Using research to improve university science teaching

and most other subjects

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copies of slides to be available

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
$\Rightarrow$ Bringing together research fields

University science & eng. classroom studies

brain research

today

cognitive psychology

Strong arguments for why apply to most fields

Science education goal—
Learn to make <u>better decisions (like scientist)</u>

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*)

I. Research on expert thinking*

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

Expert thinking/competence =

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

or ?

scientific concepts,
(& criteria for when apply)

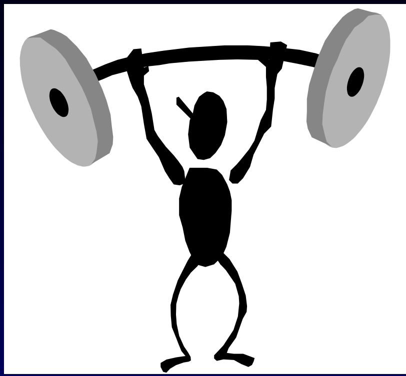
- **Ability to monitor own thinking and learning**

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



Requires brain "exercise"

- 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 <u>not:</u>

“experiential/hands-on”

“flipped classroom”

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

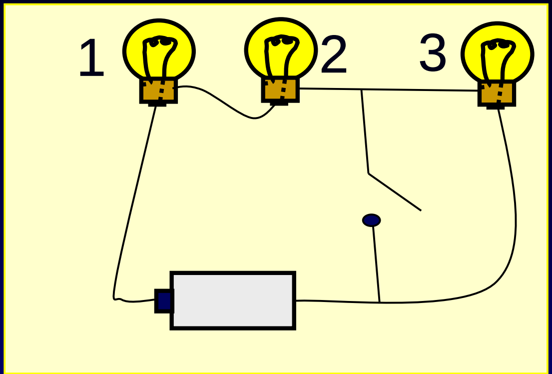
III. How to apply in classroom?
practicing thinking with feedback

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)

4. Discuss with “consensus group”, revote.

<u>Instructor listening in</u>! 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

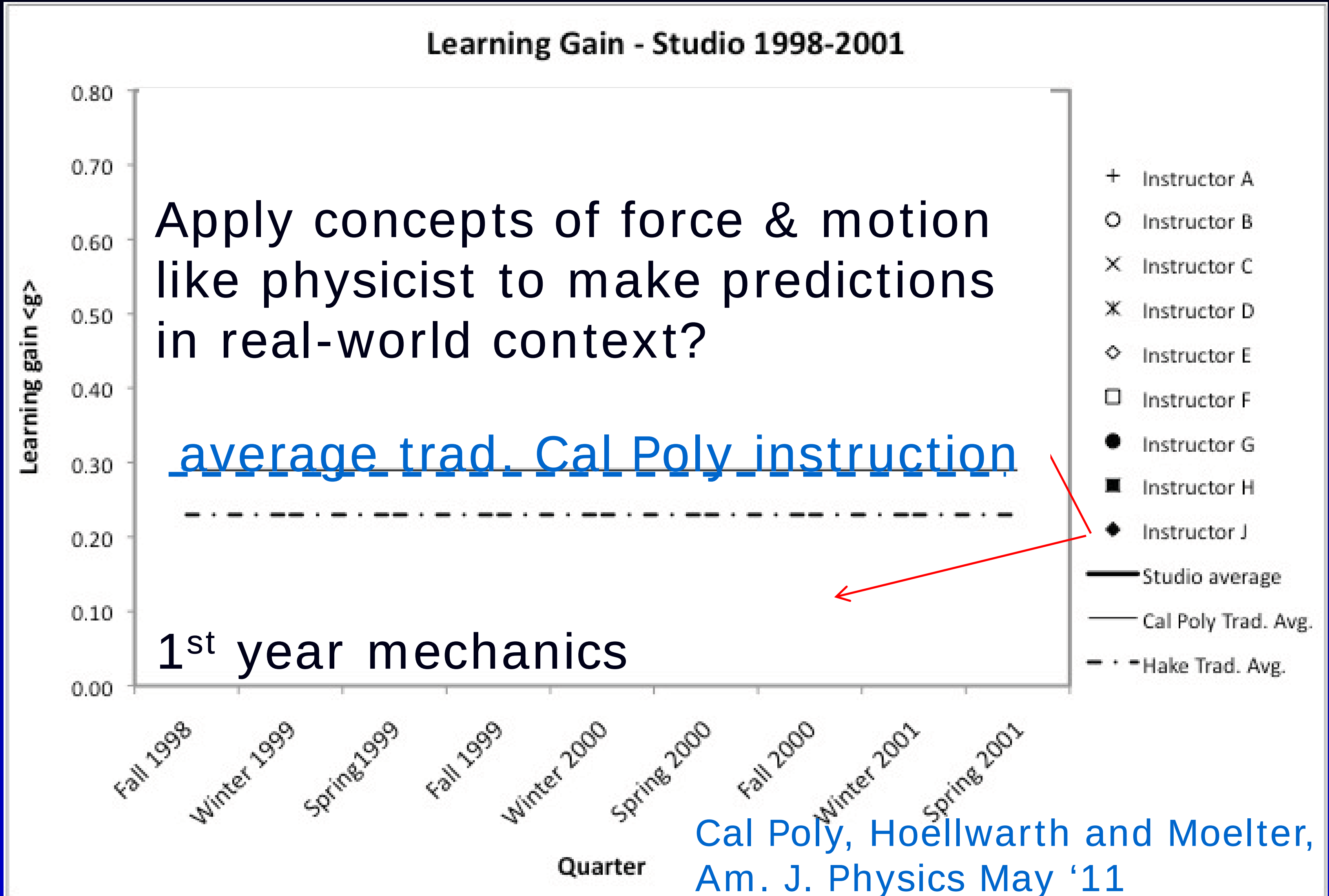
3. Evidence from the Classroom

~ 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

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

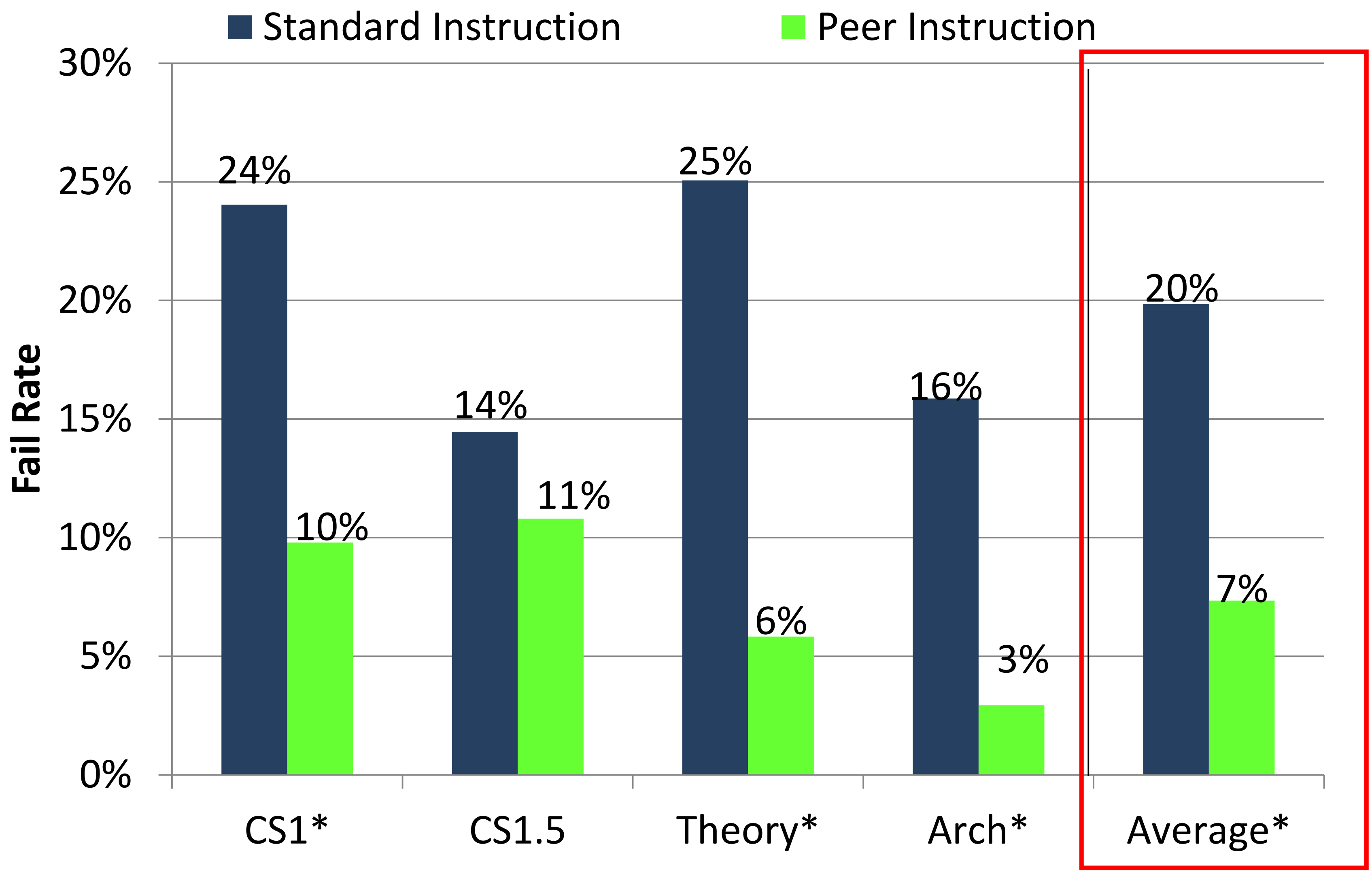
A few examples—
various class sizes and subjects



9 instructors, 8 terms, 40 students/section.

Same instructors, better methods = more learning!

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



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*

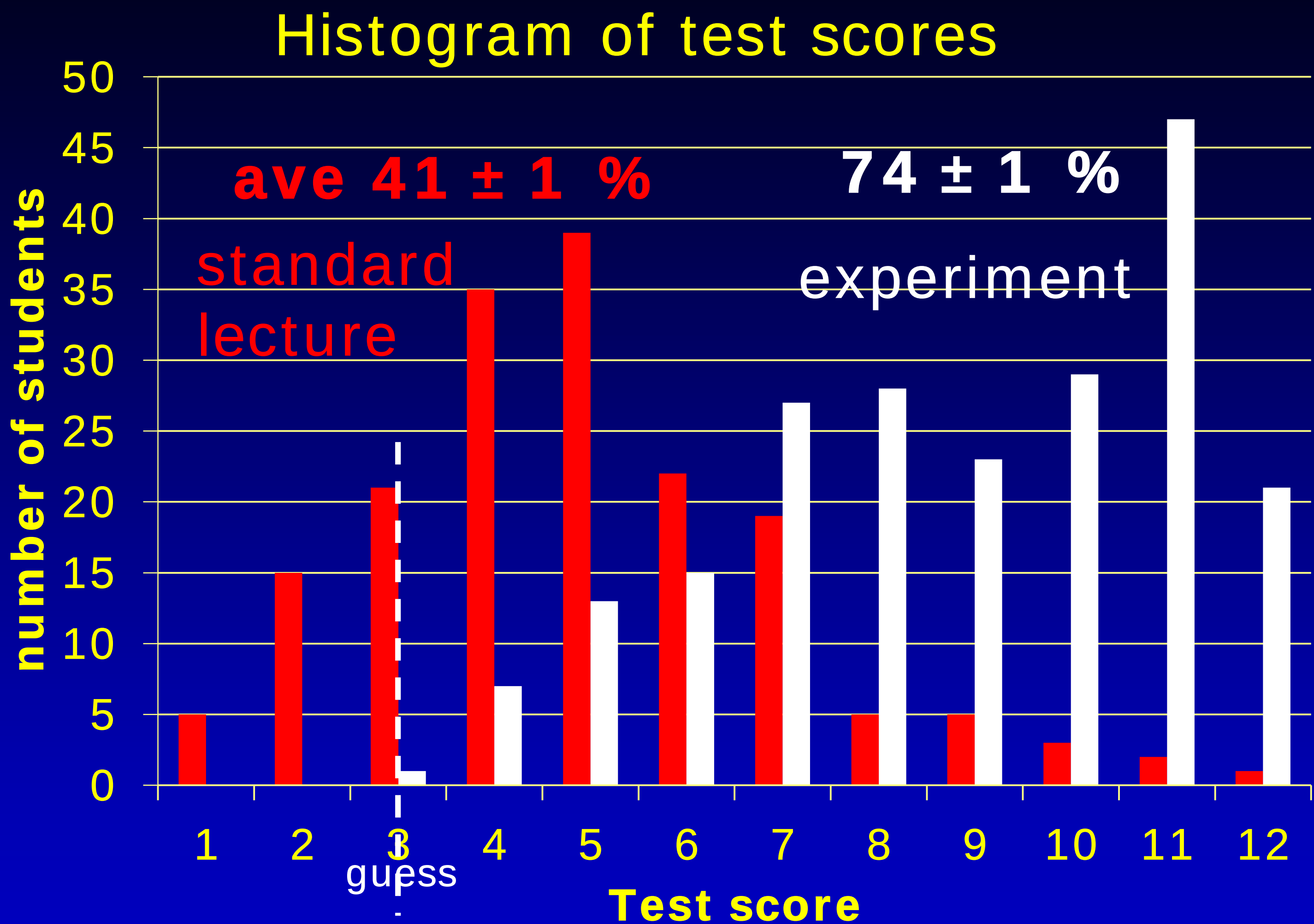
**Deslauriers, Schelew, Wieman, Sci. Mag. May 13, ‘11*

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

Advanced courses 2nd -4th Yr physics

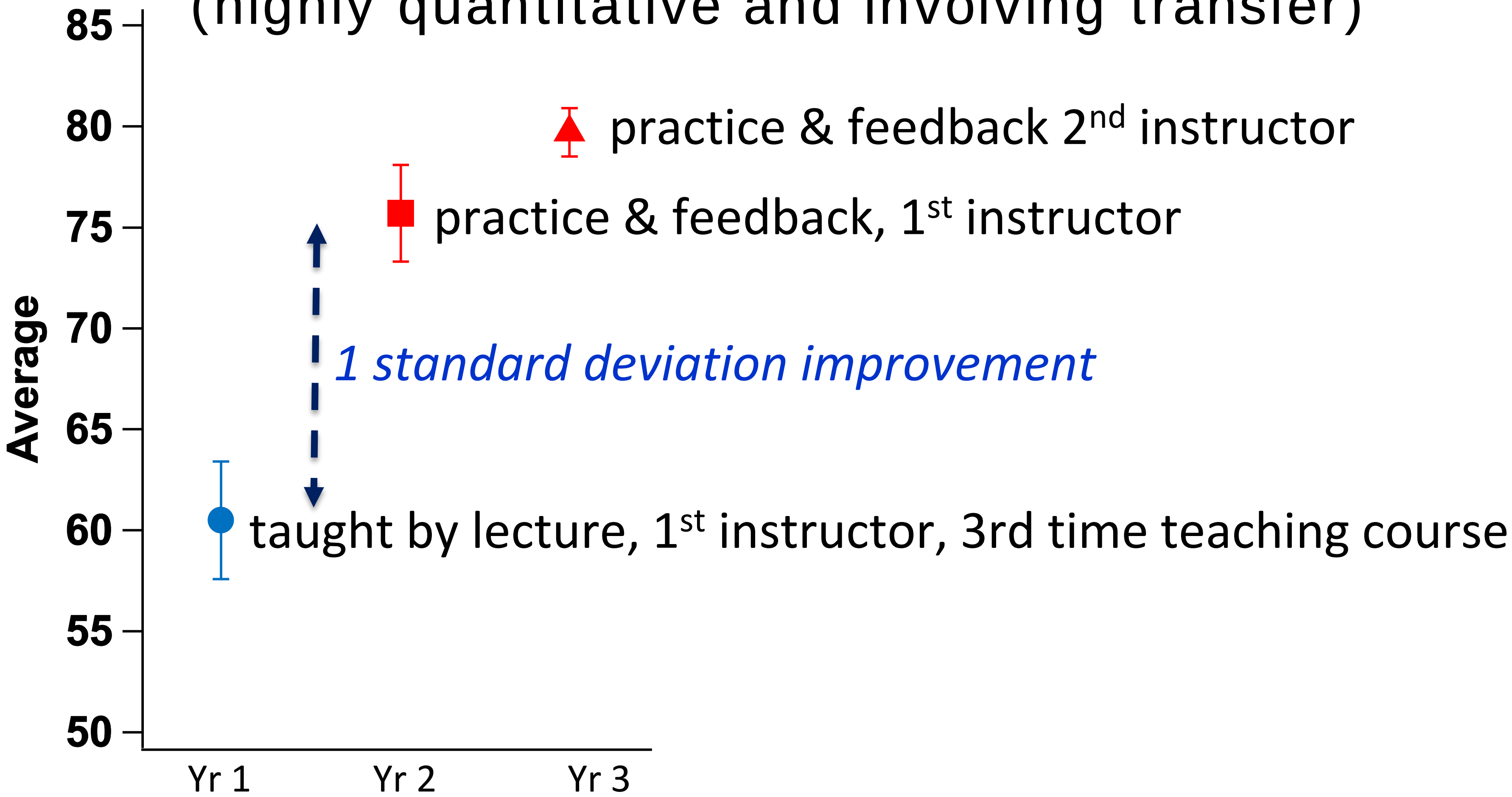
Univ. British Columbia & Stanford

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 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 *(when try)*

How to get widespread adoption?

IV. Institutional Change

train is starting to move— get on it or be left behind

Calls for changes in university STEM teaching

- NAS – DBER report 2012
- PCAST report 2012

- Program funding shifts– NSF, HHMI

- Amer. Assoc. of Univ. (AAU) 2012--
- Council of Ind. Coll. & Univ. 2017
- Amer. Acad. Arts & Sci. 2017

talking about teaching & need for members to improve !?

AAU Pres. Ann. meeting– 1st ever talk on teaching (2011)

A Message from the President (2017)

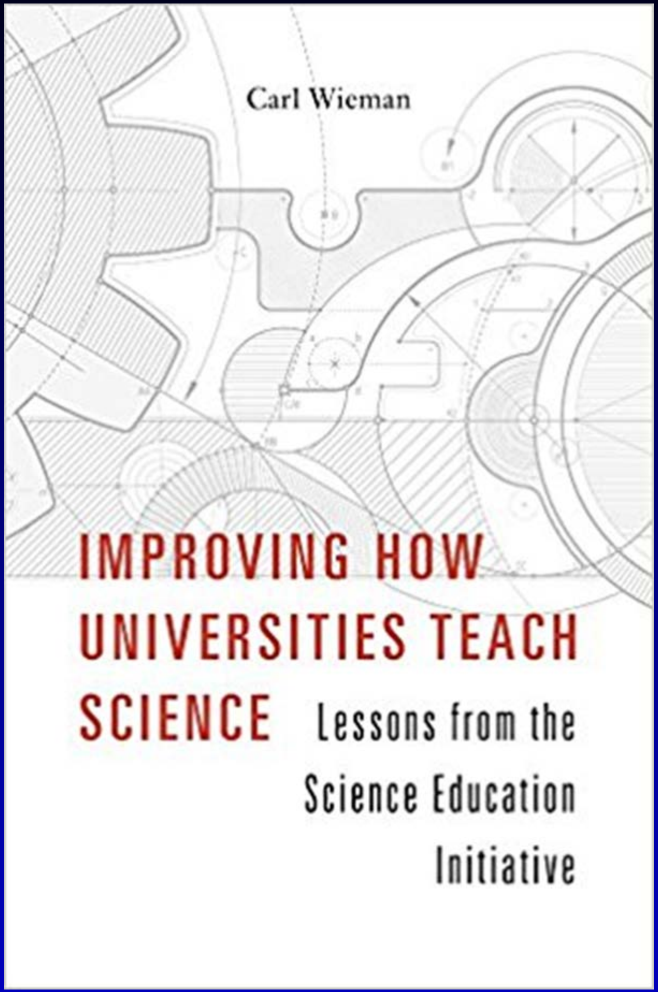
Mary Sue Coleman, Association of American Universities

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.*

…

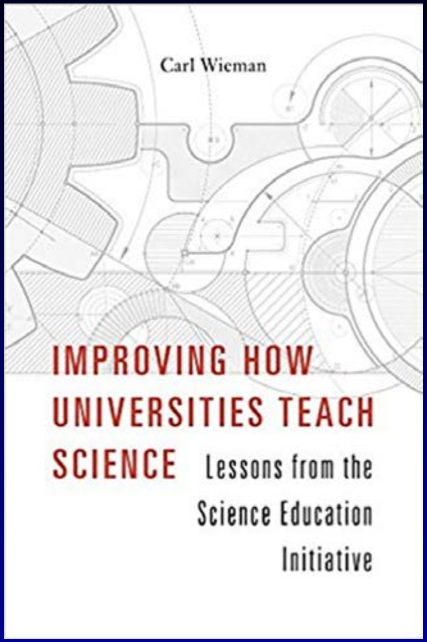
We cannot condone poor teaching of introductory STEM courses … simply because a professor, department and/or institution fails to recognize and accept that there are, in fact, more effective ways to teach. Failing to implement evidence-based teaching practices in the classroom must be viewed as irresponsible,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



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

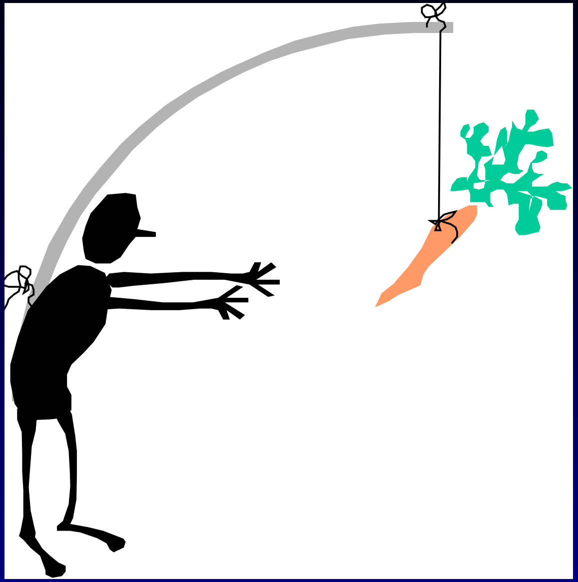
~ 30 extras below

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

differences across learners



Motivation-- essential

(complex- depends on background)

Enhancing motivation to learn

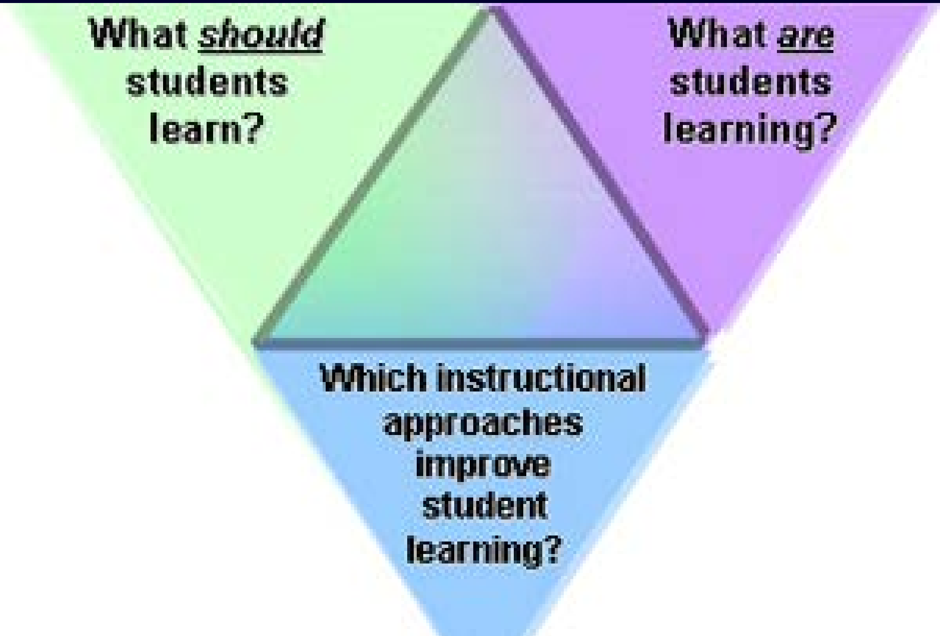
a. Relevant/useful/interesting to learner (**meaningful context-- connect to what they know and value)**

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



"SEI Trinity" for courses

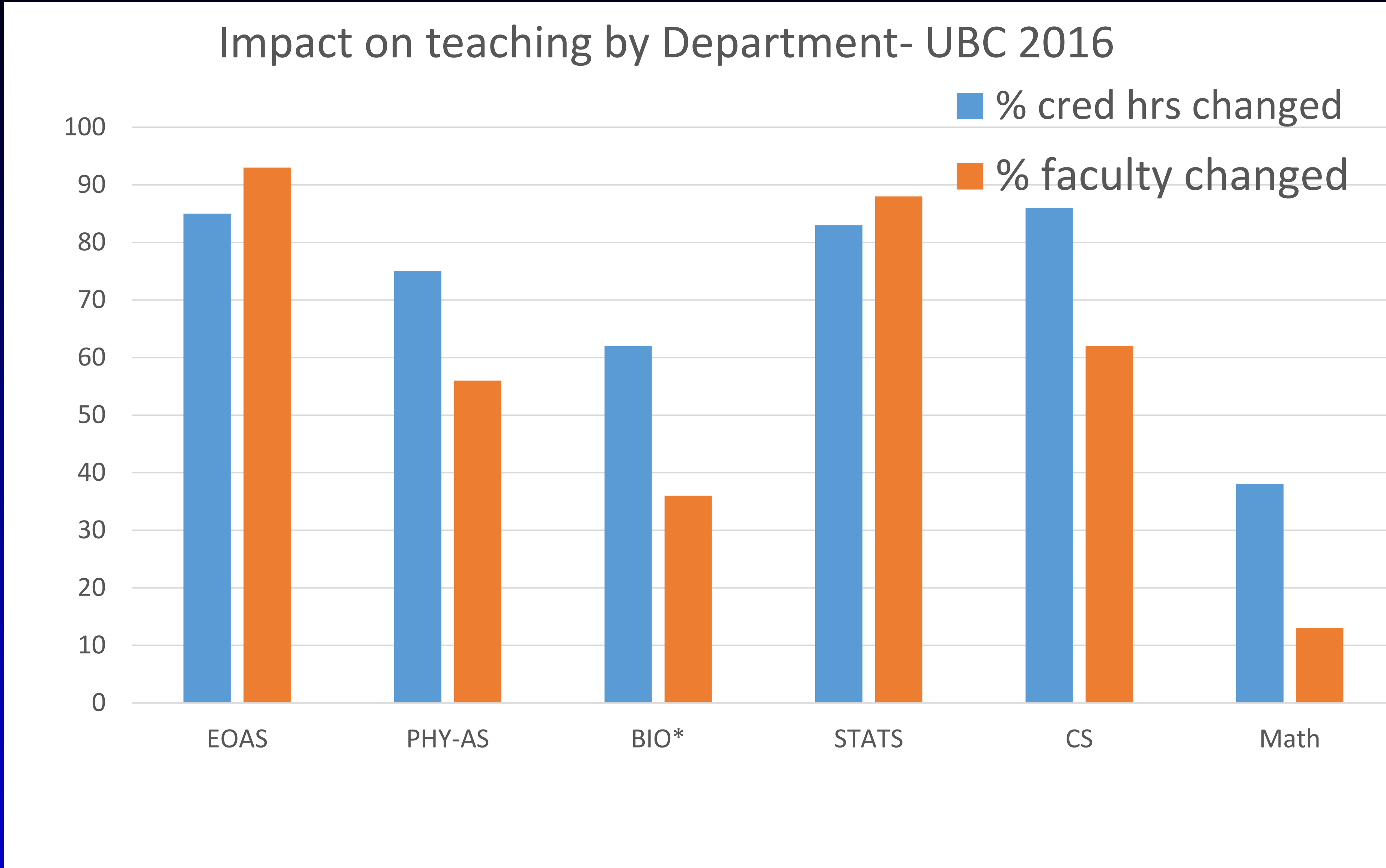
1st: Decide on learning goals. (what should students be able to *do*?)

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



Lots of success, lots of variation- lessons therein

Biology Jargon bogs down working memory, reduces learning?

	Control	Experiment
preread:	textbook	jargon-free

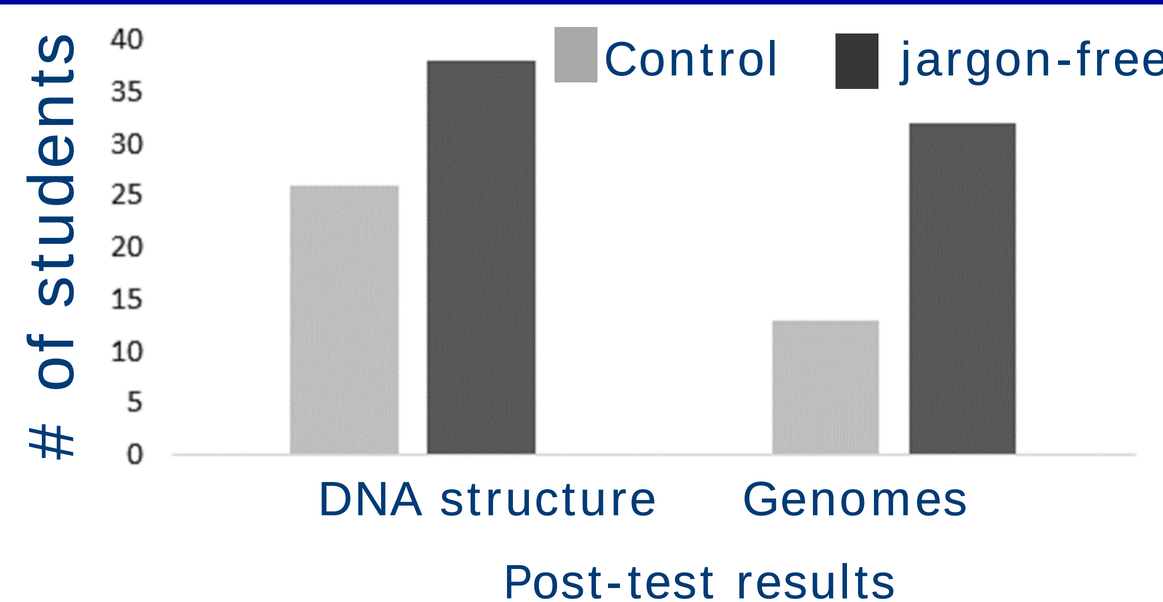
↓

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

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

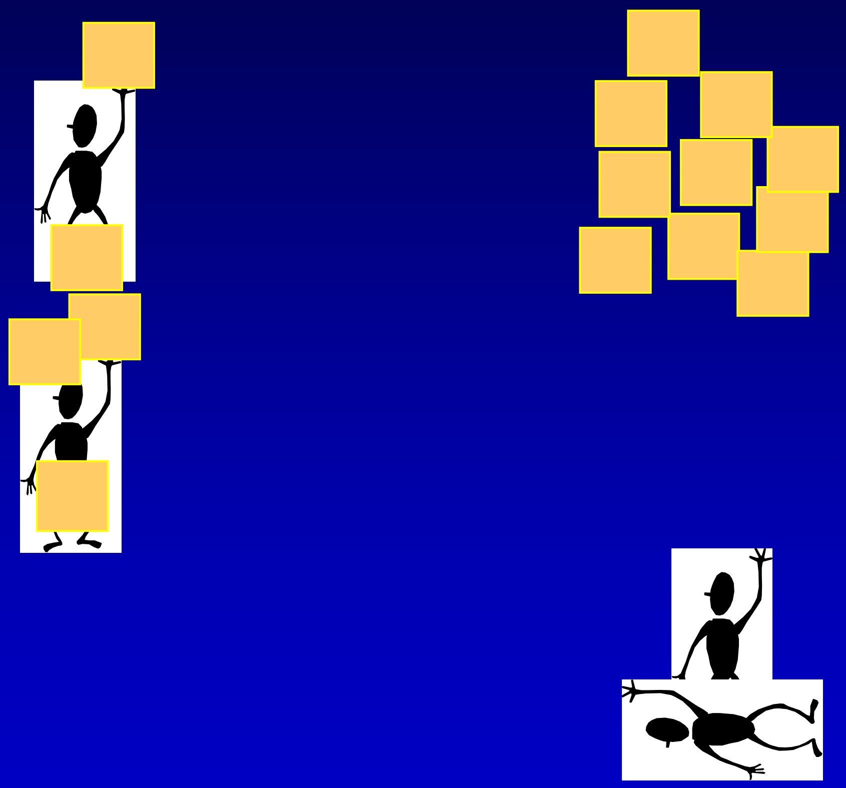
slides to be provided

Reducing demands on working memory in class

- Targeted pre-class reading with short online quiz
- Eliminate non-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!

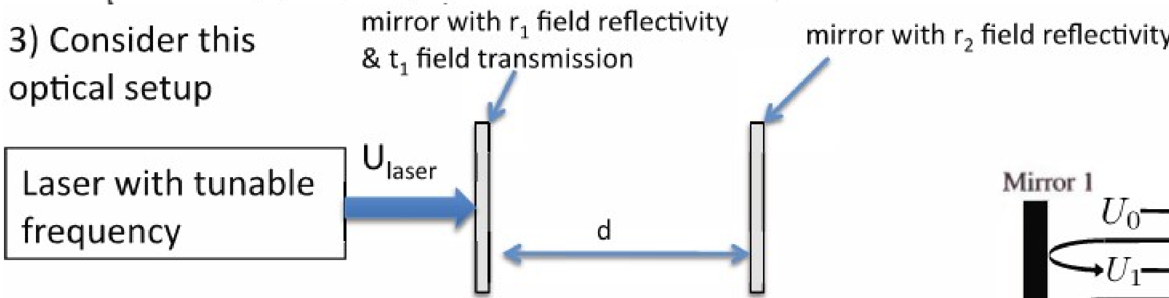
Heiner et al, Am. J. Phys. 82, 989 (2014)

No Prepared Lecture

Actions	Students	Instructors
Preparation	Complete targeted reading	Formulate/review activities
Introduction (2-3 min)	Listen/ask questions on reading	Introduce goals of the day
Activity (10-15 min)	Group work on activities	Circulate in class, answer questions & assess students
Feedback (5-10 min)	Listen/ask questions, provide solutions & reasoning when called on	Facilitate class discussion, provide feedback to class

Lecture Notes Converted to Activities

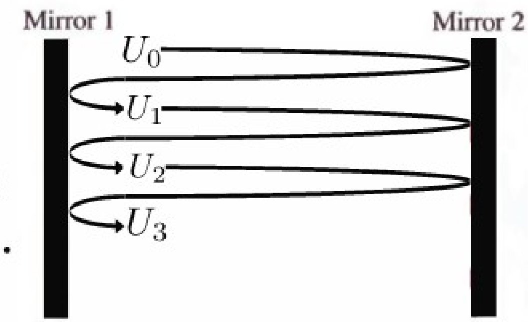
3) Consider this optical setup



Steck writes the right moving wave amplitude in the cavity as

$$U = U_0 + U_1 + U_2 + \ldots$$

where $U_{n+1} = re^{i2kd}U_n$



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_{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_{loss}. What would r be in terms of t_{loss} , r_1 and r_2 ? What if t_{loss} were complex?

3e) 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?

3f) 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?

3g) Evaluate the infinite sum for the field and derive an expression for the intensity

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.

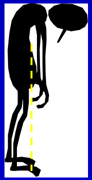
Expert

Content: coherent structure of concepts.

Describes nature, established by experiment.

Prob. Solving: Systematic concept-based strategies.

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



best predictor of physics major

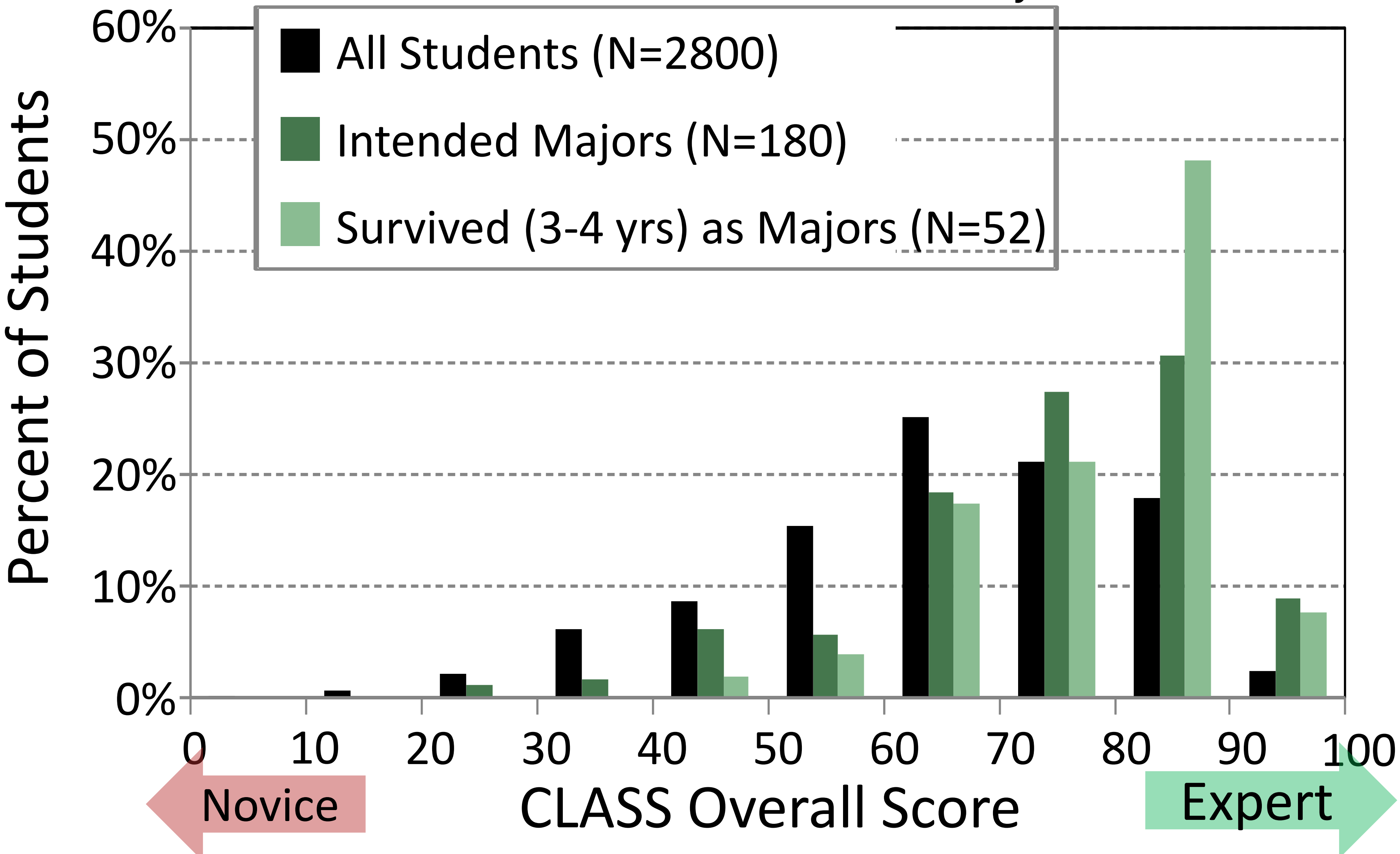
intro physics course $\Rightarrow$ *more* novice than before

chem. & bio as bad

*adapted from D. Hammer

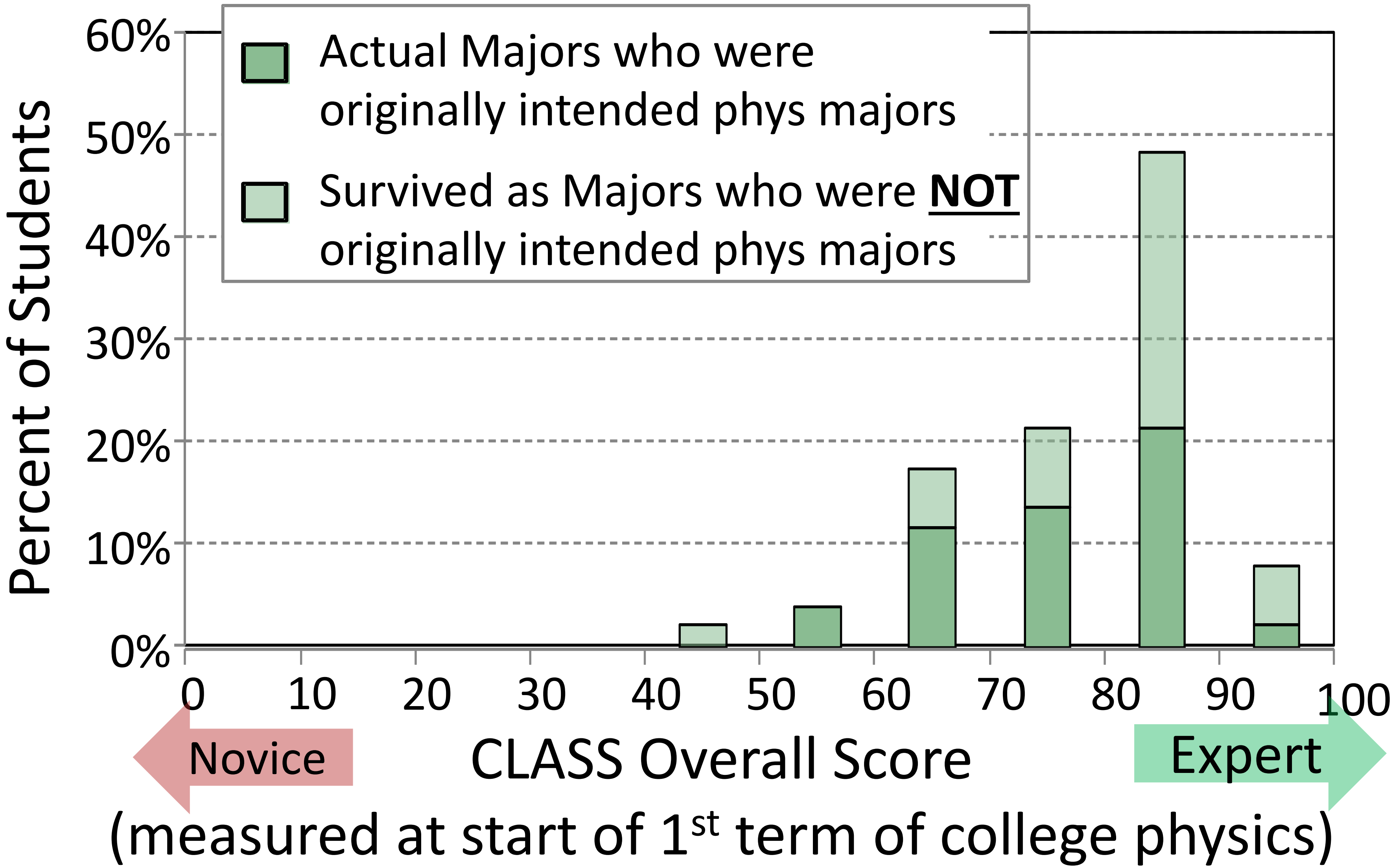
Student Perceptions/Beliefs

Kathy Perkins, M. Gratny



(measured at start of 1st term of college physics)

Student Beliefs



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 $\Rightarrow$ 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$\Rightarrow$ little benefit, student resentment.

Used/perceived to enhance engagement, communication, and learning $\Rightarrow$ 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

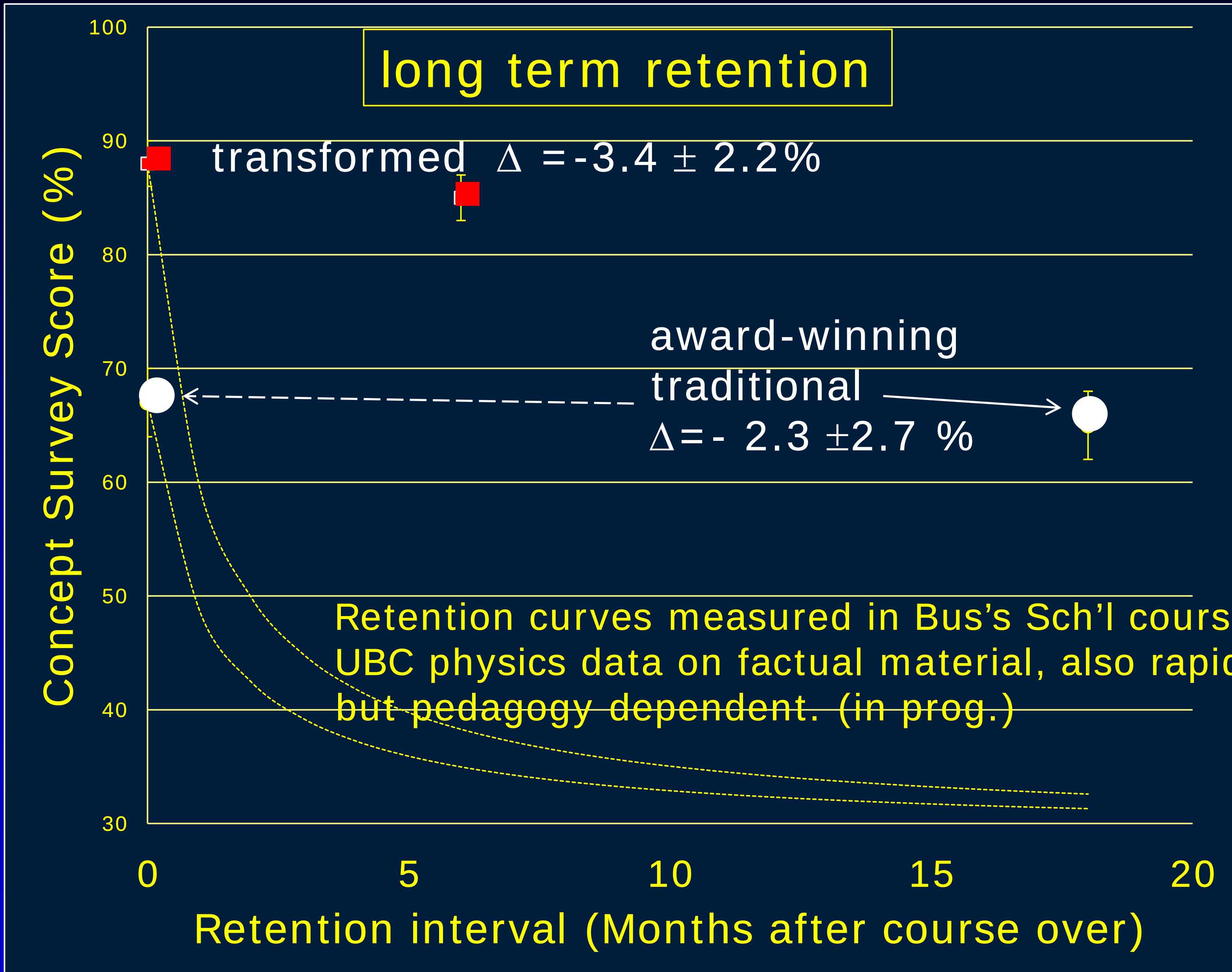
Benefits to interrupting lecture with challenging conceptual question with student-student discussion

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.


long term retention
transformed Δ =-3.4 ± 2.2%
award-winning
traditional
Δ=- 2.3 ±2.7 %
Retention curves measured in Bus's Sch'l course.
UBC physics data on factual material, also rapid drop
but pedagogy dependent. (in prog.)
Concept Survey Score (%)
100
90
80
70
60
50
40
30
0
5
10
15
20
Retention interval (Months after course over)

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

Experienced highly rated instructor-- trad. lecture

II

Very experienced highly rated instructor--trad. lecture

wk 1-11

identical on everything diagnostics, midterms, attendance, engagement

wk 1-11

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)%**

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)

<u>Institutionalizing improved research-based teaching practices.</u> *(From bloodletting to antibiotics)*

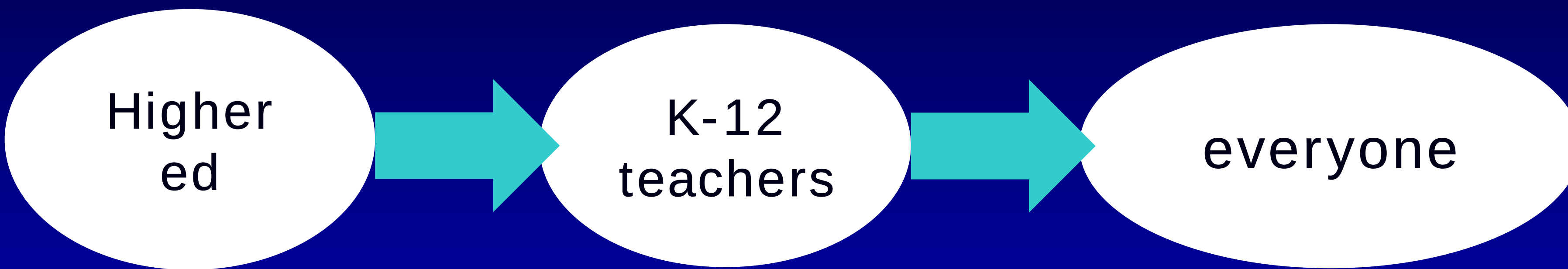
Goal of Univ. of Brit. Col. CW Science Education Initiative *(CWSEI.ubc.ca) &* Univ. of Col. Sci. Ed. Init.

- 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.

“ 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

Condition	*Noted in Study Work*	*Missed in Study Work*
Analyze + lecture	.60	.26
Analyze + analyze	.18	.15
Summarize + lecture	.23	.06