ballen, C. Wieman, Shima Salehi, J. Searle, and K. Zamudio*

Large intro bio course at Cornell

■ trad lecture



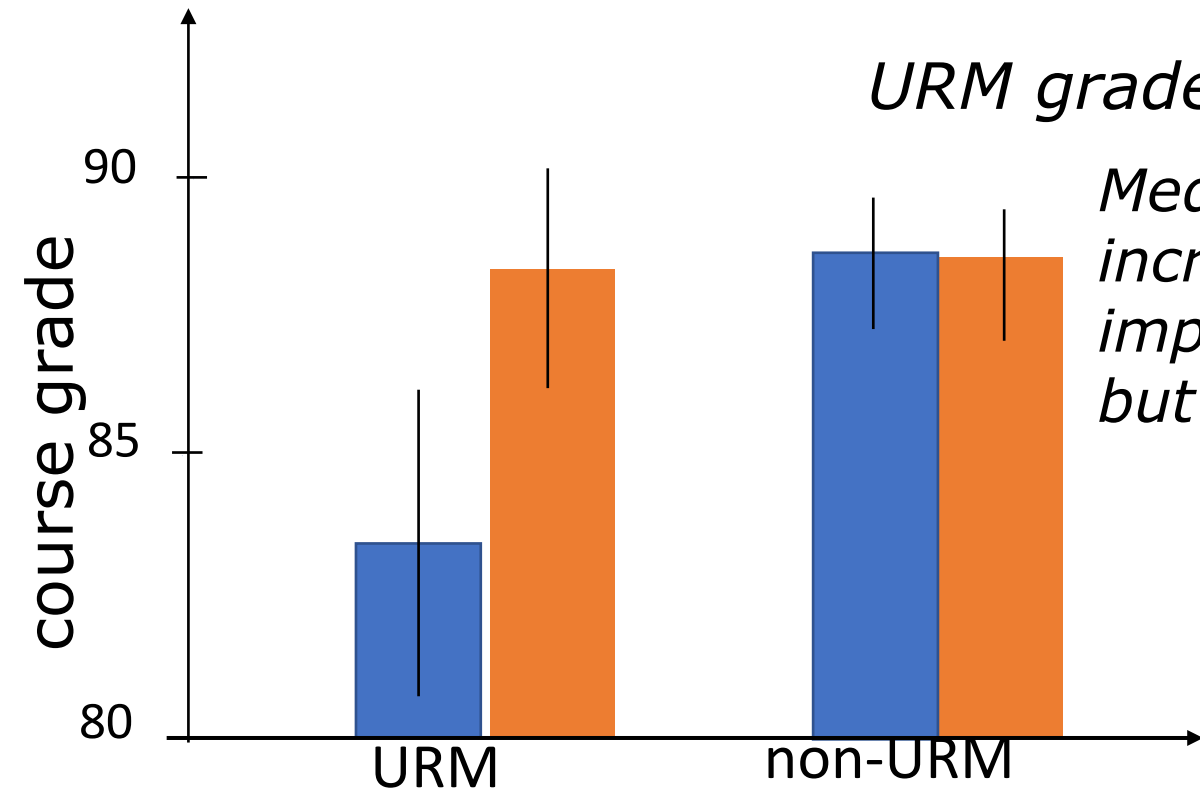
*(small correction for incoming prep)*

# Enhancing Diversity in Undergraduate Science: Self-Efficacy Drives Performance Gains with Active Learning, CBE-LSE. 16

Cissy Ballen, C. Wieman, Shima Salehi, J. Searle, and K. Zamudio

Large intro bio course at Cornell

■ yr1-trad lecture, ■ yr2- full active learning



*URM grades improve, but why?*

*Mediation analysis shows increased self-efficacy improves course grade, but only for URM students.*

“ 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  $\Rightarrow$  recognize key features

### Predicting results of novel experiment

<i>Condition</i>	<i>Noted in Study Work</i>	<i>Missed in Study Work</i>
Analyze + lecture	.60	.26
Analyze + analyze	.18	.15
Summarize + lecture	.23	.06

# 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*

# 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

differences  
across  
learners

*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)

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.)~~

# 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)
3. Analyzing and teaching effective problem solving strategies using interactive simulations.

# 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!

*Heiner et al, Am. J. Phys. 82, 989 (2014)*

## My background in education

Students: 17 yrs of success in classes.  
Come into my lab clueless about physics?



2-4 years later  $\Rightarrow$  expert  
physicists!

?????? ~ 25 years ago

Research on how people learn, particularly physics

- explained puzzle
- different way to think about learning and teaching
- got me started doing physics/sci ed research--  
controlled experiments & data!

# 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

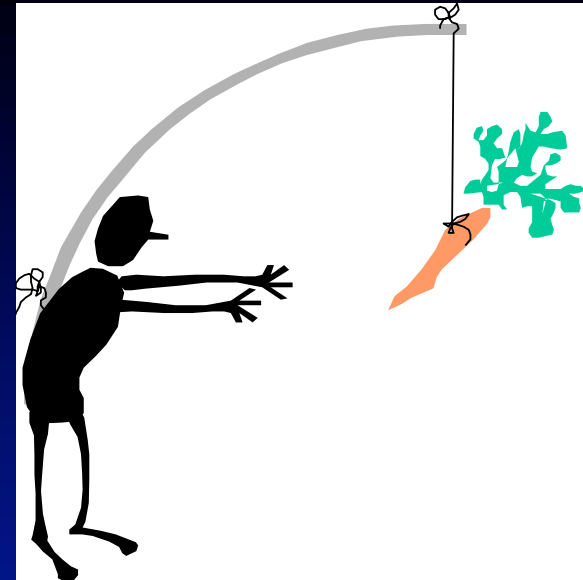
a. Relevant/useful/interesting to learner

**(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.**

# clickers\*--

Not automatically helpful--

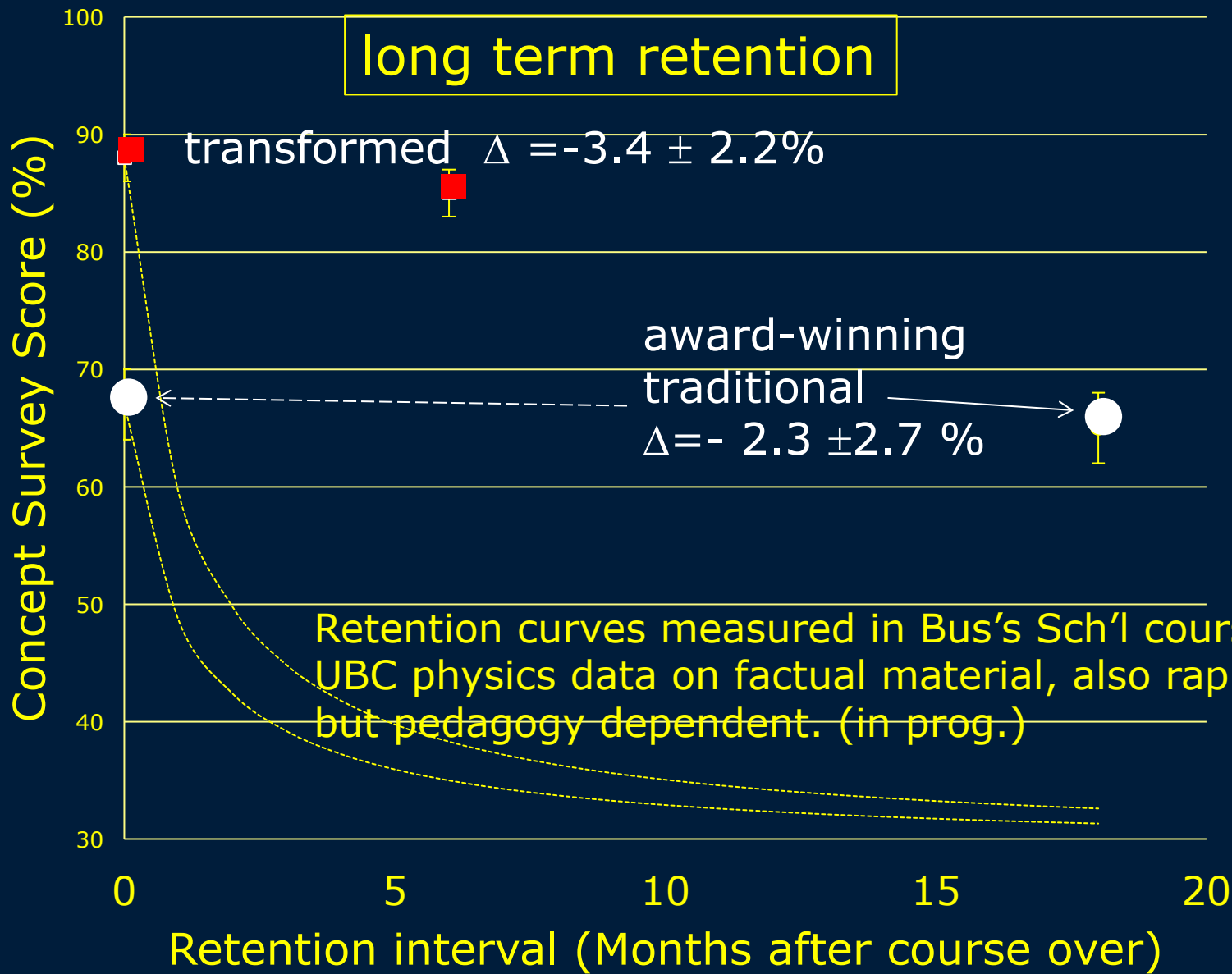
give accountability, anonymity, fast response

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](http://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.)

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 %

## 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?

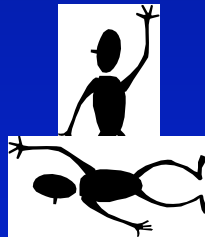
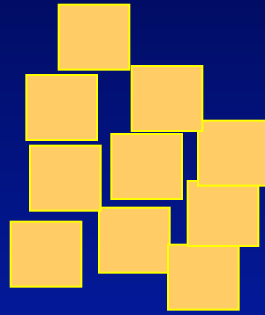
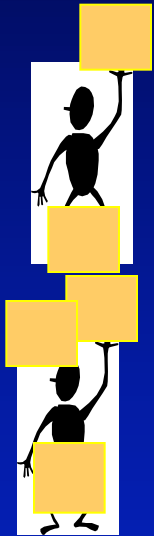
3. Class time filled with problems and questions that call for explicit expert thinking, address novice difficulties, challenging but doable, and are motivating.

4. Frequent specific feedback to guide thinking.

DP

Reducing unnecessary demands on working memory improves learning.

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



# UBC CW Science Education Initiative and U. Col. SEI

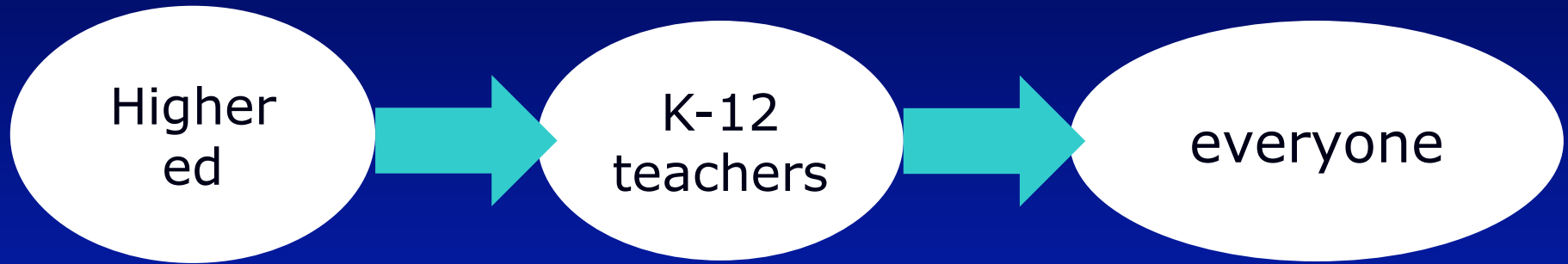
Changing educational culture in major research university science departments  
*necessary first step for science education overall*

- 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*

# 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.



# 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)
- 5. Industry**– WH Jobs Council, Business Higher Ed Forum
- 6. Government**– NSF, Ed \$\$, and more
- 7. ...**