

*Taking a scientific approach to science & eng. education**

and most other subjects

Carl Wieman

Stanford University

Department of Physics and Grad School of Education

*copies of
slides to be
available*

Boeing Colloq.
website

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

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!

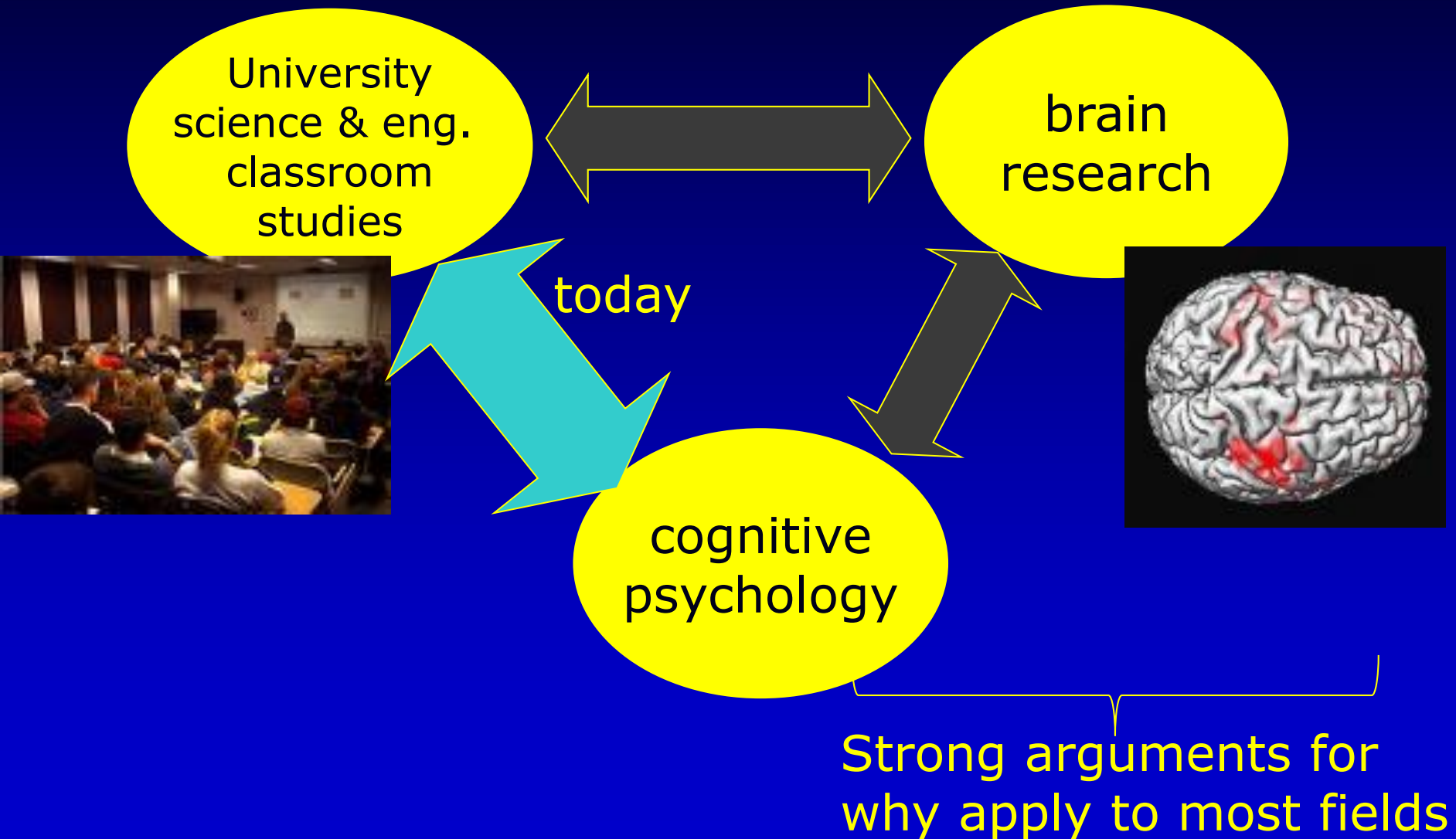
?????? ~ 25 years ago

Research on how people learn, particularly physics
(*UW pioneers*)

- explained puzzle
- got me started doing physics/sci ed research--
controlled experiments & data, basic principles!

Major advances past 1-2 decades

⇒ New insights on how to learn & teach complex thinking



change is coming...

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 ...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."

Education goal—

"Thinking/making decisions like an expert"
(e.g. faculty member)

I. What is *"thinking like an expert?"* (sci & eng., ...)

II. How is it learned?

"curriculum" = information students see

"teaching methods" = thinking they learn

III. Applying these learning principles in university classrooms and measuring results

IV. A bit on institutional change, and something faculty can use tomorrow

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, 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 & eng. thinking skills

- Decide: what concepts relevant (*selection criteria*), what information is needed, what irrelevant,
- Decide: what approximations are appropriate.
- " : potential solution method(s) to pursue.
- " : best representations of info & result (field specific).
-
- " : 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

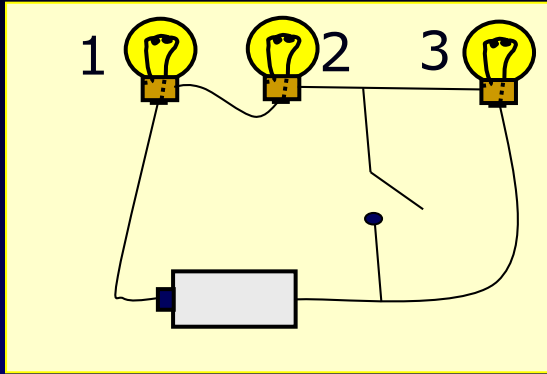
III. How to apply in classroom? *practicing thinking with feedback*

*Example– large intro physics class
(similar chem, bio, comp sci, ...)
“Peer Instruction”*



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:

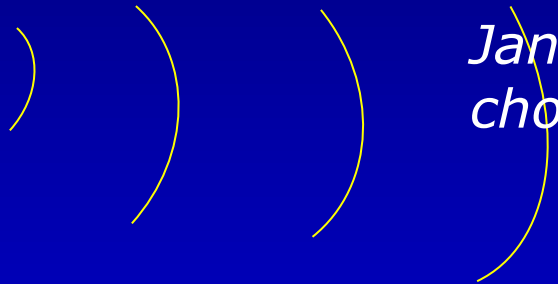
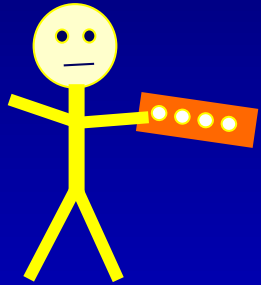


When switch is closed, bulb 2 will

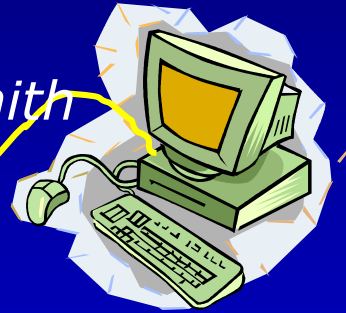
- a. stay same brightness,
- b. get brighter
- c. get dimmer,
- d. go out.

answer & reasoning

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



Jane Smith chose a.



4. Discuss with "consensus group", revote.

Different, enhanced cognitive processing = learning
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

Research on effective teaching & learning

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

Research on effective teaching & learning

*but must have enablers & still
learning how to do most effectively*

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 the discipline &
expertise in teaching it. DBER guides.

III. Evidence from the Classroom

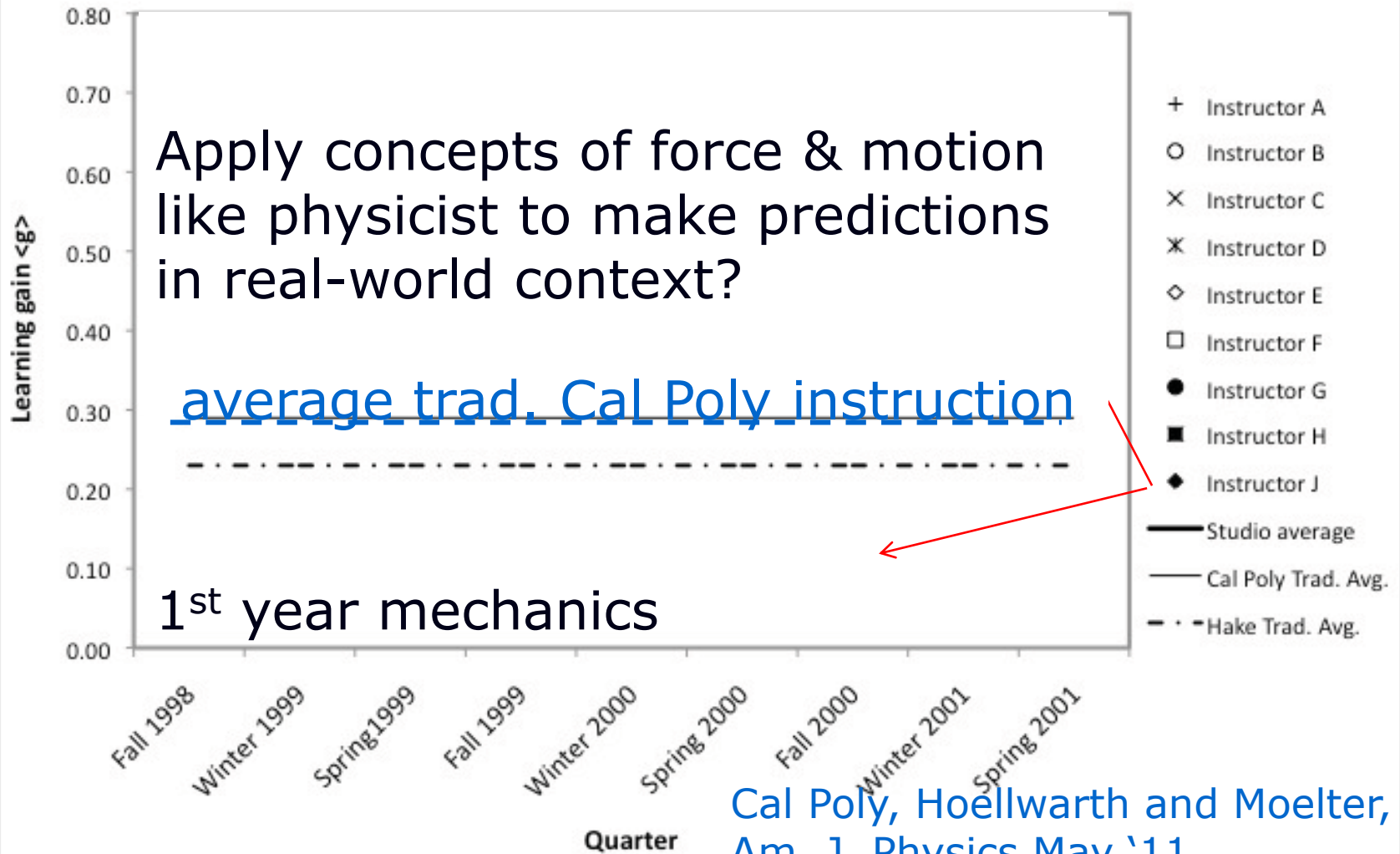
~ 1000 research studies from undergrad science and engineering comparing traditional lecture with “active learning” (or “research-based teaching”).
(many from UW Phys & Bio ed research)

- consistently show greater learning
- lower failure rates
- benefits all, but at-risk more

*A few examples—
various class sizes and subjects*

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

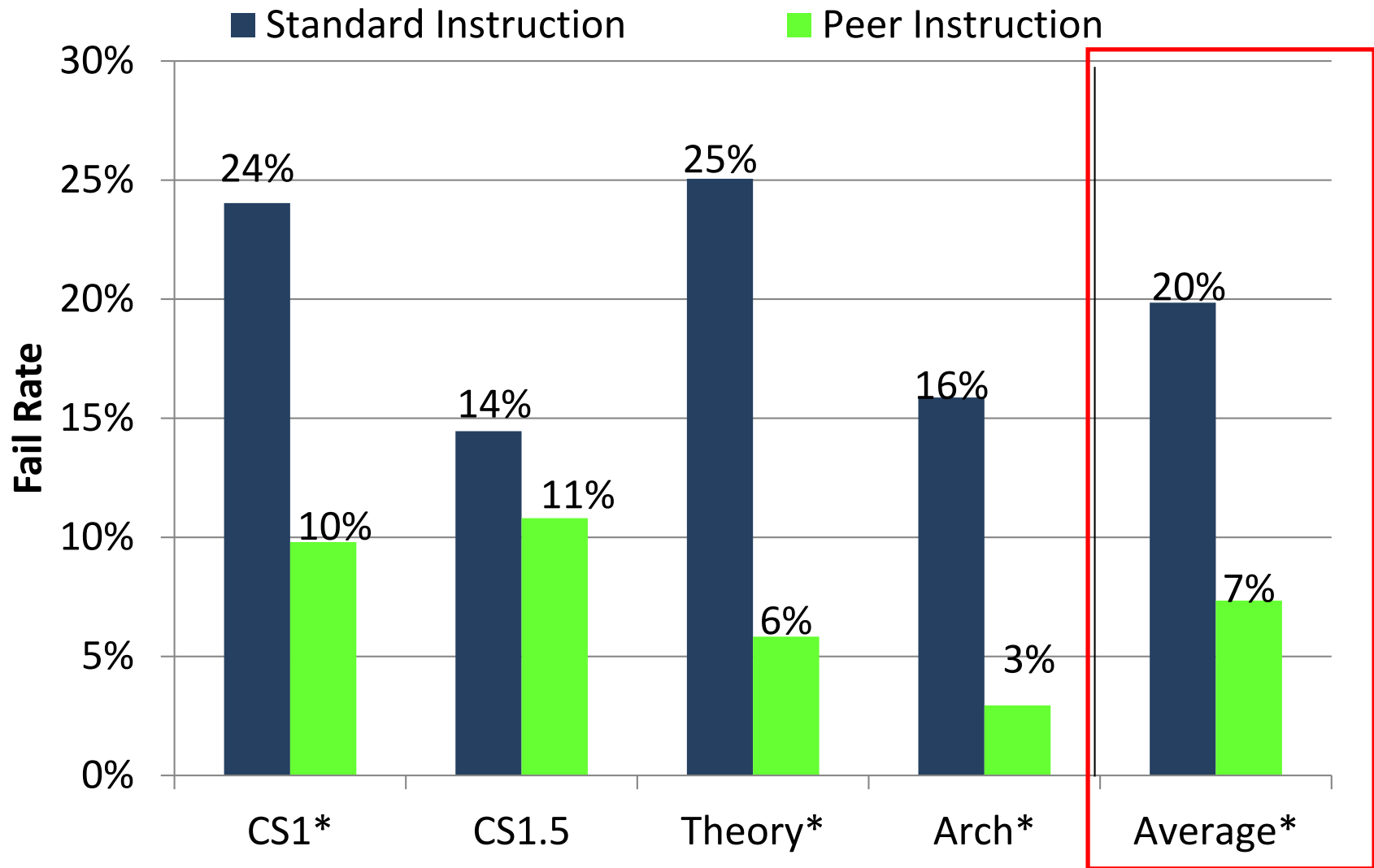
Learning Gain - Studio 1998-2001



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:

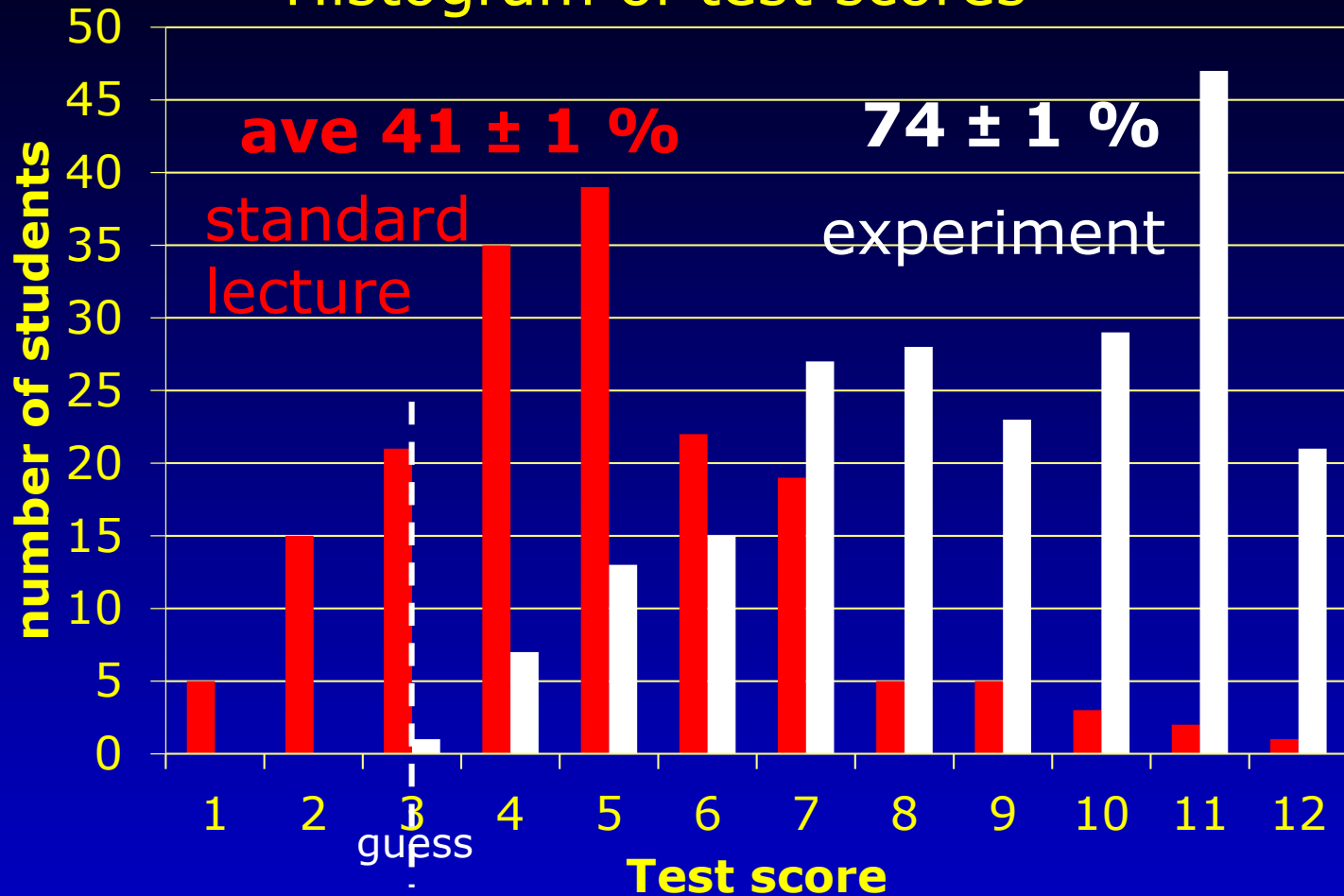
- Same learning objectives
- Same class time (3 hours, 1 week)
- Same exam (jointly prepared)- start of next class
mix of conceptual and quantitative problems

**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)

Histogram of test scores



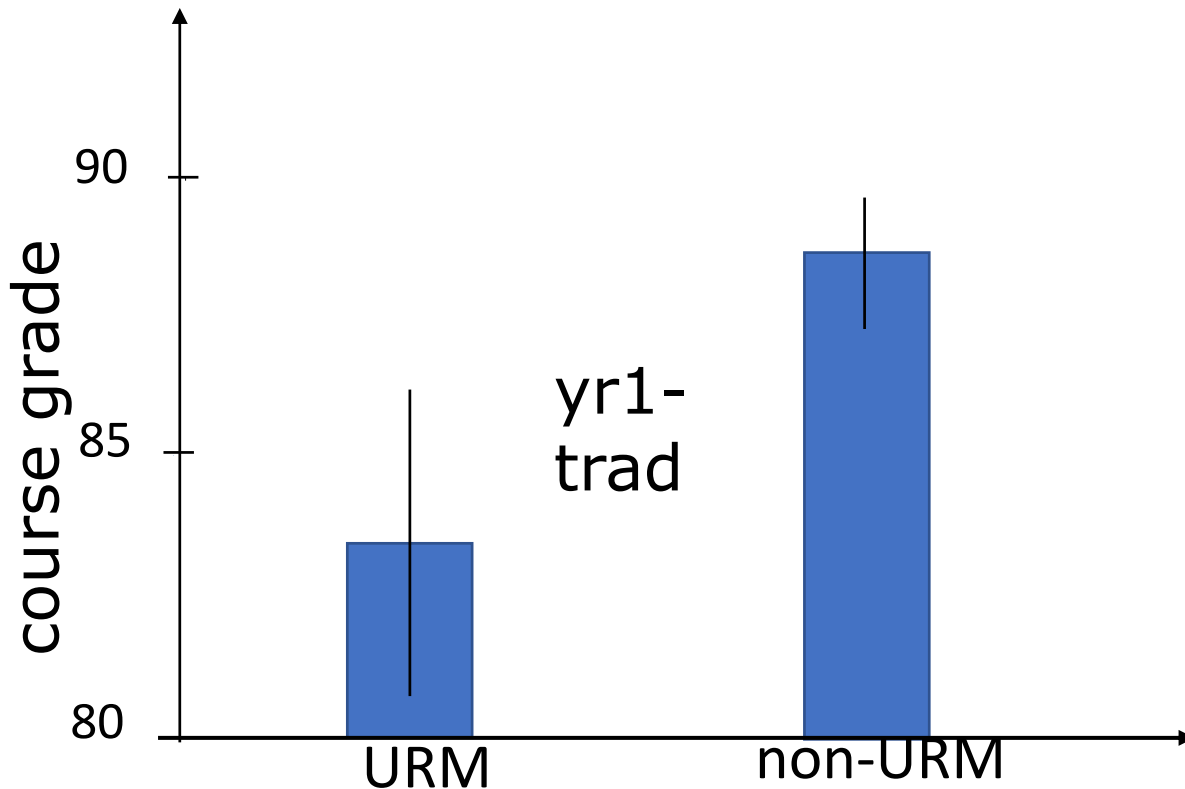
Clear improvement for entire student population.
Engagement 85% vs 45%.

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



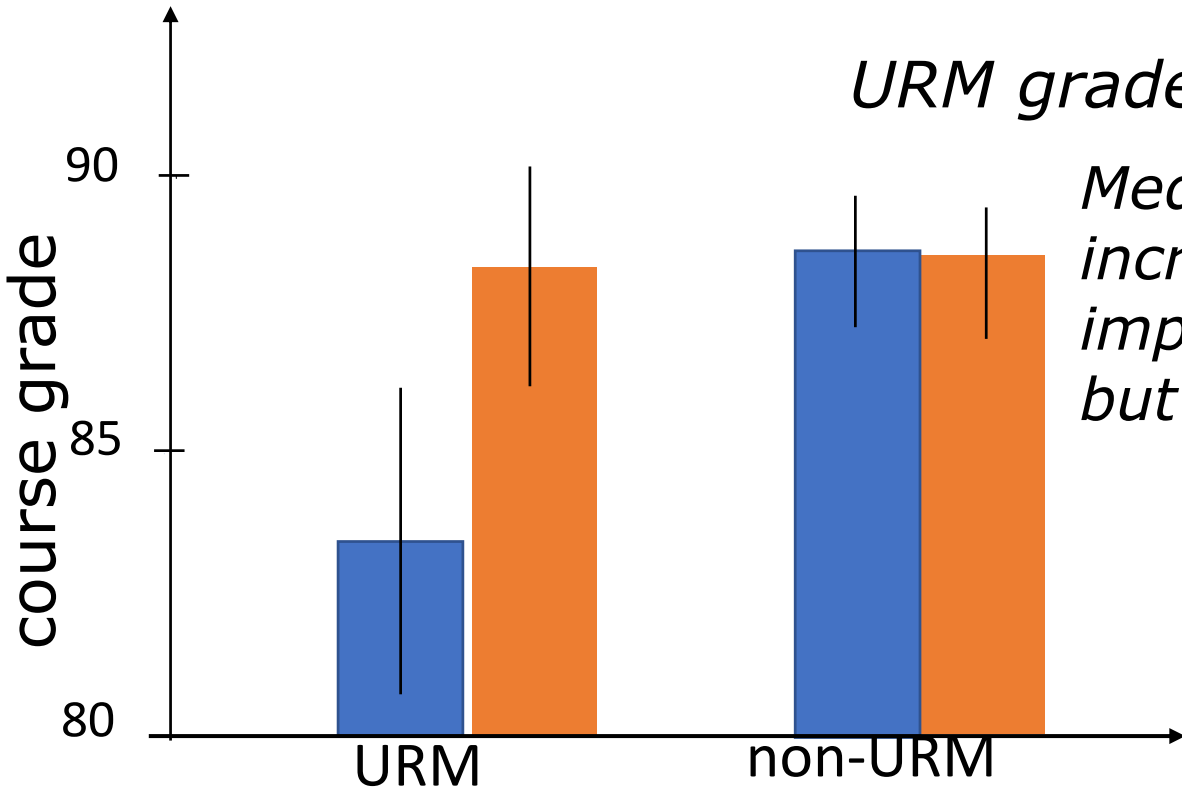
(small correction for incoming prep)

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.

Advanced courses 2nd -4th Yr physics

U. Col, UBC, & Stanford

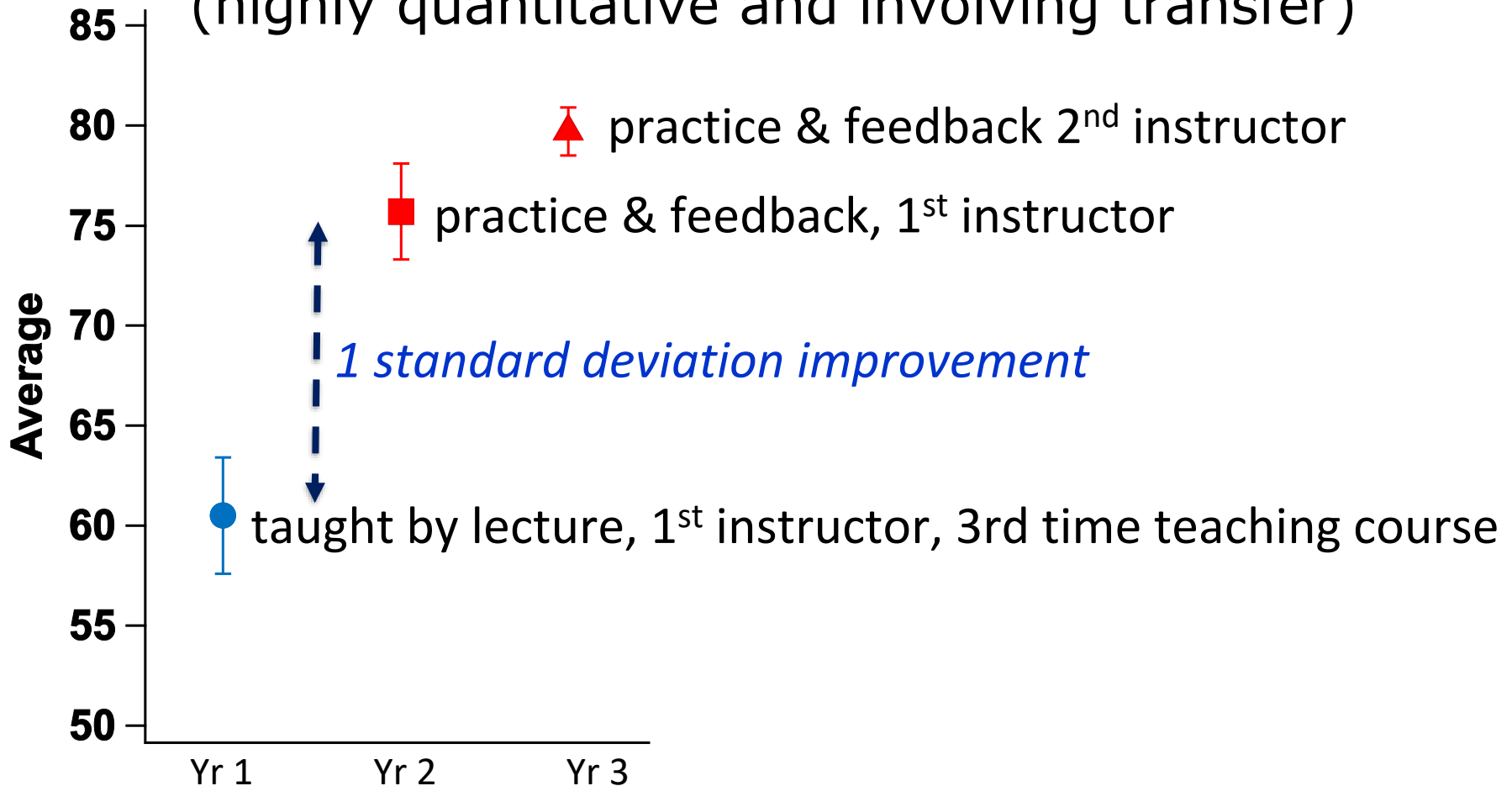


Design and implementation: Jones, Madison, Wieman, Transforming a fourth year modern optics course using a deliberate practice framework, Phys Rev ST – Phys Ed Res, V. 11(2), 020108-1-16 (2015)

Worksheets

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)

Transforming teaching of Stanford physics majors

8 physics courses 2nd-4th year, seven faculty, '15-'17

- Attendance up from 50-60% to ~95% for all.

- Covered as much material

- 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. Teaching much more rewarding, would never go back.

IV. Institutional Change

Better for students & faculty prefer
(when learn the necessary expertise, ~50 hours)

How to make the norm?

For administrators:

What universities and departments can do.
Experiment on large scale change of teaching.

~ 250 sci faculty & 200,000 credit hrs/yr UBC & CU.



Carl Wieman

**IMPROVING HOW
UNIVERSITIES TEACH
SCIENCE** Lessons from the
Science Education
Initiative

Many challenges—top 3

1. Teaching not recognized as expertise...
2. University incentive system— no meaningful evaluation of teaching
3. Organizational structures

Necessary 1st step-- better evaluation of teaching

“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 do only #4

Better way--characterize the practices used in teaching a course, extent of use of research-based methods. 5-10 min/course

“Teaching Practices Inventory”

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

Final note-- learning research you can use tomorrow

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—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.

Conclusion:

Meaningful science education—
Learn to make decisions/choices, not memorize.

Research providing new insights & data on effective teaching and learning—establishes expertise.

Improves student learning & faculty enjoyment.

Good References:

- **NEW** *"Guide to Evidence-Based Instructional Practices in Undergraduate Mathematics"*, Math. Assoc. Am. MAA.org
- 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-- resources** (implementing best teaching methods), references, effective clicker use booklet and videos

slides will be available

~ 30 extras below

Applications of research instructors can use immediately (*some very common but bad practices*)

1. Design of homework and exam problems
2. Organization of how a topic is presented
3. Feedback to students
4. Review lectures (*why often worse than useless*)
(*see cwsei research papers & instructor guidance*)

1. Designing homework & exam problems (& how to improve)

What expertise being practiced and assessed?

- Provide all information needed, and only that information, to solve the problem
- Say what to neglect
- *Possible* to solve quickly and easily by plugging into equation/procedure from that week
- Only call for use of one representation
- Not ask why answer reasonable, or justify decisions

Components of expert thinking:

- ~~• recognizing relevant & irrelevant information~~
- ~~• select and justify simplifying assumptions~~
- ~~• concepts and models + **selection criteria**~~
- ~~• moving between specialized representations
(graphs, equations, physical motions, etc.)~~
- ~~• Testing & justifying if answer/conclusion reasonable~~

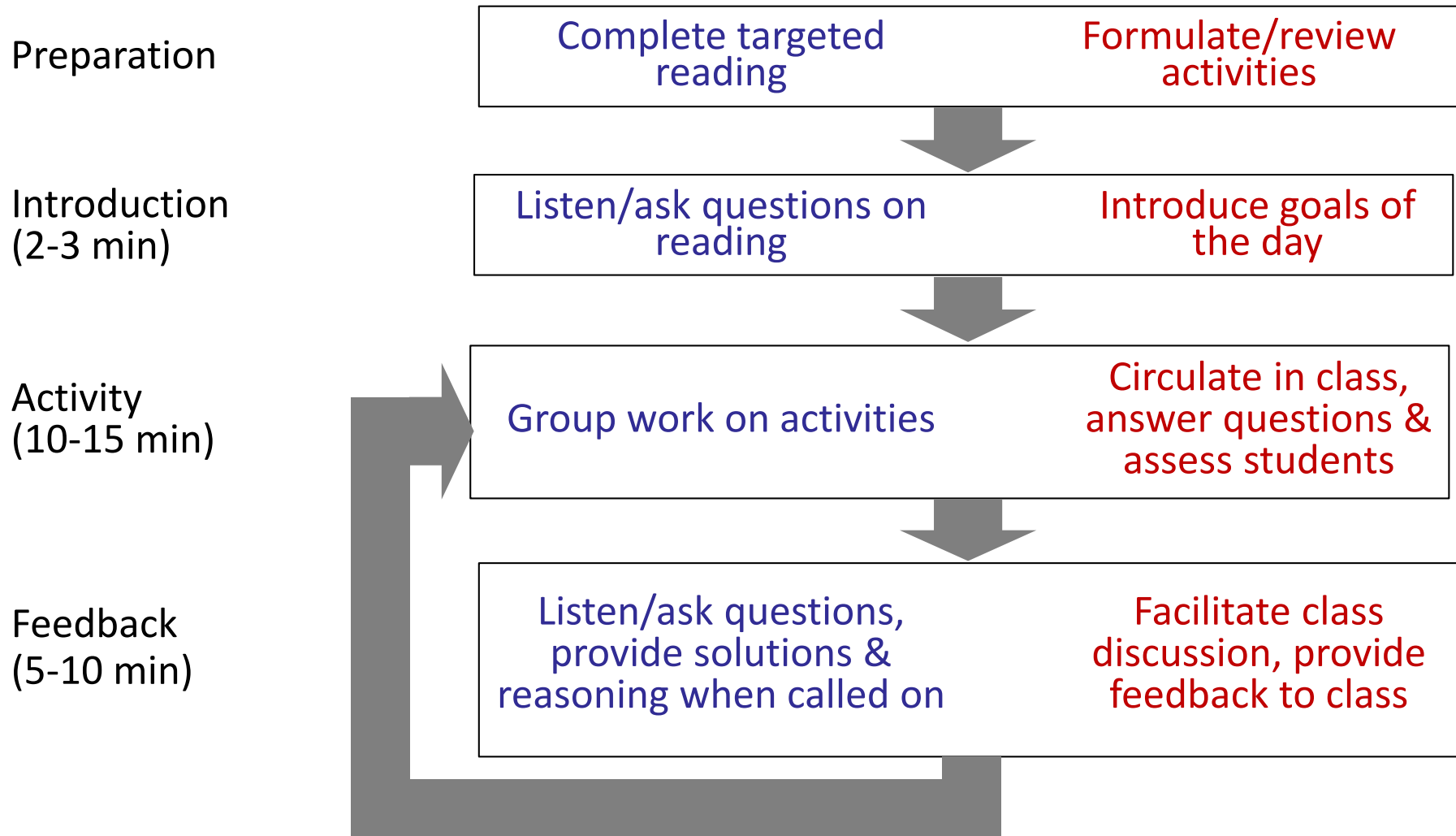
How to improve? Don't do the bad stuff.

Orchestration of active learning class where students are usually doing worksheets in groups of 3-4 at moveable table

Actions

Students

Instructors



3. Feedback to students

Standard feedback—"You did this problem 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
- how to improve
- learner acts on feedback.

Building good feedback into instruction among most impactful things you can do!

“ 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

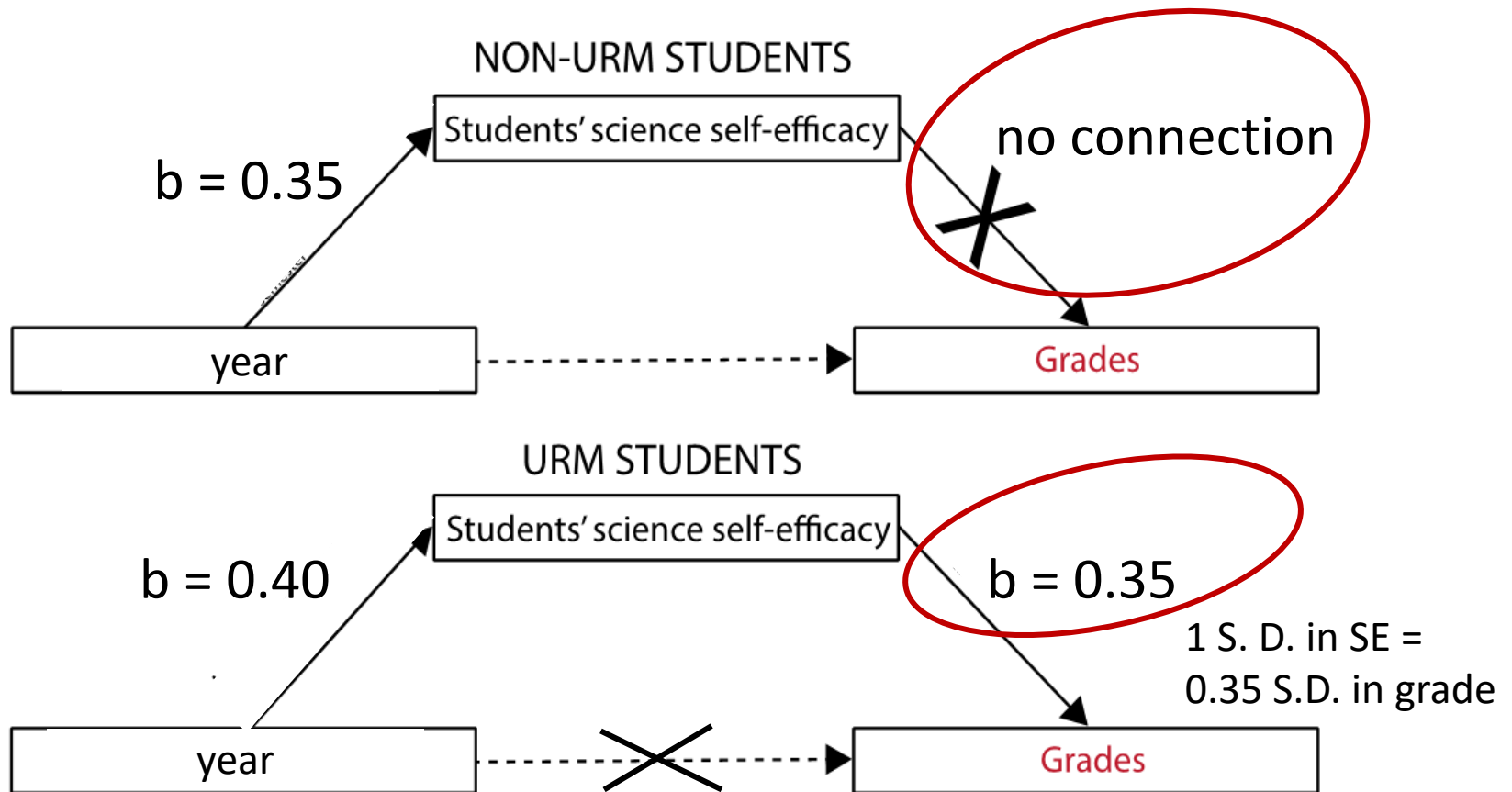
(and now engineering & social sciences)

Try yourself. ~ 10 minutes to complete.

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

Provides detailed characterization of how course is taught

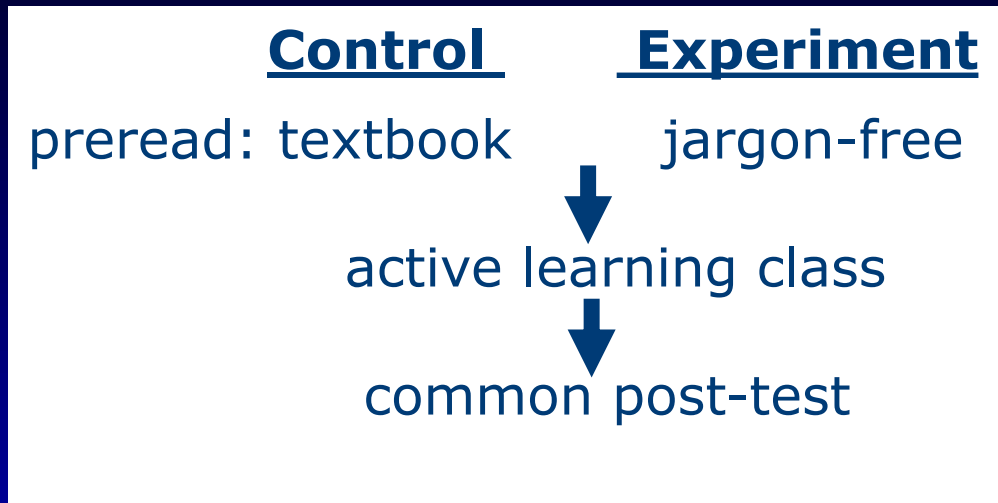
Do full mediation analysis to find out (*large N!*)



Improvement driven by improved self-efficacy for URM students
Not by greater sense of belonging.

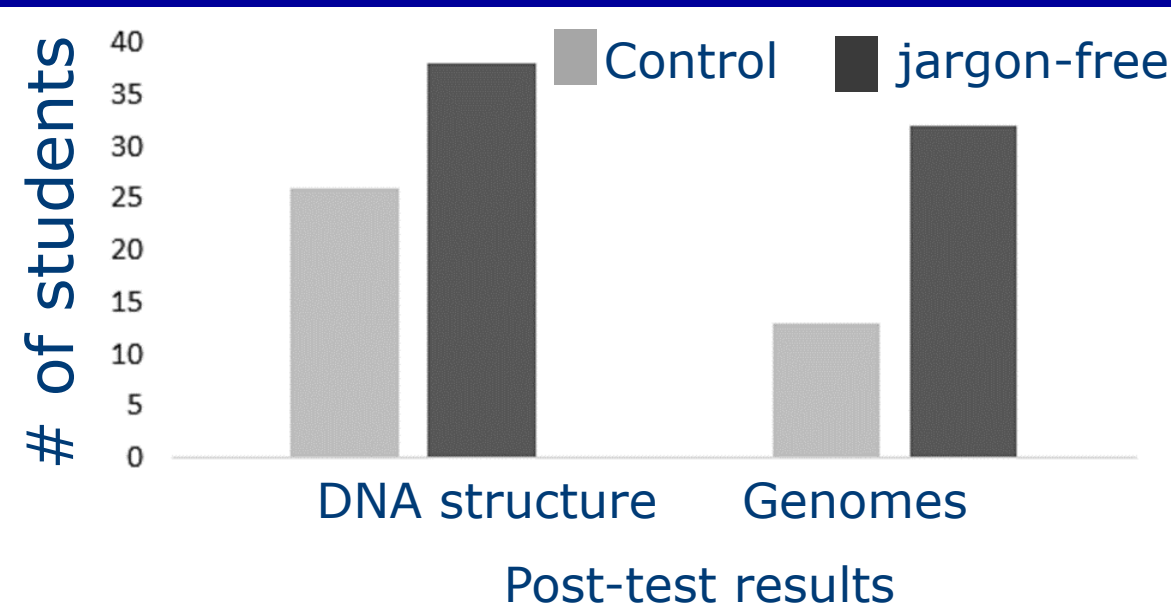
Valuable to understand mechanism. Value of complex stats.

Biology Jargon bogs down working memory, reduces learning?



“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**

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)

Effective teacher—

- Designing suitable practice tasks
- Providing timely guiding feedback
- Motivating

("cognitive coach")

requires expertise in the content!

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**

*slides to be
provided*

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

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.

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

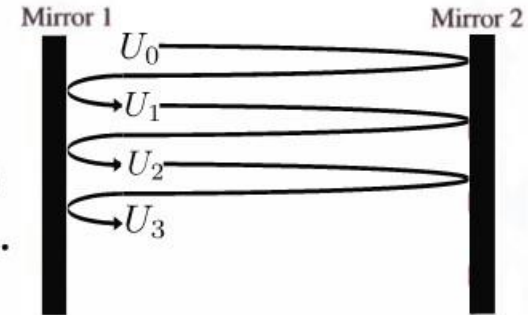
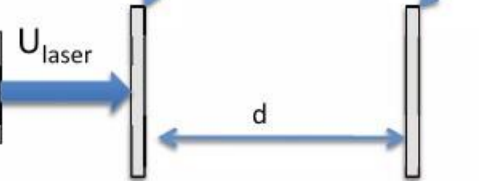
Lecture Notes Converted to Activities

3) Consider this optical setup

Laser with tunable frequency

mirror with r_1 field reflectivity & t_1 field transmission

mirror with r_2 field reflectivity



Steck writes the right moving wave amplitude in the cavity as

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

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

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

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)

Stanford Active Learning Physics courses (all new in 2015-16)

2nd-4th year physics courses, 6 Profs

| | | | | |
|----------|----------------|----------------|----------|--|
| PHYS 70 | Modern Physics | Wieman | Aut 2015 | |
| PHYS 120 | E&M I | Church | Win 2016 | |
| PHYS 121 | E&M II | Hogan | Spr 2016 | |
| PHYS 130 | Quantum I | Burchat | Win 2016 | |
| PHYS 131 | Quantum II | Hartnoll | Spr 2016 | |
| PHYS 110 | Adv Mechanics | Hartnoll | Aut 2015 | |
| PHYS 170 | Stat Mech | Schleier-Smith | Aut 2015 | |

Math classes– similar design

Other types of questions---

- What is next (or missing) step(s) in proof?
- What is justification for (or fallacy in) this step?
- Which type of proof is likely to be best, and why?
- Is there a shorter/simpler/better solution? Criteria?

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.



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 \Rightarrow 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

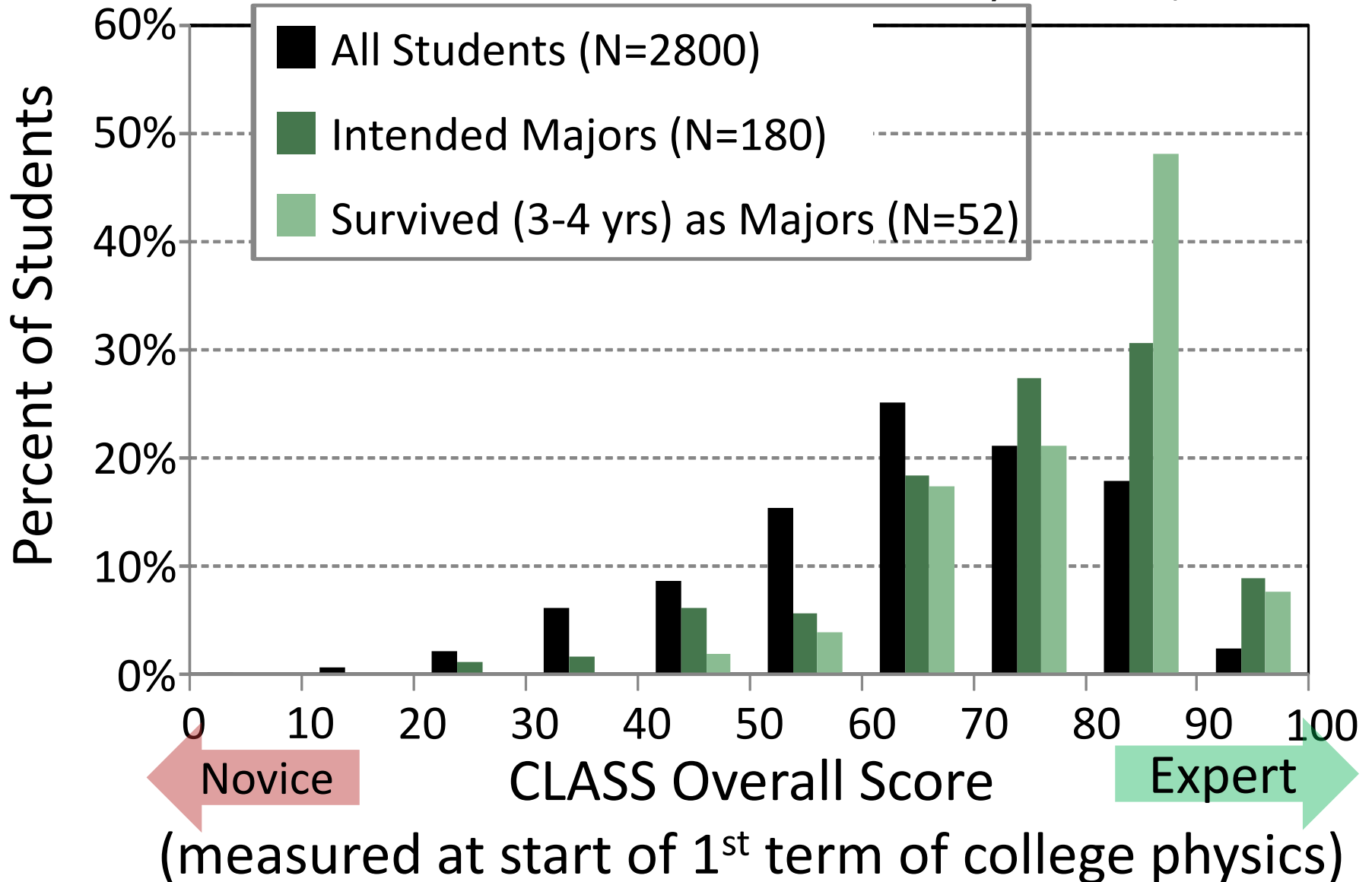
recent research ⇒ changes in instruction that
achieve positive impacts on perceptions

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

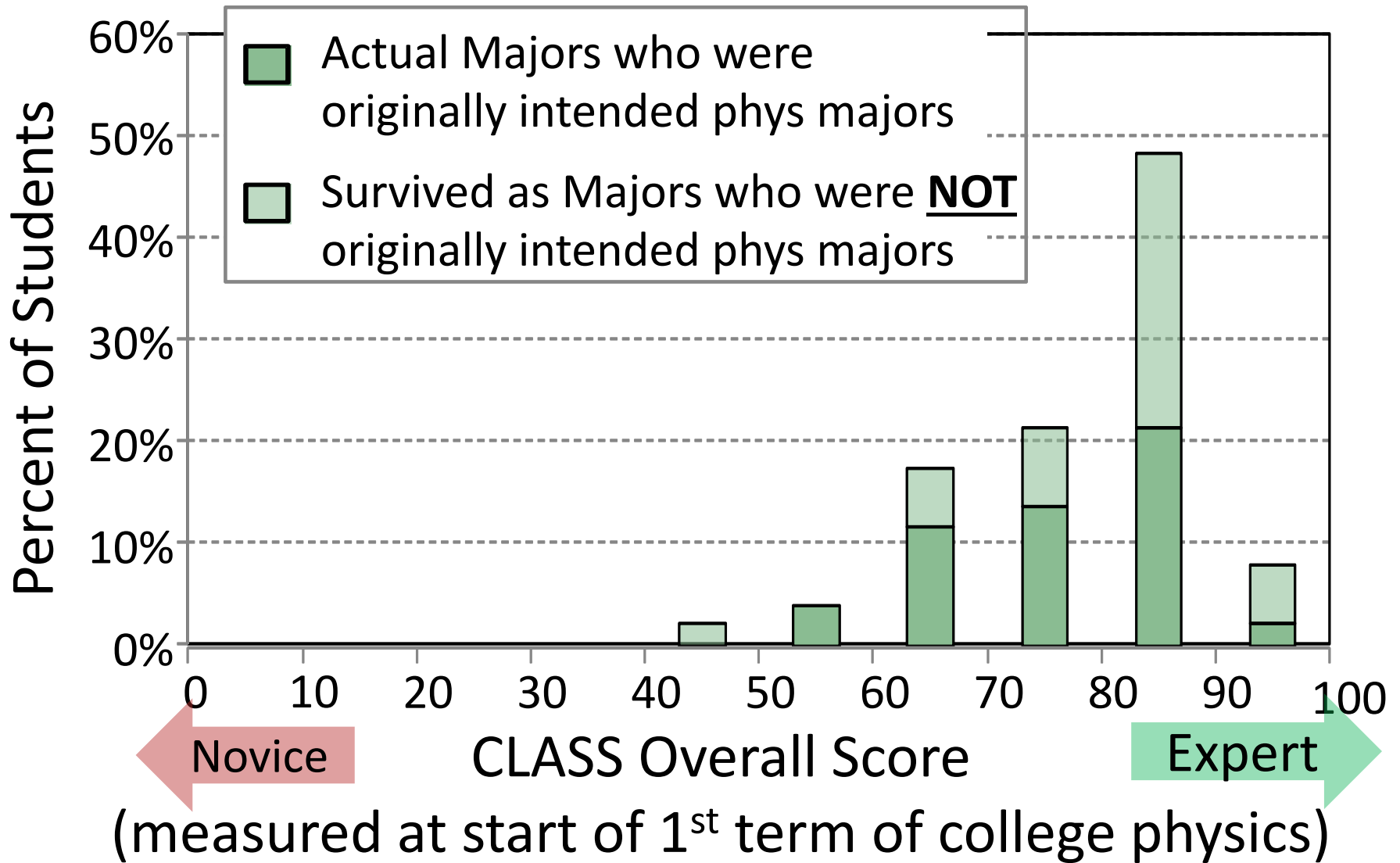
- process of science much more explicit (model development, testing, revision)
- real world connections up front & explicit

Student Perceptions/Beliefs

Kathy Perkins, M. Gratny

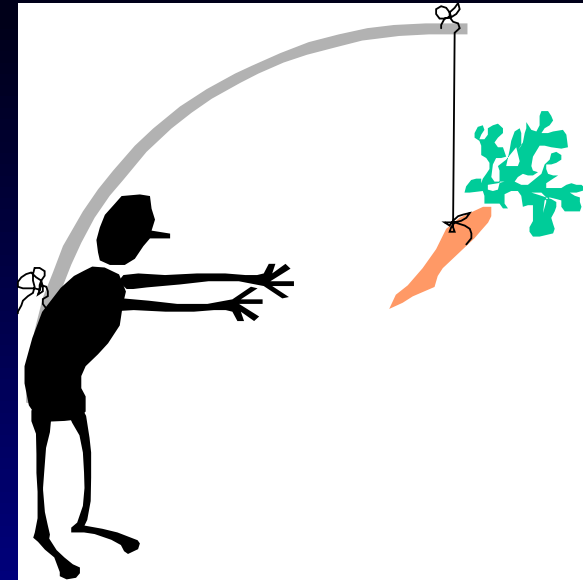


Student Beliefs



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.

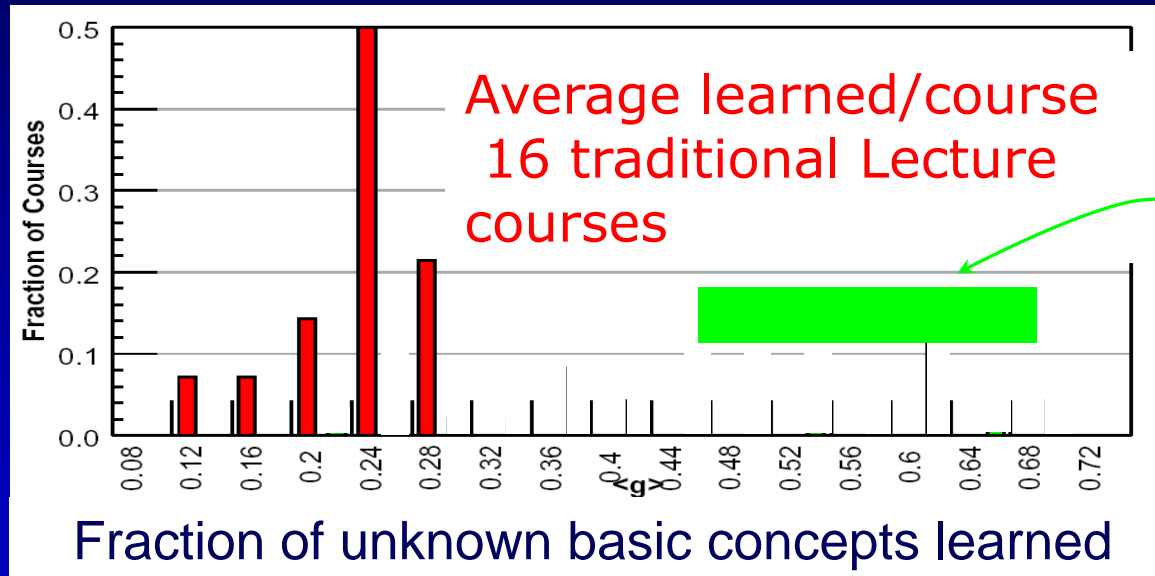
Instructor listen in on discussion. Can understand and guide much better.

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)

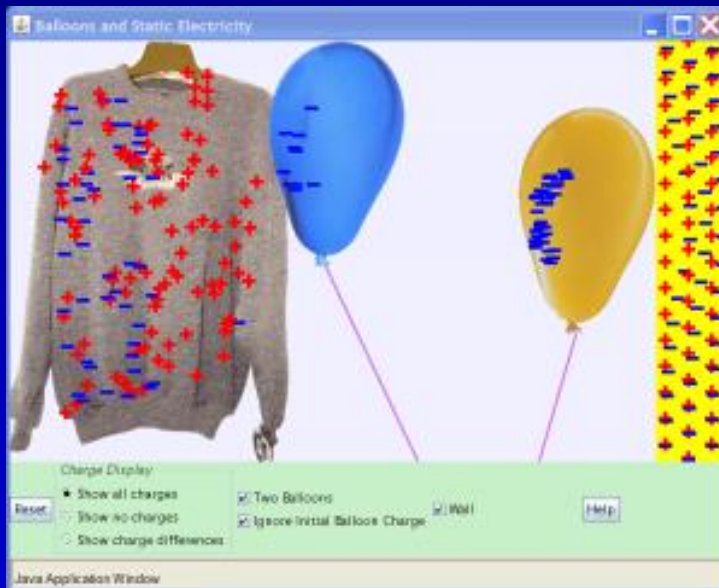


improved methods

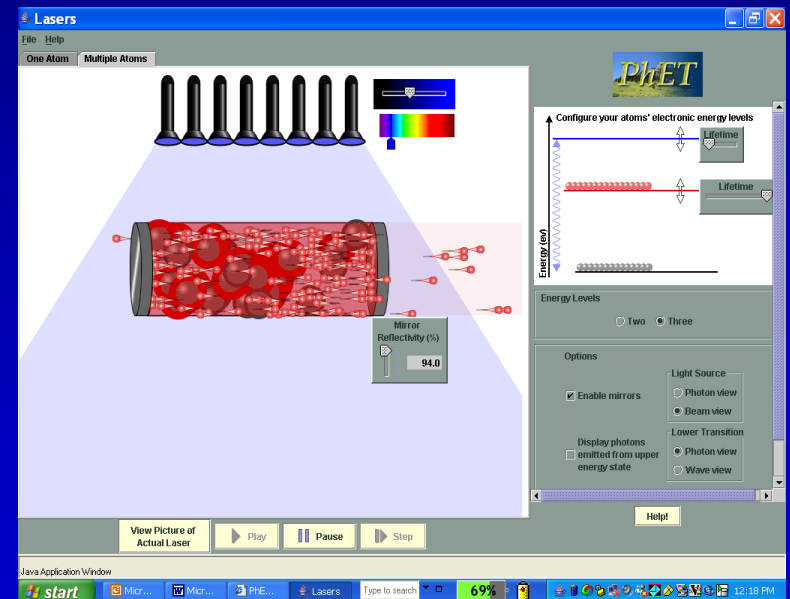
On average learn <30% of concepts did not already know.
Lecturer quality, class size, institution,...doesn't matter!

Highly Interactive educational simulations--
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

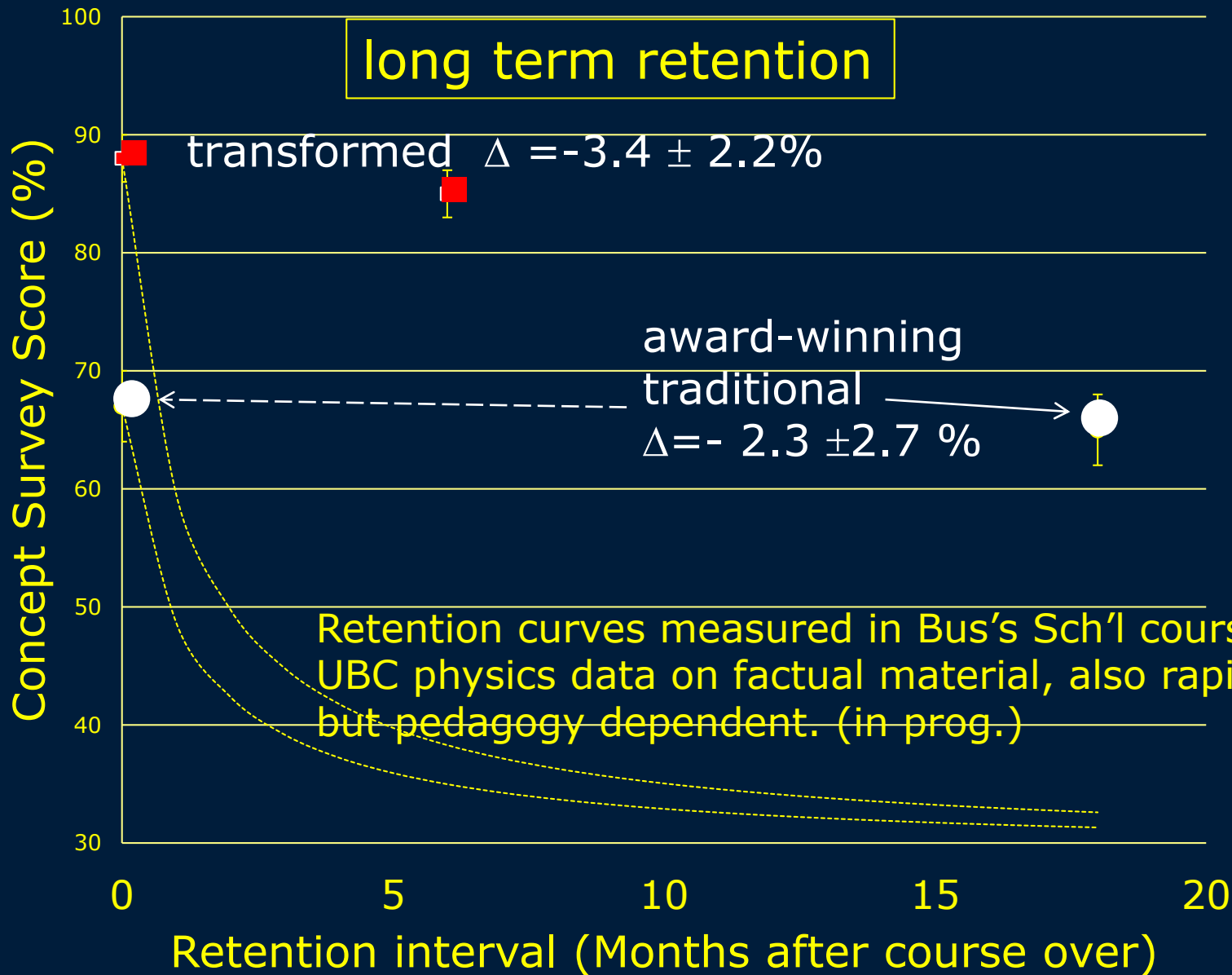
Used/perceived as expensive attendance and testing device ⇒ little benefit, student resentment.

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

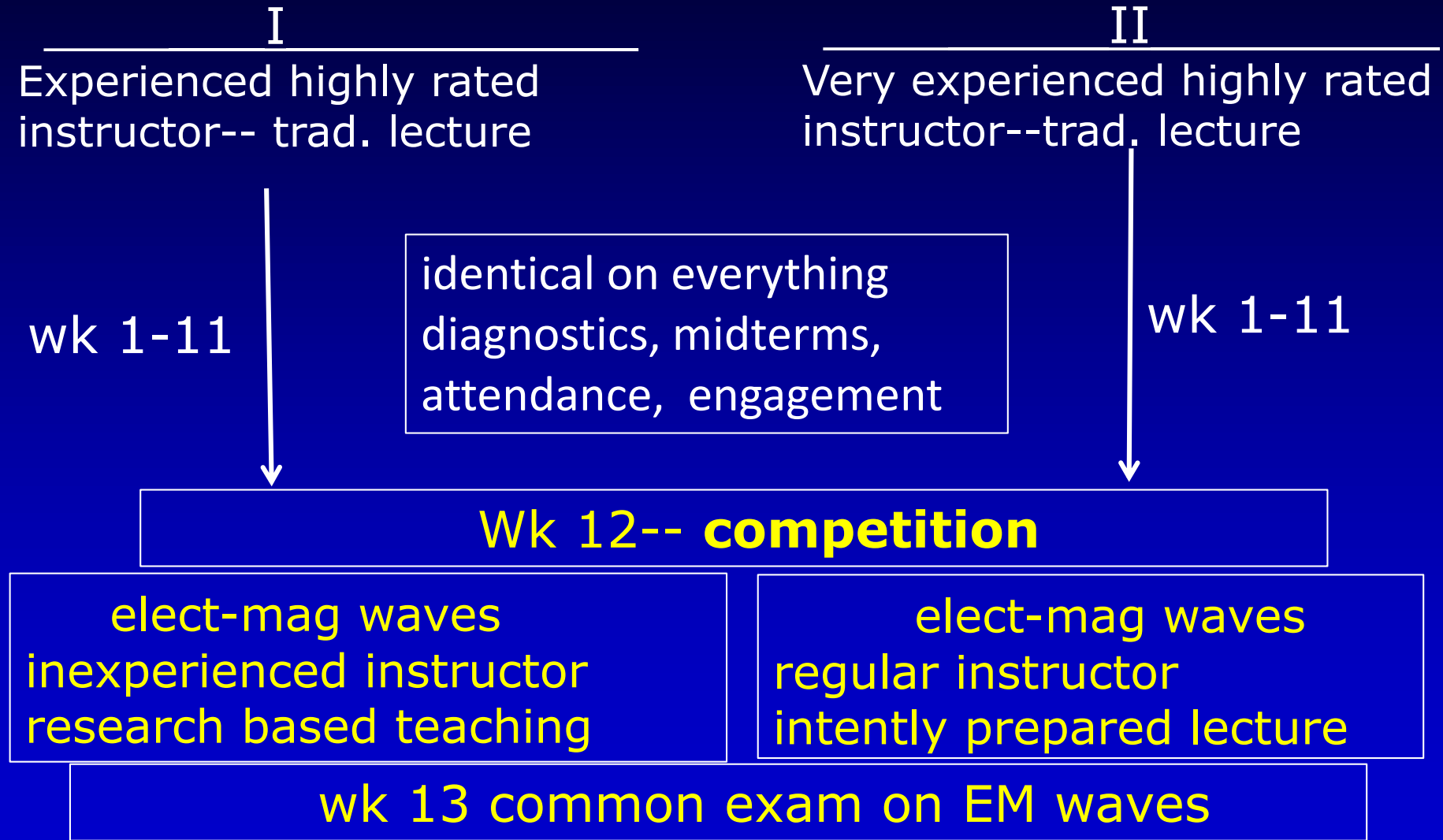
long term retention



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)



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

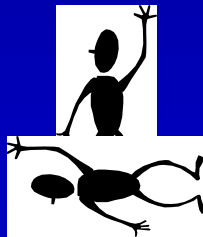
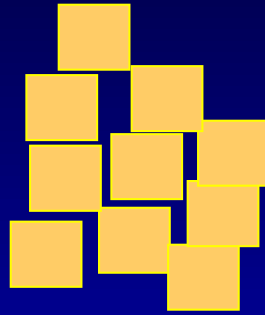
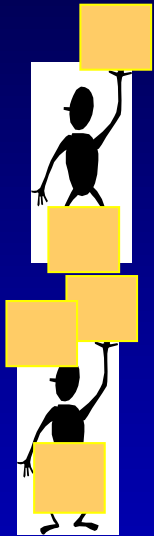
“Invention activities”-- practice coming up with mechanisms to solve a complex novel problem. Analogous to mechanism in cell.

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)

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

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.

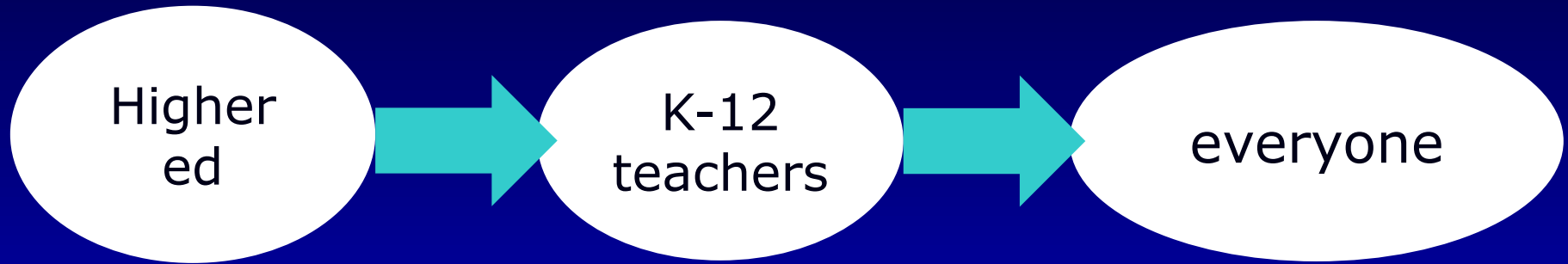
- Departmental level, widespread sustained change at major research universities
⇒ scientific approach to teaching, all undergrad courses
- Departments selected competitively
- Substantial one-time \$\$\$ and guidance

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.

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. ...**