Teaching Students to Think Like Physicists

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thinking like a physicist--teaching goal & vital educational need in modern society

30 years ago— *"Why can grad students do so well in many years of physics courses, but come into my lab and cannot do physics? (But then learn in 1-2 years.)?"*

I approached as a science question

copies of slides to be provided

Beyond opinions— a science of teaching and learning.

Doing controlled experiments.
<u>Measuring learning results</u>.

DATA and fundamental principles!
(me ~ 30 yrs ago, ~ 100 papers)

- Basic research on learning—cognitive psycholgists
- Classroom experiments undergrad science & eng.

Research done by physics/science faculty members.
Led by physics. Mostly in USA but spreading.
How well are students learning to think like physicists?

Situation with university physics 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.

Examples of physics Ed research
(then principles that explain)

<u>1. Learning from lecture*</u>

Two nearly identical 250 student sections intro physics—
same learning objectives, same class time, same test (given right after 3 classes).

Experienced highly rated traditional lecturer
(*<u>good teacher</u> by current standards*)

versus

New Ph.D. in physics, trained in scientific teaching

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

Experimental class design

1. Short pre-class readings

2. Questions to solve, respond with clickers or on worksheets.
Discuss with neighbors, instructor circulates, listens.

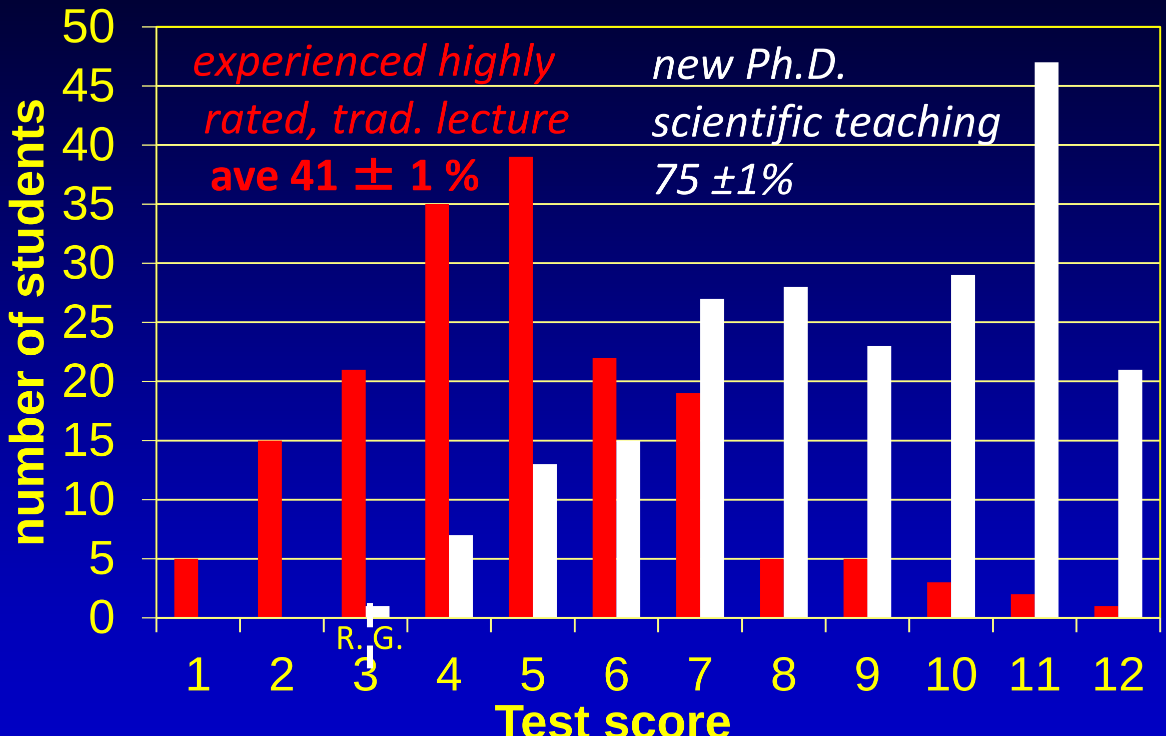
3. Discussion by instructor follows.

*<u>**Same**</u> material in <u>**same**</u> class time.*

How will results for the two sections compare?

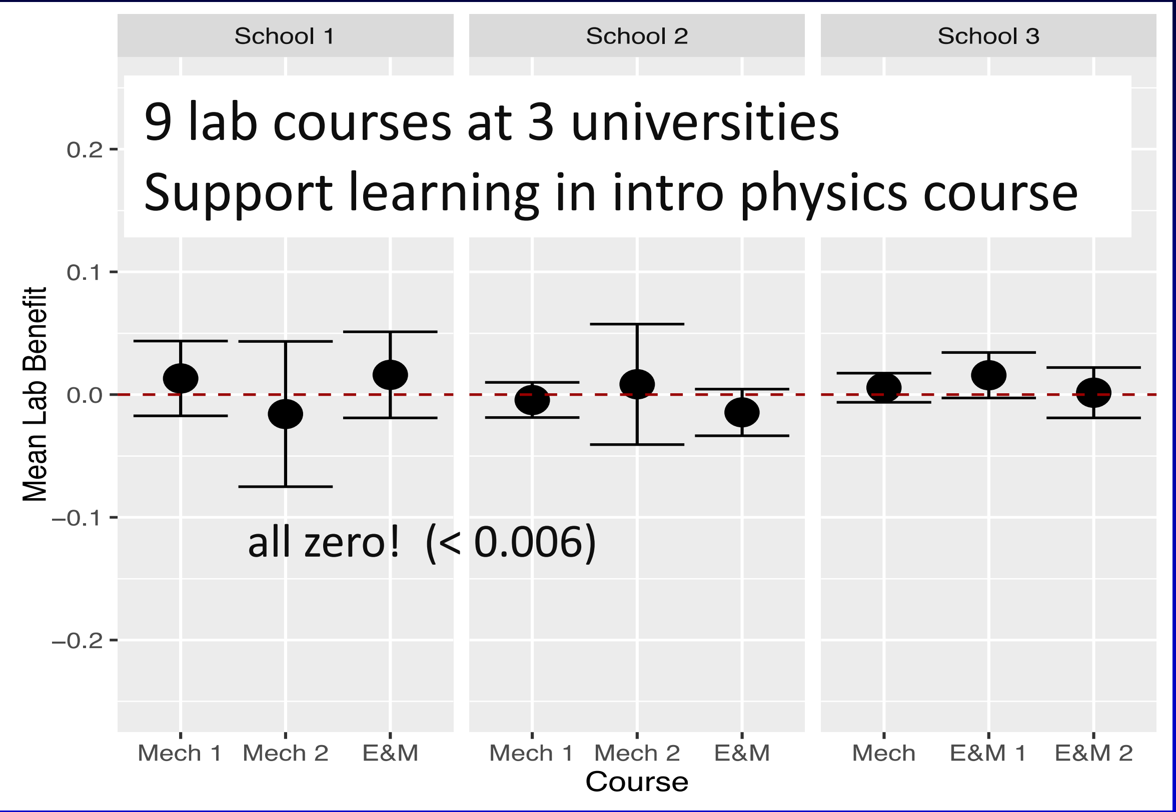
Science Mag. May 13, '11
Deslauriers, Schelew, Wieman

Histogram of test scores



Entire distribution shifted up.
Learning from traditional, "good" lecture tiny!

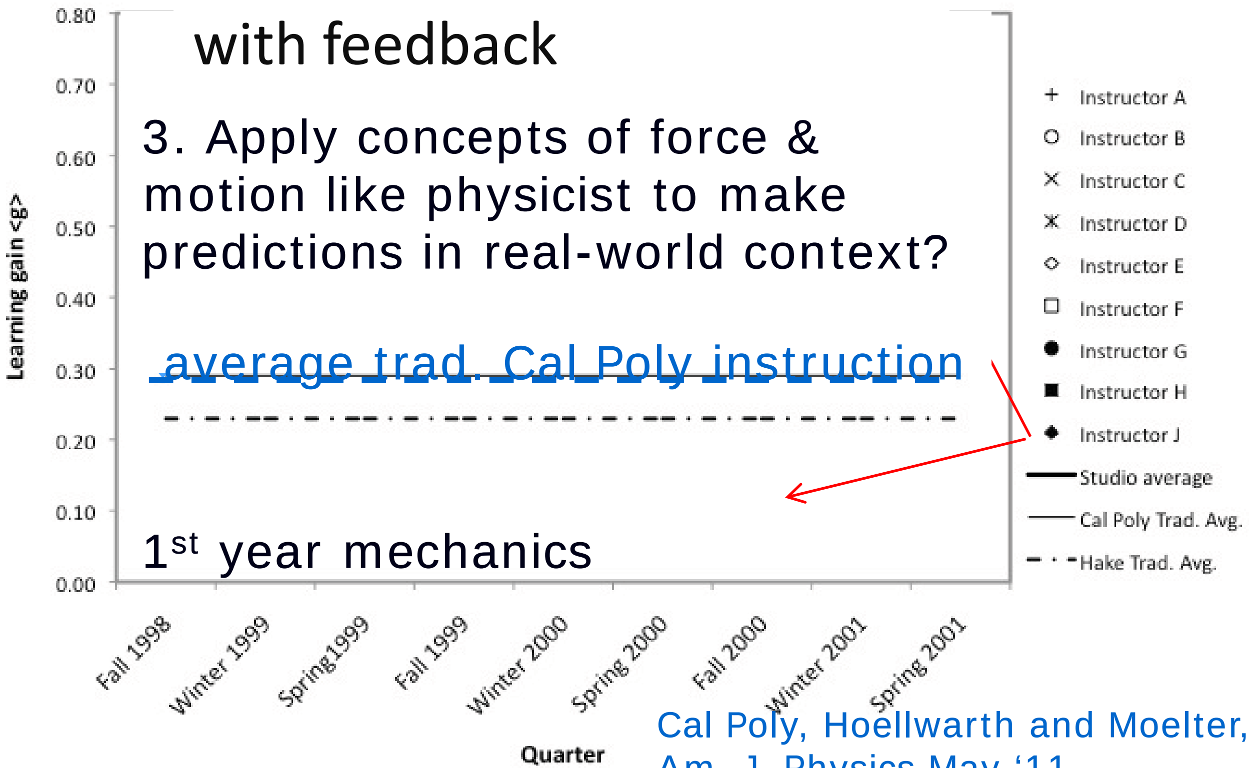
2. Value of introductory instructional labs for teaching physics content



Physics Today & refs., Jan 1. 2018, Holmes & Wieman

Scientific teaching, practice with feedback

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



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

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

4. Advanced courses-- 2-4 year physics 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)

Orchestration of active learning class

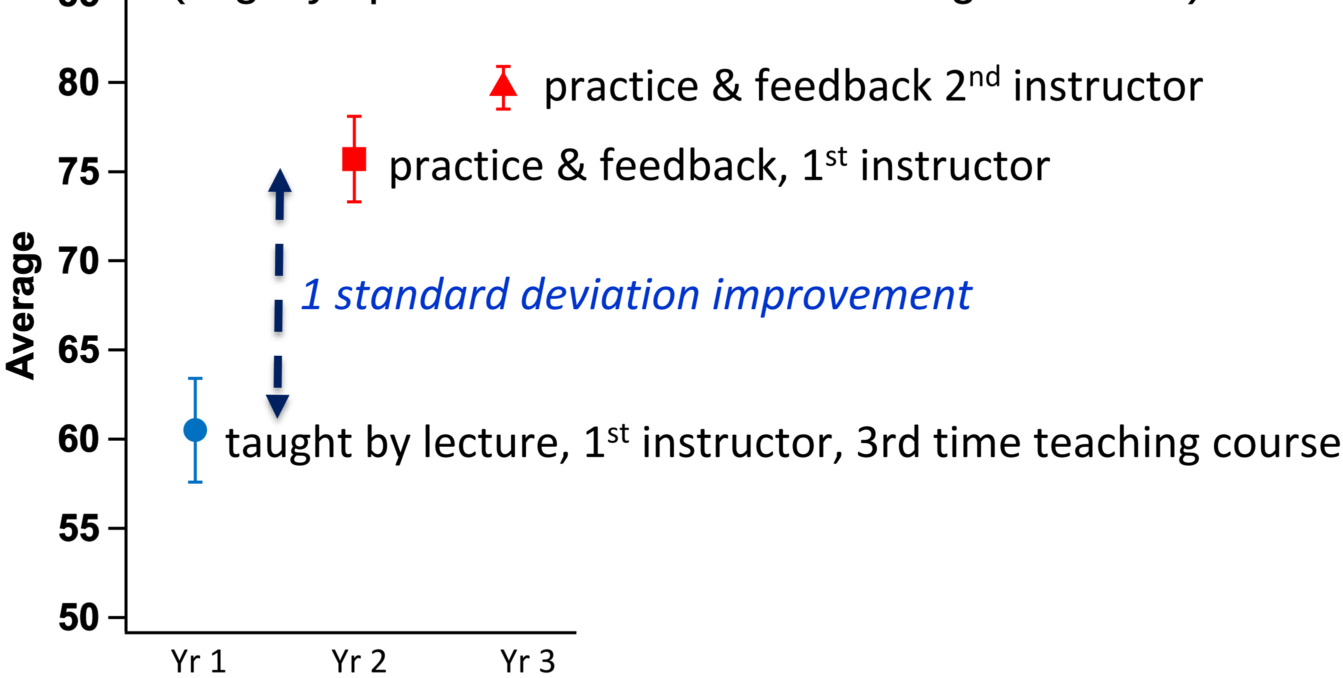
(for any size, level, or subject)

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

Final Exam Scores

nearly identical (“isomorphic”) problems

(highly quantitative and involving transfer)



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)

Stanford Outcomes

7 physics courses 2nd-4th year, seven faculty, '15-'16

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

90% positive, 4% negative

(mostly VERY positive, *"All physics courses should be taught this way!")*

- All the faculty greatly preferred to lecturing.

Typical faculty response.

New way of teaching much more rewarding.

"But traditional lectures can't be as bad as you claim. Look at us (or Nobel Prize winners) 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 **more** *successful, along with many other students.*

~ 1000 published comparing lecture method with research-based methods for teaching university science, engineering, and math

Freeman et al. metanalysis, PNAS 2017

Consistent gains in learning & completion, all disciplines, all levels.

Testing how well student learn to think like experts shows the biggest sensitivity to teaching methods.

Rest of talk- Why these results make sense

Empirical principles of learning. Application in teaching.

I. Nature of expert thinking ("scientist expertise") and how it is learned.

II. What research says are important factors for effective learning of expertise.

III. How to apply in teaching.

<u>I. Expertise research*</u> *(thinking like expert)*

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

Expert competence =

- factual knowledge
- **Mental organizational framework** ⇒ retrieval and application in solving problems.

or ?

relationships, concepts, ...

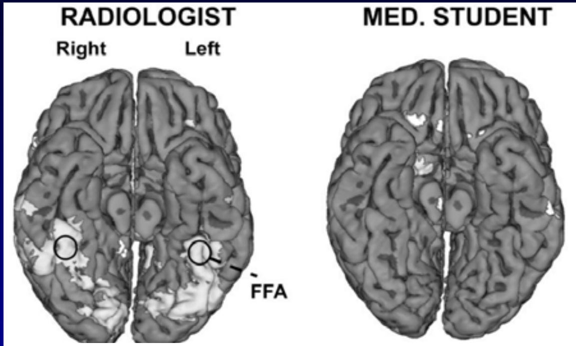
- **Ability to monitor own thinking and learning**

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

*Cambridge Handbook on Expertise and Expert Performance

biological requirement

Strenuous extended mental effort rewires brain.
New connections, new neurons.
Expertise lies in rewired brain.

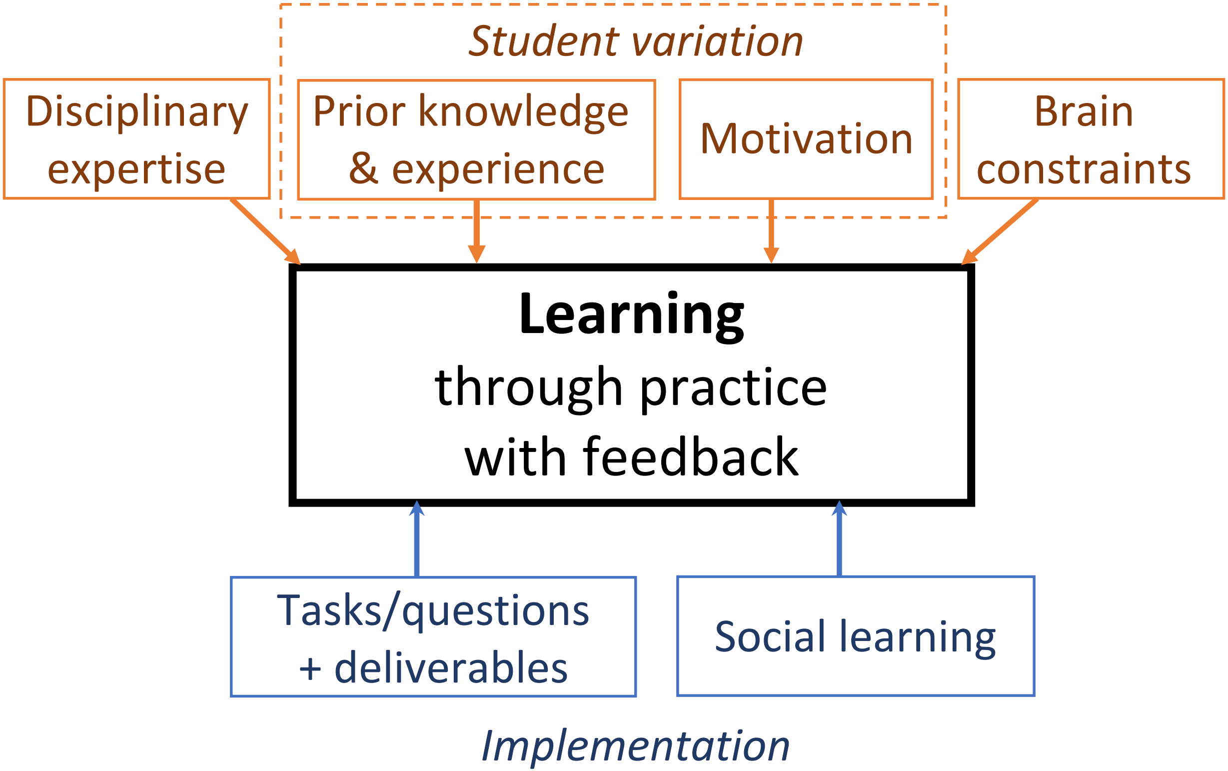


fMRI when interpreting x-ray image.

Expert brain rewired, not filled!

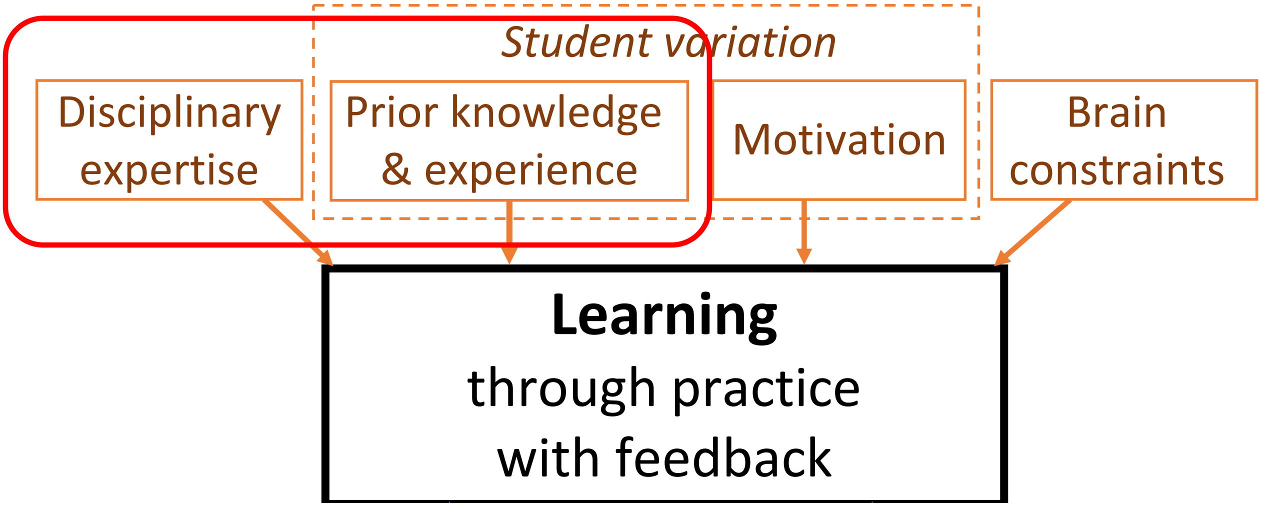
- Curriculum determines what knowledge.
- Teaching methods about rewiring brain--know when and how to use knowledge?

Scientific/research-based design principles for teaching to think like a scientist. Key factors.



Learning
through practice
with feedback

Practicing expert thinking with good feedback
(= timely, specific, actionable to improve)



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

Learning expert thinking* --

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

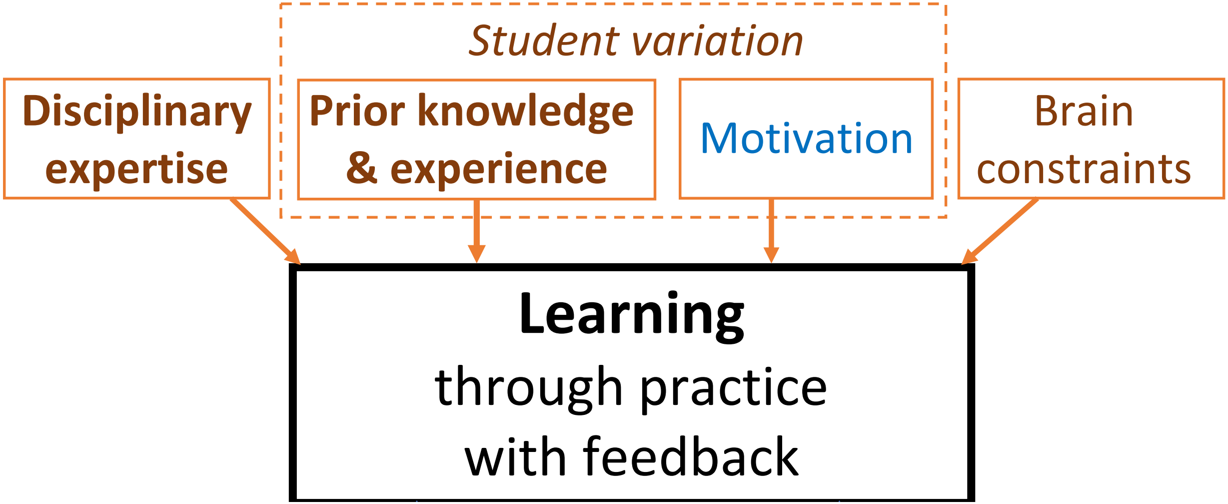
Decisions when solving physics problem

- <u>Decide</u>: what concepts/models relevant
- What information relevant, irrelevant, needed.
- <u>Decide:</u> what approximations are appropriate.
- " : potential solution method(s) to pursue.
- " : best representations of info & result.
- ….
- " : if solution/conclusion make sense- criteria for tests.

<u>Learner must practice making decisions.</u> Process & content.

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

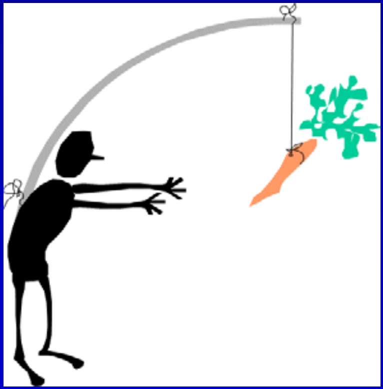
Expert thinking to practice, activity design*-

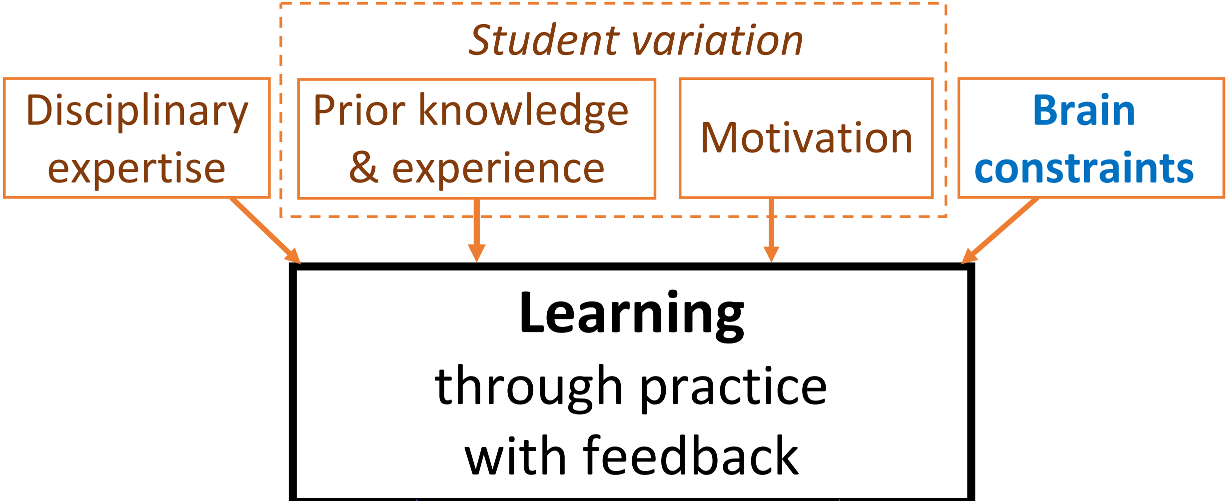
- *Prior knowledge*
- *Disciplinary expertise--* "Decisions" expert makes. Process and information required.

- *(Motivation)* **Interesting & relevant (choice of context, problem driven).**

  Some control of learning process.

  Belief that can master the material





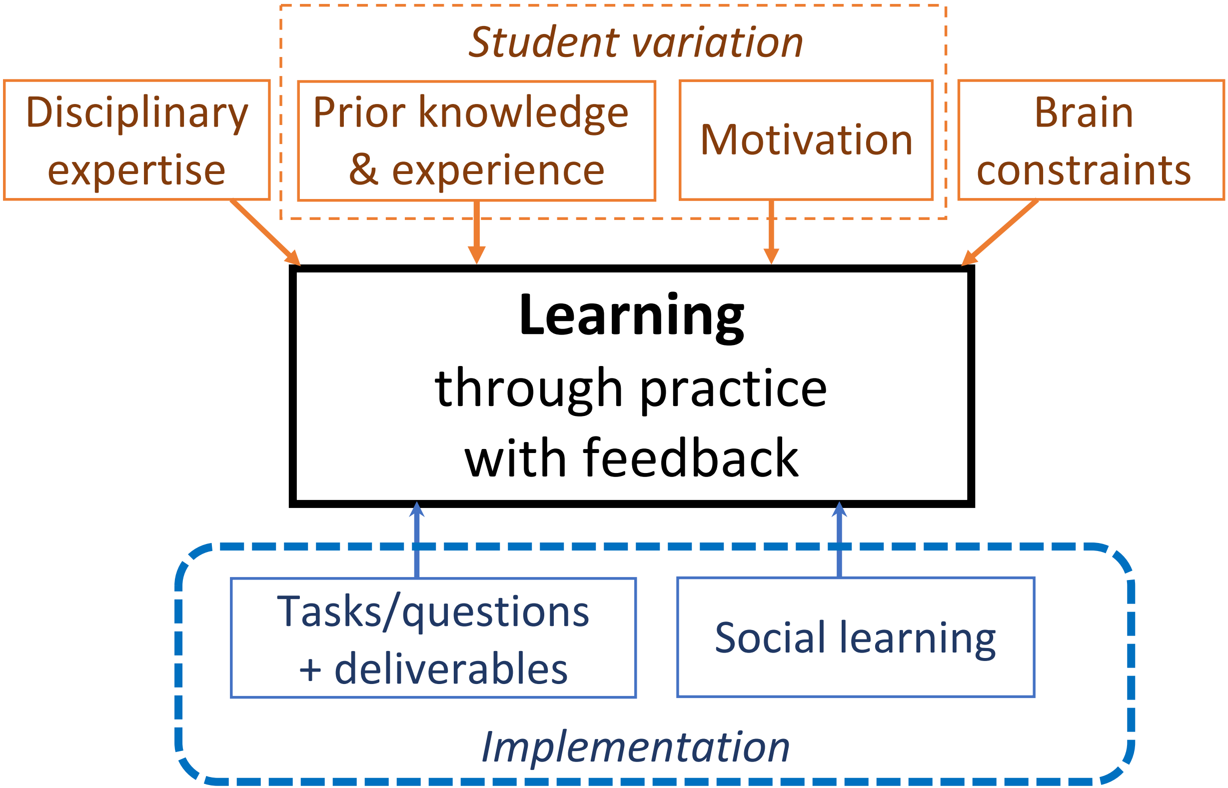
How these need to enter into design of practice activities (in class, then homework...)?

Expert thinking to practice, activity design*-

Brain constraints:

1) working memory has limit 5-7 new items.
Any additional items reduce processing & learning.
Jargon, nice picture, interesting little digression or joke <u>actually hurts learning.</u>

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

- More targeted feedback & avoids getting stuck, so more efficient
- People teaching/explaining to others triggers unique cognitive process $\Rightarrow$ learning
- **Very useful as a teacher** to listen in on student conversations!

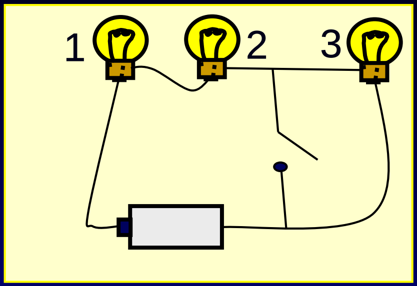
  $\Rightarrow$ *timely, specific, actionable feedback*

Example illustrating design of experimental class

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.
Instructor listening in! What aspects of student thinking like physicist, what not?

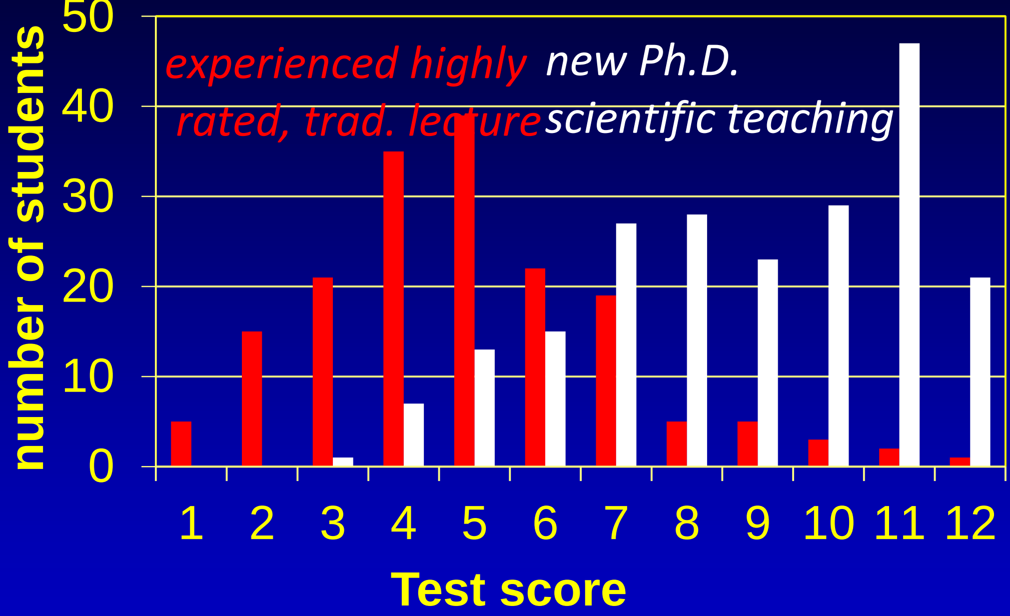
5. Demonstrate/show result

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

Brain practicing & learning new ways to think.
No such practice when listening to lecture.



Make sense.

Examples of common teaching practices. How research on learning reveals faults.

(lessons teachers can use tomorrow)

1. Organization of how a topic is presented.

Standard teaching practice: Begin with formalism, definitions, principles, equa's, then use to solve problems.

What is wrong with this?

a) Not motivating–no idea as to relevance or value,

b) Bigger issue– poor knowledge organization.

Random separate pieces of information.

Overwhelms working memory, cuts off processing.

Solution— first present important problem, bring in material as tools needed to solve.

Expert knowledge organization-- material as tools to solve particular types of problems. Recognizing key features.

2. Organization of course and exams.

Standard teaching practice--chap. 3 material--
Lectures, HW, exam ch. 3, done.
chap. 4 ditto, done.
Material organized in brain chronologically by chap.

But real problems not labelled with chap. number!
Expertise— deciding when and how to use material.

Solution– regularly return to earlier material, how related to current, when does and **does not** apply.

B. T. 3. Feedback on answers

Standard practice– student has something wrong. Feedback—"That is wrong, here is correct solution."

Why bad?
Research on feedback—simple right-wrong with correct answer ~ zero value.

Learning happens when feedback timely and specific. What thinking was incorrect and why, and how to improve.

B. T. 4. Instructor talking.

Standard teaching practice— instructor spends 90+% talking while students listen passively, maybe take notes, ask occasional question.

Why bad—student brain is not practicing expert thinking– essential for “brain exercise” & rewiring.

Learning from expert feedback-<u>telling highly effective, but only if brain prepared first.</u>

If students struggle with problem first, then told, x10 learning compared to telling, then practice. *(Schwartz & Bransford)*

A scientific approach to teaching & learning

More effective ways to teach

Better evaluation of teaching—use best practices

$\Rightarrow$ better science education needed for all in modern society

Good References to learn more:

D. Schwartz et al., "The ABCs of how we learn",

S. Ambrose et. al. "How Learning works"

A. Ericsson & Pool, "Peak: Secrets from New Science of Expertise"

Science education initiative website

cwsei.ubc.ca– lots of instructor resources, references, short guides on specific implementation details.

copies of slides available

Expert thinking to practice, activity design*-

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Interference suppressed by repeated recall.

Essential next step...

A better way to evaluate teaching
Change Magazine, Jan-Feb. 2015, C. Wieman
(student evaluations have many serious limitations)

"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. Extent of use of best research-based best practices

<u>How it is possible to cover as much material?</u>
(if worrying about covering material not developing students expert thinking skills, focusing on wrong thing, but...)

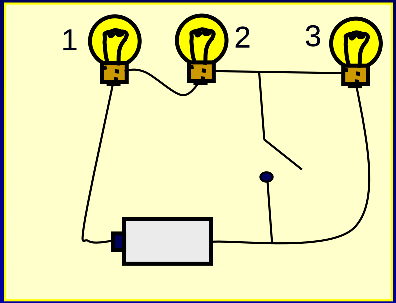
- transfers information gathering outside of class,
- avoids wasting time covering material that students already know

Advanced courses-- often cover <u>more</u>

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

What is happening in these classes?

Students are solving tasks



When switch is closed, bulb 2 will
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"Answer individually with clicker, then discuss with students around you. Come up with reasons for right answer and why the others are wrong. Revote with clicker."

Instructor is circulating, listening in, coaching, then leads follow-up discussion/feedback. Many additional questions.

Experiment:

1) go to lecture, take notes, learn as much as possible (AMAP)
2) go to lecture, don’t take notes, learn AMAP
3) stay home, study instructors notes 1 hour, learn AMAP

correct answer. b. 3,2,1. Learn least going to lecture and taking notes.

Why? Discuss.

2>1. Taking notes just added distraction, “cognitive load", compared to focusing on understanding in class.
3>2. Reading over notes, better pace, organization, more processing *(when decent notes!)*

Experiment #1: 3 equivalent groups of students.

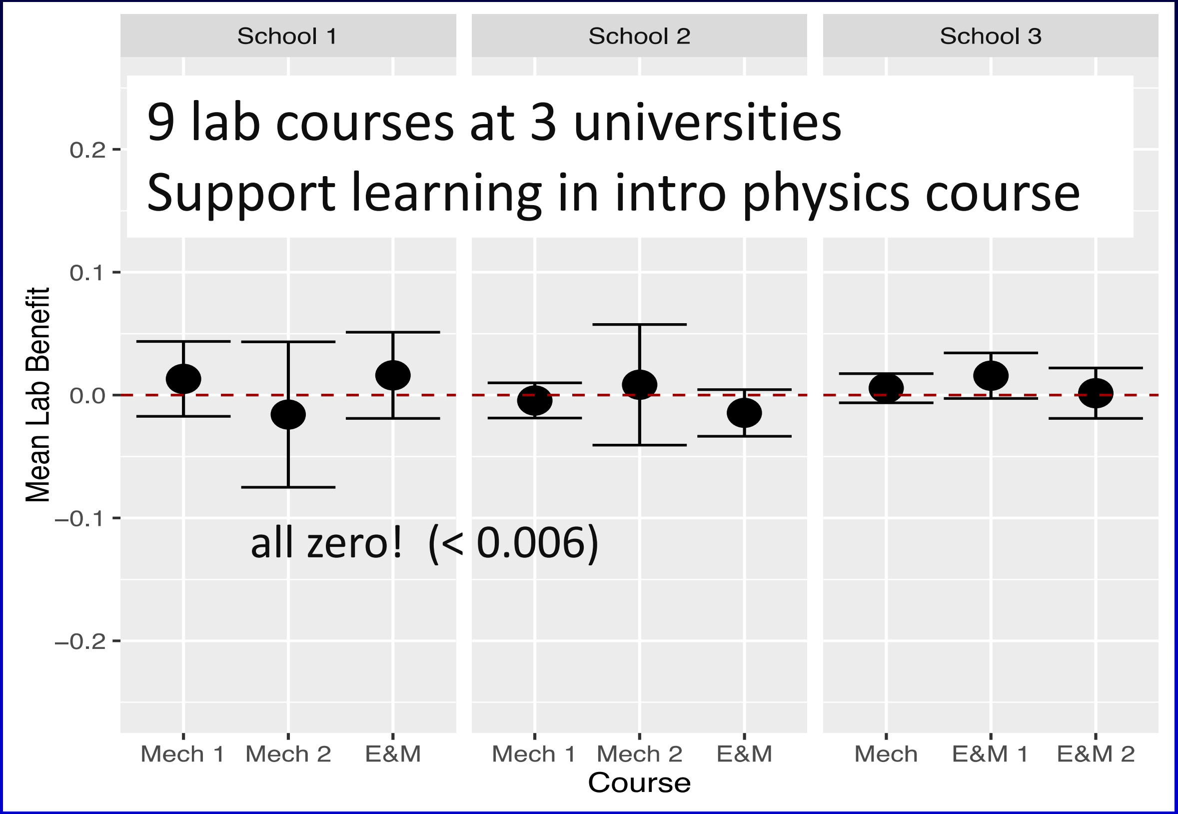
1) go to lecture, take notes, learn as much as possible (AMAP)
2) go to lecture, don’t take notes, learn AMAP
3) stay home, study instructors notes 1 hour, learn AMAP (*good instructor notes*)

then all get same test on the material covered in lecture.

Predict learning: most to least (write down choice, then raise hand to vote)

a. 1,2,3 b. 3,2,1 c. 2,1,3 d. 2,3,1, e. 3,1,2

2. Value of introductory instructional labs for teaching physics content



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