Teaching students to think like physicists

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copies of slides to be available

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

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

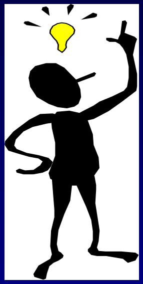
II. Applying learning principles in university courses and measuring results

III. Brief comments on future steps.

- Widespread change in university teaching *(better way to evaluate!)*
- Specific ideas you can use tomorrow.

My background in education

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



2-4 years later ⇒ 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-- controlled experiments & data, basic principles! (~ 100 papers)

What were my grad students failing to learn?

"thinking like physicists" = how make decisions

Goal of university education:
Students learn to make better decisions

At course and program level: In relevant contexts, use the knowledge and reasoning of discipline to make good decisions with <u>limited</u> information ("expertise")

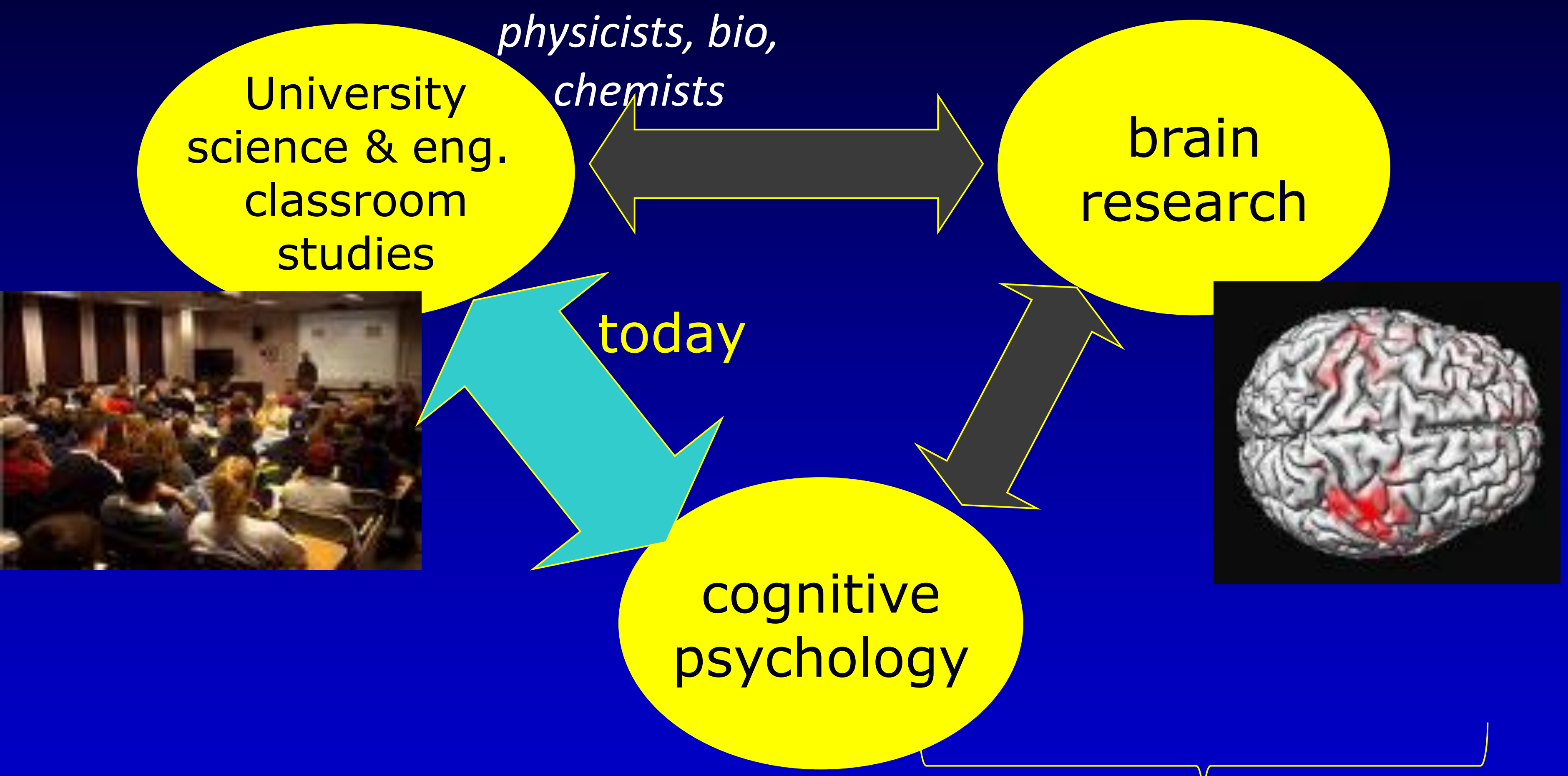
Rest of talk– how to teach and measure

30 sec – think of decisions physicists make in solving authentic problems:

- *what simplifications appropriate;*
- *what information needed & what irrelevant;*
- *appropriate mental model;*
- *criteria for "reasonable" answer….*

Major advances past 1-2 decades

⇒ New insights on how to learn & teach complex thinking



Strong arguments for why apply to most fields

Basic result– rethink how learning happens

old/current model

knowledge

soaks in, varies with brain

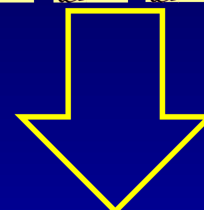
Primary educational focus of universities:

- contents of knowledge “soup”
- admitting best brains
- blaming K-12 for deficiencies

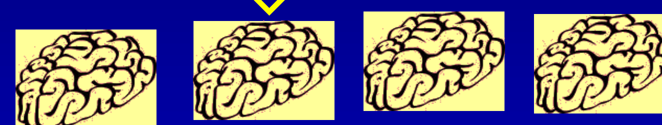
new research-based view

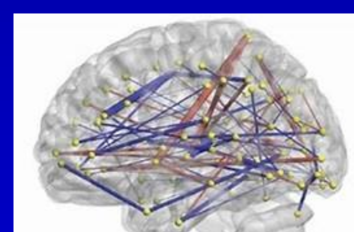
brain changeable

 ~ same



transformation



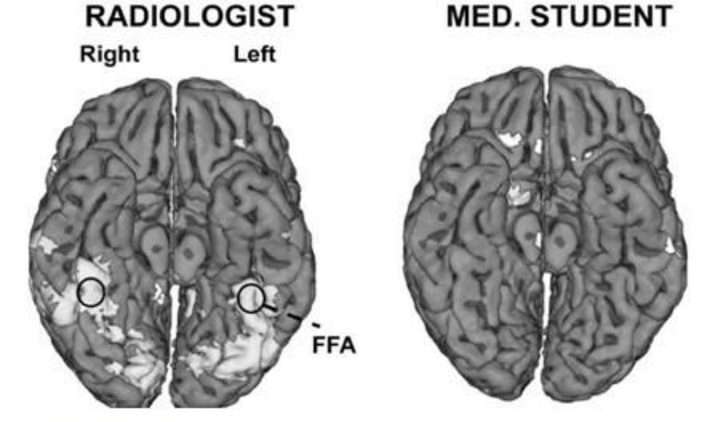


Changes in response to intense thinking. Improved capabilities. Very dependent on teaching methods.

Strenuous extended mental effort- biological requirement. Forms new connections, new neurons.

Builds and strengthens decision-making neural connections. Expertise lies in rewired brain.

For Prof level expertise, requires 1000's of hours.



fMRI-- interpreting x-ray image

In more mundane terms--

Best way to learn to make good decisions?

a. *Being told what the decision should be, if you ever encounter a similar situation (and realize it).*

b. *Practice making decision, then get specific feedback on how to improve. Repeat…*

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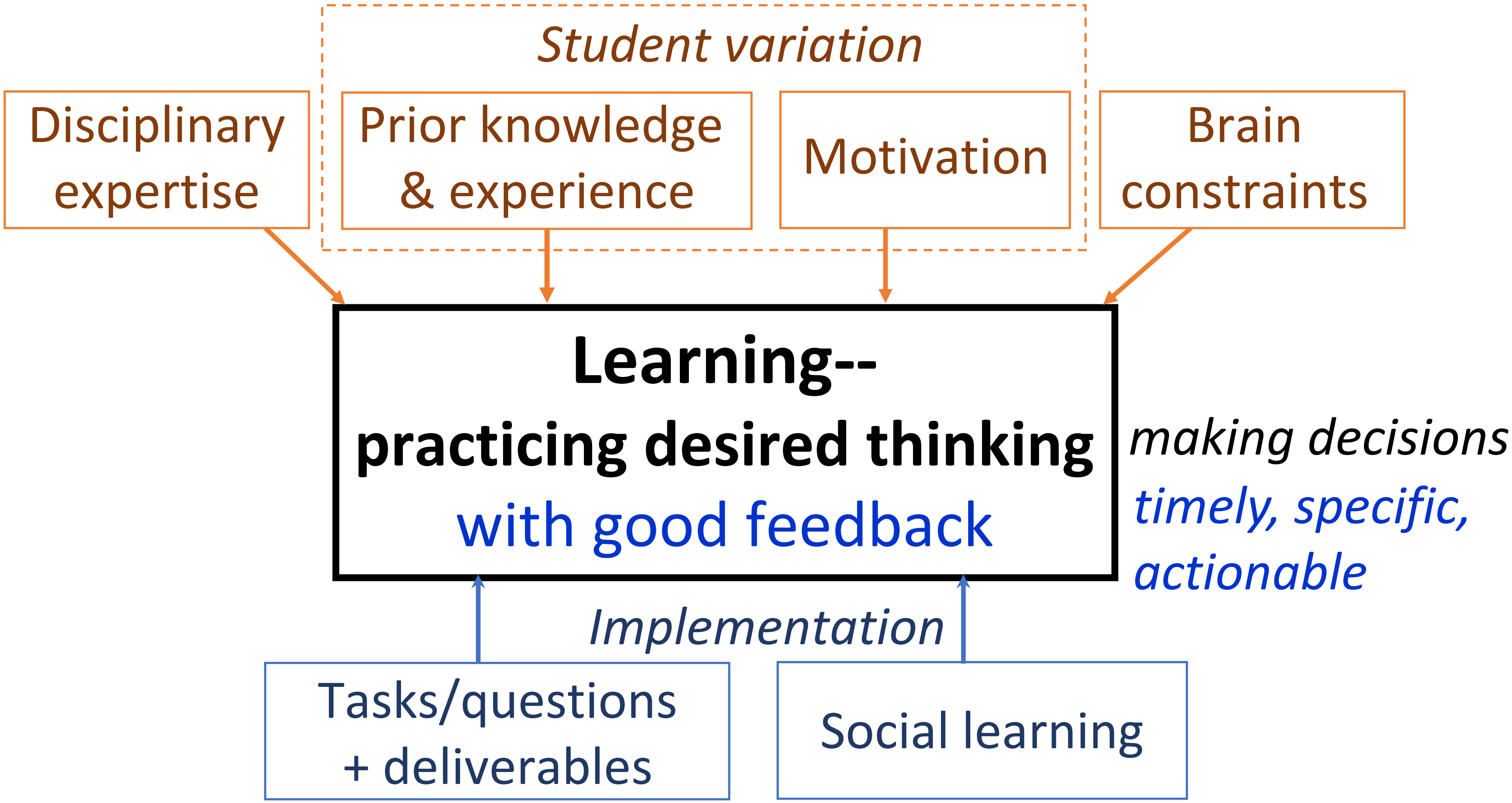
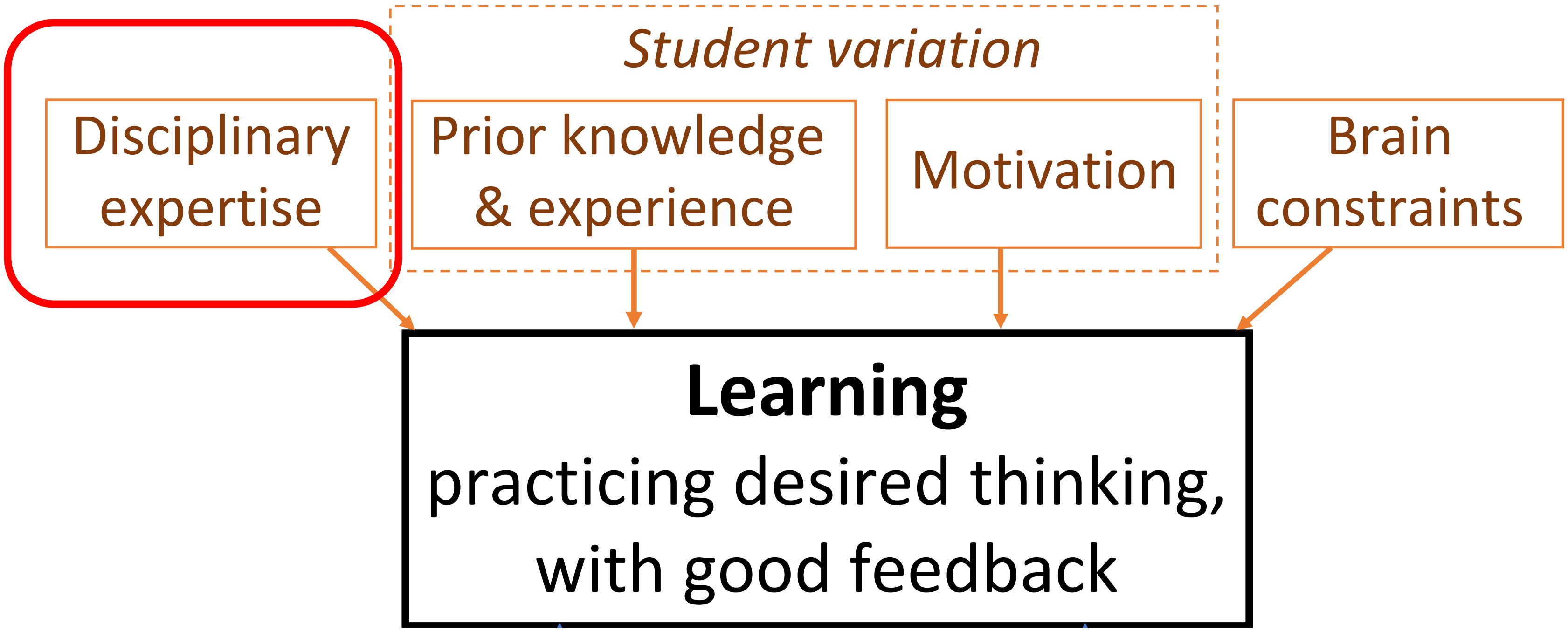
Teaching to think (*make decisions*) like expert, what research says is important



<u>Defines teaching expertise.</u>

Practices that research shows produce more learning.



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

Learning expert thinking*--

- Challenging tasks/questions
- Practicing desired thinking skills *(expertise)*

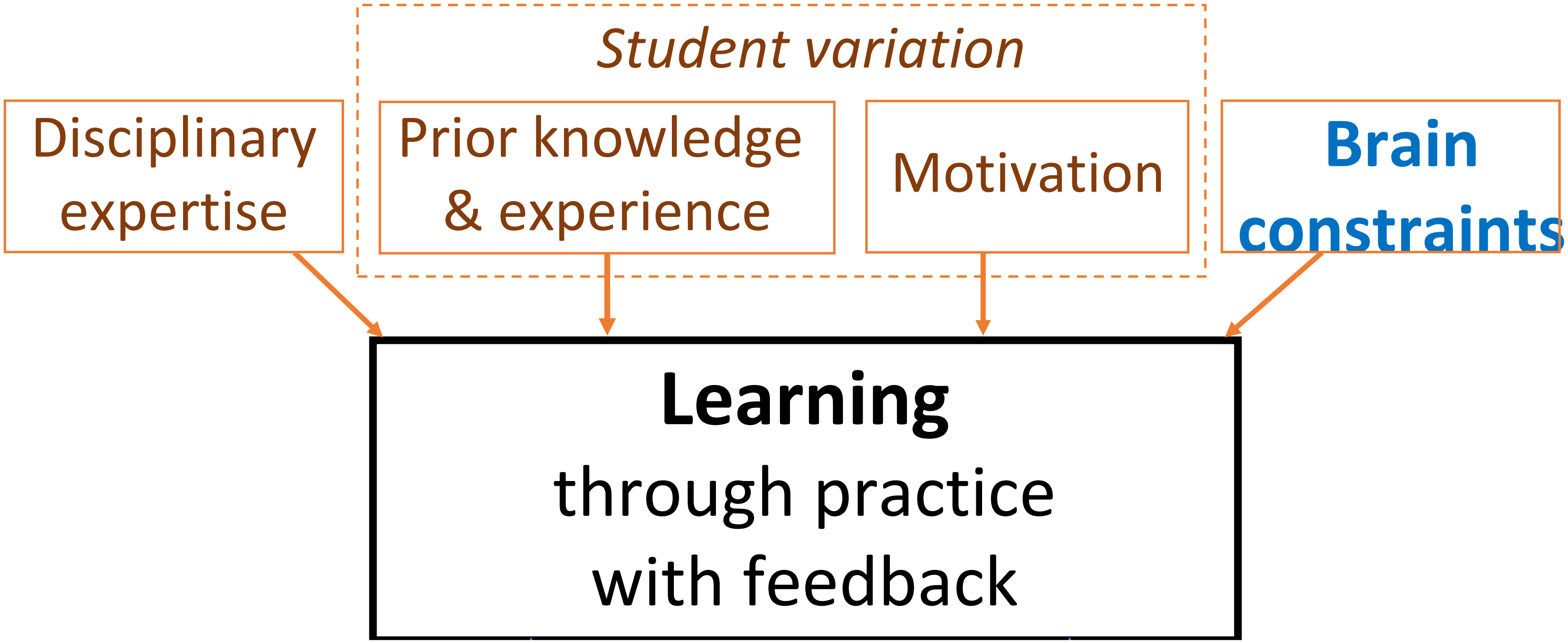
Decisions when solving real physics problem

- Decide: what concepts/models relevant
- Decide: *What* information relevant, irrelevant, needed.
- Decide: what approximations are appropriate.
- “ : potential solution method(s) to pursue.
- ....
- “ : if solution/conclusion make sense- criteria for tests.

*Learner must **practice making decisions**.*

Large difference between making decision (good or not) vs. being told outcome to use. (Holmes, Keep, Wieman, TBP)

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



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

Expert thinking to practice-- activity design*

Brain constraints:

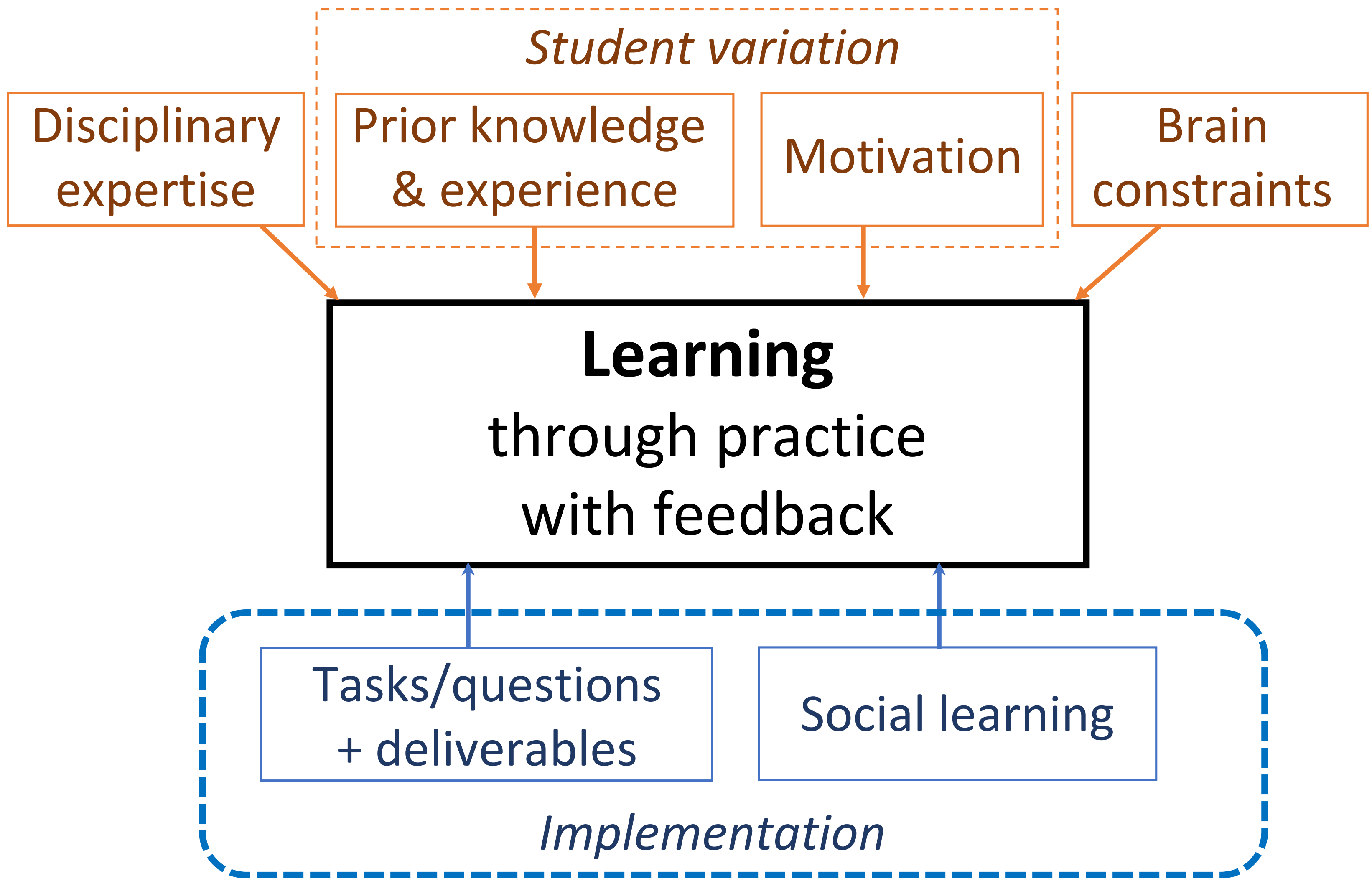
1) working memory has limit 5-7 new items.

Additional items reduce processing & learning.

- Split attention (checking 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.

Interference suppressed by repeated interleaved recall


Student variation
Disciplinary expertise
Prior knowledge & experience
Motivation
Brain constraints
Learning
through practice
with feedback
Tasks/questions + deliverables
Social learning
Implementation

Implementation—

1. Design good tasks (as above) but with **deliverables** *(define task & instructor use to guide feedback)*

2. **Social learning** (working in groups, in class 3-4)

Talking to fellow students better than hearing expert instructor explain??

(or thinking about individually?)

Yes, but **only** if properly designed!

- Efficiency. More targeted feedback & less time stuck
- People teaching/explaining to others triggers unique cognitive process $\Rightarrow$ learning
- **Very useful for teacher--** listen in on discussions!
  $\Rightarrow$ *timely, specific, actionable feedback*

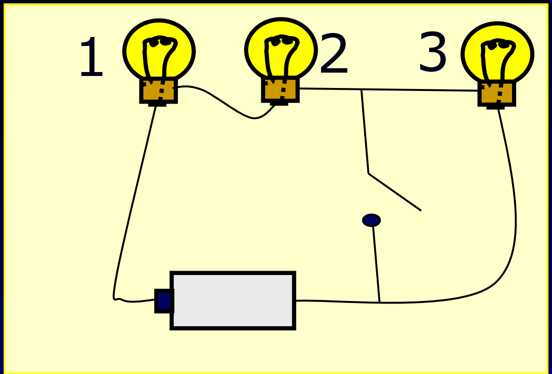
How to apply in classroom?
practicing thinking with good feedback

Example– large intro physics class (similar chem, bio, comp sci, ...)

Teaching about electric current & voltage

1. Preclass assignment--Read pages on electric current. Learn basic facts and terminology without wasting class time. Short online quiz to check/reward.

2. Class starts with question:

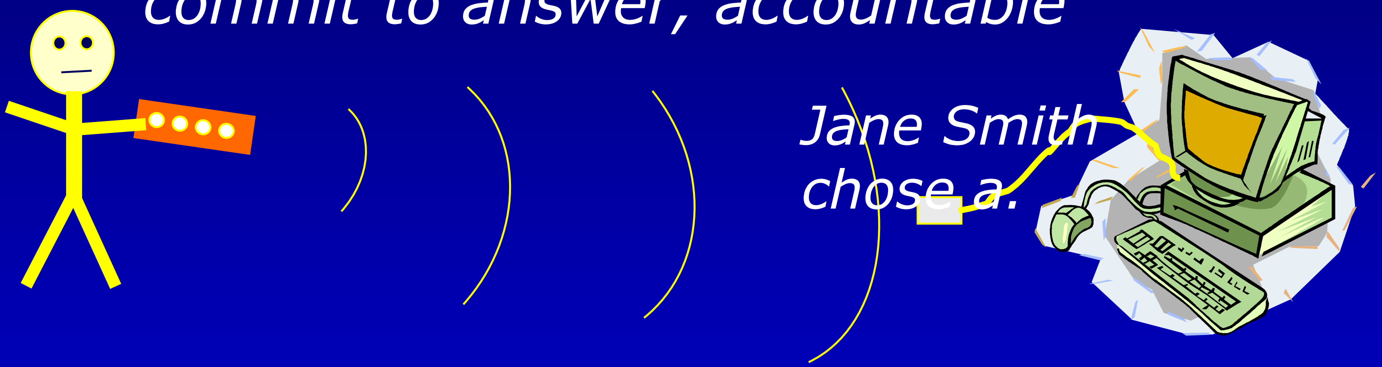


When switch is closed, bulb 2 will
a. stay same brightness,
b. get brighter
c. get dimmer,
d. go out.

answer & reasoning

3. Individual answer with clicker

commit to answer, accountable



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--
(deciding on applying, testing conceptual models, critiquing reasoning…)

Feedback that improves thinking—other students, informed instructor, demo

III. Evidence from the Classroom

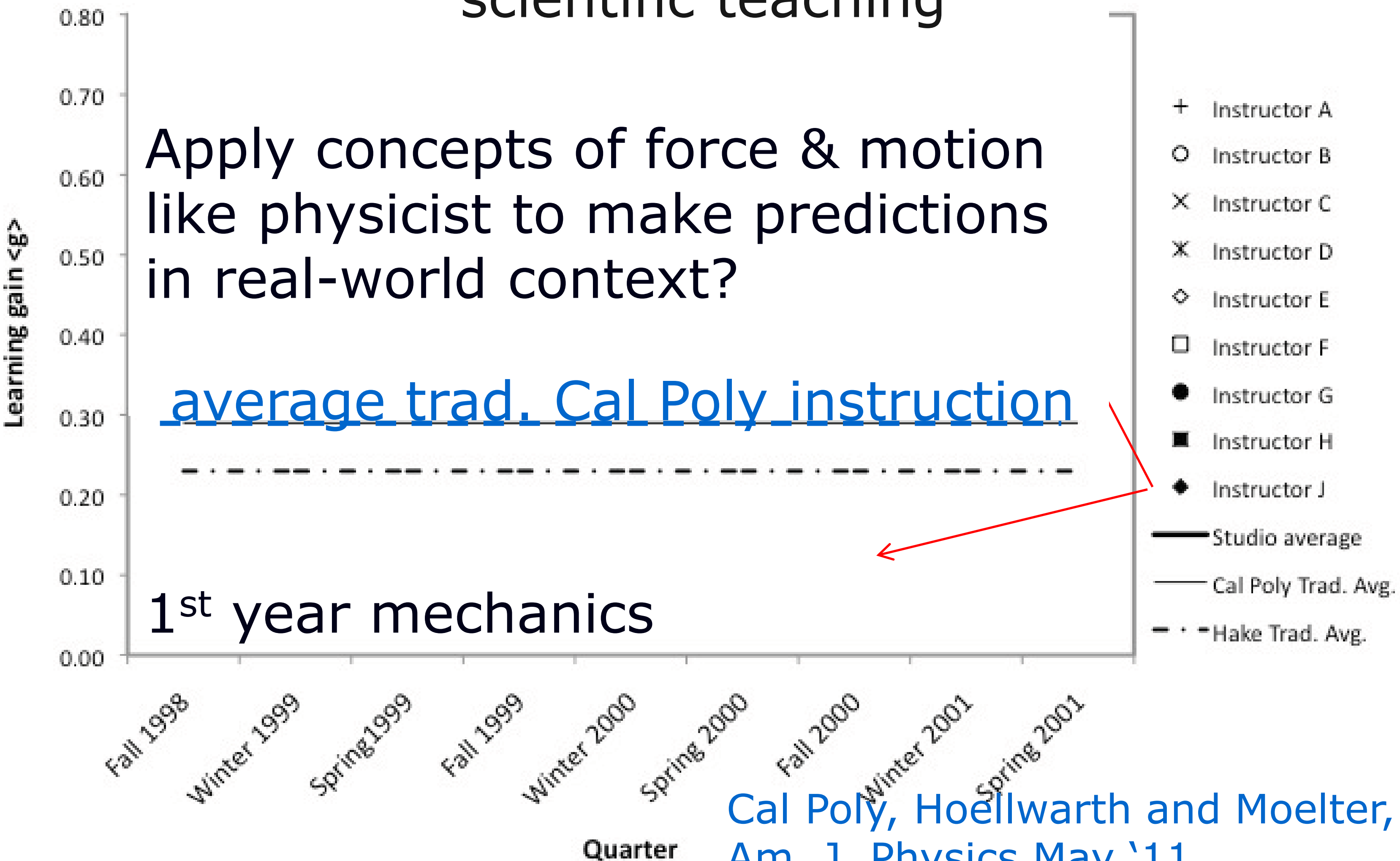
~ 1000 research studies from undergrad science and engineering comparing traditional lecture with "active learning" (or "research-based teaching").

- consistently show greater learning
- lower failure & dropout rates

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

A few examples—
various class sizes and subjects

scientific teaching



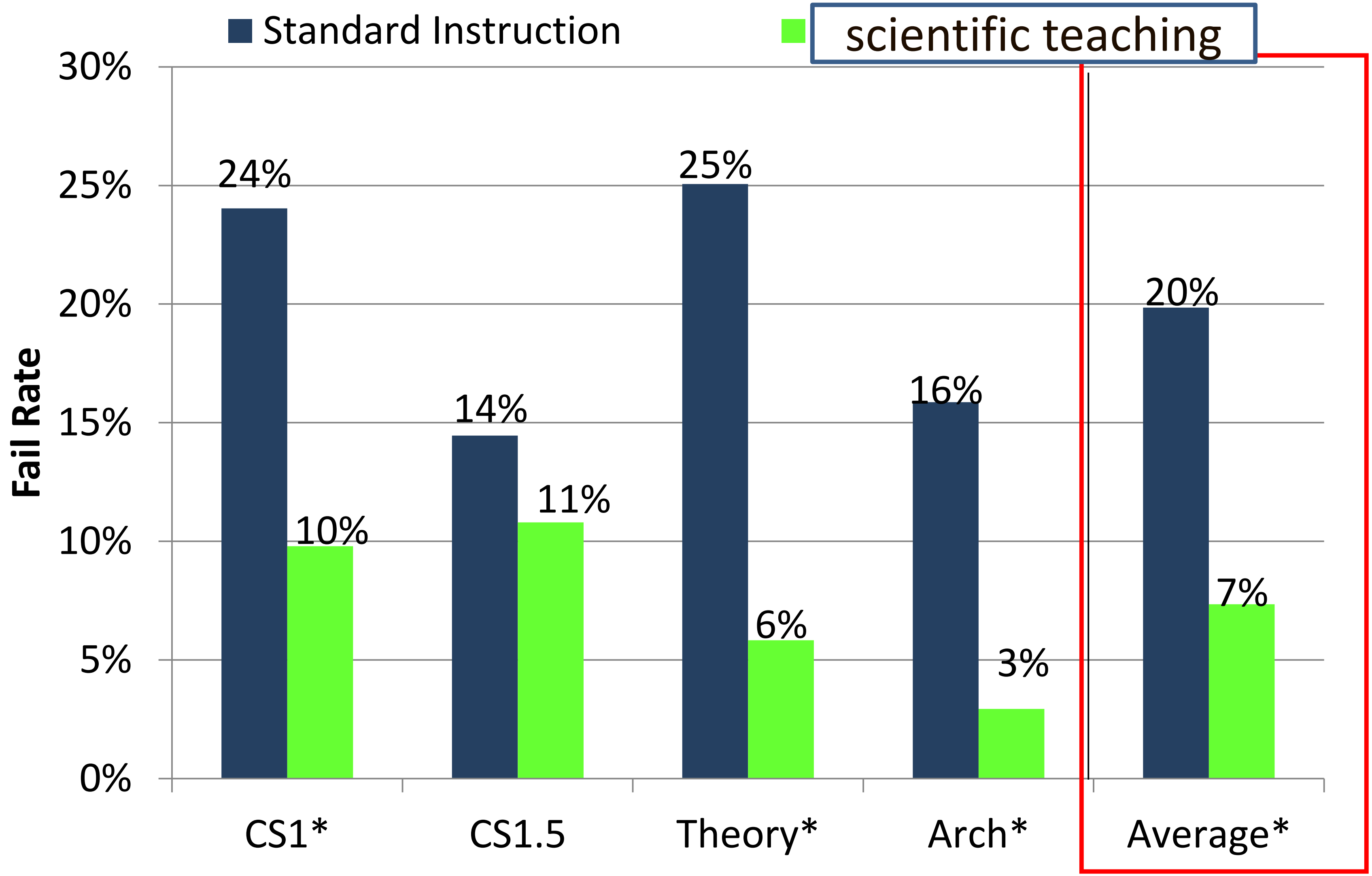
Apply concepts of force & motion like physicist to make predictions in real-world context?

1st year mechanics

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*



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

Learning **in the in classroom***

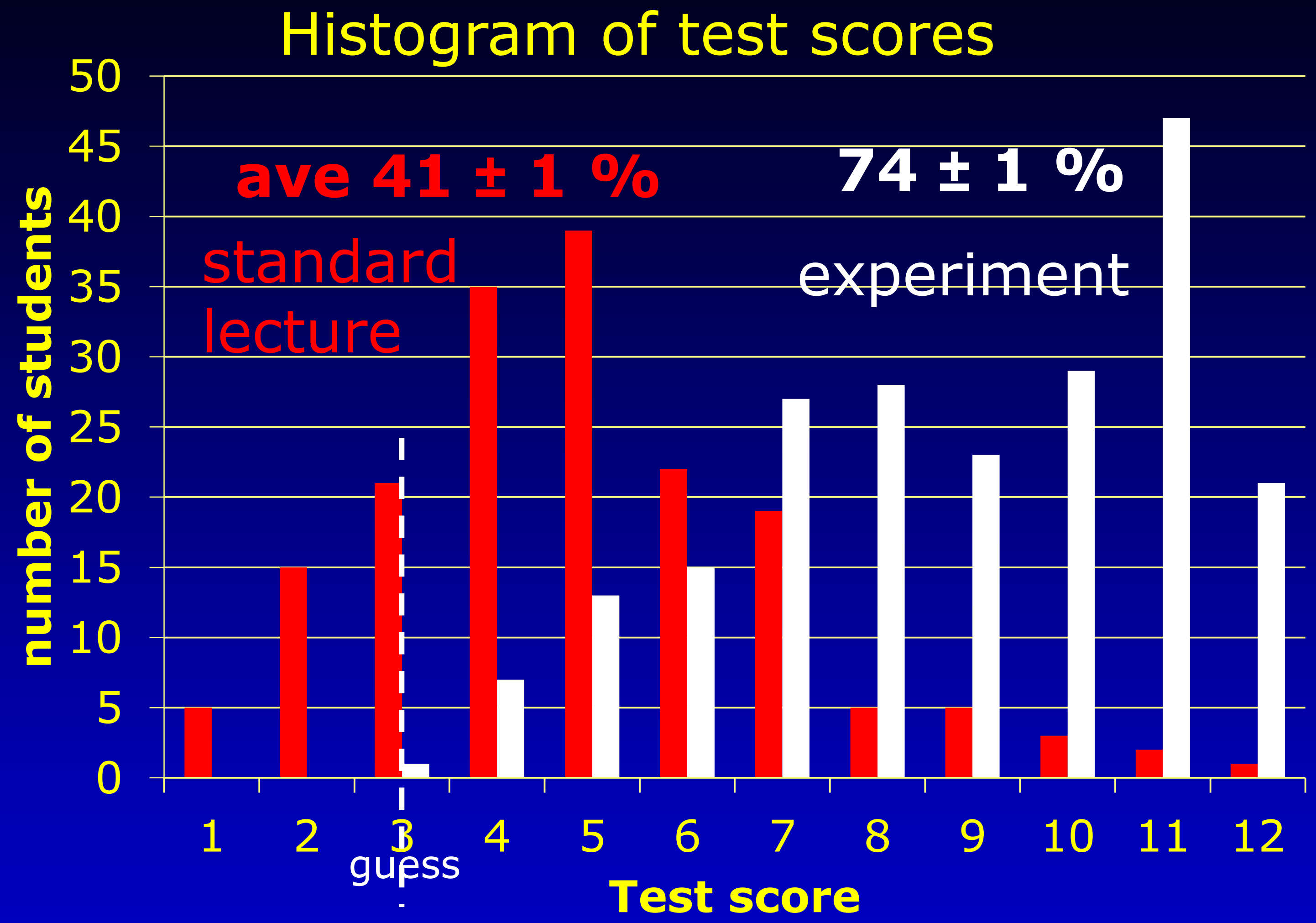
Comparing the learning in two ~identical sections UBC 1st year college physics. 270 students each.

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 material to cover *(Can't cover as much?)*
- Same class time (3 hours, 1 week)
- Same exam (jointly prepared)- start of next class

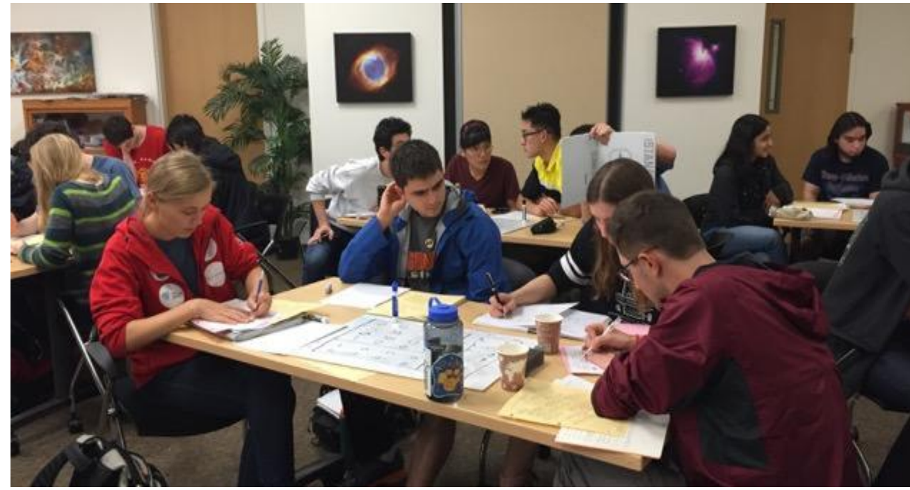
**Deslauriers, Schelew, Wieman, Sci. Mag. May 13, '11*



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

Advanced courses

U. Col, UBC, & Stanford 2nd -4th year physics



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

Structure of active learning class

Good for any subject, level, class size

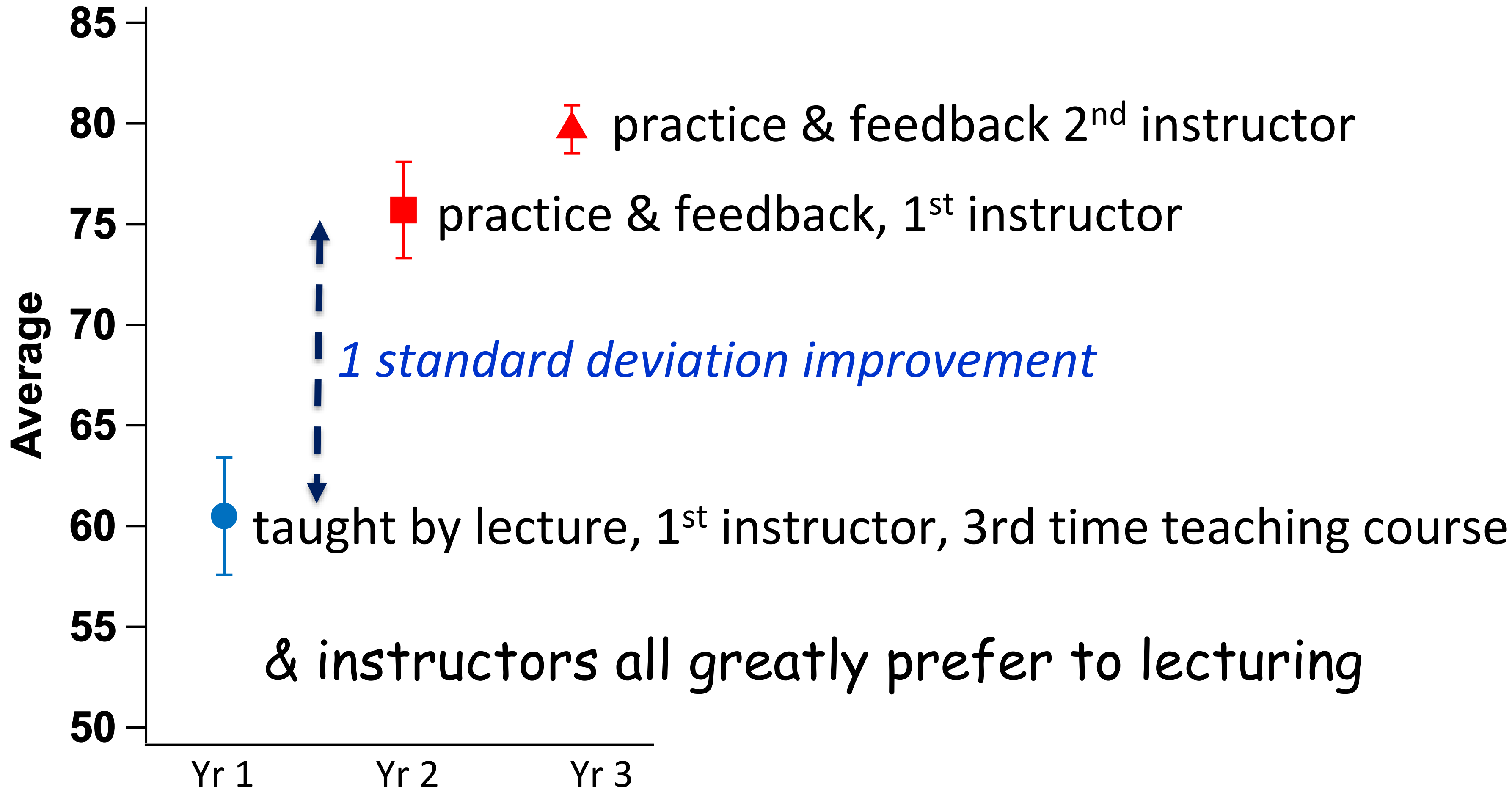
Actions	Students	Instructors
Preparation	Complete targeted reading	Formulate/review activities
Introduction (2-3 min)	Listen/ask questions on reading	Introduce goals of the day
Activity (10-15 min)	Group work on activities	Circulate, answer questions & assess students
Feedback (5-10 min)	Listen/ask questions, 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 about that thinking—more effective teaching & feedback**

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)

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 comments:

90% positive, only 4% negative

(mostly 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.

"But traditional lectures can't be as bad as you claim. Look at 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) *If better teaching, w*ould have been **m*ore*** *successful, along with many other students.*

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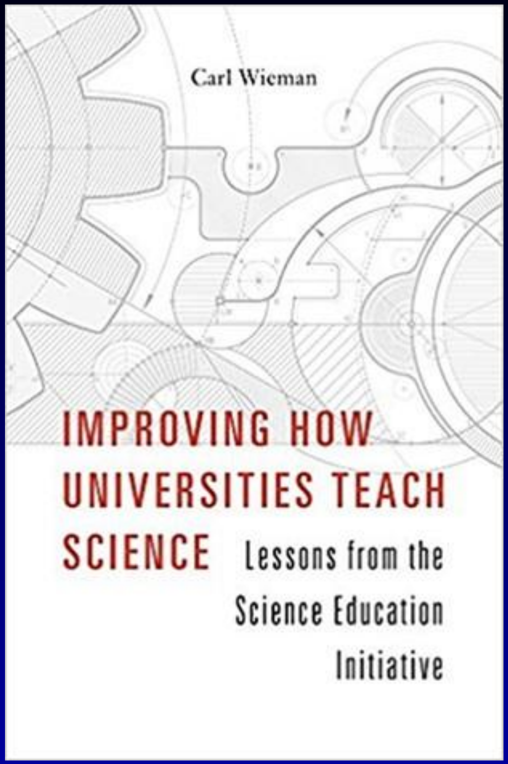
For administrators:



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-

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

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. 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.

Conclusion:

Research providing new insights & data on effective teaching and learning of university science.
Better way to teach. Better way to evaluate teaching.

Potential to dramatically improve education.
Still using teaching equivalent to blood letting.

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

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!

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.

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.

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

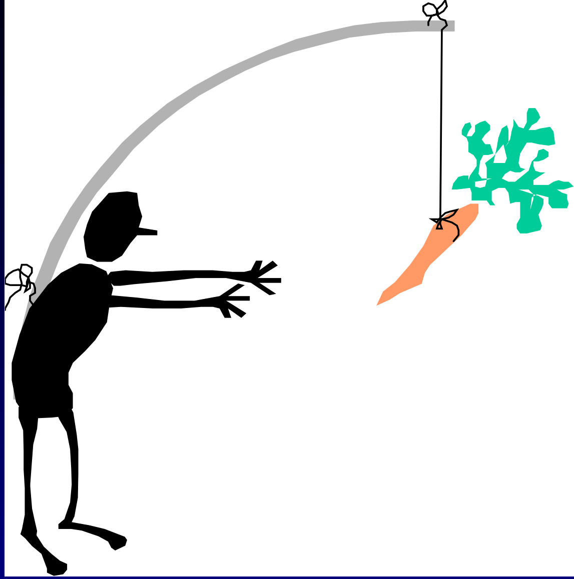
Can get >80% of students to do pre-reading if:

- 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)

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

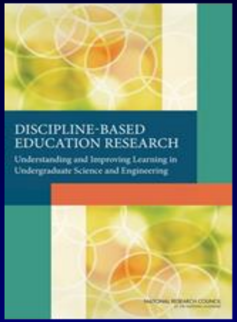
b. Sense that **can** master subject and how to master, recognize they are improving/accomplishing

c. Sense of personal control/choice

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 …."

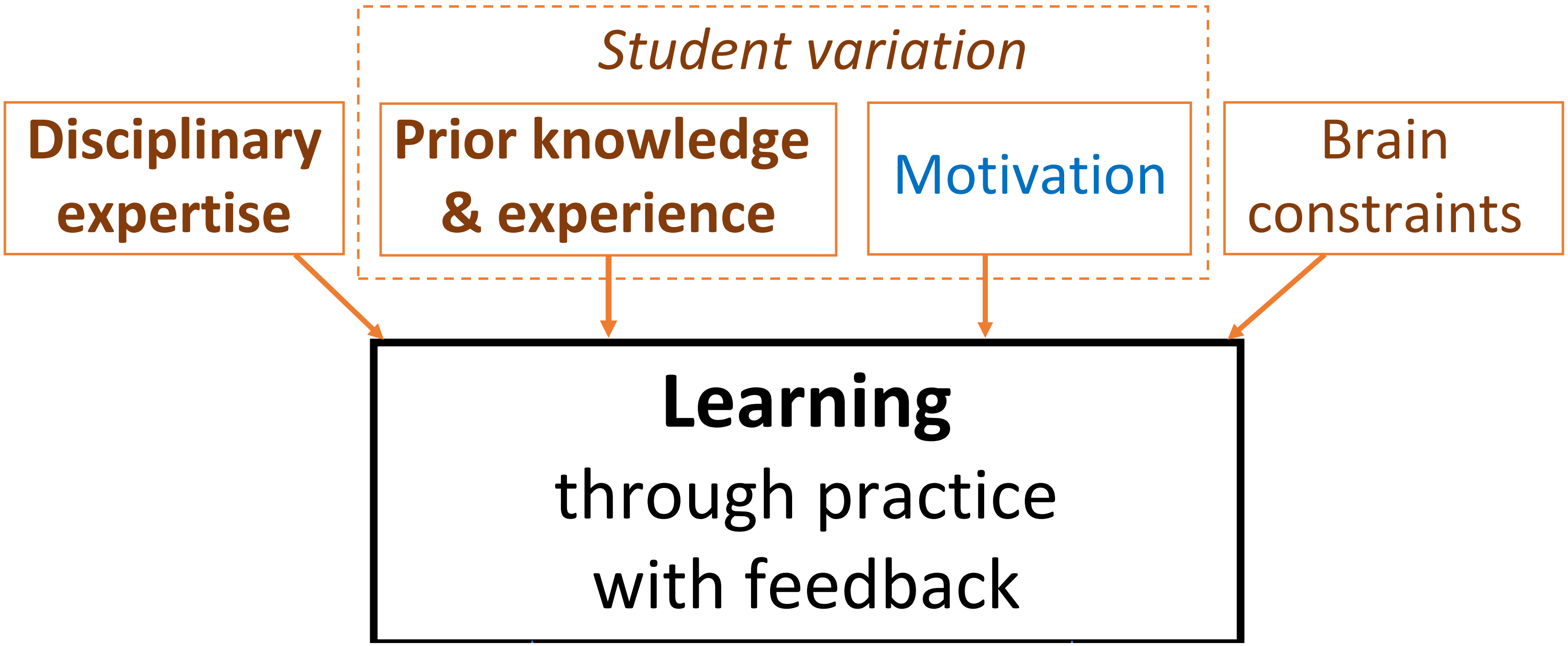
“ A time for telling” Schwartz and Bransford,
Cognition and Instruction (1998)

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



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

“Discipline-based education research” (DBER)

Tenured faculty in disciplines (biology, chem, physics...) studying teaching and learning of undergraduate students. Experiments, controlled comparisons in classrooms. **Testing effectiveness of different teaching methods, discovering better ones.**

Largely in N. America but spreading

Started in physics ~ 50 years ago *(myself 30 years)*
Now in all science & engineering disciplines

Edging into math & social sciences

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

Does this apply to non-STEM disciplines?

Yes. Defining feature of a discipline is a set of agreed upon standards for making relevant decisions with limited information. *(i.e. what makes a good scholar)*
(Wieman, Daedalus, May 2019)

How decide on:

What is worthwhile scholarly work?

What is valid information?

What is suitable argument from information to conclusions?

What is appropriate form of presentation of work?

….

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.

Effective teacher—

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

("cognitive coach")

requires expertise in the content!

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

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$\Rightarrow$ 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

I. Research on expert thinking*

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

Expert thinking/competence =

·factual knowledge

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

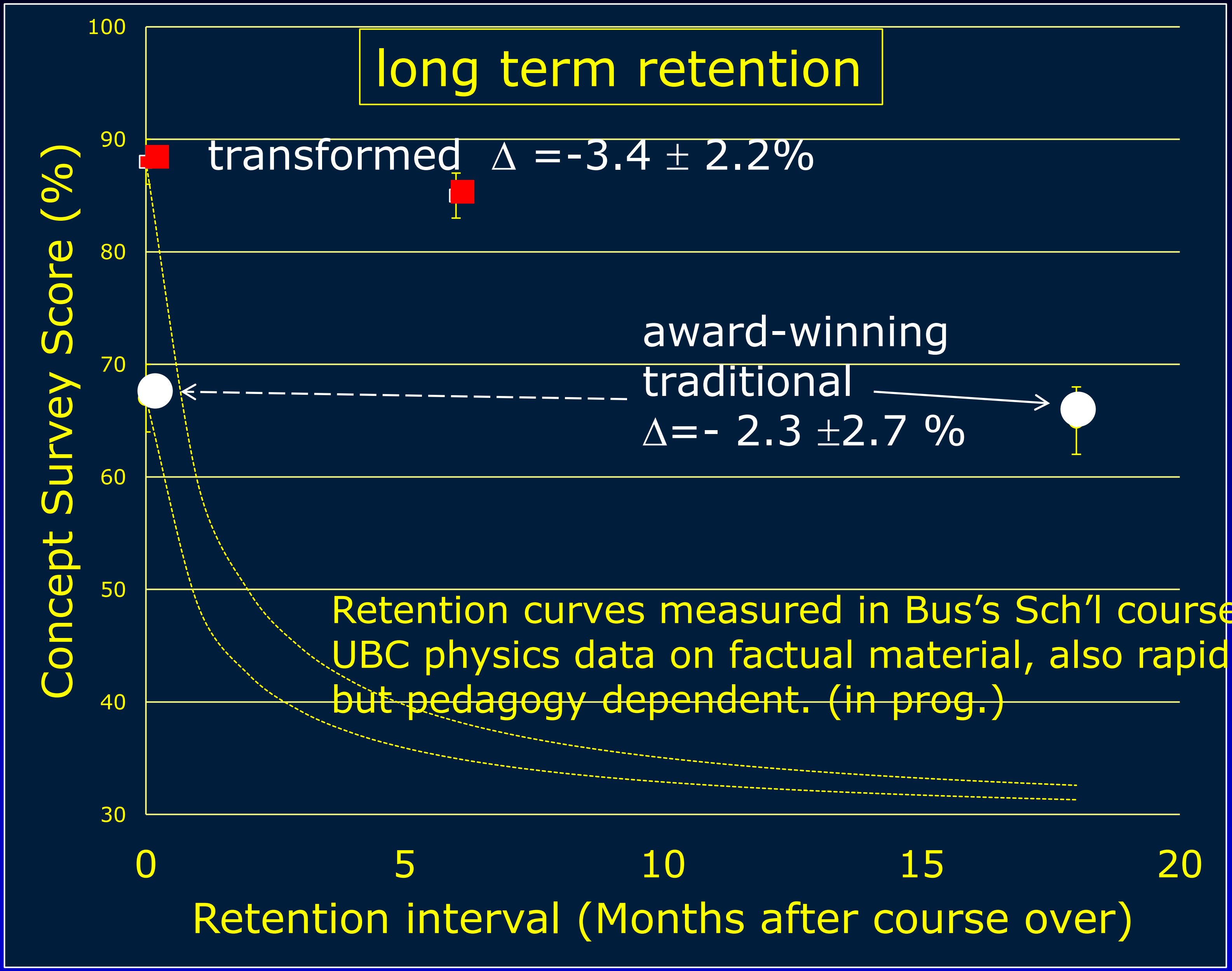
or ?

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)

Situation with university science teaching now much like medicine in 19th century.

Methods used and believed in for hundreds of years

But science—controlled comparisons, data, and scientific principles, provided new methods.
Much more effective.
(but takes a while for doctors to learn & use)

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.

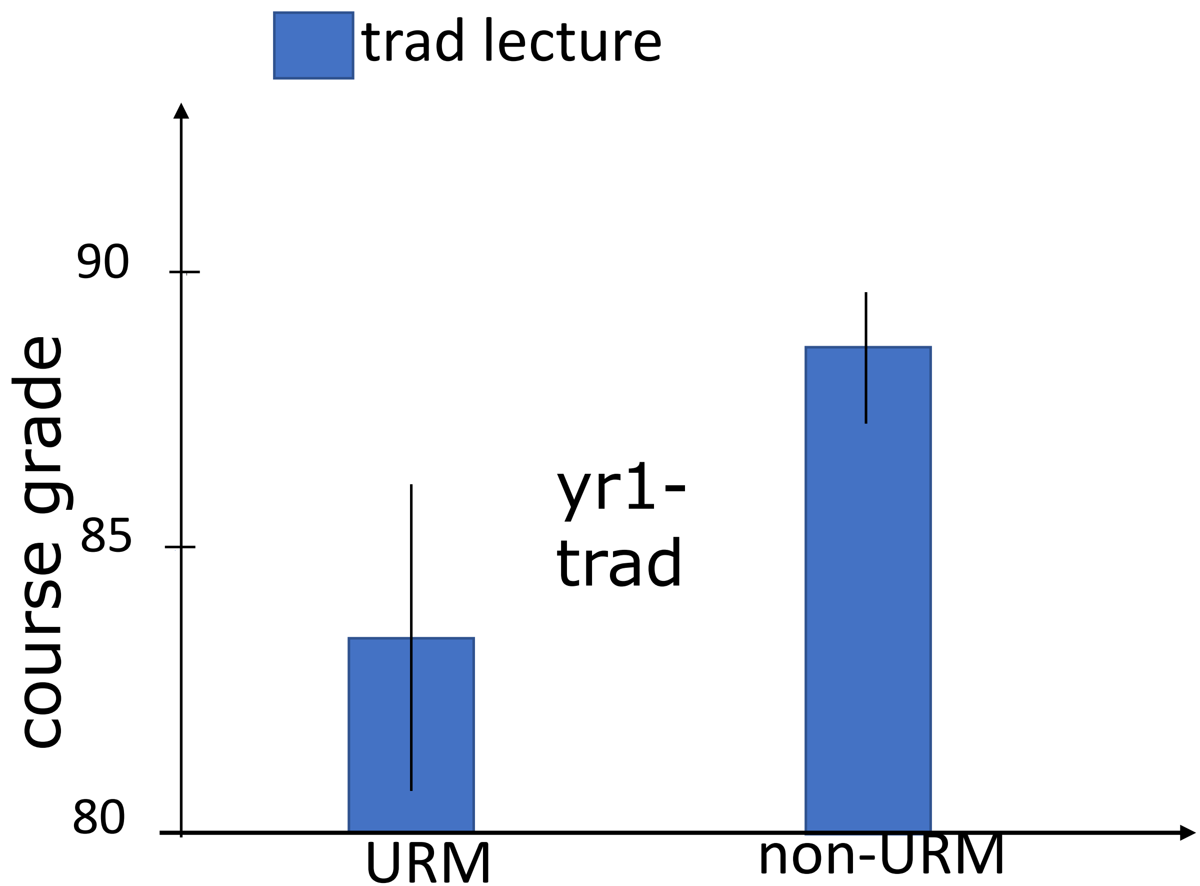
- Departmental level, widespread sustained change at major research universities
  $\Rightarrow$scientific approach to teaching, all undergrad courses
- Departments selected competitively
- Substantial one-time $$$ and guidance

Extensive development of educational materials, assessment tools, data, etc. Available on web.
Visitors program

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



(small correction for incoming prep)

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