# Taking a scientific approach to science education

*and most other subjects*

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*Department of Physics and Grad School of Education*

copies of slides to be available

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

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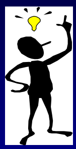
I. Introduction– Educational goals & research-based principles of learning

II. Applying learning principles in university courses and measuring results

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-- experiments & data, basic principles!
  (~ 100 papers)

What is the goal of education?
**Students learn to make better decisions.**

At university course and program level:
*In relevant contexts, use the knowledge and reasoning of the discipline to make good decisions ("expertise").*

*Rest of talk– research on how to teach most effectively*

## Major advances past 1-2 decades

⇒ New insights on how to learn & teach complex thinking (make decisions like "expert", biologist, physicist, ...)

*physicists, bio, chemists*

University science & eng. classroom studies

brain research

today

cognitive psychology

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

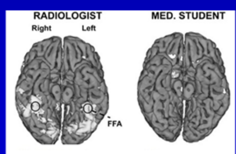
new research-based view

brain changeable

~ same

**transformation**

Change neurons by intense thinking. Improved capabilities.




fMRI-- interpreting x-ray image

**Teaching methods dominate impact**

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 Prof with good student ratings.
**Experiment**–- new physics Ph. D. trained in principles & methods of research-based teaching.

They agreed on:

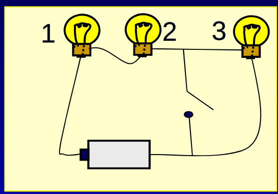
- Same material to cover *(Cover as much?)*
- Same class time (1 week)
- Same exam (jointly prepared)- start of next class

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

Experimental:

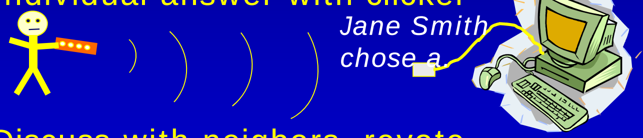
1. Short preclass reading assignment--Learn basic facts and terminology without wasting class time.

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




4. Discuss with neigbors, revote.
 **<u>Instructor listening in</u>**! What aspects of student thinking like physicist, what not?

5. Demonstrate/show result

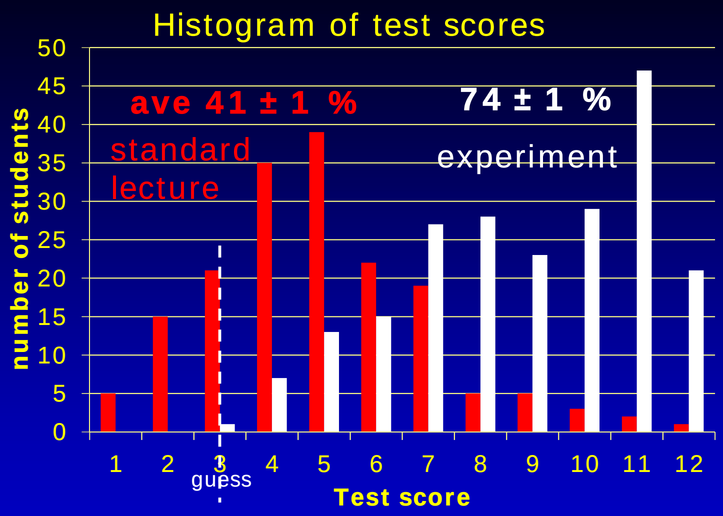
6. Instructor follow up summary– feedback on which models & which reasoning was correct, & **<u>which incorrect and why</u>**. Many student questions.

*For more mathematical topics, students write out on worksheets.*

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

**Feedback**—other students, <u>informed instructor</u>, demo

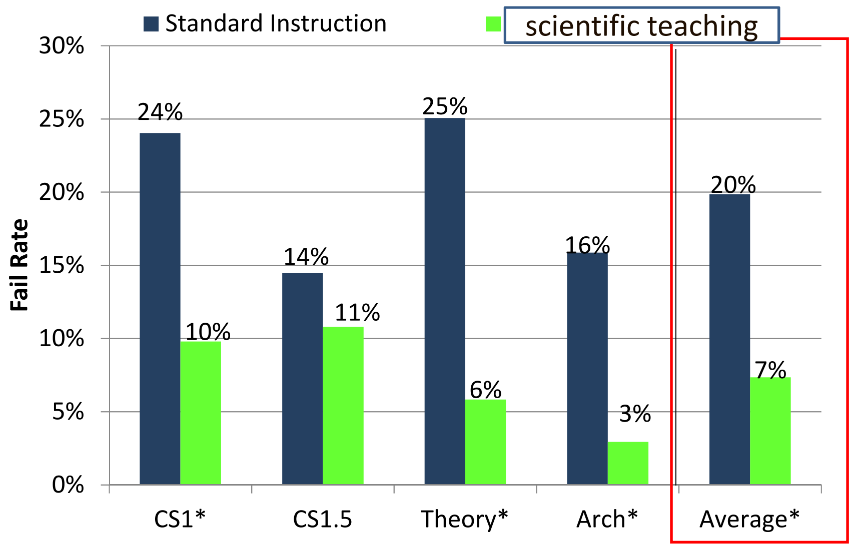
Surprise quiz covering learning objectives, traditional lecture vs experimental section?




Learning from lecture tiny.
Clear improvement for entire student population.

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

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*

## Evidence from the Classroom

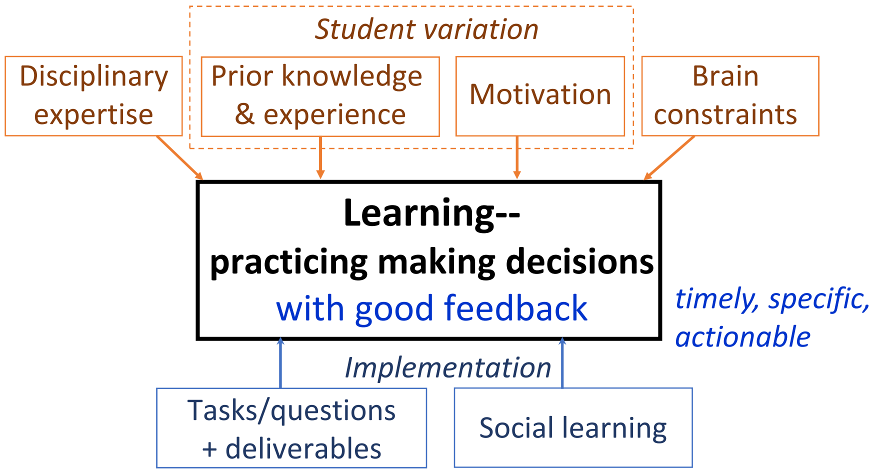
~ 1000 research studies from undergrad science and engineering comparing traditional lecture with "active learning" (or "research-based teaching").

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

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

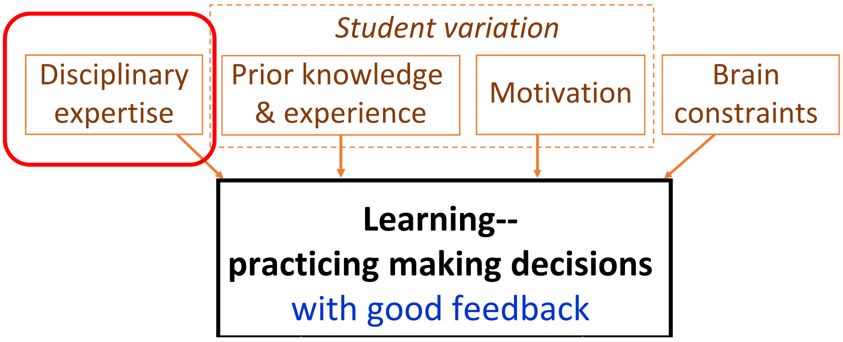
*but many factors matter*

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




**Defines teaching expertise.**

Practices that research shows produce more learning.




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

<u>Wieman Group Research (post-secondary)</u>

1. Problem solving (AP, SS, KW, MF, CK, EB)
a. Analyzing problem solving process; assessing in learners, how to teach.
b. Identify decisions by experts in solving problems: science, engineering, and medicine.
   Creating decision-based assessments of expertise: medicine, mech eng., chem. eng., ...

2. Engin Brumbacher- *how to teach scientific thinking*— scientific model adoption and use. *(generally applicable)*

3. Success in introductory physics. What determines, and how to improve outcomes? (SS, EB)

4. Intro physics instructional labs. Assessment and improvement. Natasha Holmes, now Assist Prof physics Cornell.

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

*Student variation*

Disciplinary expertise | Prior knowledge & experience | Motivation | Brain constraints

**Learning--**
**practicing making decisions**
with good feedback

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

Learning expert thinking* --

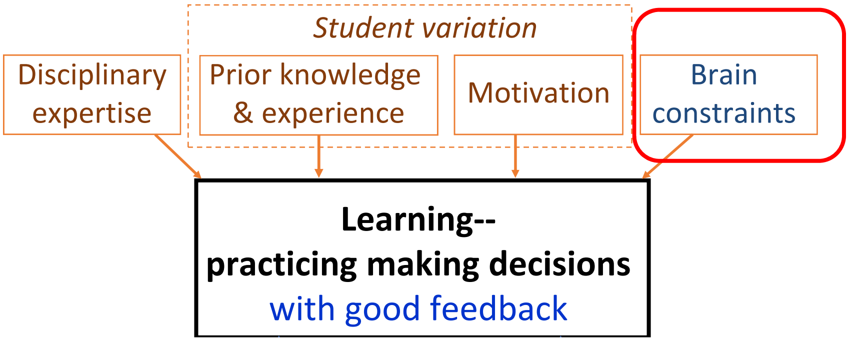
= Practicing making relevant decisions


***Decisions when solving sci & eng problem***

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

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

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




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

## Thinking to practice-- activity design

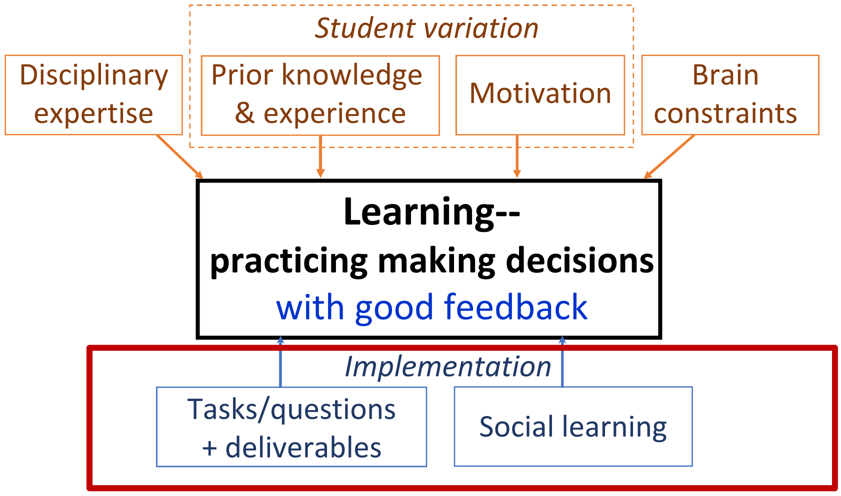
*Brain constraints:*

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 <u>actually hurts.</u>

2) long term memory– <u>biggest problem is recall after learning additional stuff--interference.</u>
Interference suppressed by repeated interleaved recall

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




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??

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

## Research-based instruction—Advanced Courses

*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*

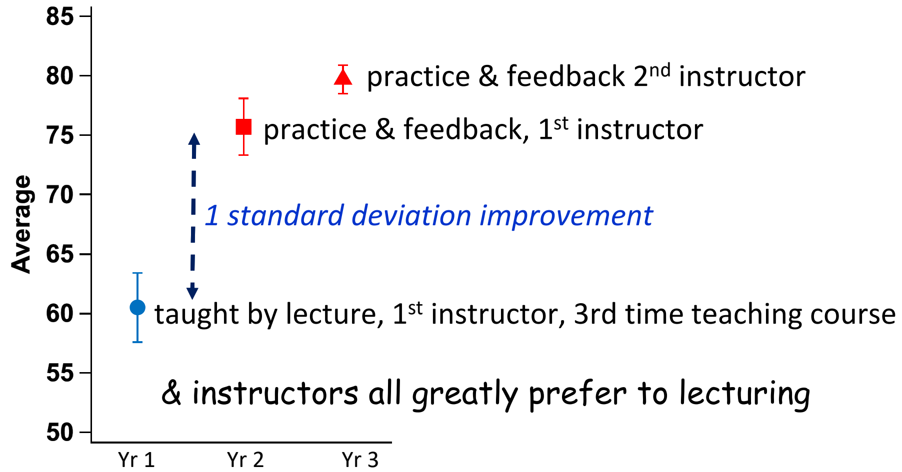
| Actions | Students | Instructors |
| --- | --- | --- |
| Preparation | Complete targeted reading | Formulate/review activities |
| Introduction (2-3 min) | Listen/ask questions on reading | Introduce goals of the day |
| Activity (10-15 min) | Group work on activities | Circulate, answer questions & 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 $2^{nd}$-$4^{th}$ 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.

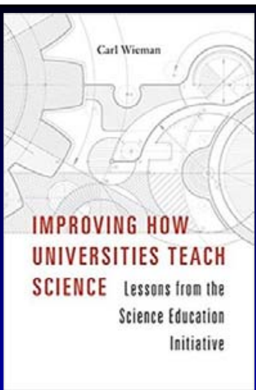
**Typical response across ~ 250 faculty at UBC & U. Col. Teaching much more rewarding.**

Conclusion:
Research has established teaching expertise at university level. Practices that are more effective.

When learned and applied:
- students learn more
- students and teaching staff prefer

Potential to dramatically improve post secondary education.

## How to make it the norm at universities?




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 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)

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

## Necessary 1st step-- better evaluation of teaching

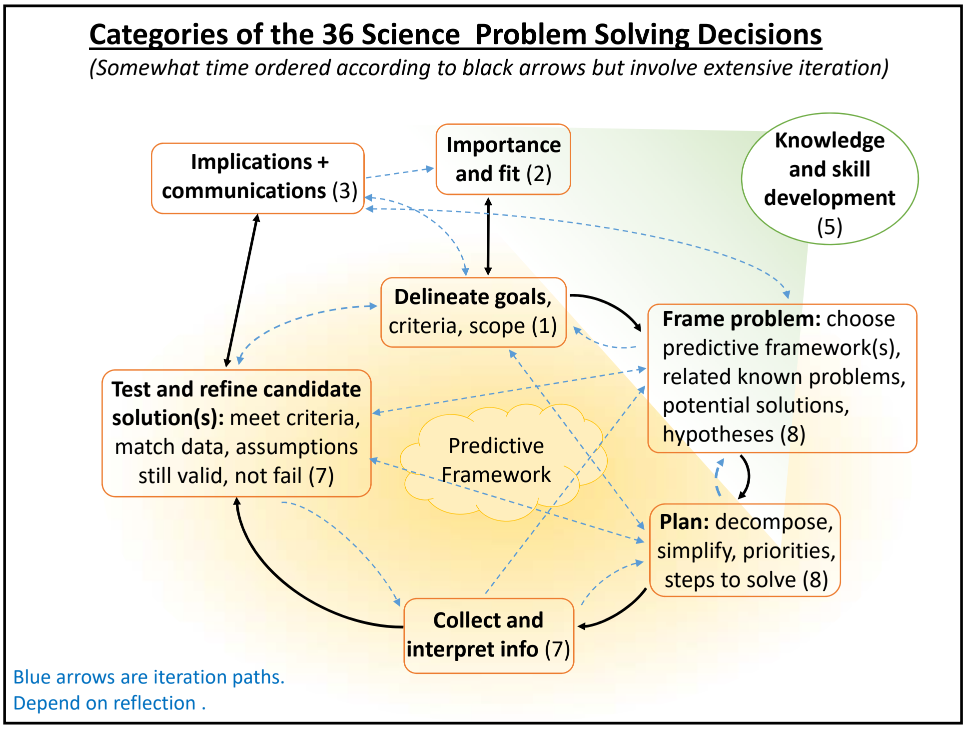
**"A better way to evaluate undergraduate science teaching"**
Change Magazine, Jan-Feb. 2015, Carl Wieman

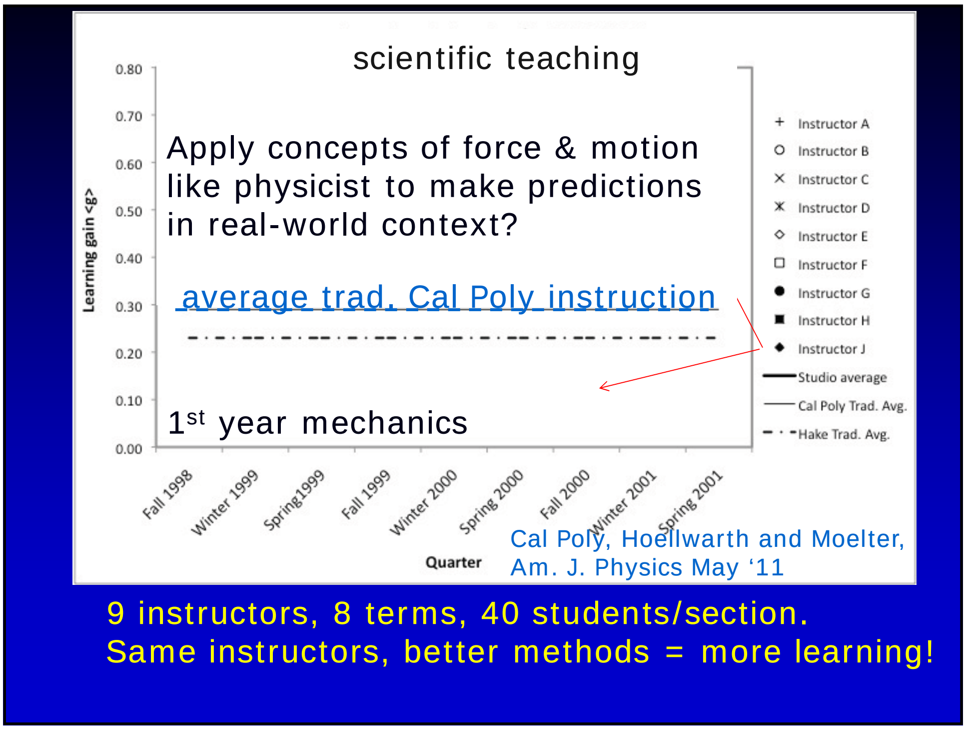
Requirements:

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


Categories of the 36 Science Problem Solving Decisions
(Somewhat time ordered according to black arrows but involve extensive iteration)
Implications + communications (3)
Importance and fit (2)
Knowledge and skill development (5)
Delineate goals, criteria, scope (1)
Frame problem: choose predictive framework(s), related known problems, potential solutions, hypotheses (8)
Test and refine candidate solution(s): meet criteria, match data, assumptions still valid, not fail (7)
Predictive Framework
Plan: decompose, simplify, priorities, steps to solve (8)
Collect and interpret info (7)
Blue arrows are iteration paths.
Depend on reflection .


scientific teaching
Apply concepts of force & motion like physicist to make predictions in real-world context?
average trad. Cal Poly instruction
1st year mechanics
Learning gain <g>
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Fall 1998
Winter 1999
Spring1999
Fall 1999
Winter 2000
Spring 2000
Fall 2000
Winter 2001
Spring 2001
Quarter
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!

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 ⇒ 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:

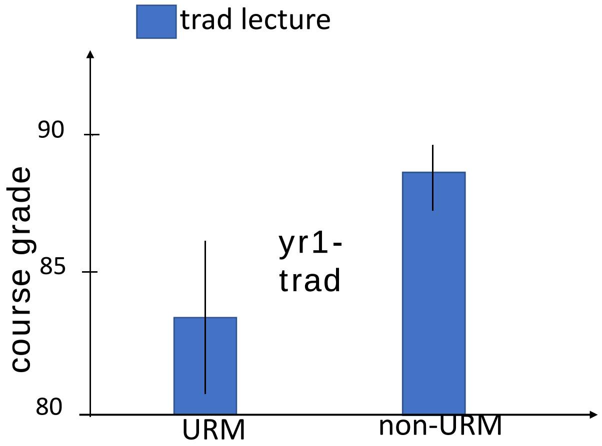
- ~~recognizing relevant & irrelevant information~~
- ~~select and justify simplifying assumptions~~
- ~~concepts and models~~ ~~**+ selection criteria**~~
- ~~moving between specialized representations (graphs, equations, physical motions, etc.)~~
- ~~Testing & justifying if answer/conclusion reasonable~~

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*

Large intro bio course at Cornell




*(small correction for incoming prep)*

**Enhancing Diversity in Undergraduate Science: Self-Efficacy Drives Performance Gains with Active Learning**, CBE-LSE. 16

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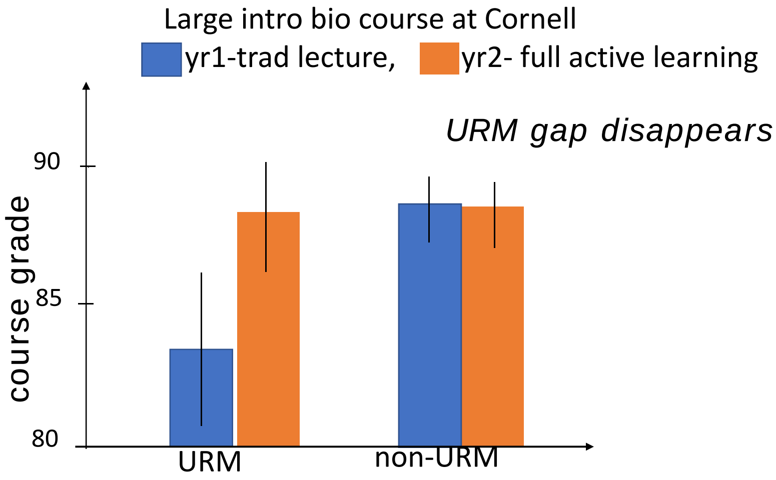



<u>Applications of research instructors can use immediately *(some very common but bad practices)*</u>

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)*

## 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?
....

## How it is possible to cover as much material?

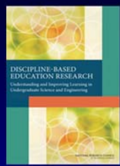
*(if worrying about covering material not developing students expert thinking skills, focusing on wrong thing, but…)*

•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, <u>but only</u> 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

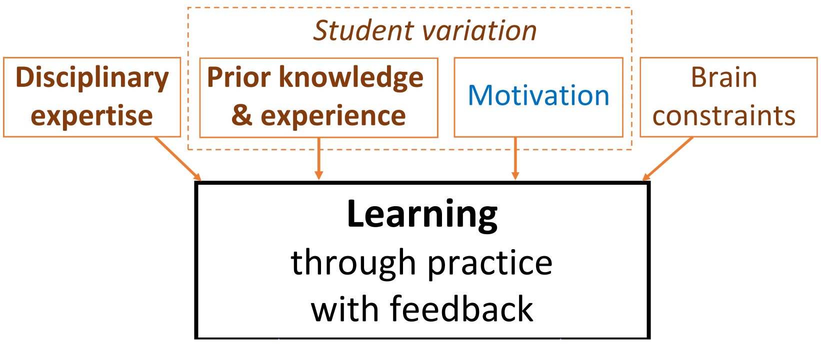
Purpose: Prepare students for in-class activities; move learning of less complex material out of classroom

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

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

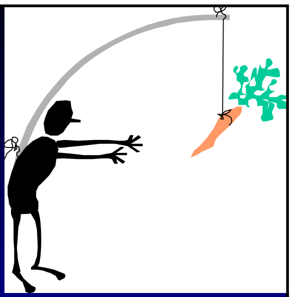
- Online or quick in-class quizzes for marks (tangible reward)
- Must be targeted and specific: students have limited time
- DO NOT repeat material in class!

*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

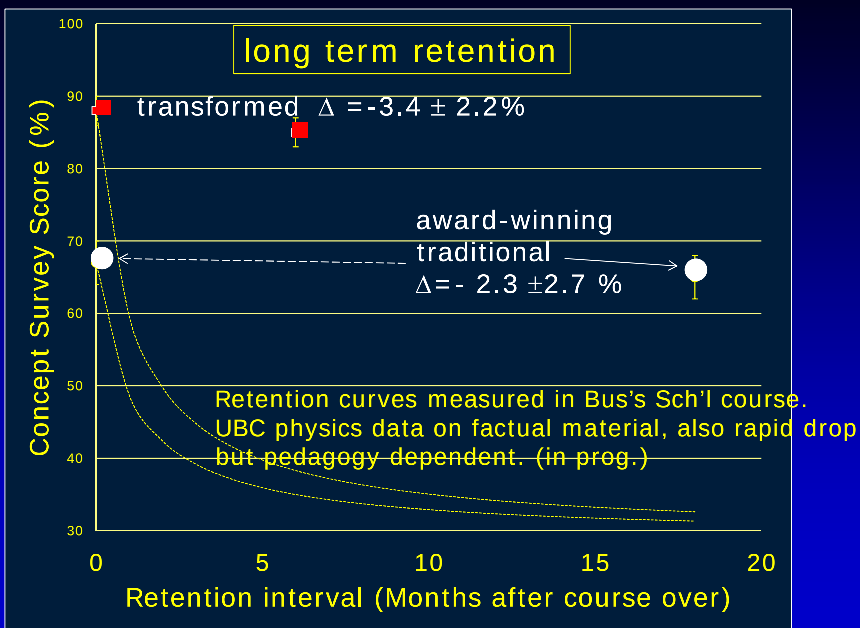
or ?

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*



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