Taking a scientific approach to engineering education*

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

~ 25 years doing research on how people learn physics, science & engin.

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. e. expert engineer)*

University science & engin. classroom studies

brain research

today

cognitive psychology

Strong arguments for why apply to most fields

Education goal—
"Thinking/<u>making decisions</u> like an expert"
(e.g. good engineer-engin. faculty member)

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

II. How is it learned?

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

IV. A bit on institutional change

I. Research on expert thinking*

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

Expert thinking/competence =

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

or ?

concepts, 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!*

*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 basic methods & materials relevant *(may meet design criteria)*
- Decide: what potential solution method(s) to pursue.
- " : what information needed to evaluate & select, what information/factors can ignore
- ....
- Examine possible failure modes. (construction, cost, break)

Content knowledge needed, but only as part of above—guide **how and when to use**.

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

Engineer of future?

better tools (computer etc.)
new knowledge
basic thinking/problem solving likely the same

best preparation:
don't worry very much about teaching specific content
teach to solve problems, and learn recognize when need and how to learn new things, and use new tools

How to measure if students are learning?
~~Isolated high stakes exams, artificial & unreliable~~

Better:
Give realistic scenarios– make decisions & justify

Research on effective teaching & learning

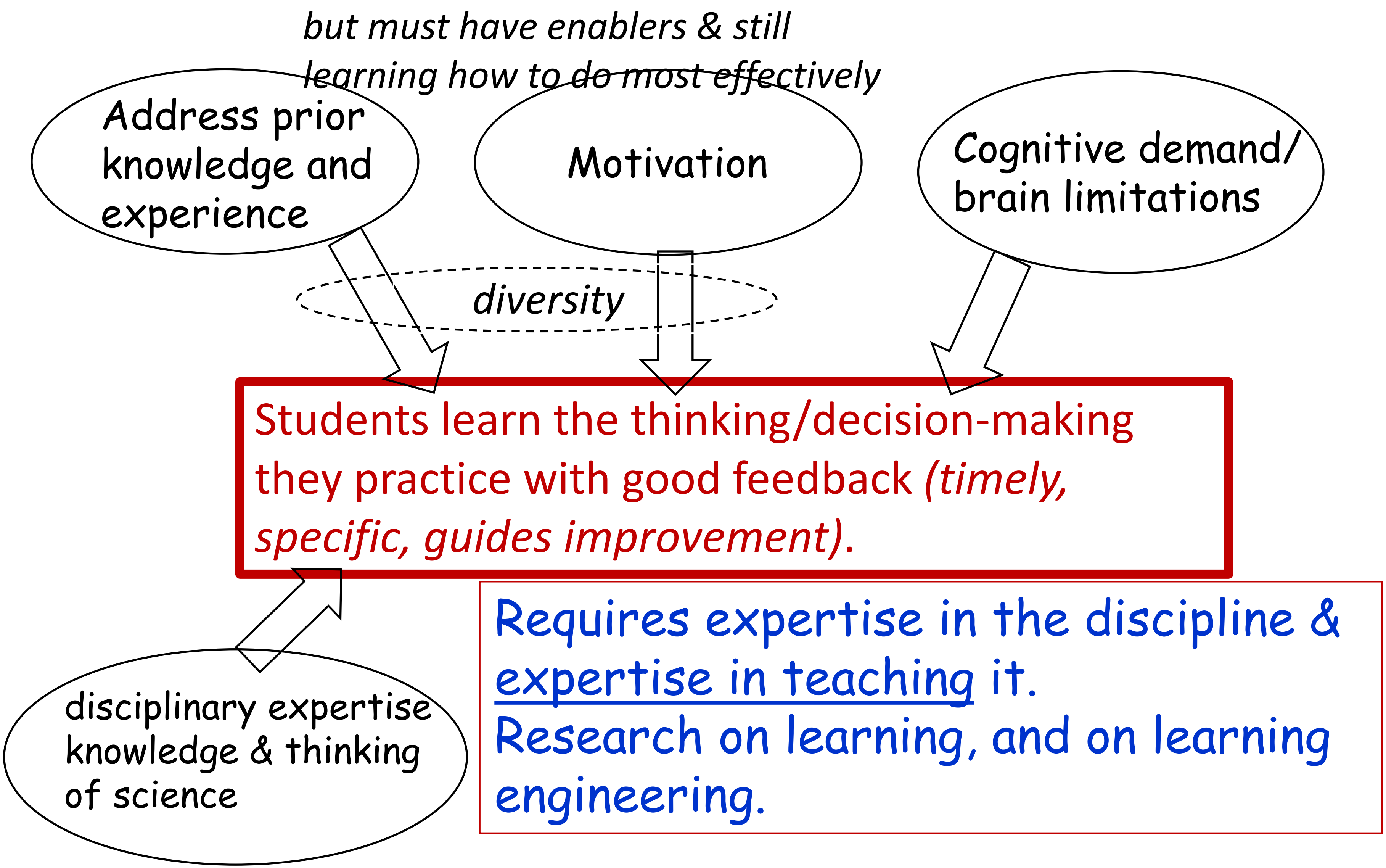
<u>Wieman rule of learning</u>

Curriculum (set of courses and topics) determines content that students learn.

<u>Teaching methods determine what thinking students learn.</u>

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

Research on effective teaching & learning



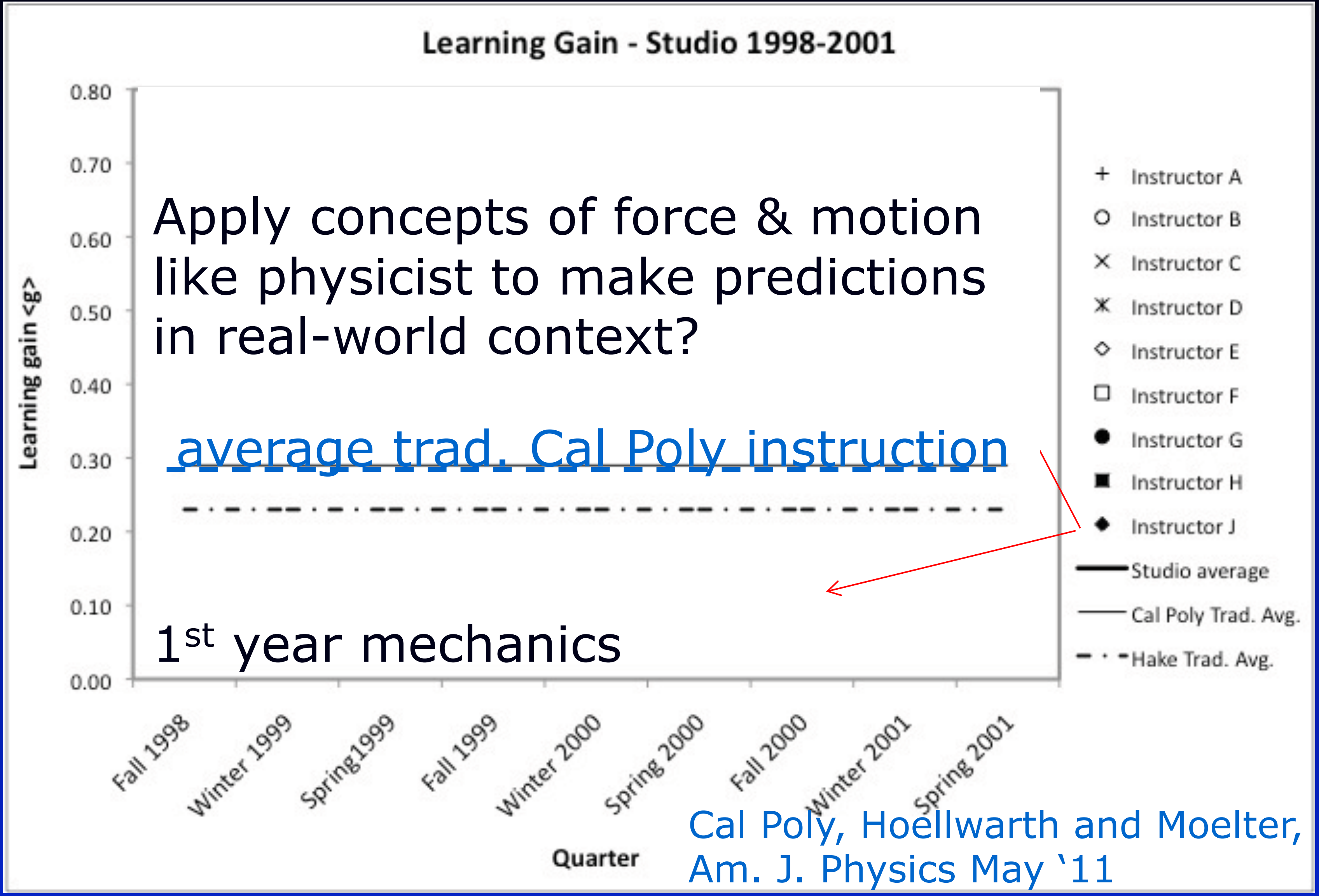
III. Evidence from the Classroom

~ 1000 research studies from undergrad science and engineering comparing traditional lecture with "active learning" (or "research-based teaching").

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

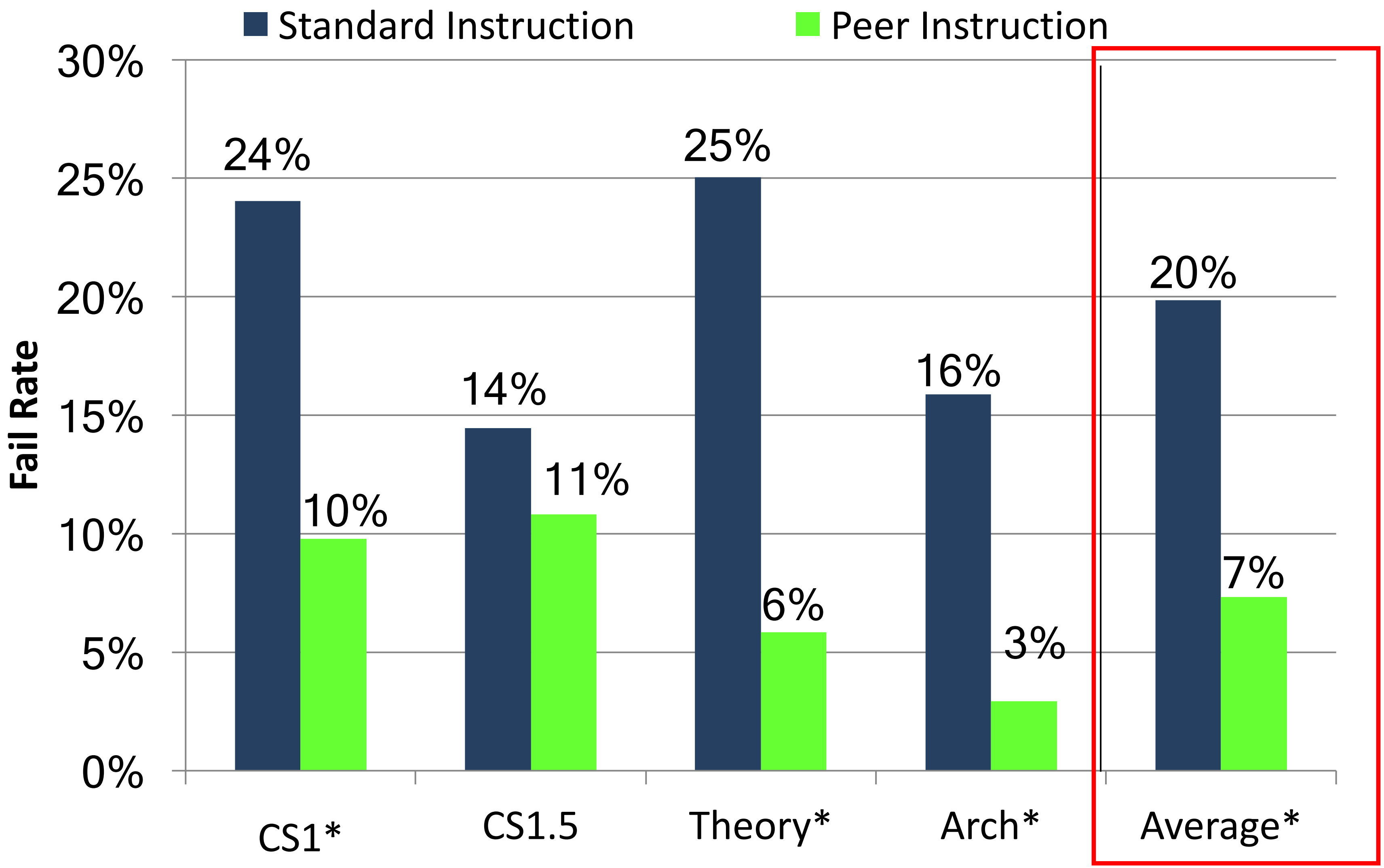
Massive meta-analysis all sciences & eng. similar.
PNAS Freeman (UW), et. al. 2014

A few examples—



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 (N =270) UBC 1st year college physics for pre-engineers.

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

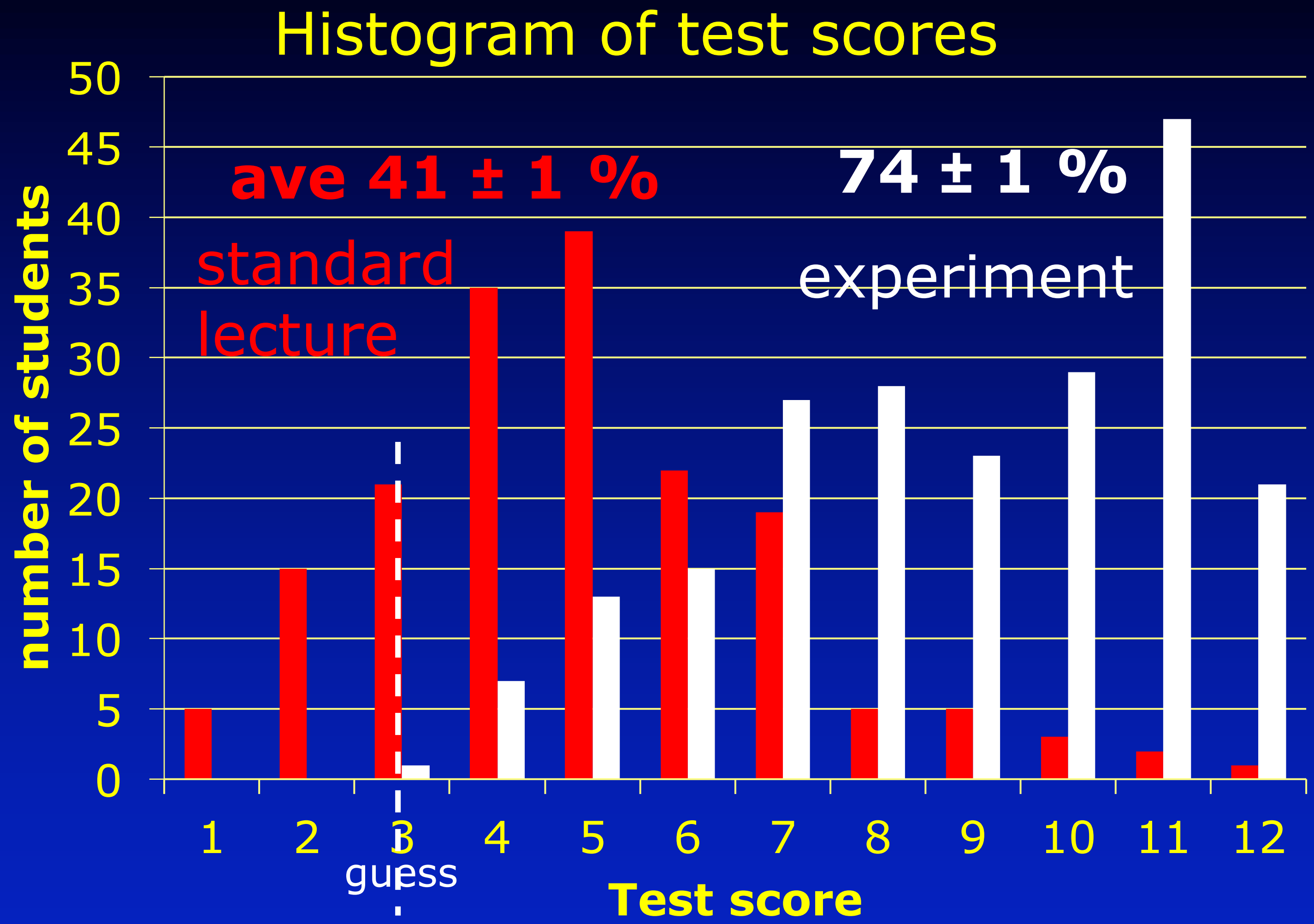
**Deslauriers, Schelew, Wieman, Sci. Mag. May 13, '11*

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

U. Col, UBC, & Stanford

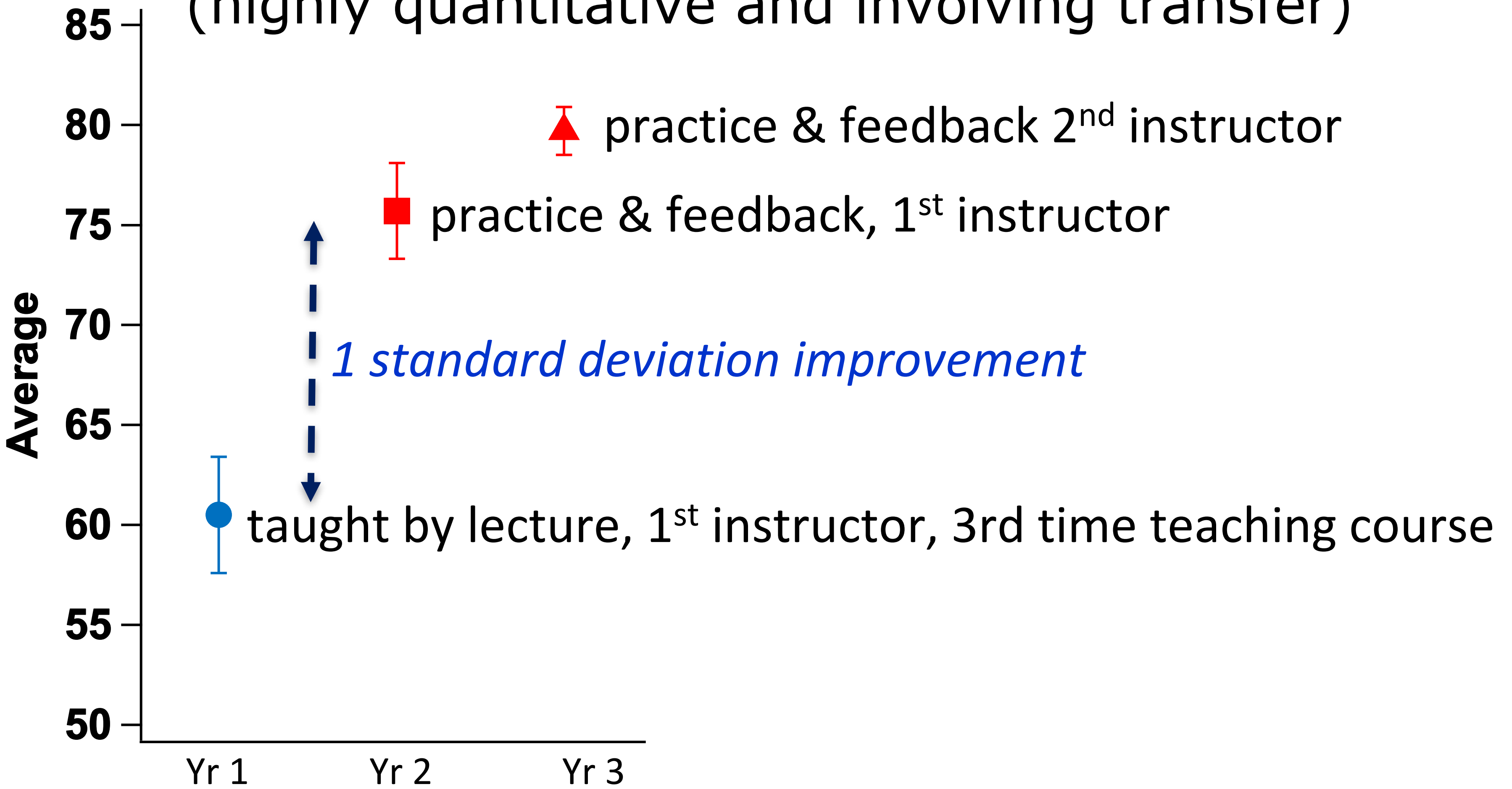
Design and implementation: Jones, Madison, Wieman, Transforming a fourth year modern optics course using a deliberate practice framework, Phys Rev ST – Phys Ed Res, V. 11(2), 020108-1-16 (2015)

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 2^{nd}-4^{th} year, seven faculty, ‘15-’17

- Attendance up from 50-60% to ~95% for all.
- Student anonymous comments:

90% positive (mostly VERY positive, *“All physics courses should be taught this way!”*)
only 4% negative

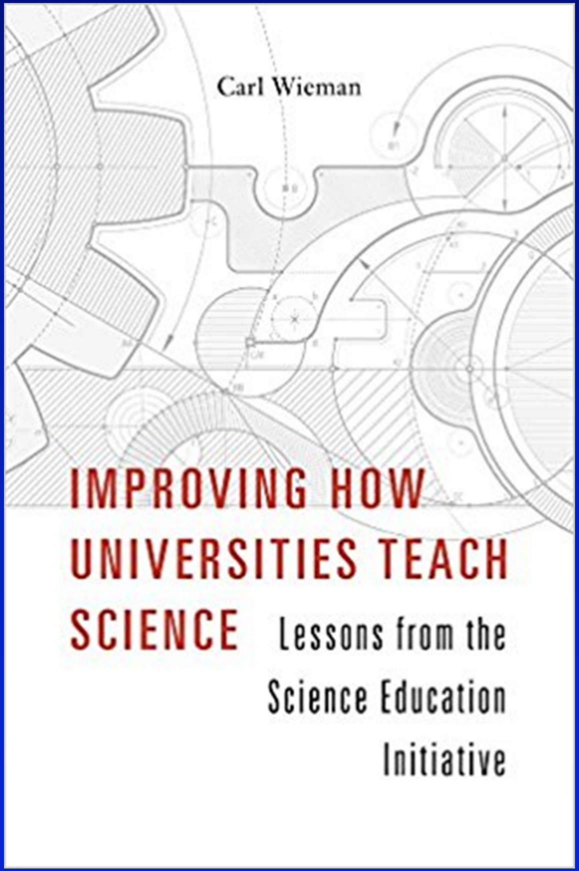
- All the faculty greatly preferred to lecturing.

Typical response across ~ 250 faculty at UBC & U. Col. Teaching much more rewarding, would never go back.

IV. Changing how universities teach

Research-based teaching better for students & faculty prefer *(when learn how, ~50 hours)*

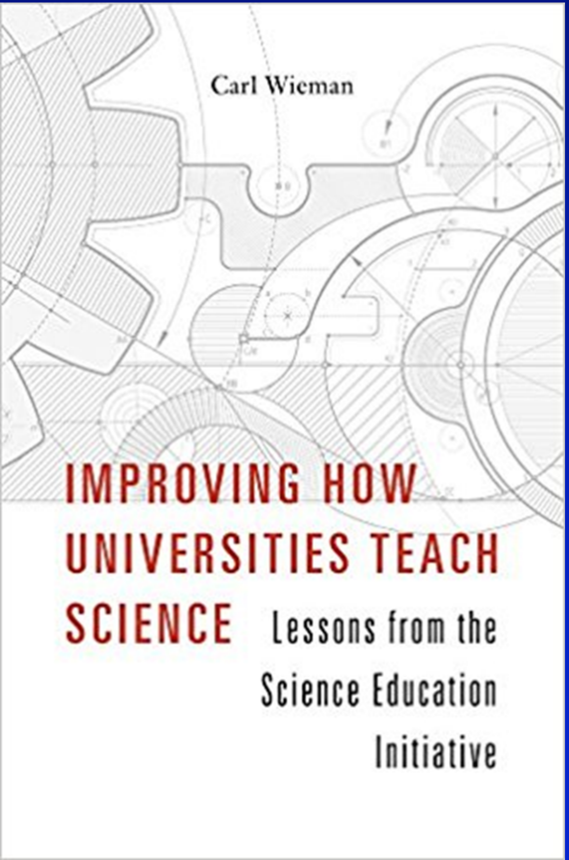
How to make the norm?



SEI-- Experiment on large scale change of teaching. Public research universities. Colorado & U. Brit. Columia

changed ~ 250 sci faculty & 200,000 credit hrs/yr

Large competitive grant program for departments.
⇒ Hire teaching expertise into departments.
Work with faculty to change teaching.



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

Conclusion:

Research providing new insights & data on effective teaching and learning, particularly learning to think like scientist or engineer.

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. Mostly with specific guidance on different & better ways to teach.

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.

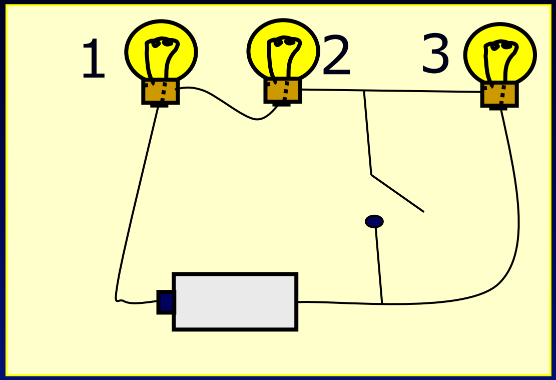
III. How to apply in classroom?
practicing thinking with feedback

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)

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

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
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

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 ⇒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

Biology Jargon bogs down working memory, reduces learning?

	Control	**Experiment**
preread:	textbook	jargon-free

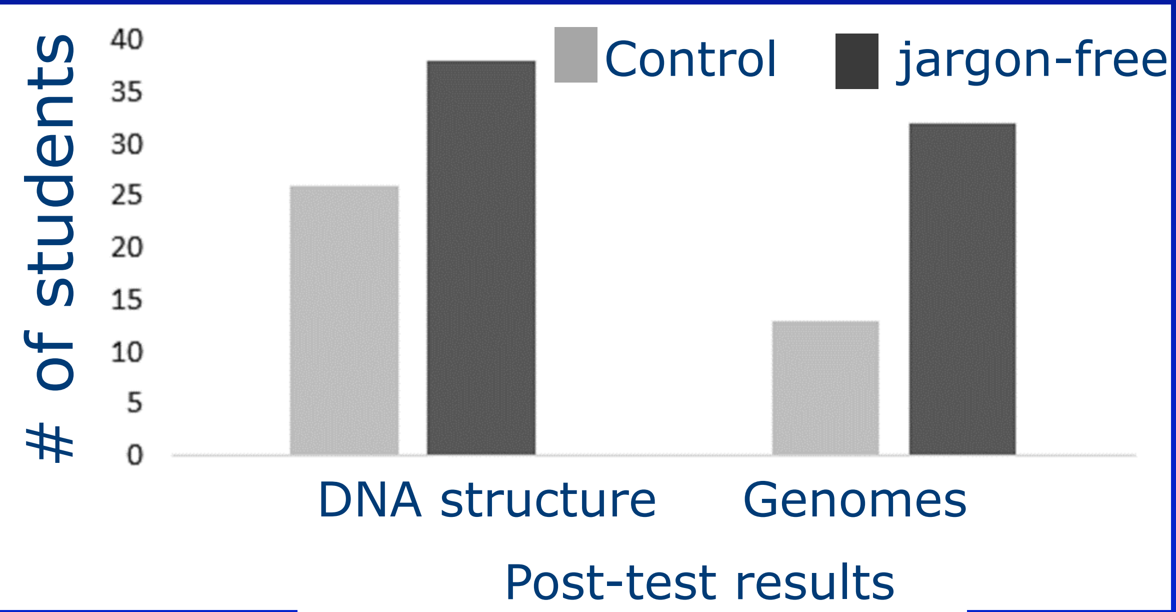
↓

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!

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

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

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

MUCH less than in typical lecture

slides to be provided

Reducing demands on working memory in class

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

Pre-class Reading

Purpose: Prepare students for in-class activities; move learning of less complex material out of classroom

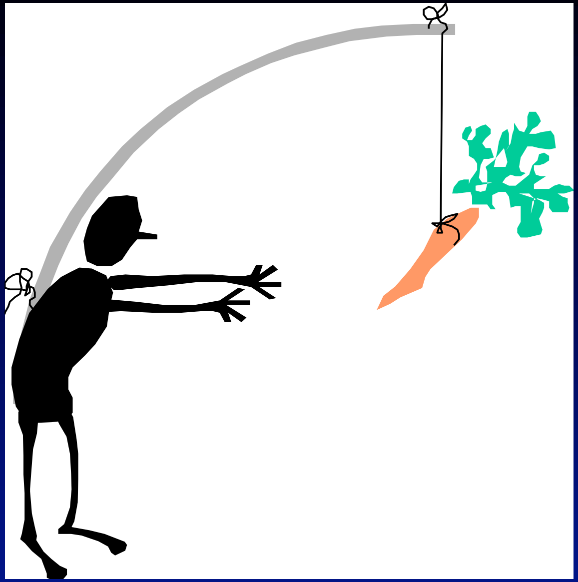
Spend class time on more challenging material, with Prof giving guidance & feedback

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)

<u>Motivation-- essential</u>
(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.

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

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. …

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