Teaching students (and learning) **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. Intro. Educational goal.

II. Research-based principles for teaching.

III. Applying in physics research and course settings. Demonstrations of results.

Educational goal- student learn to think like a physicist
??
= **Solving problems** (novel, real world) like a skilled physicist.
in intro classes, just developing. As grad students, more sophisticated

How to teach problem solving?

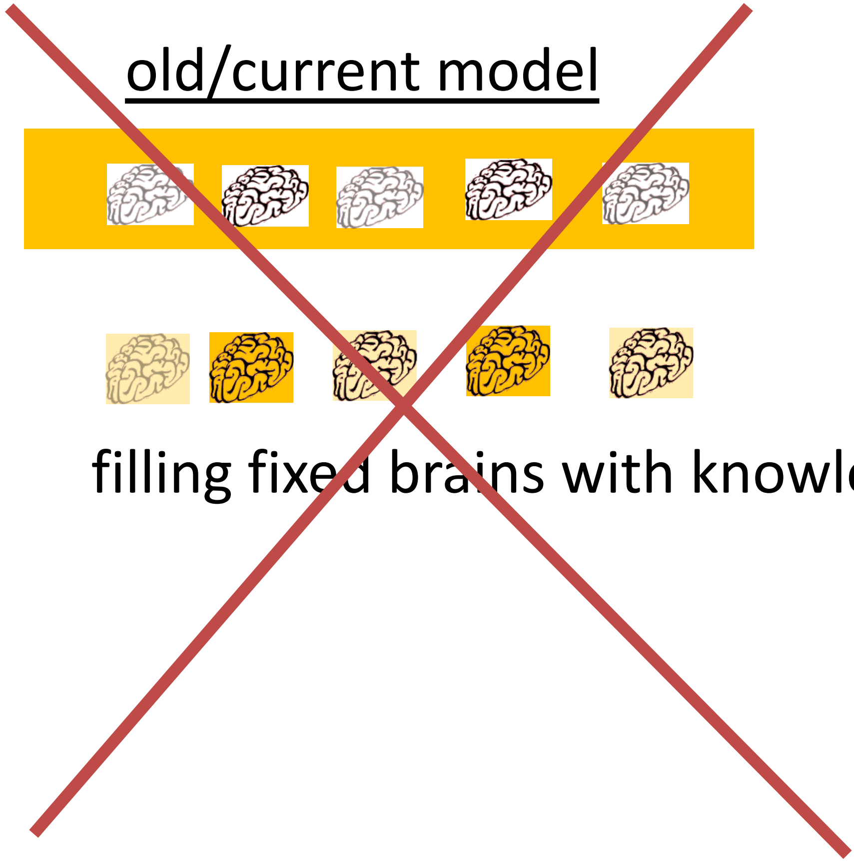
"Here is problem to solve, try it. Fail? Try another..."

Sometimes series of steps to follow.
Offer hints & tell assumptions. Little help.

How to do better?
Research-based principles for teaching problem-solving.

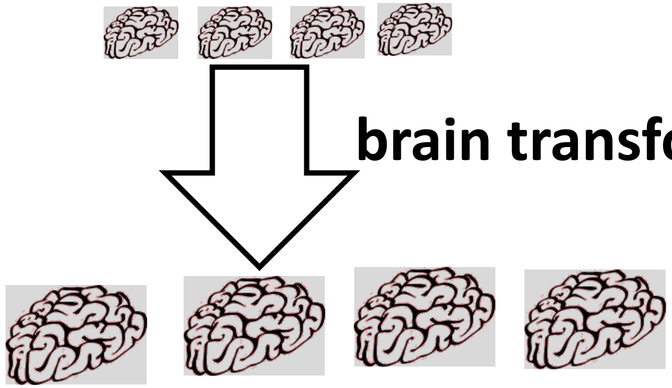
Rethinking how brain learns complex thinking

old/current model



filling fixed brains with knowledge

new research-based view



brain transformation

Change neurons by intense thinking.
Improved capabilities.

II. Research-based principles for teaching

Brain learns what it practices intently. Like muscle development.

Various teaching methods: ‘flipped classroom”, “active learning”, “student-centered instruction”, “experiential learning”, ...

Labels too general—need to describe the cognitive processes in learner’s brain.

Guiding principles from research. Predict behavior under variety of conditions.

Principles of instruction from research on teaching problem-solving

Apply at all levels. Training grad students in research settings and students in any physics course.

- ❑ deliberate practice
  - motivation
  - decision based problem solving
  - student agency
  - guiding feedback
  - problem first learning

- ❑ social learning

A. Ericsson extensive studies of development of expertise. Discovered it required particular type of practice "deliberate practice."

Deliberate practice—

- not simple practice, rather **intense** focus on improving subskills.
- broken down into subskills, practice to mastery individually, then together.
- feedback on how to improve. Timely & specific.
- challenging, require intense effort, stretch capabilities. Motivation critical.

Implementation of deliberate practice in teaching problem-solving

1. **Motivating learning**

- meaningful interesting context
- student’s sense can and how to master-feeling of accomplishment
- sell students on teaching methods and how to best learn

<u>2. Identify subskills.</u> Physics problem solving is complex process, what are the subskills to be practiced and mastered?

problem-solving decisions!

Wieman Group Research (Price et al. ://doi.org/10.1187/cbe.20-12-0276)

Analyzed how ~50 experts in science and engineering, solved authentic problems in their discipline. Choices between alternatives. Process defined by making set of decisions.

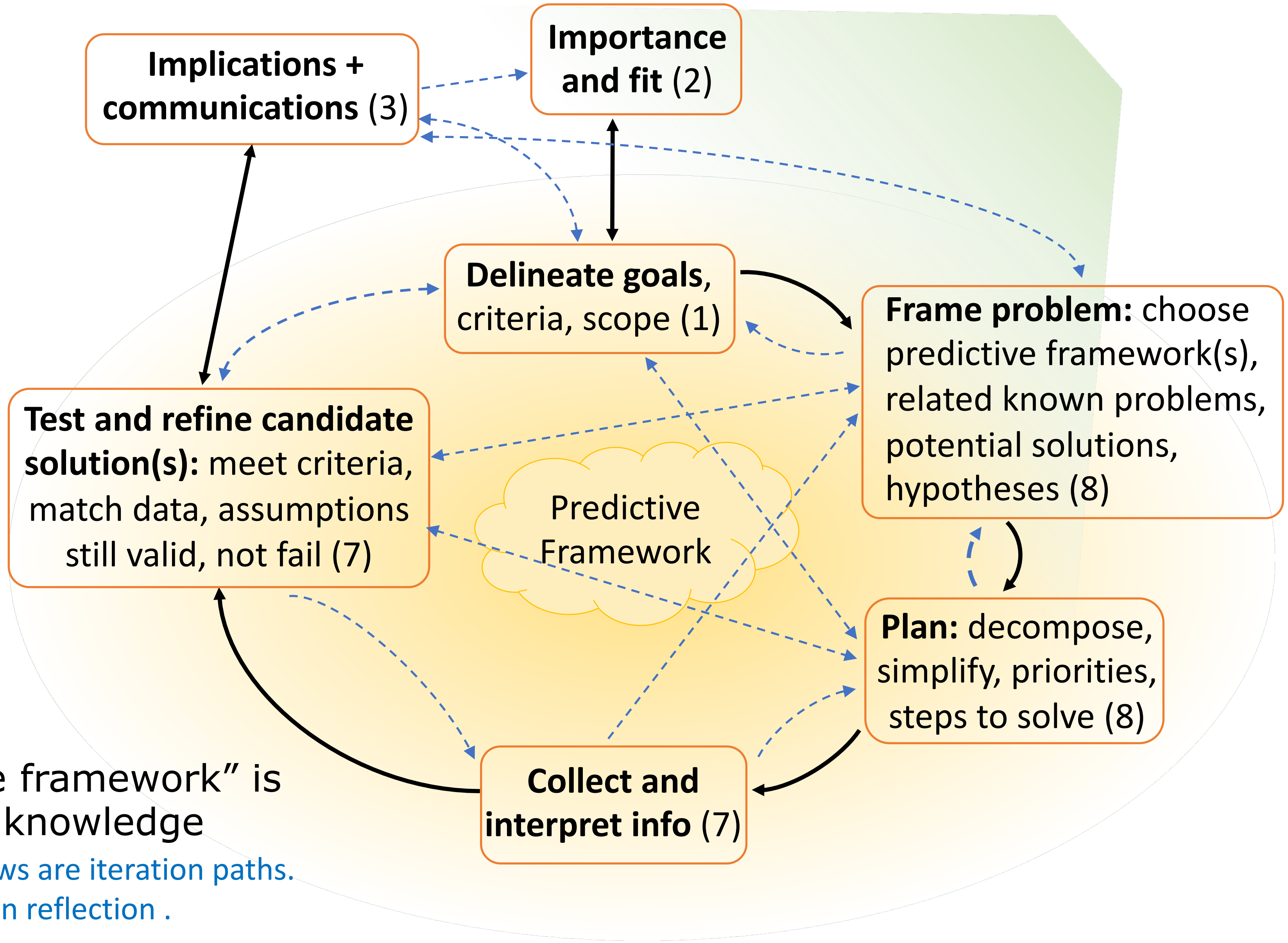
Same set of 29 decisions, all science & engineering! e.g.

- Decide: What concepts/models relevant?
- Decide: What information relevant, irrelevant, needed?
- Decide: What approximations are appropriate?
- Decide: What potential solution method(s) to pursue?.
- ....

All decisions made with limited information—"educated guess"

Categories of the 29 Science & Engin. Problem Solving Decisions

(Somewhat time ordered but involve extensive iteration)



"Predictive framework" is organized knowledge

Blue arrows are iteration paths.
Depend on reflection .

List of the problem-solving decisions

1. What is important in field?
2. What opportunities fit solver's expertise?
3. What are the goals, criteria, constraints?
4. What features and concepts are important?
5. What mental model to apply?
6. How to narrow down the problem?
7. What are related problems that will help?
8. What are potential solutions?
9. Is the problem solvable?
10. What approximations & simplifications are appropriate?
11. How to decompose into subproblems?
12. Which aspects of problem are most difficult or uncertain?
13. What information is needed?
14. How to prioritize among competing considerations?

15. What is the plan to get needed info?
16. What calculations or data analysis are needed?
17. How to represent and organize information?
18. How believable is information?
19. How do results compare to predictions based on mental model?
20. Are there any significant anomalies?
21. What conclusions are appropriate?
22. What is best solution?
23. Reflect: Were assumptions and simplifications appropriate?
24: Reflect: Is any additional knowledge/info needed?
25: Reflect: How well is problem-solving approach working?
26: Reflect: How adequate is solution?
27: What are broader implications of results or solution?
28: Who is the audience for communication?
29: What is the best way to present work?

audience– 1) which most important? 2) most difficult? Think, then discuss.

Most important and most difficult?

Probably reflection decisions (#23-26).
Important because error correcting. Difficult- analyzing own thinking.

Most decisions apply to learners at all levels, but not all.

Role of knowledge
Same set of 29 decisions, all science & engineering,

but, **making** each decision requires specialized disciplinary knowledge. Knowledge organized to make decisions. Mental models connecting important features. Run many mental experiments.

Knowledge best learned in context of use in making decisions.

3. ***Student agency***. Students have to practice making the decisions themselves. But may be prompted to make. (Holmes, Keep, Wieman, Phys. Rev. Phys. Educ. Res. 16, 010109 – 2020)

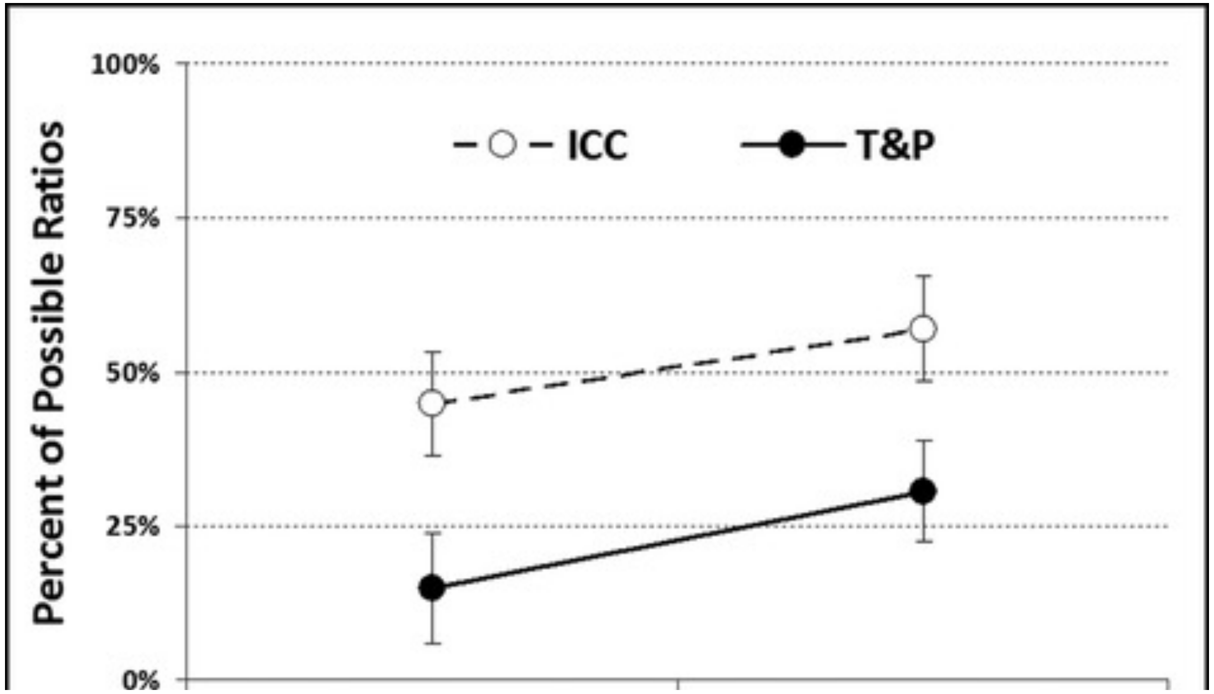
4. **Good feedback**. Timely, specific, actionable. How to improve.

5. **"Problem first" learning**. . Nonintuitive but solid data. Schwartz, Bransford - Cognition and instruction, 1998

Not tell student information first, then have them apply it. Student first struggles with problem/decisions, **then** told the knowledge needed to solve.

Benefits of problem first *(Shwartz, Kapur):*

- Focuses on general key features.
- Organize knowledge learned better for later application & transfer.
- Motivates learning relevant knowledge. Why useful.



Teaching about density. Performance on 2 transfer problems.
Problem first (ICC). Teach & practice (T&P)

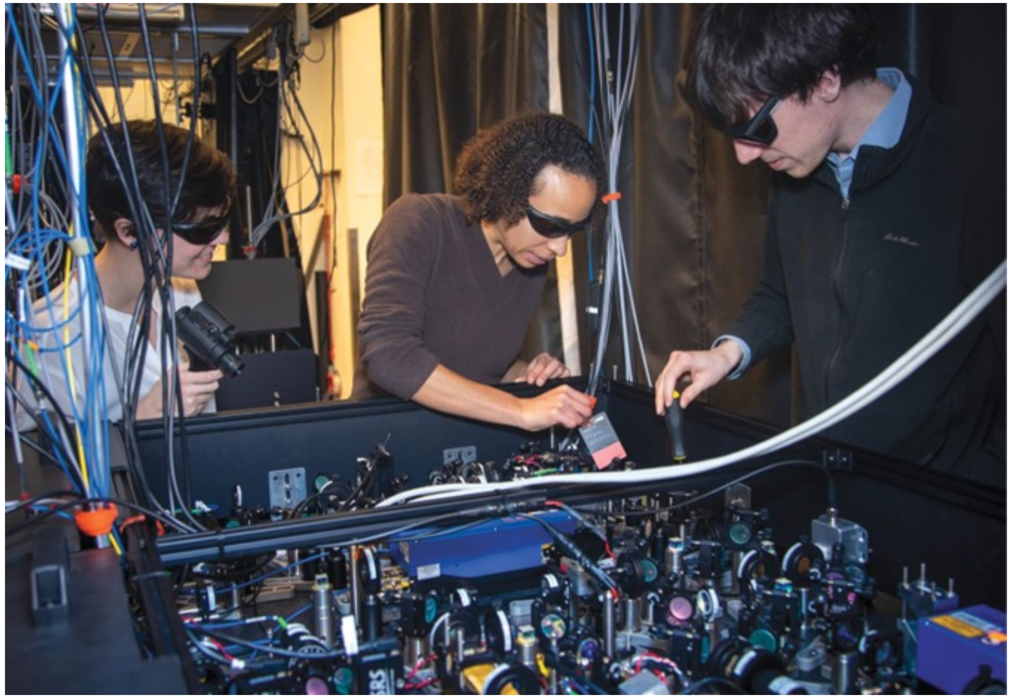
from Schwartz, D. L., et al. (2011). J. Ed. Psych., 103(4), 759–775.

Applying these ideas in teaching/training settings

- Research lab (graduates and postdocs)
- Courses (all levels)

Optimum training in research setting (most natural)

- Advisor gives student challenging problem.
- Student works intently on it.
- Reports back, gets feedback, new challenge.
- Learn from errors & repeat
- Many hours!
- Practice making all 29 decisions.



caveat- other factors experts noted as important for career success:

- staying current in field
- collaboration skills
- acquiring experience & related intuition

Teaching students in courses to think like physicists?

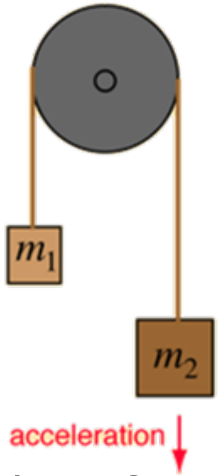
- deliberate practice in problem solving
  - motivation
  - decision based problem solving
  - student agency
  - guiding feedback
  - problem first learning
- social learning

Applying these principles in classroom

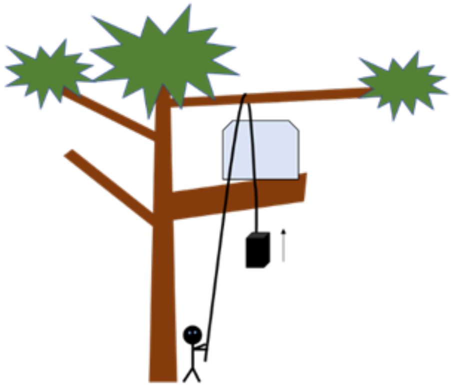
Students collaboratively practice making decisions & solving problems, guided by instructor. Continue on homework.

Deliberate practice in problem solving

Start with authentic meaningful problem, explicitly practice making decisions. Appropriate subset. Solving requires material to be covered in course.



massless frictionless pulley, find the acceleration.
Bad. Artificial, few decisions.



How much weight can you pull up to treehouse? How strong a rope is needed? Worth getting a pulley?
Authentic, more decisions. More motivation.

Our research:students perceive physics as describing real world **less after** intro class!

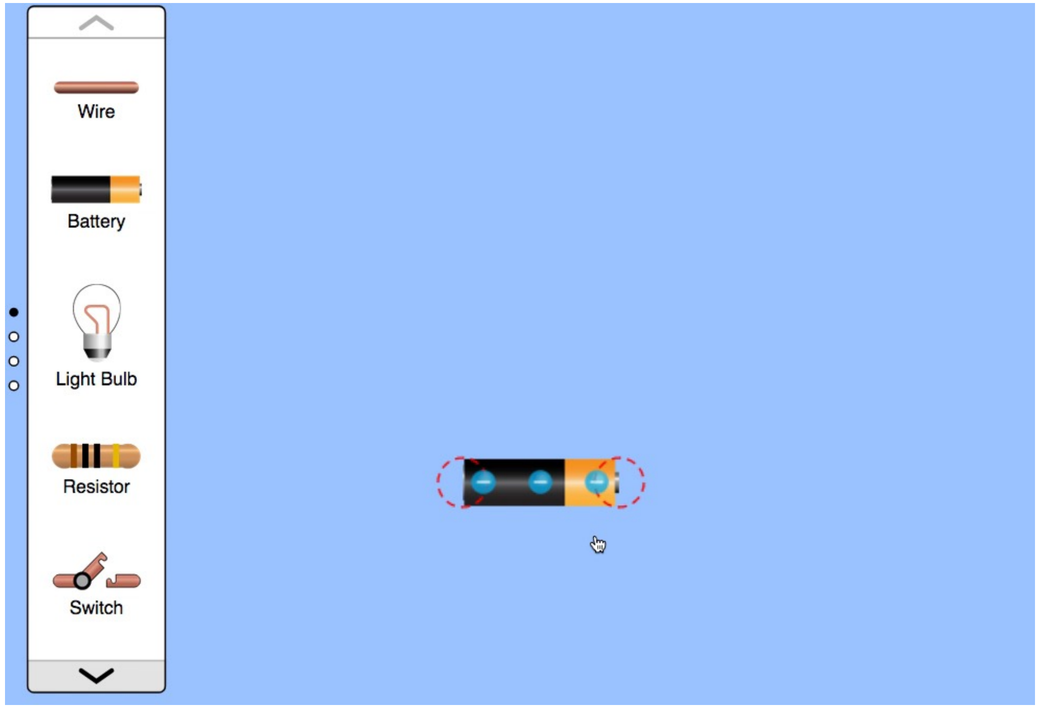
Deliberate practice in problem solving in classes (cont.)

Problem first learning. Problem students can engage with key concepts. Prepare to learn. Not easy to design.

Technology can help (phet interactive simulations).

1.task:Batteries and wires- figure out requirements for making light bulb light?

then told about ohms law etc.



Deliberate practice in problem solving in classes (cont.)

Student agency & Prompting decisions.
Problem solutions require making and justifying decisions. “What concepts apply” “How plan solution?” “Is answer reasonable?” etc. Students turn in, get feedback.

Good feedback. Timely, specific, actionable. Often most difficult element when many students. Helps when students working in groups.

Deliberate practice in problem solving in classes (cont.)

Social learning-students working together

- Immediate personalized peer feedback. Instructor monitoring work & discussions.
- Also teaching improves learning. “I understood this subject much better after I taught it.”

Much studied result. Process of teaching others triggers unique cognitive processes. Enhanced understanding.

Students teaching and critiquing each other in groups of 3-4 optimizes.

Need to arrange details properly. Norms of behavior, deliverables, & time for individual thinking.

Structure of 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 decision making and reasoning**
- **instructor providing informed timely feedback**

Potential errors in teaching problem solving- few decisions in class or on HW and exams. Never practice.

We analyzed HW problems in physics courses. All involved only 2-3 decisions/problem on average. Advanced had the least.*

- Problems artificial. Remove context and decisions required in real-world problems.
- Students given all the information needed and only that information.
- Told what assumptions to make.
- Problems always decomposed into parts.
- Solutions not require explaining & justifying solution steps/decisions.
- Inadequate feedback. Too delayed, not specific.

- In research setting, just told what decisions should be, not practice making them. Some decisions never encountered.

** Montgomery, Price, Wieman, to be published*

Does it work?

III. Demonstrations of results when principles applied.

1. Advanced modern optics course
2. Intro physics courses

Deliberate practice– repeated practice solving problems/making decisions.
Working in small groups.
Instructor monitoring thinking—telling was primarily feedback.

Demonstration #1. Fourth year modern optics course

Instructor took lectures and converted into worksheets, focusing on the decision steps and math-physics connection.

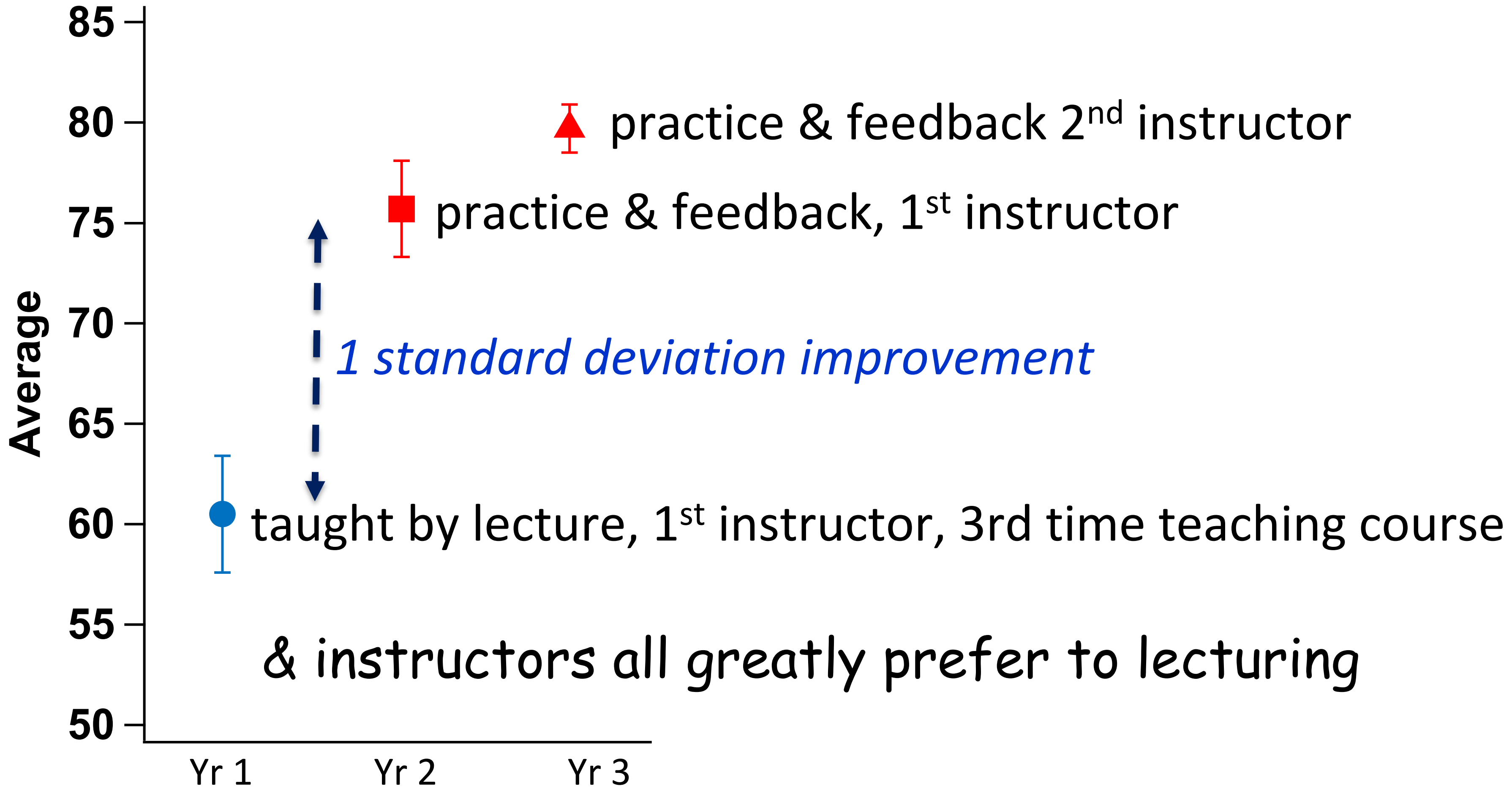
Students work out in small groups. Complete worksheets.
Monitored by instructor.
Regular feedback and guidance.

Nearly all Stanford undergrad physics classes now taught this way.
Also works for graduate classes. QFT at Cornell (Lepage)

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)

Final Exam Scores

nearly identical challenging 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)

Demo 2. A more equitable physics 1 course (with Eric Burkholder)*

Discovered that incoming preparation was strong predictor of grade in physics 1. Created new version of physics 1 to try and change.

- Real world problems
- Used problem solving template, selected set of 10 decisions to make
- Class format-- small group problem solving & worksheets.

Results-

- greatly reduced dependence of student grades on incoming preparation
- improved problem solving
- drop & failure rate 1/3 of conventional
- better performance in subsequent physics course

*Burkholder, et al., Wieman, Equitable approach to introductory calculus-based physics courses focused on problem solving, Phys. Rev. Phys. Educ. Res. 18, 020124

Conclusion—Problem-solving essential skill of physicists. Learn by deliberate practice of problem-solving decisions. Develops new capabilities in brain.

copy of slides available

<u>Good References:</u>

- 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"*

- A Detailed Characterization of the Expert Problem-Solving Process in Science and Engineering: Guidance for Teaching and Assessment, A. Price et al, ://doi.org/10.1187/cbe.20-12-0276

- Equitable approach to introductory calculus-based physics courses focused on problem solving, Eric Burkholder , et al.

Phys. Rev. PER, 18, 020124 (2022)

A. Framing

Visual Representation A basic sketch illustrating what is happening, the important quantities (forces, velocity, weight, energy, etc.), and what you are solving for. (3pts)

Relevant Concepts (2pt)

Similar Problems Previously solved problems with same concepts can provide guidance for solving. (1pt)

Assumptions and Simplifications Any details you are neglecting. (1pt)

Information Needed This includes values given in the problem and values you might need to estimate or look up. (2pts)

B. Planning

Solution Plan (3pts)

Rough Estimate What do you expect the answer to be and why? . (2pts)

C. Execution

Carry out your plan for solving. Plug in numbers as very last step. (3pts)

D. Answer Checking

Compare to Estimate (1pt)

Limits Test Look at dependencies (for example, how increasing a variable affects an answer). Equations should make sense in limits (angles 0 and 90, weight zero or large, ...). (2pts)

Units Check Double check math, units, and use of vectors versus scalars. (1pt)

Getting (Un)stuck If you aren't able to reach a solution, determine where you got stuck for partial credit (you can consult with peers). (1 pt) extras below, not in talk

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.

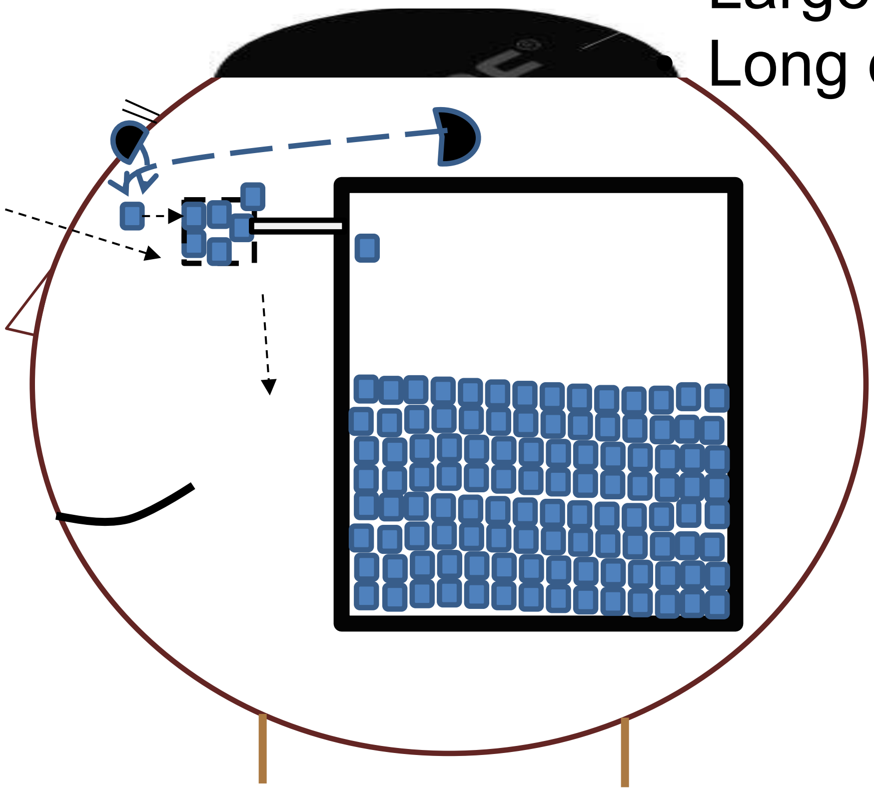
Principle- minimizing cognitive load

Memory *(simplified)*

1. "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 LTM



2. **Long term memory**
- Large capacity
- Long duration

"Cognitive load" means how much working memory is being used. Split attention, jargon, too much material too fast, all can overwhelm WM. Make learning impossible.