Taking a scientific approach to science education

copies of slides to be available

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

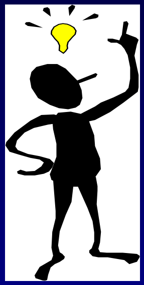
I. Introduction– Educational goals & research-based principles of learning

II. Applying learning principles in university courses and measuring results

III. Teaching expertise (for university science/physics)

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!

?????? ~ 30 years ago

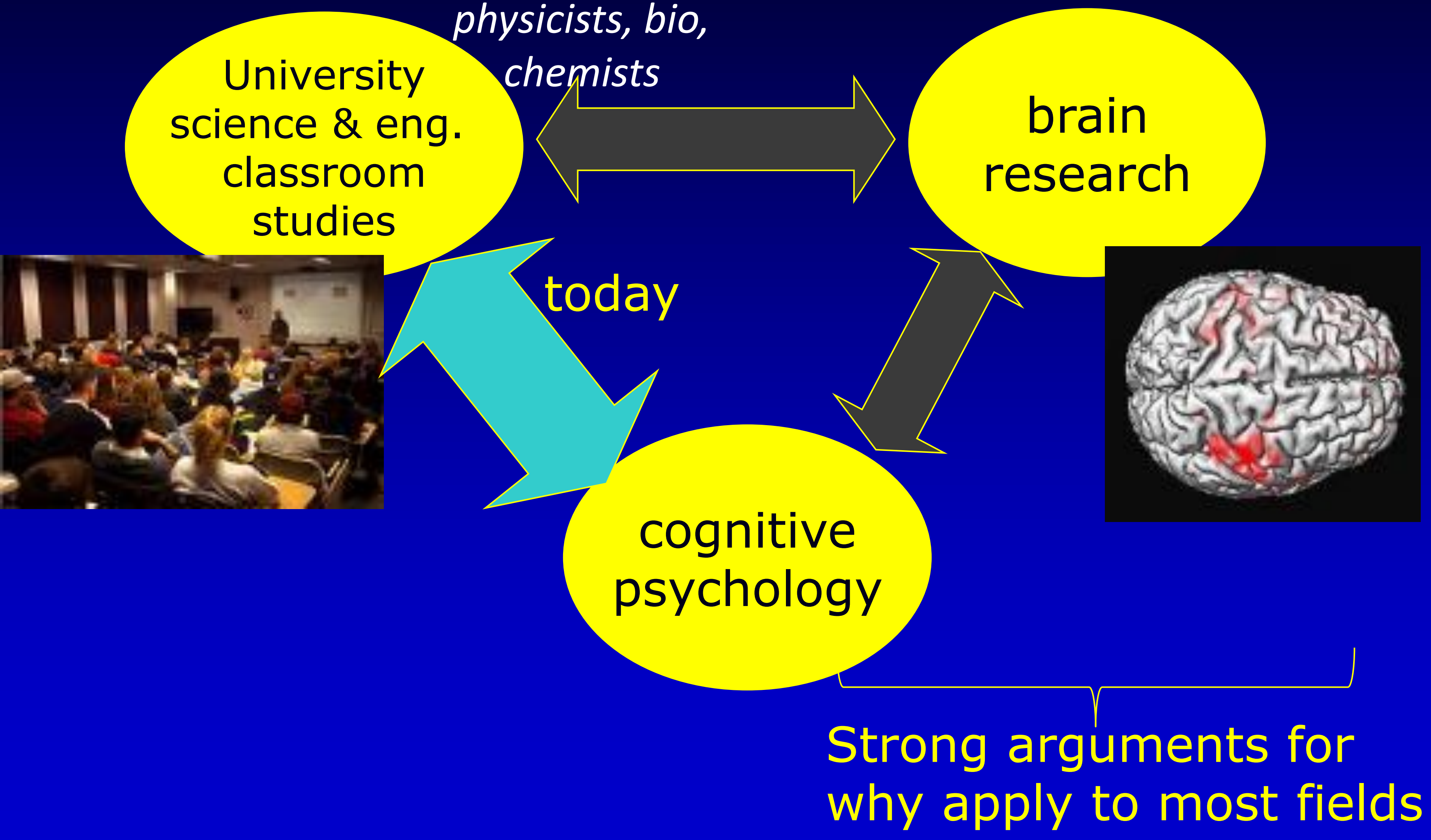
Research on how people learn, particularly physics

- explained puzzle
- I realized were more effective ways to teach
- got me started doing science ed research-- experiments & data, basic principles! (~ 100 papers)

"Expertise"– solving problems like a good physicist

Major advances past 1-2 decades

⇒ New insights on how to learn & teach complex thinking



Basic result– rethink how learning happens

old/current model

knowledge

soaks in, varies with brain

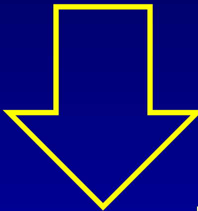
Primary educational focus of universities:

- contents of knowledge "soup"
- admitting best brains

new research-based view

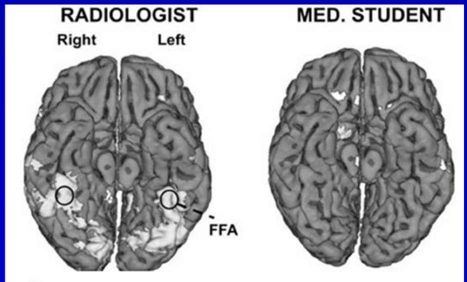
brain changeable

~ same



transformation

Change neurons by intense thinking. Improved capabilities.



fMRI-- interpreting x-ray image

I. Introduction– Educational goal (*better decisions*) & research-based principles of learning

II. Applying learning principles in university courses and measuring results

Basics of most university science classroom research:

1. Test how well students learn to make decisions like expert (*physicist, biologist, …*).

2. Compare results for different teaching methods:

a. *Students told what to do in various situations ("lecture")*

b. Practice making decisions in selected scenarios, with feedback. ("active learning", "research-based")

Learning **in large class***

Comparing the learning in class for two ~identical sections. UBC 1st year college physics. 270 students each.

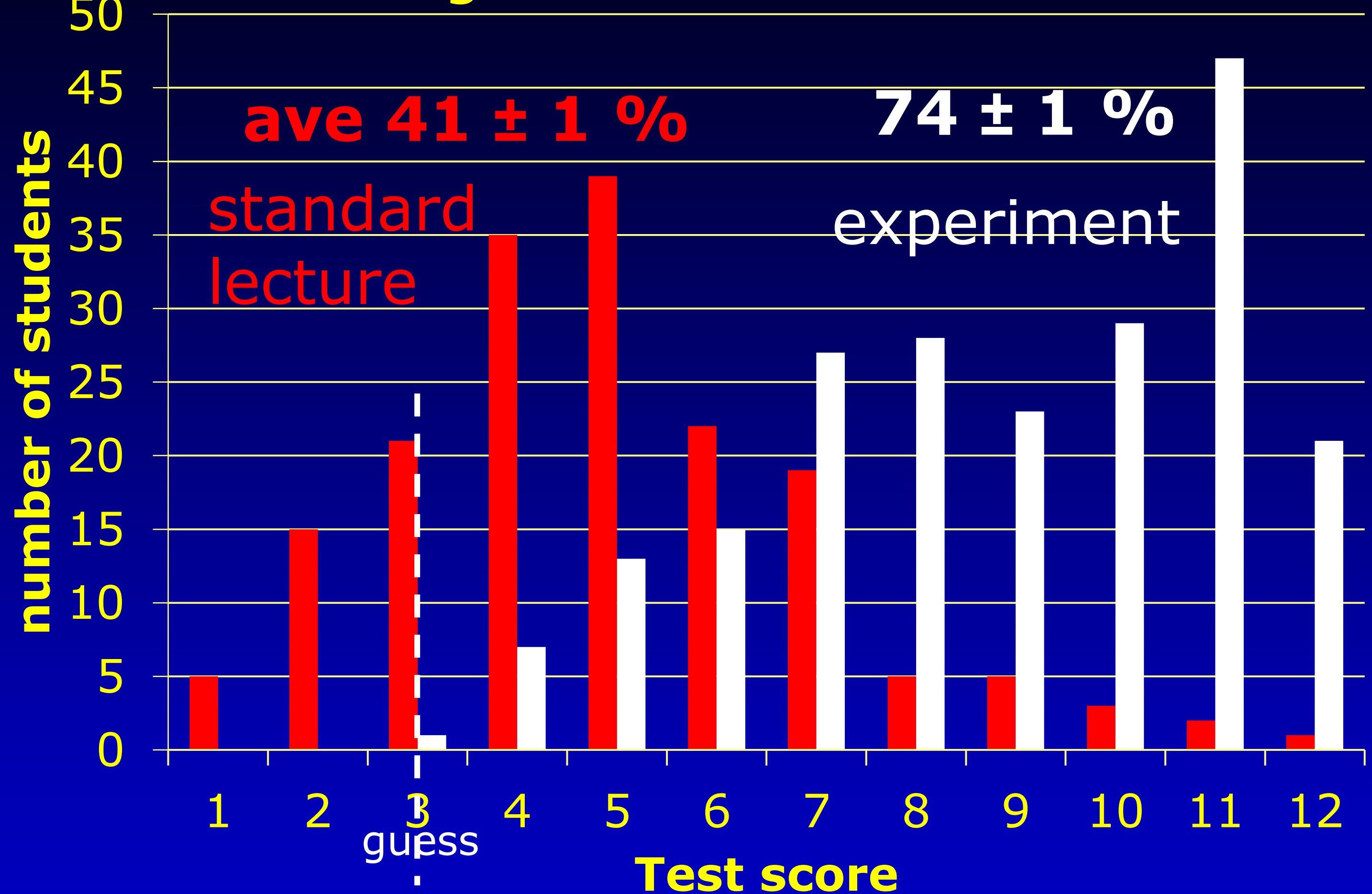
Control--standard lecture class– highly experienced Professor with good student ratings.
Experiment–- new physics Ph. D. trained in principles & methods of research-based teaching.

They agreed on:

- Same material to cover *(Cover as much?)*
- Same class time (1 week)
- Surprise quiz (jointly prepared)- start of next class

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

Histogram of test scores



Learning from lecture tiny.

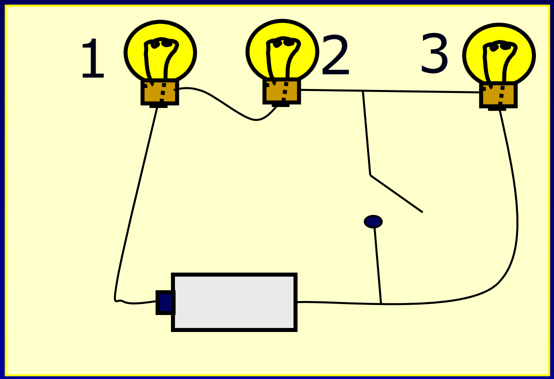
Clear improvement for <u>entire</u> student population.

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

Experimental class:

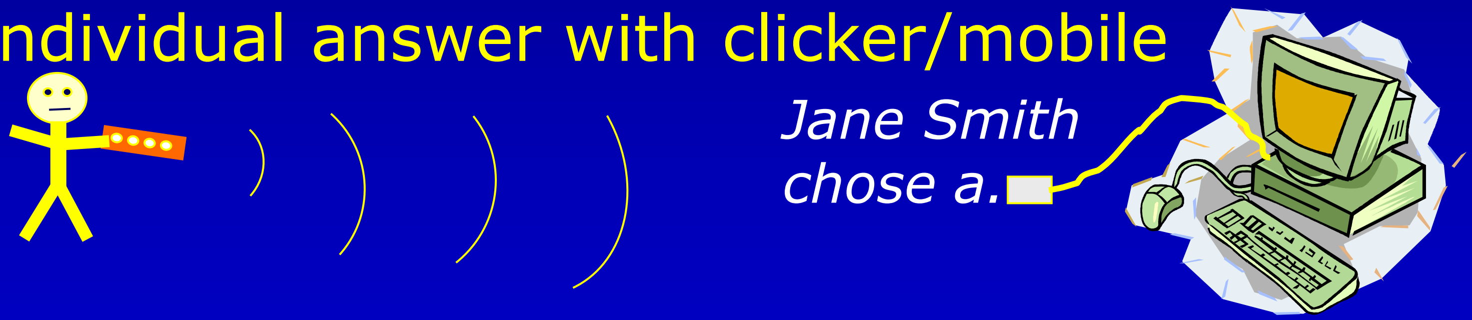
1. Short preclass reading assignment--Learn basic facts and terminology without wasting class time.

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.

3. Individual answer with clicker/mobile



4. Discuss with neighbors, revote. *("Peer instruction")*

Instructor circulating and listening in on conversations!

What aspects of student thinking like physicist, what not?

5. Demonstrate/show result

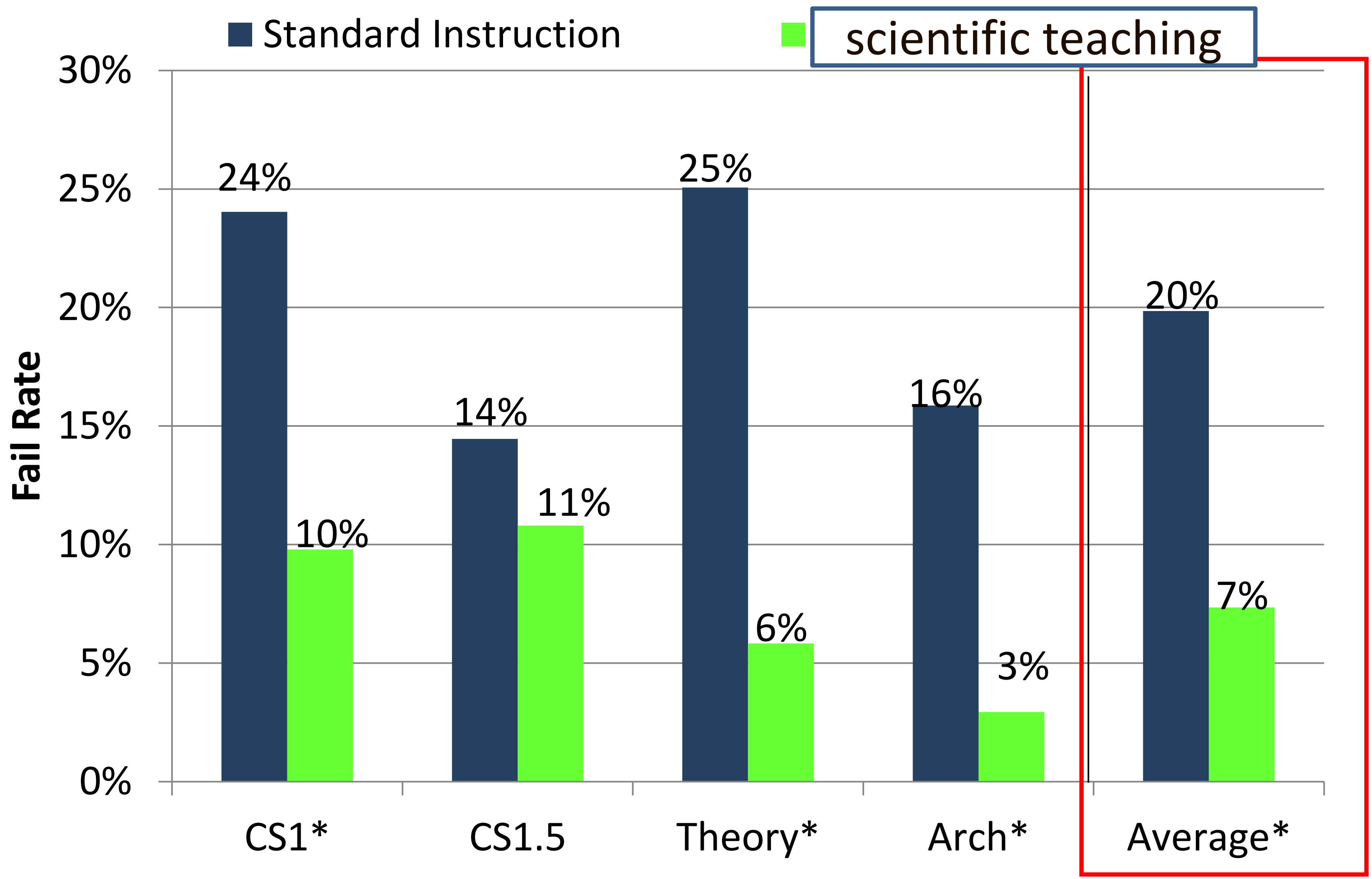
6. Instructor follow up summary– feedback on which models & which reasoning was correct, & **which incorrect and why**. Many student questions.

For more mathematical topics, students write out on worksheets.

Students practicing thinking like physicists-- (choosing, applying, testing conceptual models, critiquing reasoning...)

Feedback—other students, informed instructor, demo

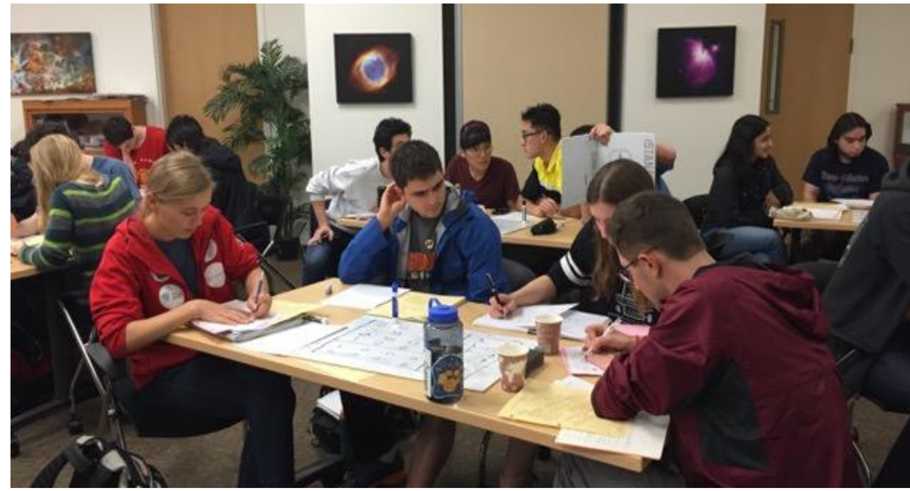
Similar comparison of teaching methods. Computer science & looking at fail/drop rates over term. U. Cal. San Diego,



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

Beth Simon et al., 2012

Research-based instruction—Advanced Courses



Stanford--8 physics majors courses 2nd-4th year

... Graduate Quantum Field theory (Cornell Univ.)

Design and implementation: Jones, Madison, Wieman, Phys Rev ST – Phys Ed Res, V. 11(2), 020108-1-16 (2015)
--complete worksheets. 1 standard deviation improvement.

Structure of active learning class

Good for any subject, level, class size

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** *fill out worksheets*	Circulate, answer questions & assess students
Feedback (5-10 min)	Listen/ask questions, provide solutions & reasoning when called on	**Facilitate class discussion, provide feedback to class**

Two essential features: students are thinking—practicing expert reasoning, instructor more knowledgeable feedback

Works quite similar online-- 3-4 in each breakout room

Evidence from the University Classroom

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

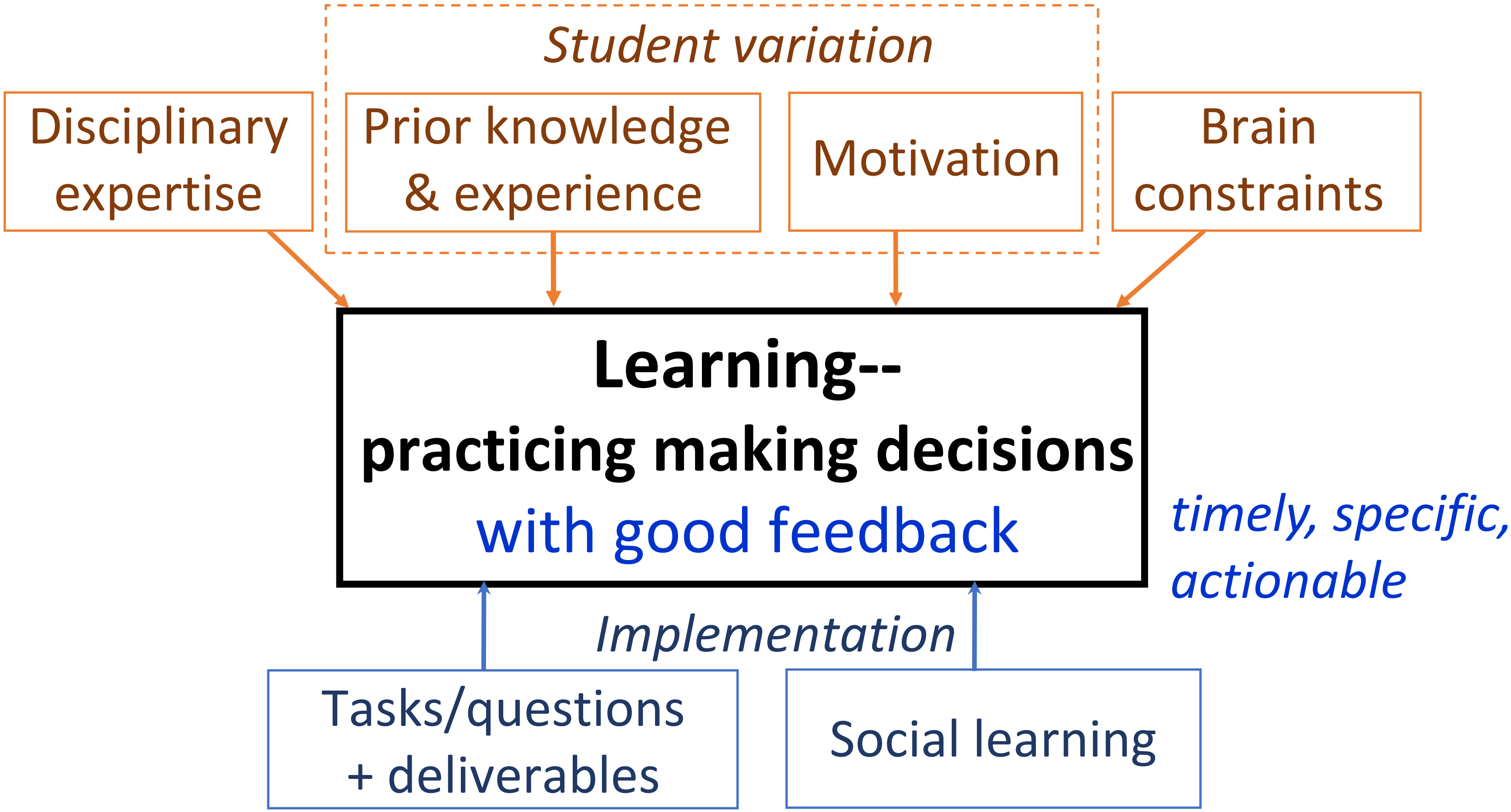
- results dominated by teaching methods used, no other significant "teacher variables"
- consistently show greater learning
- lower failure & dropout rates

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

III. Teaching expertise

What does research say produces the most learning for university science?
(all sciences and engineering)

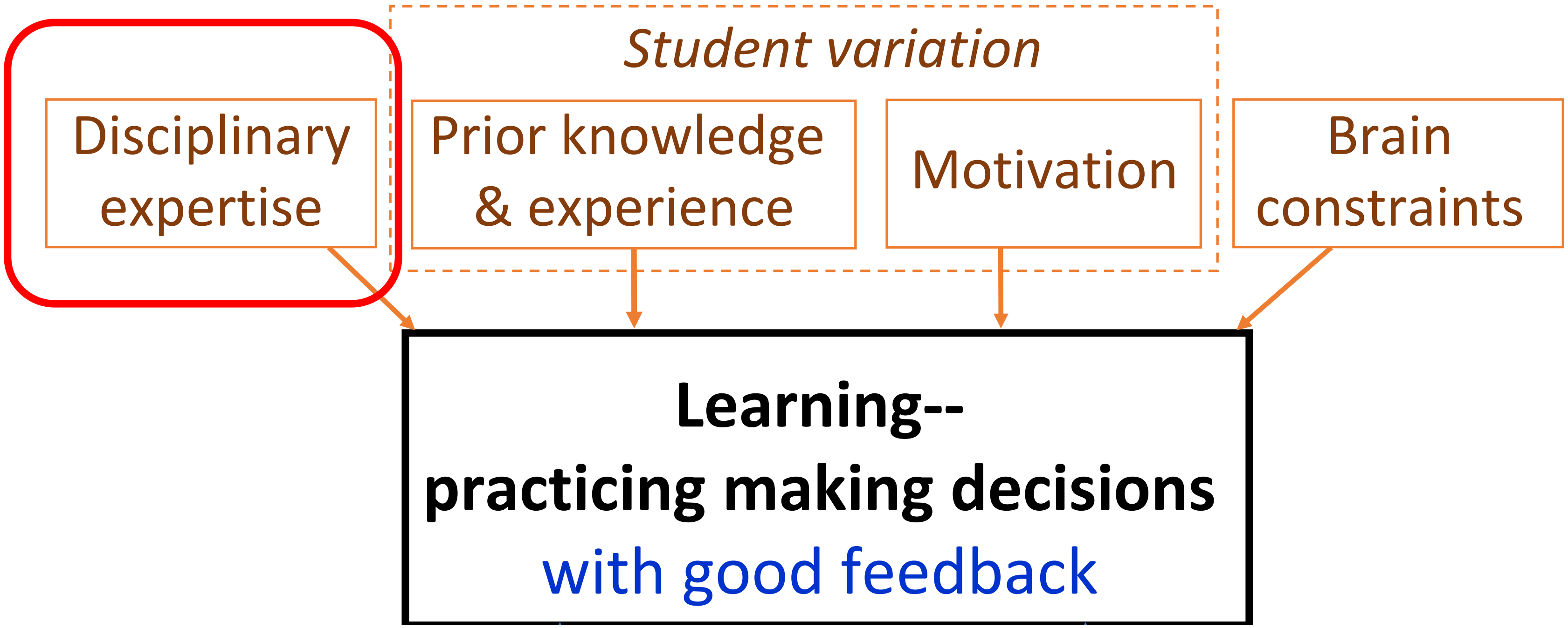
Teaching to think (*make decisions*) like expert, what research says is important



<u>Defines teaching expertise.</u>

Practices that research shows produce more learning

Measure with "Teaching Practices Inventory"



How enter into design of practice activities (in class, then homework...)?

Wieman Group Research

How experts in science, engineering, and medicine solve authentic problems.

Make decisions with limited information.

Same set of 29 decisions!

making the decisions requires specialized knowledge

Argenta Price, Shima Salehi, Karen Wang, Michael Flynn, Candice Kim, Eric Burkholder

Learning expert thinking--

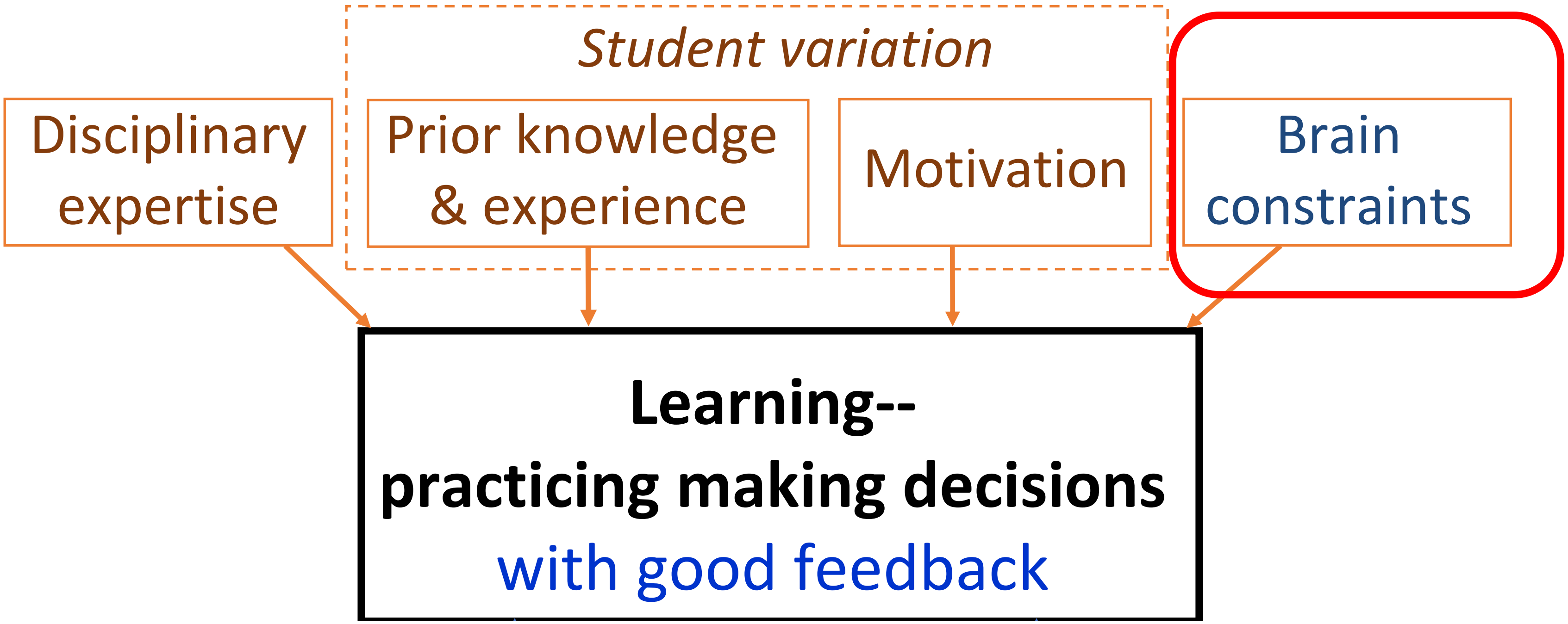
= Practicing making problem solving decisions

<u>Decisions</u> when solving any sci & eng problem

https://arxiv.org/abs/2005.11463

- <u>Decide</u>: what concepts/models relevant
- <u>Decide</u>: *W*hat information relevant, irrelevant, needed.
- <u>Decide:</u> what approximations are appropriate.
- " : potential solution method(s) to pursue.
- ....
- does solution/conclusion make sense, how to test?

Usually removed from typical school problems!
Students learning knowledge, not how to use!



How enter into design of practice activities (in class, then homework...)?

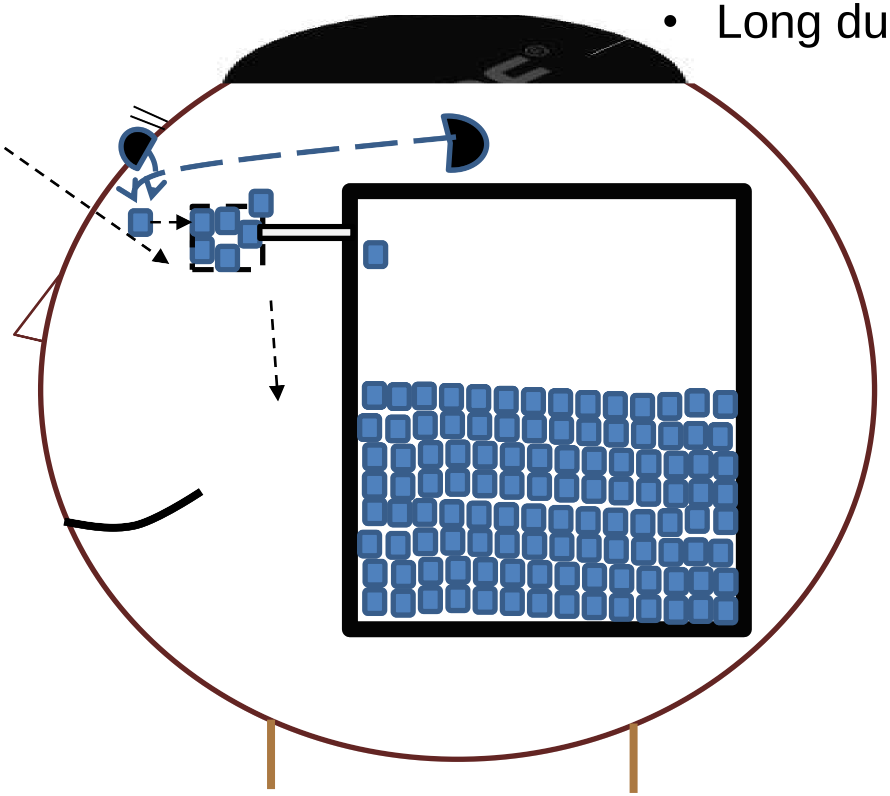
Brain Constraints

1. Long term memory
- Large capacity
- Long duration

<u>Memory *(simplified)*</u>

2. "Short-term working memory" *(buffer)*
- tiny capacity (5-7 items)
- time scale of minutes

(what can pay attention to)



When hear or see new items, pushes out old. Not processed and into long term memory.

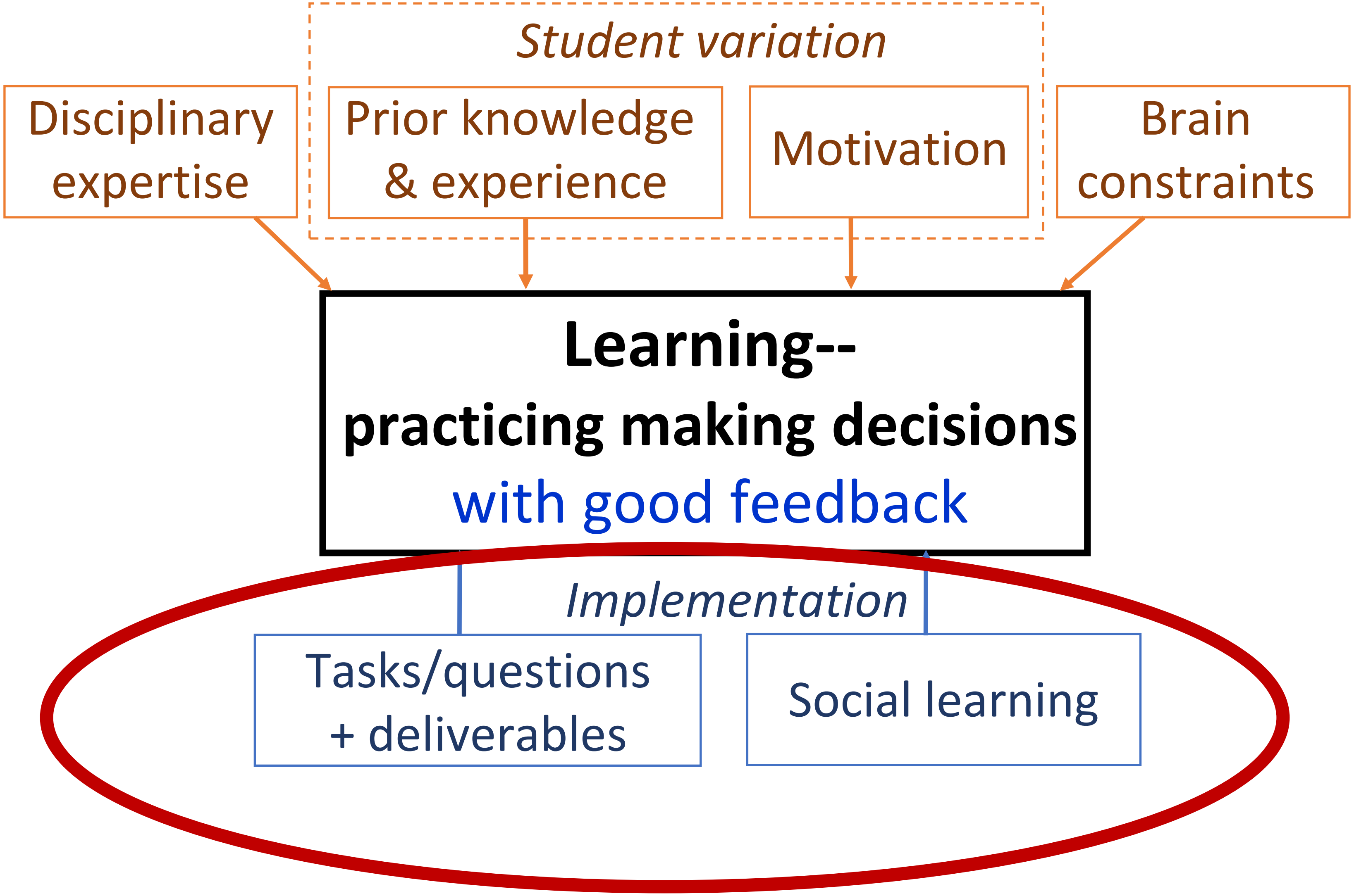
Brain constraints:

1) working memory has limit 5-7 new items. 1 hr class. Additional items reduce processing & learning.

- Split attention (checking phone, email, ...)—learning disaster
- Jargon, nice picture, interesting little digression or joke actually hurts.

2) long term memory– biggest problem is recall after learning additional stuff--interference.

Not just learn once and done. Interference suppressed by repeated interleaved recall


Student variation
Disciplinary expertise
Prior knowledge & experience
Motivation
Brain constraints
Learning--
practicing making decisions
with good feedback
Implementation
Tasks/questions + deliverables
Social learning

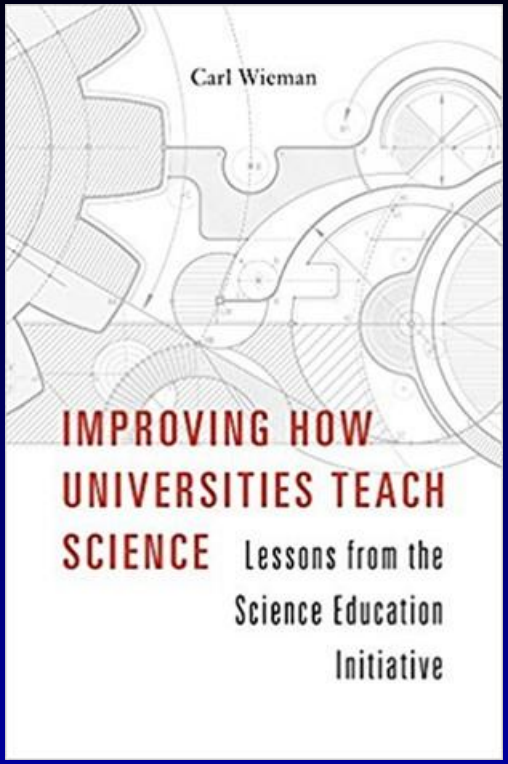
Implementation—

1. Design good tasks (as above) with **deliverables** and **norms** for small group interactions.

2. **Social learning:** working in groups (N=3-4) in class.
Talking to fellow students better than hearing expert instructor explain??

- People teaching/explaining to others triggers unique cognitive process $\Rightarrow$ more learning
- **Very useful as a teacher** to listen in on student conversations!

Conclusion--Research shows how to achieve much better learning in university science courses than traditional lecture & principles for why it works.



For administrators:

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

Changed teaching of ~250 science instructors & 200,000 credit hrs/yr UBC & U. Colorado

Important results:

1. Large scale change is possible. (Entire departments)
2. When faculty learn how to teach this way (~50 hrs) they prefer to lecturing. Costs the same.
3. Need to recognize, support, and incentivize teaching expertise.
4. **Need better way to evaluate teaching-**

“But traditional lectures can’t be as bad as you claim. Look at all us university professors who were taught by traditional lectures.”

Bloodletting was the medical treatment of choice for ~ 2000 years, based on exactly the same logic.

Need proper comparison group. (science)

Conclusion:

Research has established teaching expertise at university level.

Potential to dramatically improve post secondary education, particularly in physics.

slides will be available

Good References:

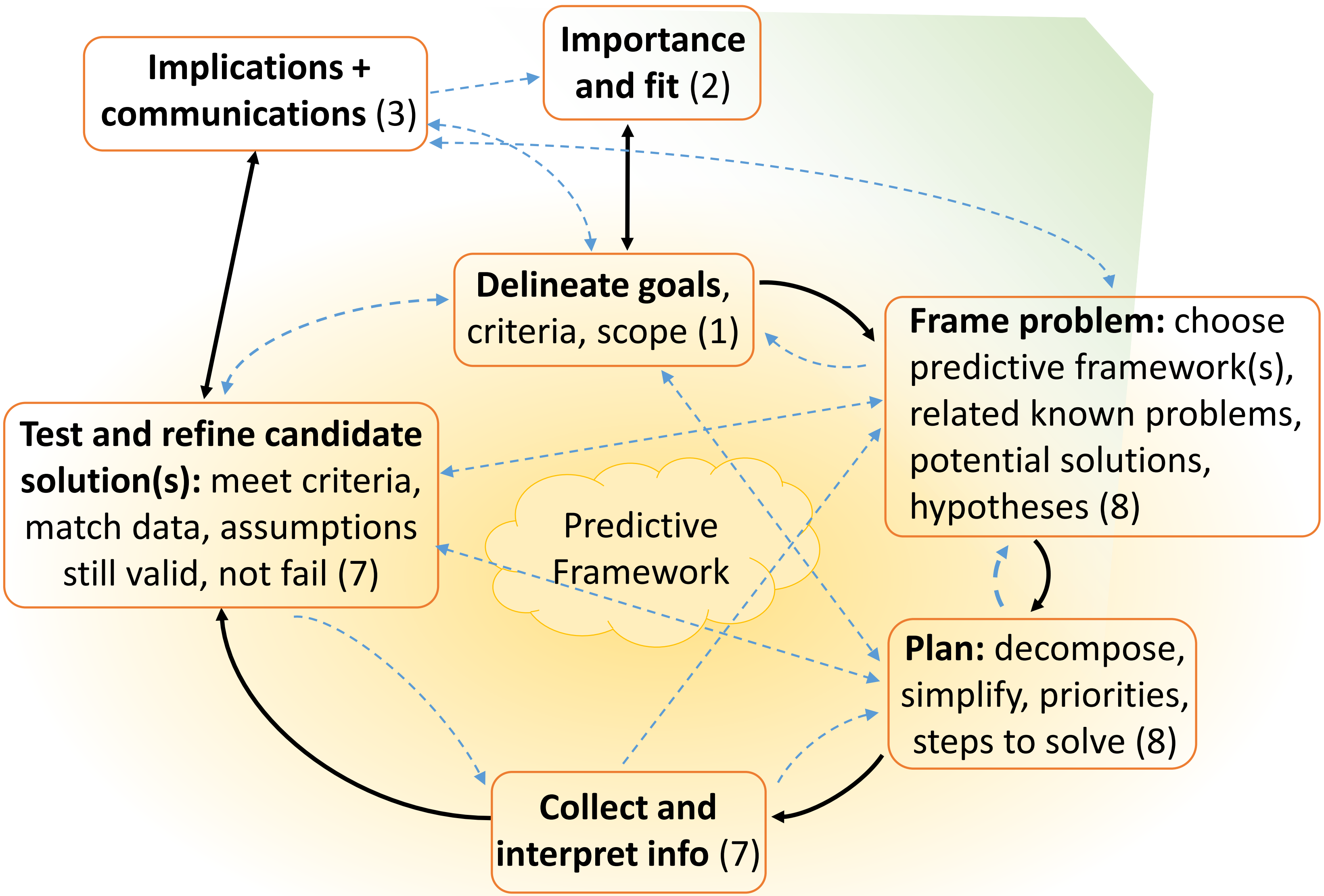
- S. Ambrose et. al. *"How Learning works"*
- D. Schwartz et. al. *"The ABCs of how we learn"*
- Ericsson & Pool, *"Peak:..."*
- Wieman, *"Improving How Universities Teach Science"*

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

~ 20 extras below

Categories of the 29 Science Problem Solving Decisions

(Somewhat time ordered but involve extensive iteration)



https://arxiv.org/abs/2005.11463

Transforming teaching of Stanford physics majors

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

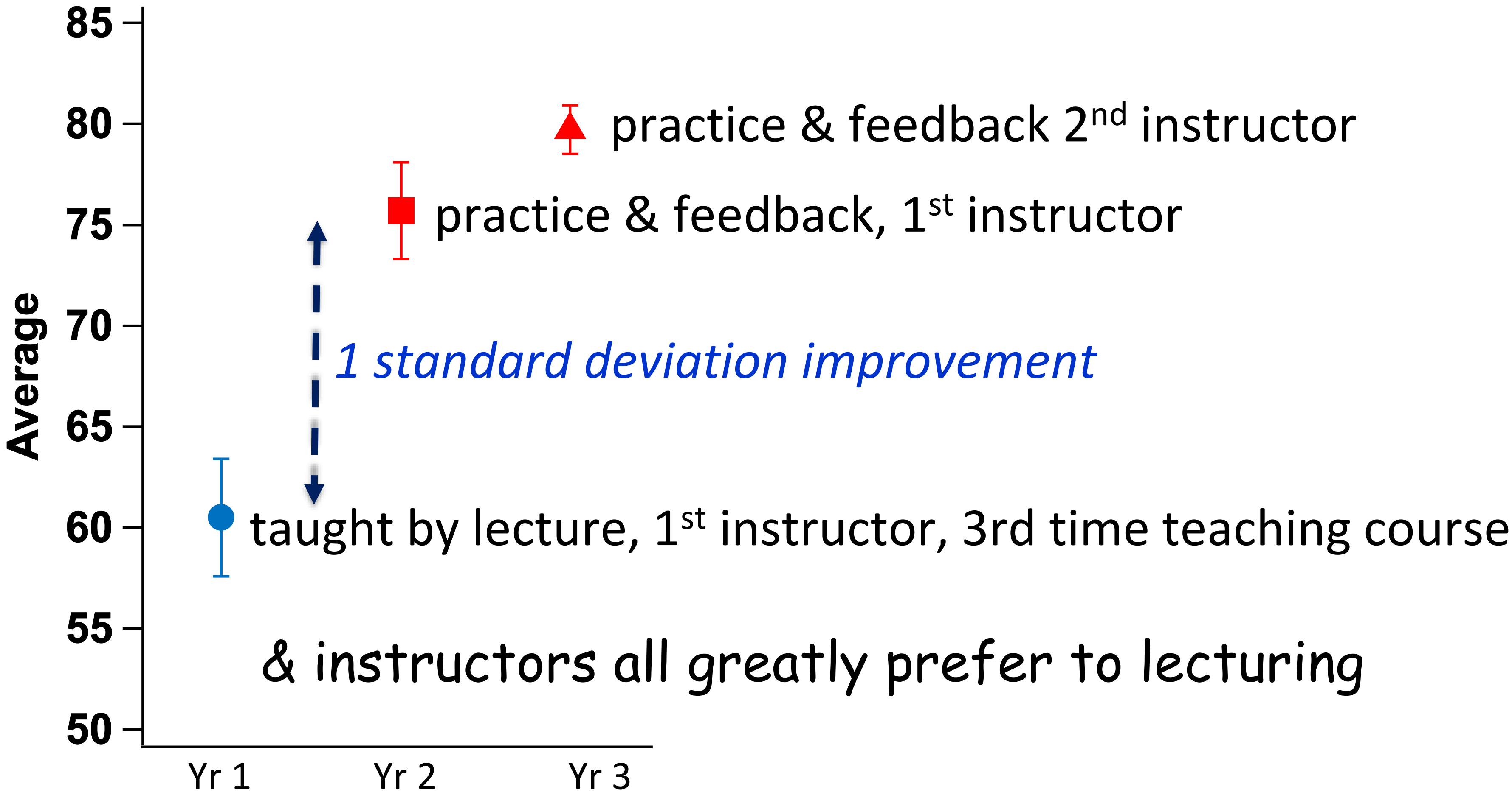
- Attendance up from 50-60% to ~95% for all.
- Student anonymous evaluation overwhelmingly positive

(4% negative, 90% positive): **(most VERY positive, *"All physics courses should be taught this way!")***

- All the faculty greatly preferred to lecturing.

Typical response across ~ 250 faculty at UBC & U. Col. Teaching much more rewarding.

Final Exam Scores
nearly identical problems



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)

Necessary 1st step-- better evaluation of teaching

"A better way to evaluate undergraduate science teaching"
Change Magazine, Jan-Feb. 2015, Carl Wieman

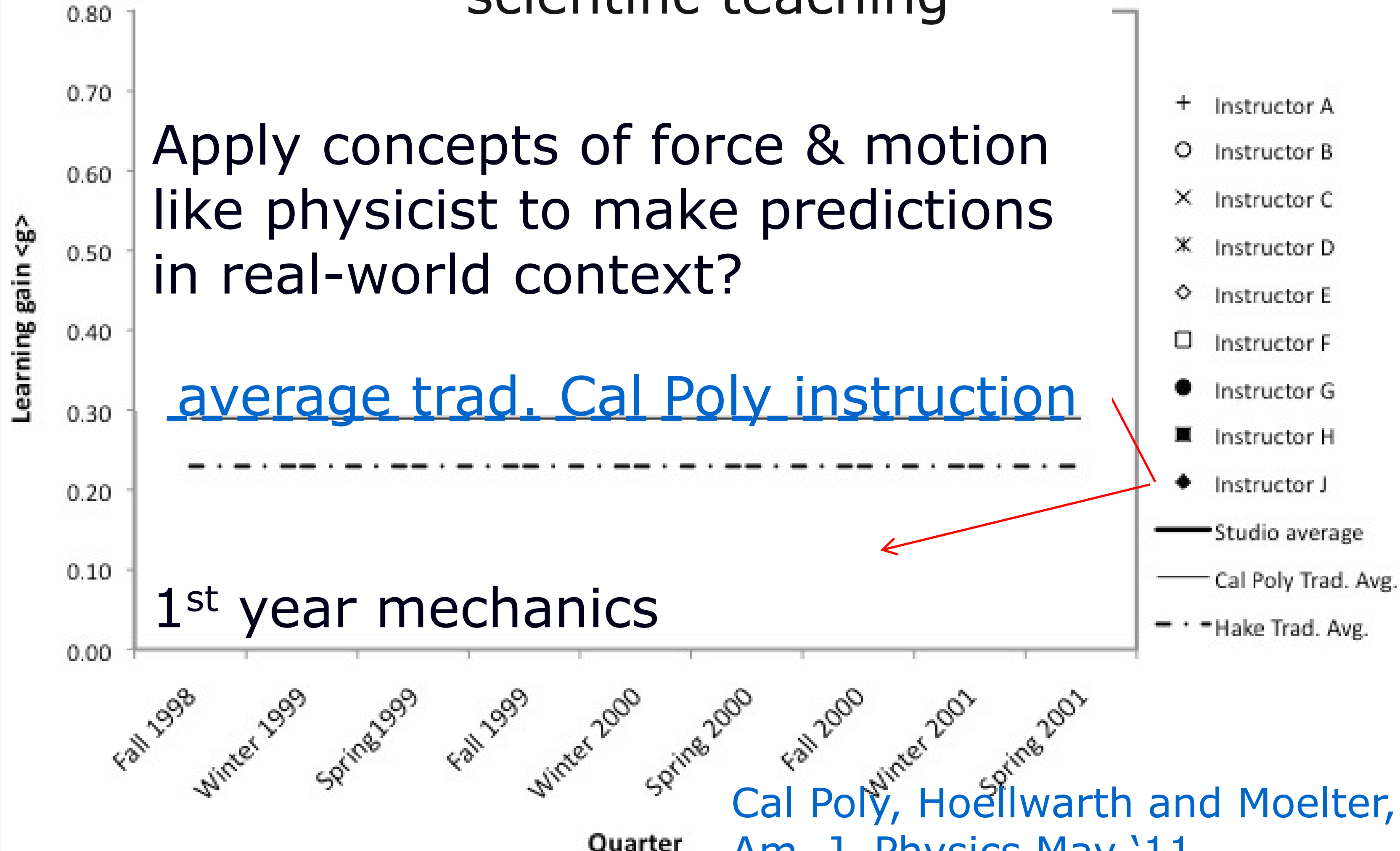
Requirements:

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

scientific teaching



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

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

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

1. Organization of how a topic is presented
2. Feedback to students
4. Review lectures *(why often worse than useless)*

(see cwsei research papers & instructor guidance)

1. Organization of how topic is presented.

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.

- Student does not have this system for organizing knowledge. Can only learn as disconnected facts, not linked to problem solving. Not recall when need.
- Much higher demands on working memory = less capacity for processing.
- Unmotivating— see 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.

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!

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

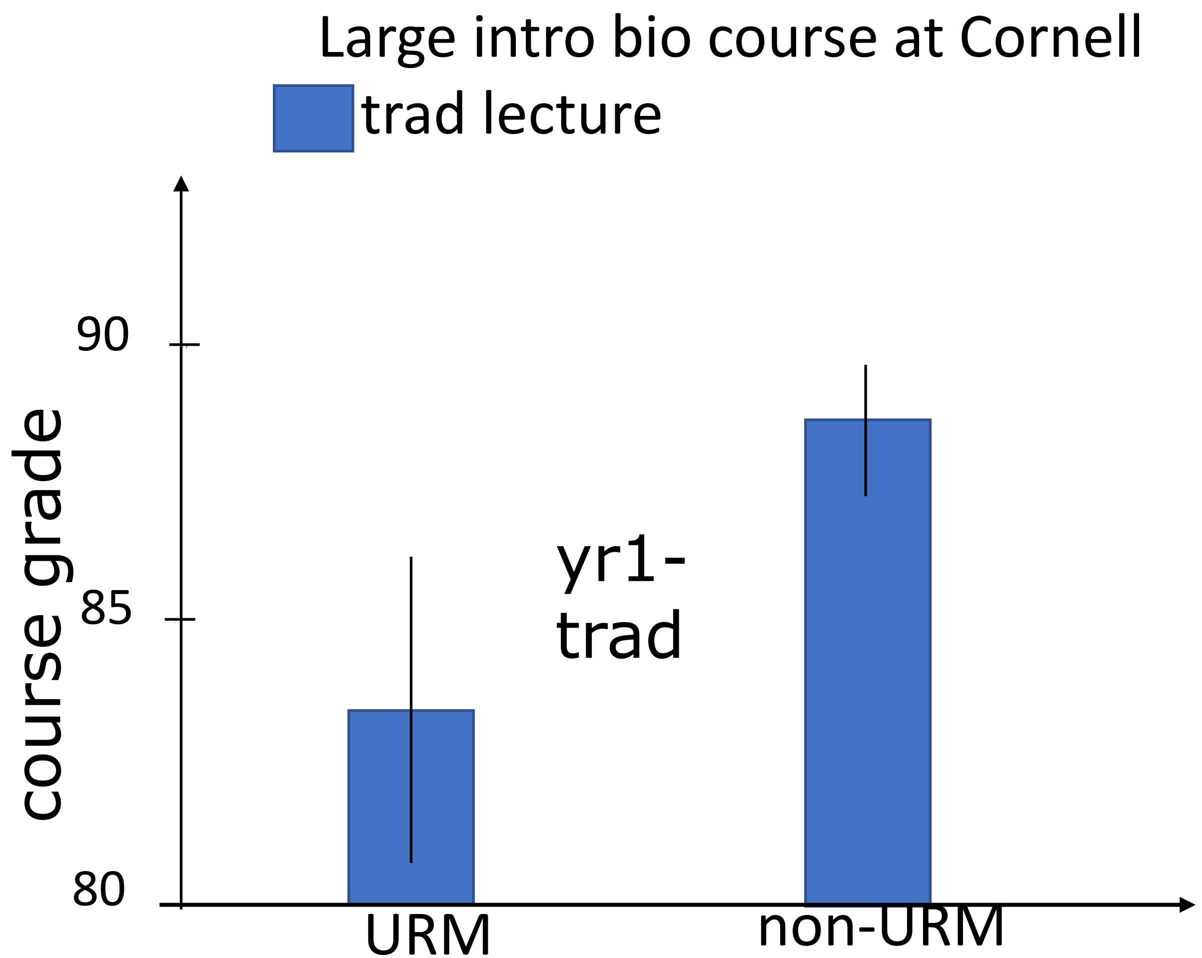
Components of expert thinking:

- ~~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.

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



(small correction for incoming prep)

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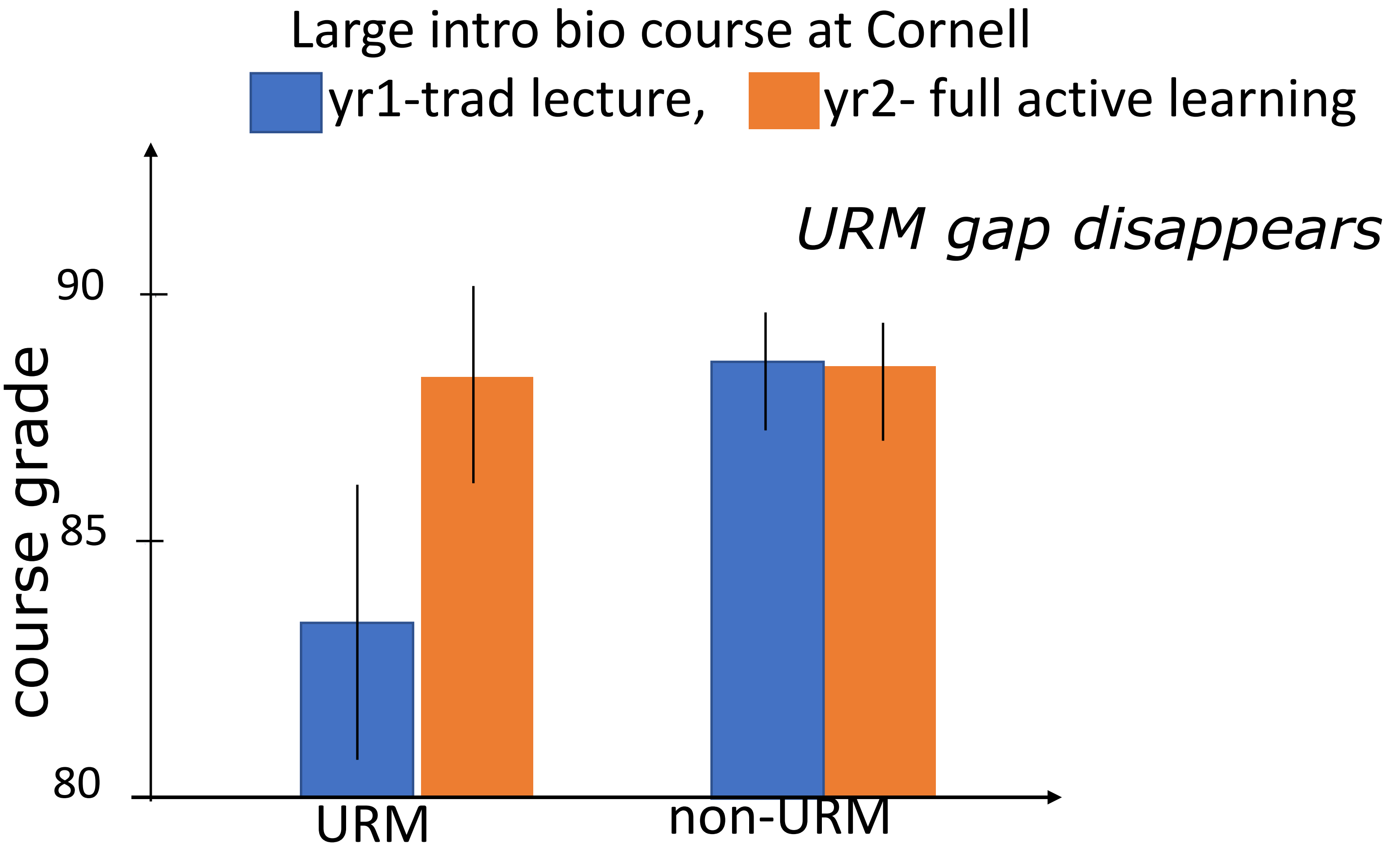


Applications of research instructors can use immediately *(some very common but bad practices)*

1. Organization of how a topic is presented
2. Design of homework and exam problems
3. Review lectures *(why often worse than useless)*

(see cwsei research papers & instructor guidance)

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

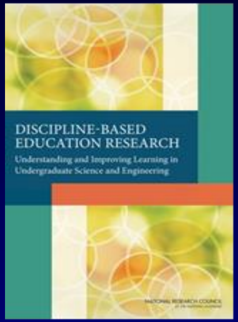
Advanced courses-- often cover more

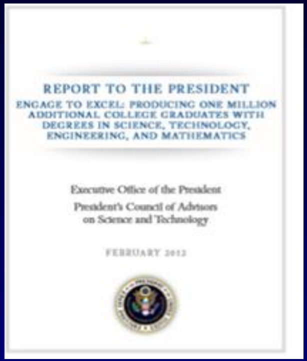
Intro courses, can cover the same amount. But typically cut back by ~20%, as faculty understand better what is reasonable to learn.

Most university instructors and administrators don't know about, but growing recognition of research:

- US National Acad. of Sciences (2012)
- PCAST Report to President (2012)

Calling on universities to adopt





Amer. Assoc. of Universities (60 top N. Amer. Univ.'s—Stanford, Harvard, Yale, MIT, U. Cal, …)

Pre 2011-- *"Teaching? We do that?"*

2017 Statement by President of AAU--

"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 …."

" 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

Pre-class Reading

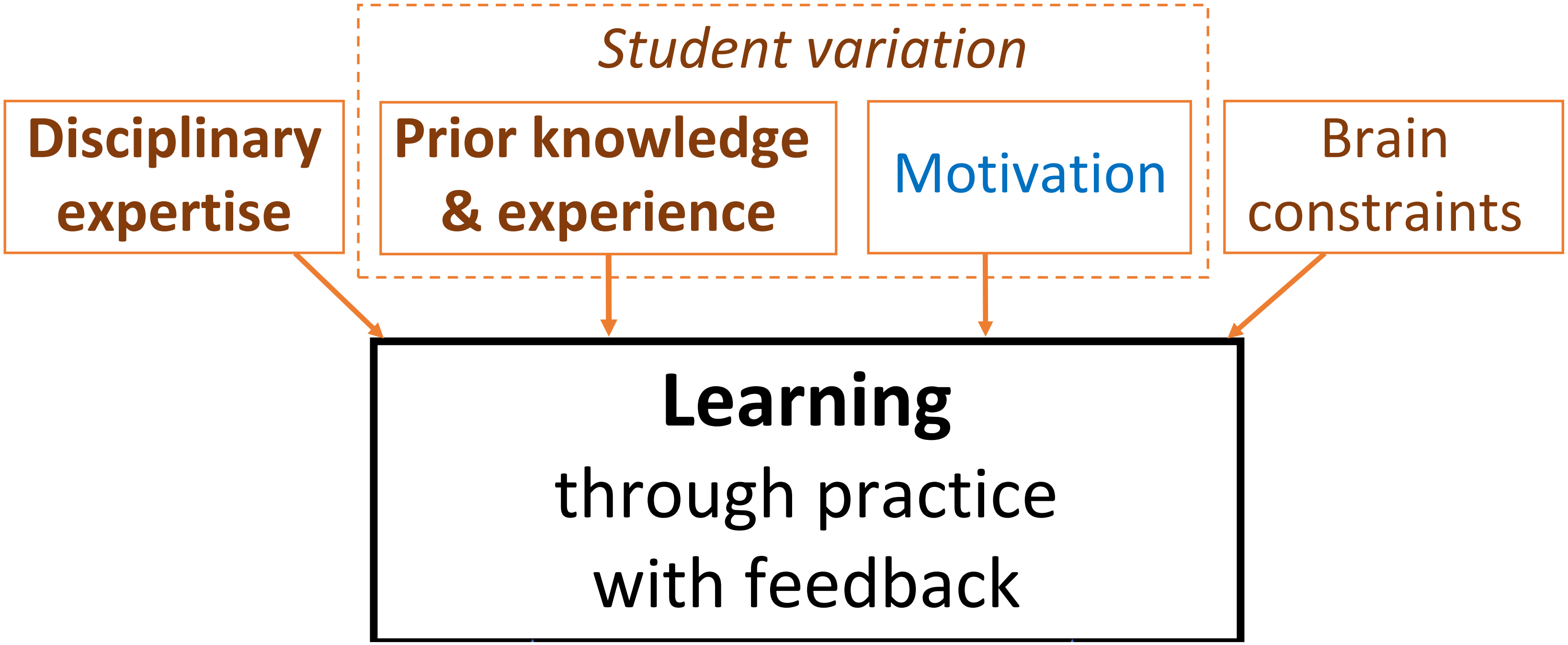
Purpose: Prepare students for in-class activities; move learning of less complex material out of classroom

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

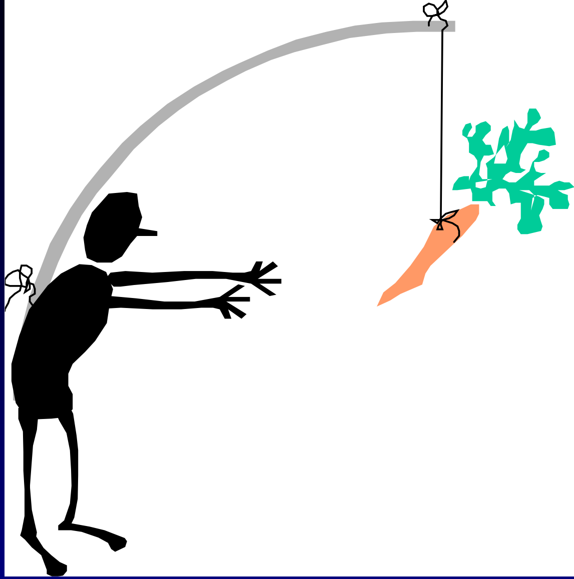
Can get >80% of students to do pre-reading if:

- 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)



How enter into design of practice activities (in class, then homework...)?



<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

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.

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.

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

I. Research on expert thinking*

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

Expert thinking/competence =

•factual knowledge

• **Mental organizational framework** ⇒ retrieval and application

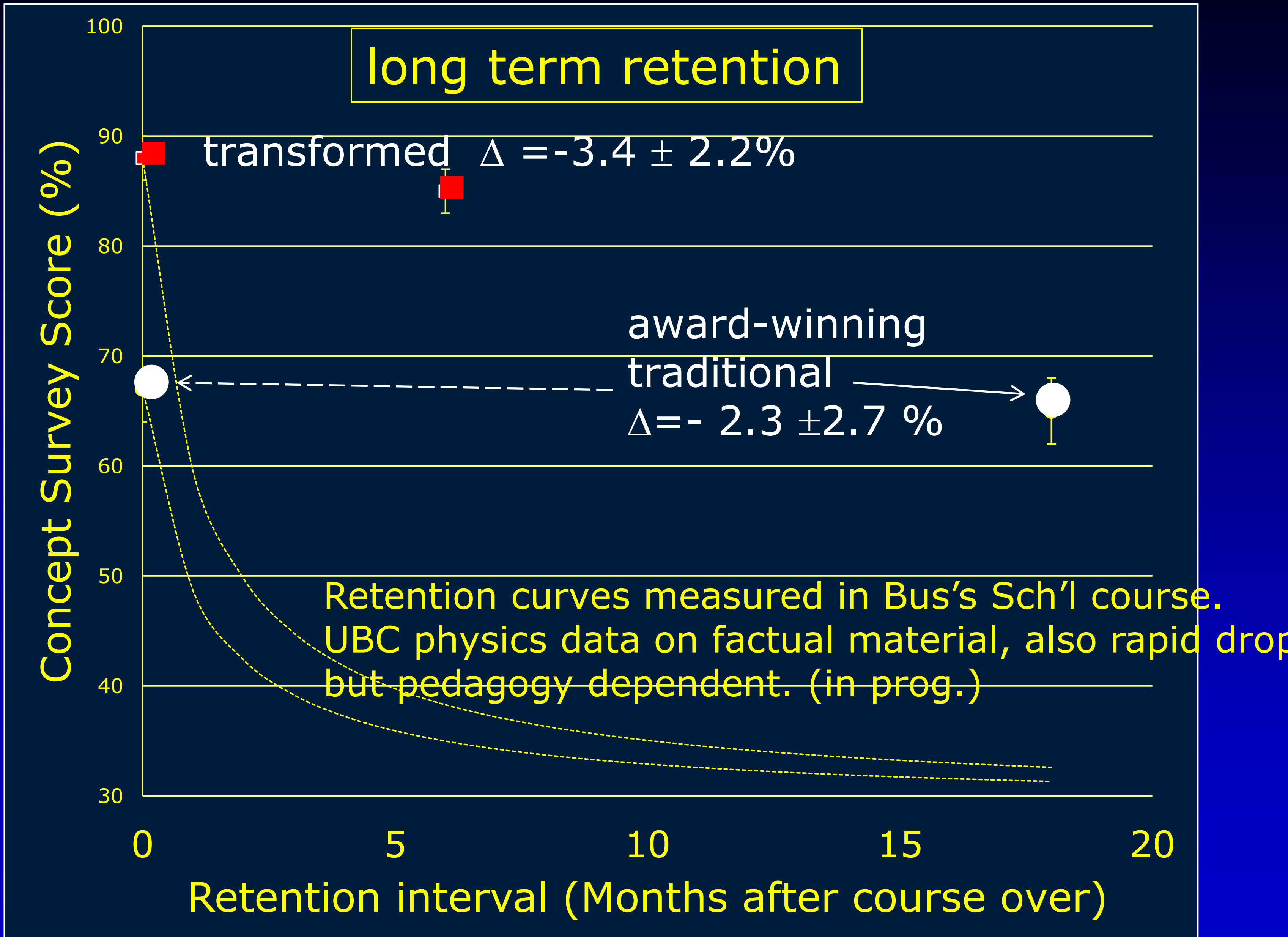
or ?

concepts & mental 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


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)

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