Taking a scientific approach to Physics education*

and most other subjects

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

copies of slides to be available

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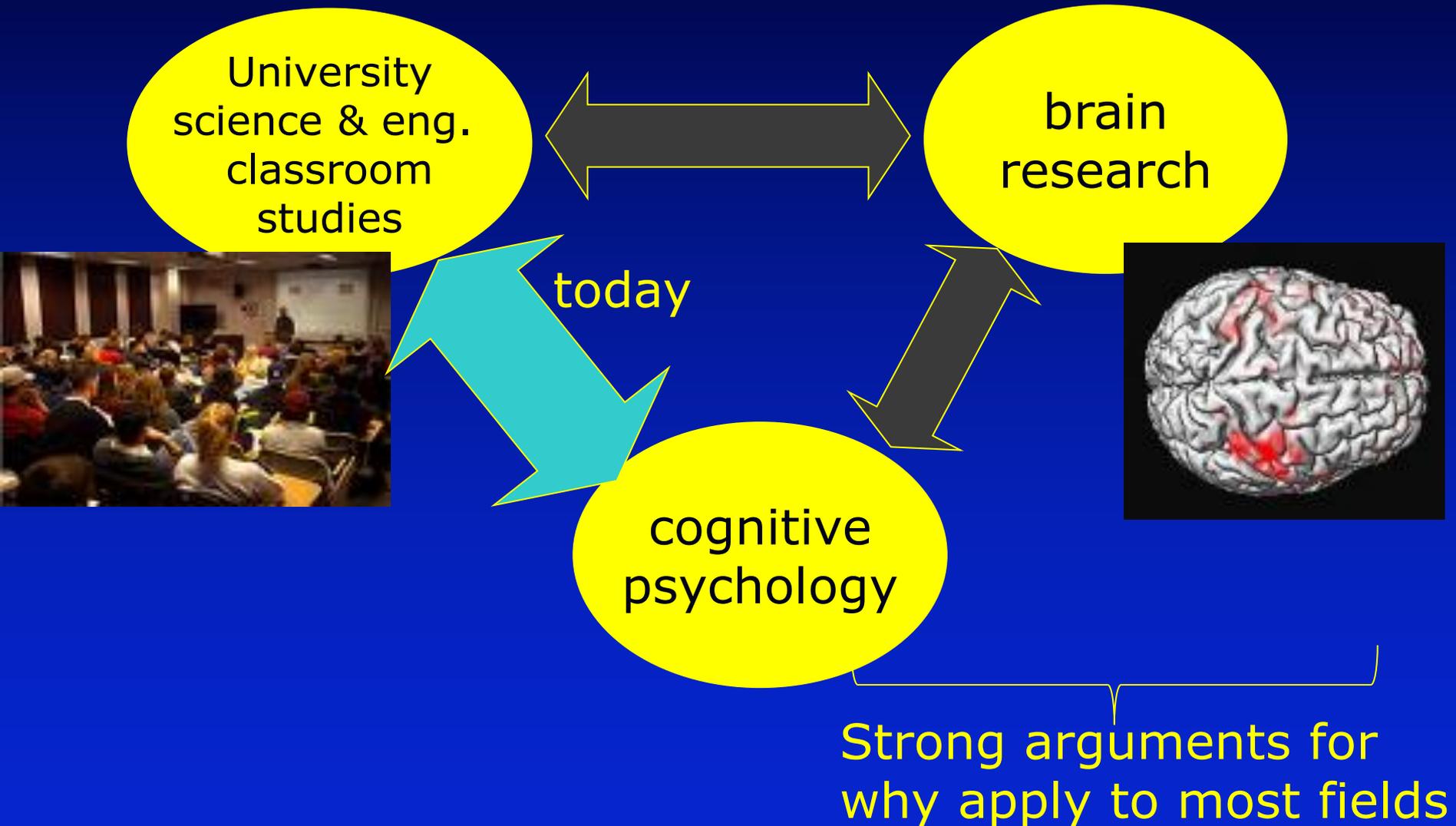Come into lab clueless about physics?

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!

Major advances past 1-2 decades
⇒ Bringing together research fields

University science & eng. classroom studies

brain research

today

cognitive psychology

Strong arguments for why apply to most fields

Physics/Science education goal—
Not all become physicists, ...
All learn to make <u>better decisions/choices.</u>
"Thinking like a physicist"

I. What is *"thinking like a physicist/expert?"*

II. How is it learned?
(curriculum determines what topics students see, pedagogy determines what thinking they learn)

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

IV. A bit on institutional change if time

V. Something instructors can use in next class.

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, mental models
(& criteria for when apply)

good for nails
bad for windows

Expert has rich array of predictive mental models, analogous to set of tools for different functions. Labelled by basic features and where to use.

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, mental models

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

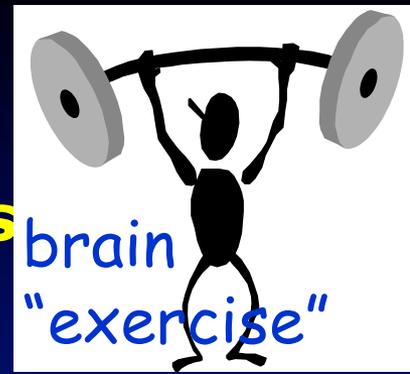New ways of thinking-- everyone requires MANY hours of intense practice to develop.

Brain changed—*rewired, not filled!*

II. Learning expertise*--
Challenging but doable tasks/questions
- Practicing specific thinking skills
- Feedback on how to improve
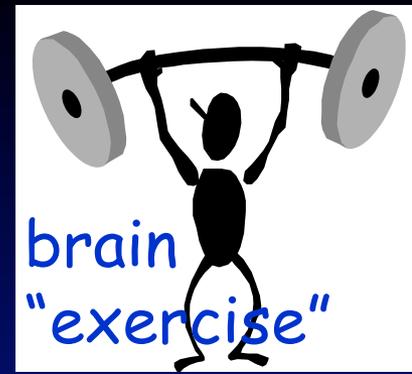
Physics thinking skills–

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

brain "exercise"

Physics/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.
- " : 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, ...)

<u>Teaching about electric current & voltage</u>

1. Preclass assignment--Read pages on electric current. Learn basic facts and terminology without wasting class time. Short online quiz to check/reward.
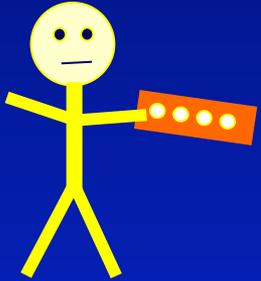
2. Class starts with question:
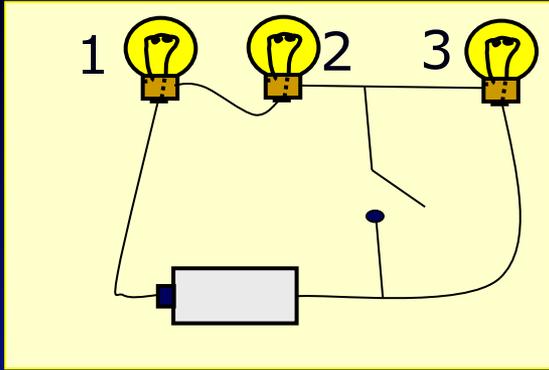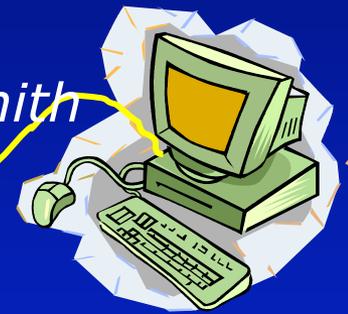
When switch is closed, bulb 2 will
a. stay same brightness,
b. get brighter
c. get dimmer,
d. go out.

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

Homework extends & builds upon

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).*

Requires expertise in the discipline & expertise in teaching it.

disciplinary expertise knowledge & thinking of science
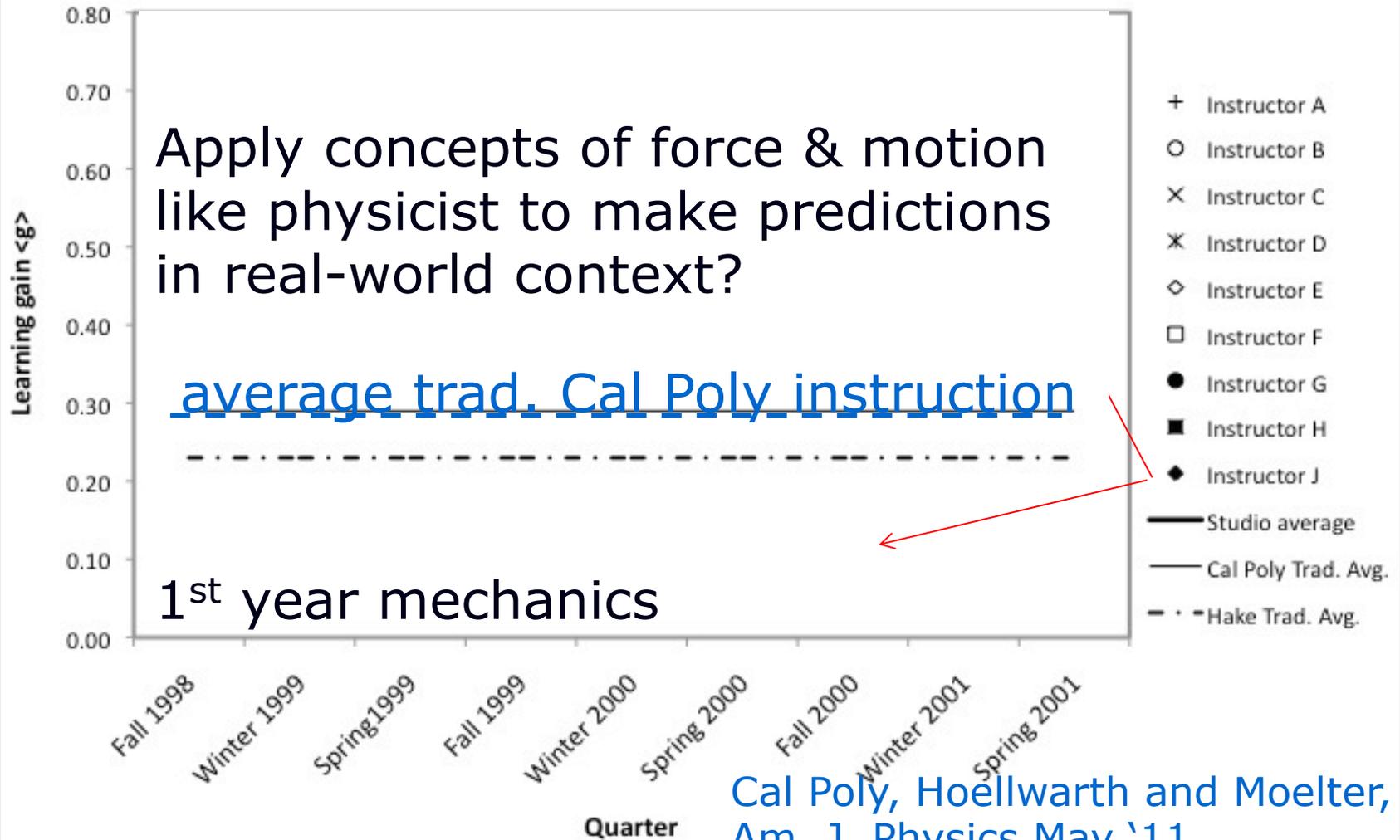
3. Evidence from the Classroom

~ 1000 research studies from undergrad science and engineering comparing traditional lecture
with "scientific teaching".

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

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

A few examples—
various class sizes and subjects

Learning Gain - Studio 1998-2001

Apply concepts of force & motion like physicist to make predictions in real-world context?

average trad. Cal Poly instruction

1st year mechanics

Instructor A
Instructor B
Instructor C
Instructor D
Instructor E
Instructor F
Instructor G
Instructor H
Instructor J
Studio average
Cal Poly Trad. Avg.
Hake Trad. Avg.

Cal Poly, Hoellwarth and Moelter, Am. J. Physics May '11

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*

■ Standard Instruction   ■ Peer Instruction

Fail Rate

CS1*   CS1.5   Theory*   Arch*   Average*
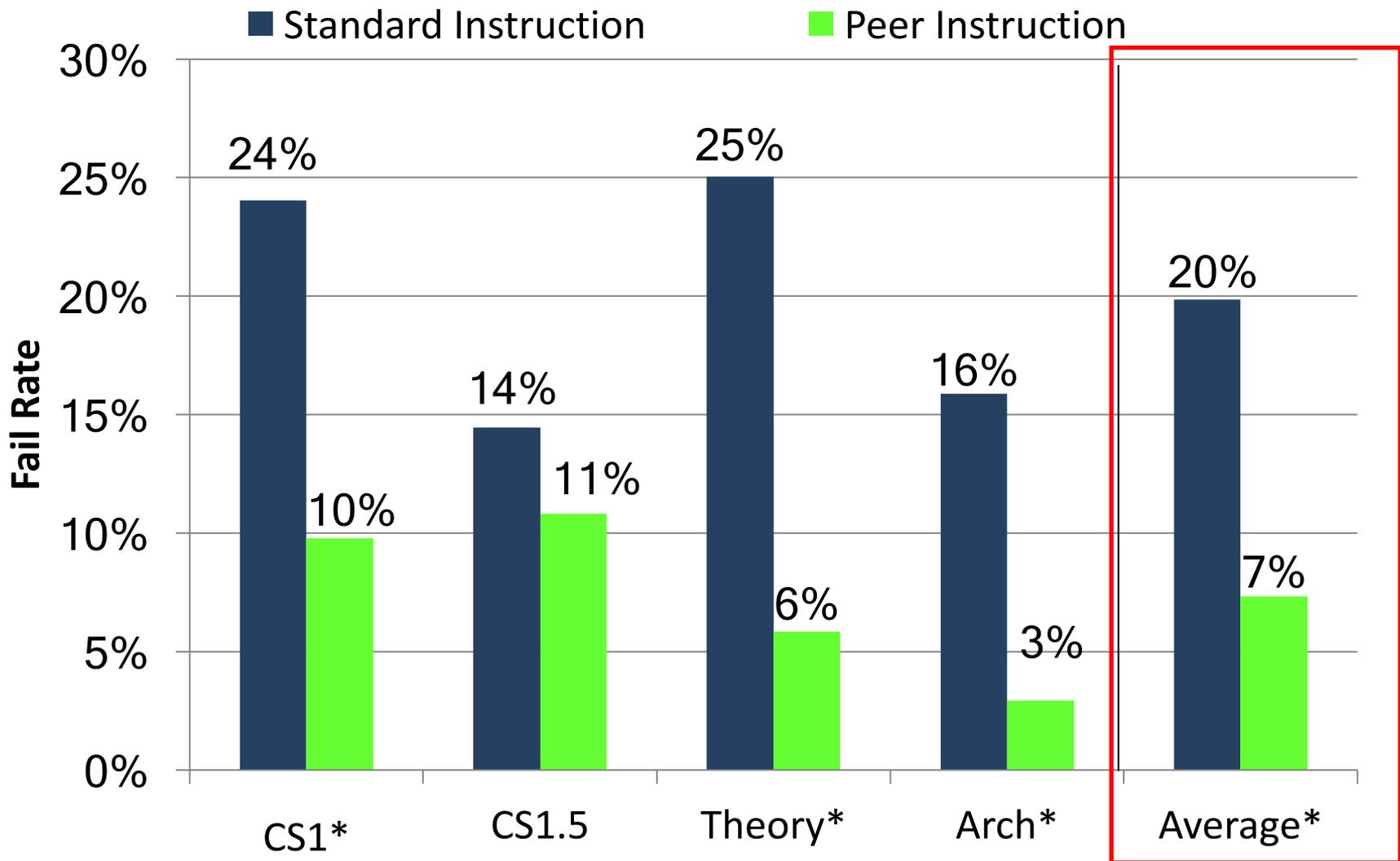
same 4 instructors, better methods = 1/3 fail rate

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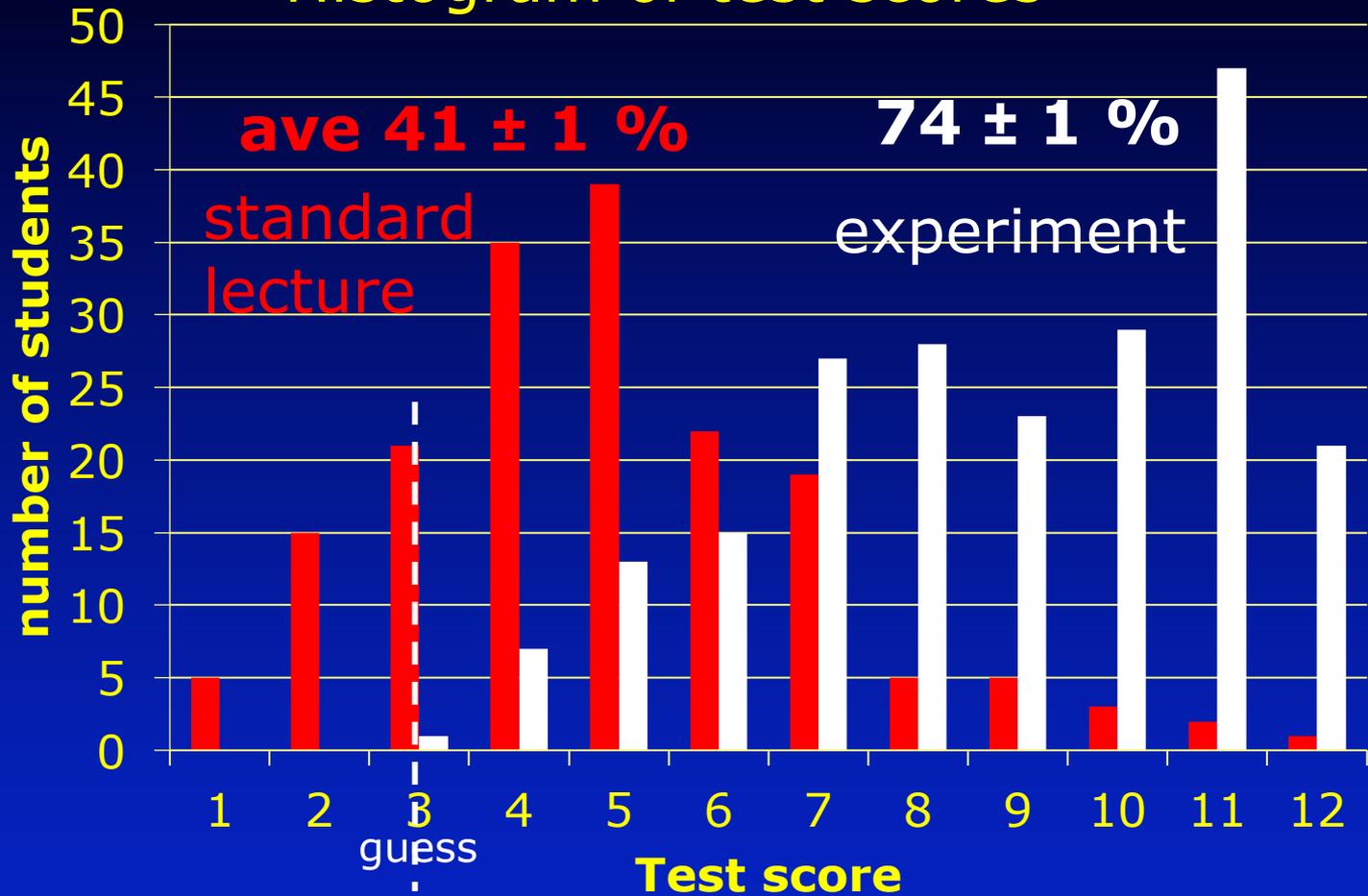
They agreed on:
- Same learning objectives
- Same class time (3 hours, 1 week)
- Same exam (jointly prepared)- start of next class
  mix of conceptual and quantitative problems

*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.
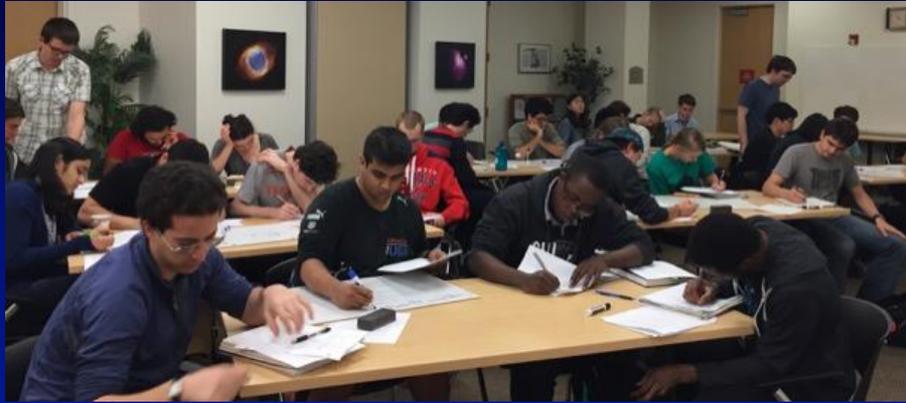(but still talking ~50% of time)

Histogram of test scores

ave 41 ± 1 % 74 ± 1 %

standard lecture experiment

number of students

50
45
40
35
30
25
20
15
10
5
0

1 2 3 4 5 6 7 8 9 10 11 12

guess

Test score

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)

No Prepared Lecture

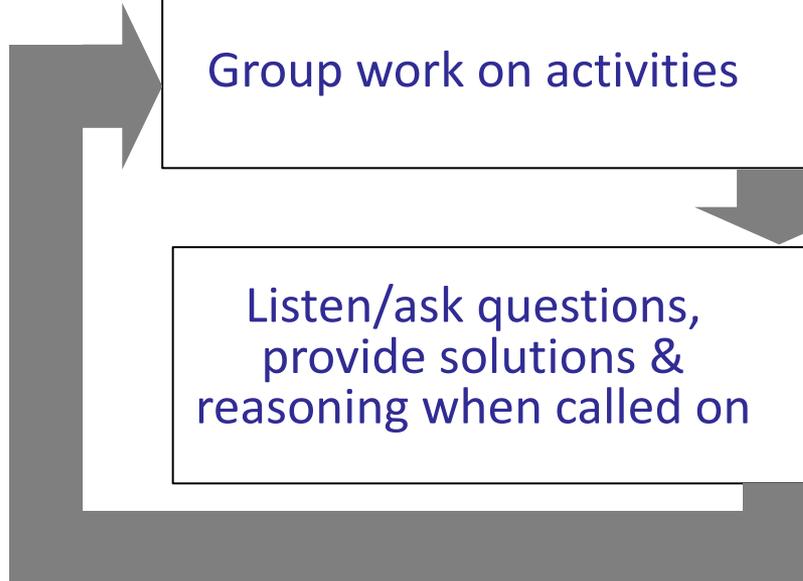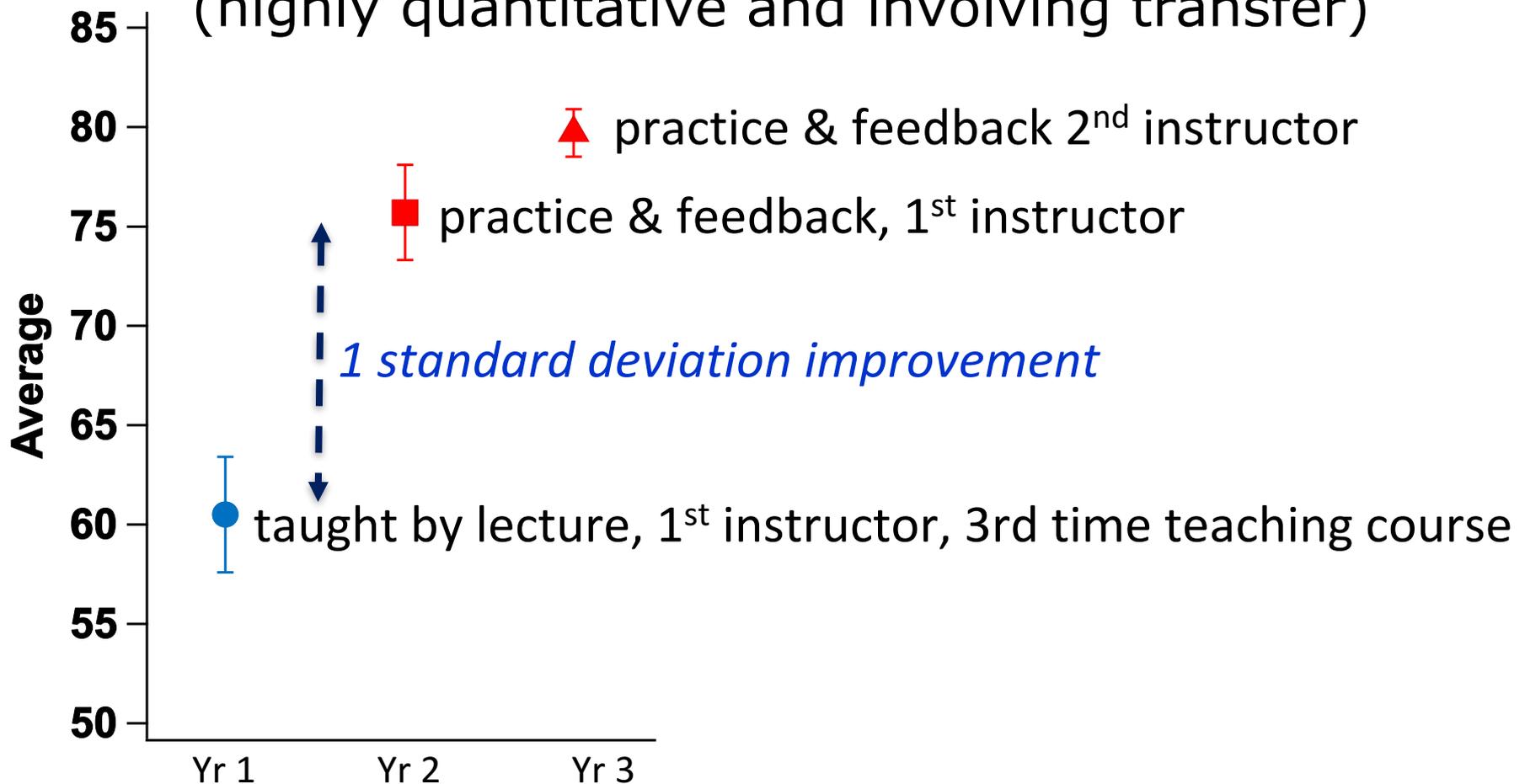| Actions	Students	Instructors
Preparation	Complete targeted reading	Formulate/review activities
Introduction (2-3 min)	Listen/ask questions on reading	Introduce goals of the day
Activity (10-15 min)	Group work on activities	Circulate in class, answer questions & assess students
Feedback (5-10 min)	Listen/ask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

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

▲ practice & feedback 2nd instructor

■ practice & feedback, 1st instructor

1 standard deviation improvement

● taught by lecture, 1st instructor, 3rd time teaching course

Y-axis: **Average** (50, 55, 60, 65, 70, 75, 80, 85)

X-axis: Yr 1, Yr 2, Yr 3

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
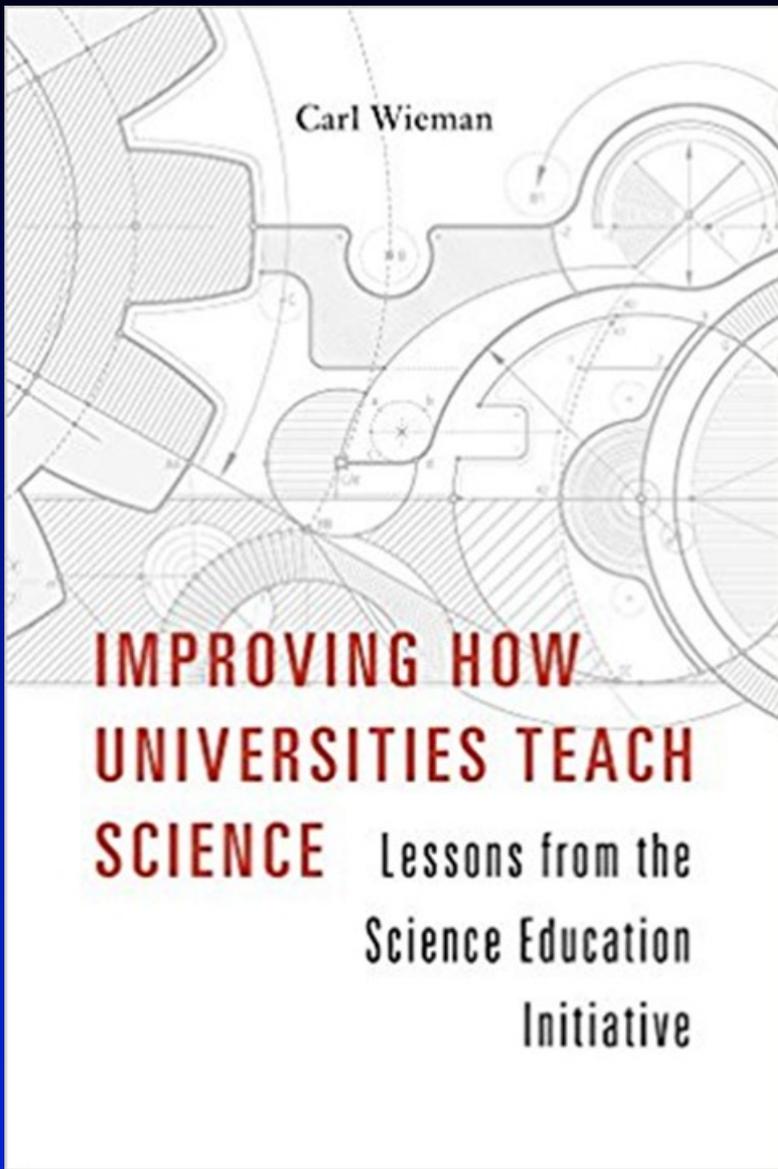
- All the faculty greatly preferred to lecturing.

Typical response across ~ 250 science faculty at UBC & U. Col. New way of teaching much more rewarding, would never go back.

Institutional Change

Better for students & faculty prefer *(when try)*

How to make universal?

IMPROVING HOW UNIVERSITIES TEACH SCIENCE Lessons from the Science Education Initiative

Carl Wieman

What universities and departments can do. Experiment demonstrating teaching transformation process.

Transformed the teaching of ~200 science faculty and ~ 150,000 credit hours/year at UBC.

Factors that help and hinder.

Necessary 1st 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

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 $\Rightarrow$ 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 on—establishes expertise of teaching.

Improves student learning & faculty enjoyment.

slides will be available

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-- resources** (implementing best teaching methods), references, effective clicker use booklet and videos

~ 30 extras below

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.)
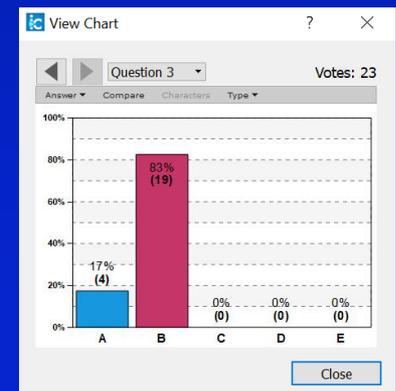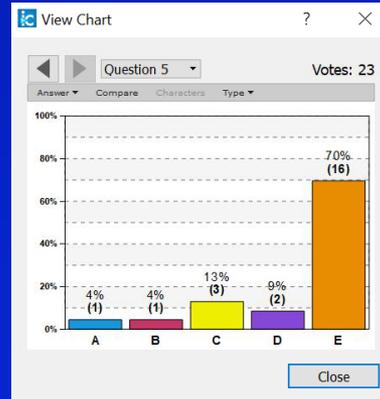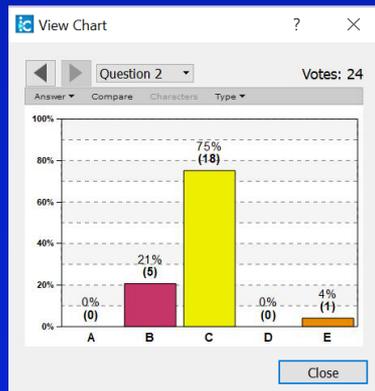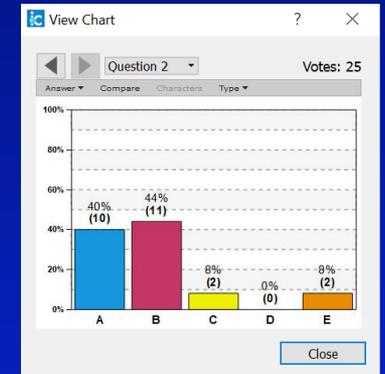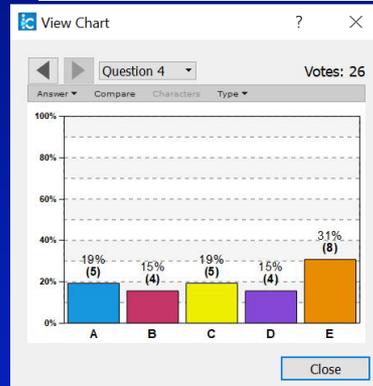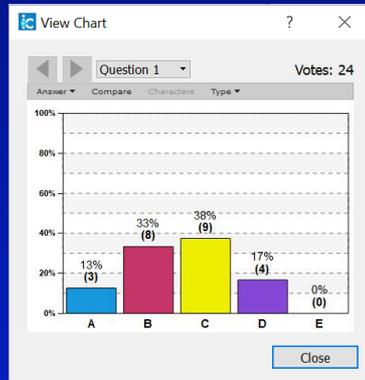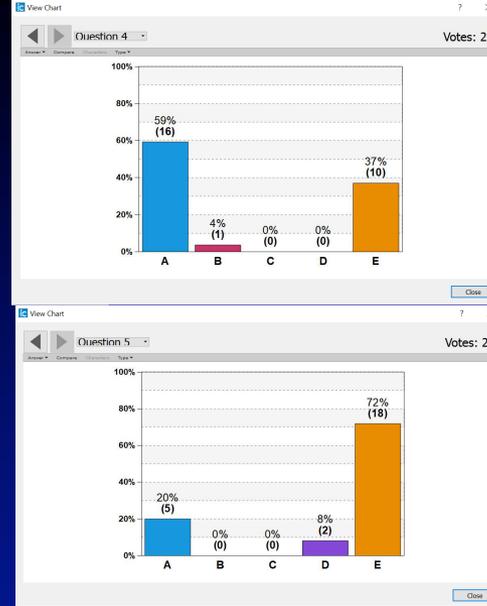
<u>Effective teacher—</u>
- Designing suitable practice tasks
- Providing timely guiding feedback
- Motivating

("cognitive coach")

Requires disciplinary expertise

Learning from peer discussion.

Questions on concepts covered in class. Intro QM. (clickers last term)

first individual response

after group discussion

individual response

after discussion

"Practice-with-feedback/Research-based/
Active learning"

What it is <u>not:</u>
"experiential"
"flipped classroom"
"student centered"

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

Is centered on <u>thinking to be learned</u>.
Lots of "instructor"-- Design of task, feedback and elaboration to "prepared" students*.

*("A time for telling", Schwartz & Bransford)

- **NEW** "*Guide to Evidence-Based Instructional Practices in Undergraduate Mathematics*", Math. Assoc. Am. *MAA.org*

Lecture Notes Converted to Activities

3) Consider this optical setup

Laser with tunable frequency

U_{laser}

mirror with r_1 field reflectivity & t_1 field transmission

mirror with r_2 field reflectivity

d

Mirror 1   Mirror 2

U_0
U_1
U_2
U_3

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

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

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

"A time for telling" Schwartz and Bransford, Cognition and Instruction (1998)

People learn from telling, <u>but only</u> 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

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.

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

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)

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-essentential jargon and information
- Explicitly connect
- Make lecture organization explicit.

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
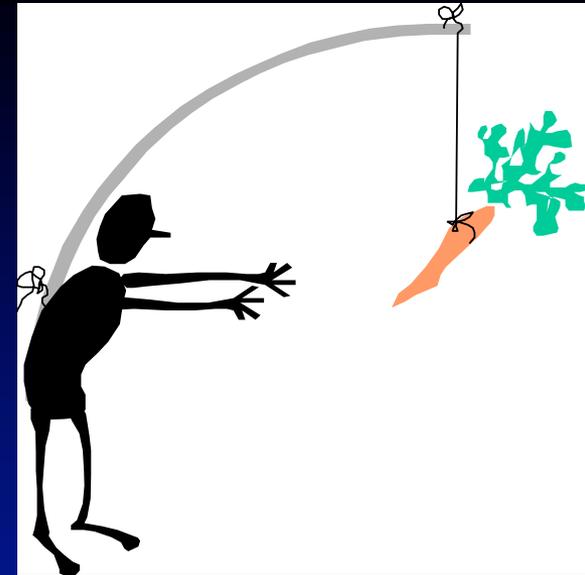*(complex- depends on background)*

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

<u>How it is possible to cover as much material?</u>
(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>
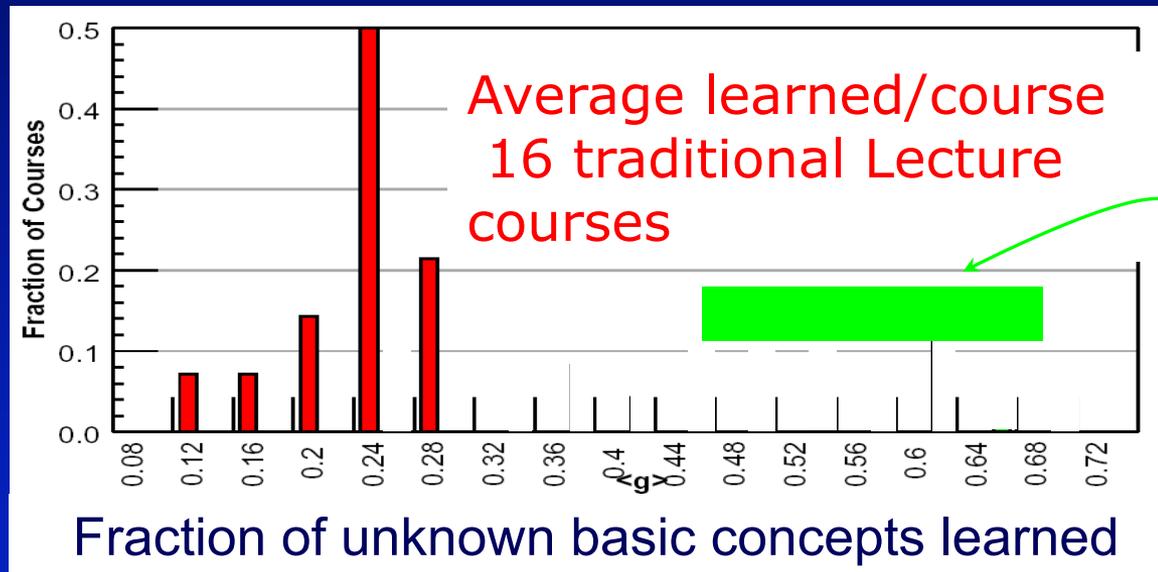
Intro courses, can cover the same amount.
But typically cut back by ~20%, as faculty understand better what is reasonable to learn.

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)

Average learned/course
16 traditional Lecture courses

improved methods

Fraction of unknown basic concepts learned

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).

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
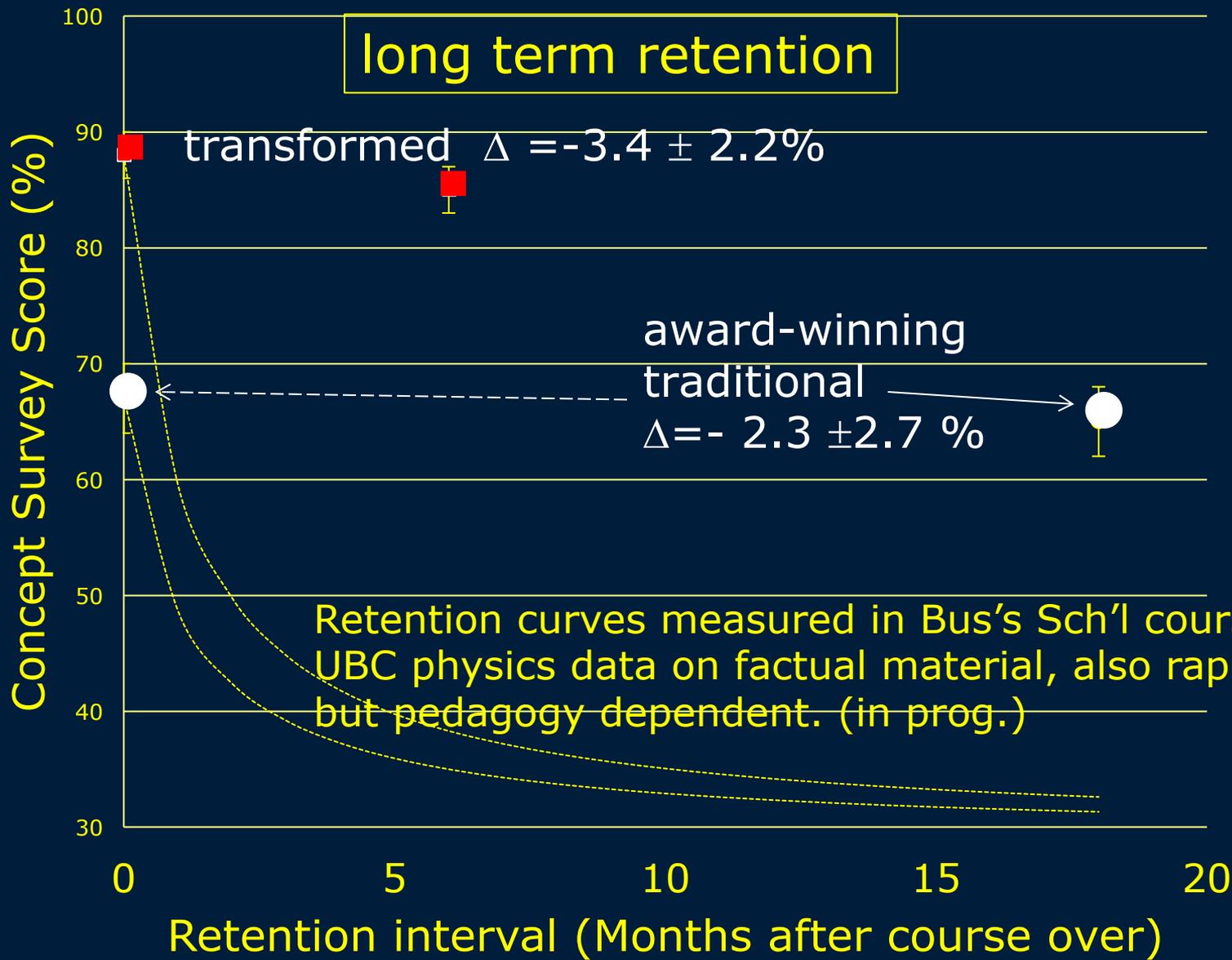
Design principles for classroom instruction
1. Move simple information transfer out of class.
Save class time for active thinking and feedback.

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

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