Expertise in physics: learning and teaching it*

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= “thinking like physicist”
arguably goal of every course & grad training

*based on the research of many people, some from my science ed research group
How I thought about physics expertise & how taught.

think hard, figure out subject

tell students how to understand it

give problem to solve

- yes: done
- no: students lazy or poorly prepared

tell again Louder
Figure out, then tell students

my enlightenment

grad students
17 yrs of success in classes. Come into lab clueless about physics?

2-4 years later ⇒ expert physicists!

Research on expertise and how learned (particularly physics)

• explained puzzle
• different way to think about learning
• how to improve teaching
Educational goal– learn to think about and use physics like physicist would

I. Exactly what is “thinking like physicist”

II. How is it learned?

III. Examples from college classroom research
   intro to very advanced
I. Expertise research*

historians, scientists, chess players, doctors,…

Expert competence =
• factual knowledge
• **Mental organizational framework** ⇒ retrieval and application patterns, relationships, scientific concepts

or ?

• Ability to monitor own thinking and learning
  ("Do I understand this? How can I check?")

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

*Cambridge Handbook on Expertise and Expert Performance
II. Learning expertise*--

Challenging but doable tasks/questions
Practicing all the elements of expertise with feedback and reflection. Motivation critical!

Requires brain “exercise”

Some components of science expertise
• concepts and mental models + selection criteria
• recognizing what information is needed to solve, what irrelevant
• does answer/conclusion make sense- ways to test
• moving between specialized representations (graphs, equations, physical motions, etc.)

Other physics expertise (use in research)? Discuss.

Knowledge important but only as integrated part. When and how to use.

* “Deliberate Practice”, A. Ericsson research accurate, readable summary in “Talent is over-rated”, by Colvin
What is the role of the teacher in development of expertise?

“cognitive coach”. Designing practice tasks, motivating, giving feedback

Subject expertise of teacher is essential—
- designing practice tasks
  (What is thinking like a physicist? How to practice specific components & at proper level?)
- feedback/guidance on learner performance
  Most important-- how to improve
- why worth learning & how to learn-- motivating

But in designing good practice tasks— like research, can copy what works. The rest is easier to add. Example--
Measuring how well can apply mechanics concepts like physicist to make predictions in novel context

Pre to post comparison

average trad. Cal Poly instruction

1st year mechanics

9 instructors, 8 terms, 40 students/section. Same prescribed set of student activities.

Hoellwarth and Moelter, Am. J. Physics May '11
Most (all?) physics education research is finding different ways to have students actively practicing expert thinking with good feedback.

Some examples of doing this explicitly:
1. Big intro lecture comparison. Learning in class.
2. Advanced modern optics—practicing expert thinking in class.
Learning in the in classroom*

Comparing the learning in two identical sections of 1\textsuperscript{st} yr physics for engineers. 270 students each.

**Control**--standard lecture class– highly experienced Prof with good student ratings.

**Experiment**-- physics postdoc trained in principles & methods of effective teaching of expertise.

They agreed on:
- Same learning objectives
- Same class time (3 hours, 1 week)
- Same exam (jointly prepared)- start of next class

*Deslauriers, Schewlew, Wieman, Sci. Mag. May 13, ’11*
Class design

1. Targeted pre-class readings

2. Questions to solve, respond with clickers or on worksheets, discuss with neighbors

3. Discussion by instructor follows, not precedes.

4. Activities address motivation (relevance) and prior knowledge.
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.

3. Individual answer with clicker
\(\text{accountability=intense thought, primed for learning}\)

Jane Smith chose a.

4. Discuss with “consensus group”, revote.
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 physicist thinking—feedback that guides thinking—other students, informed instructor, demo
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*Deslauriers, Schewlew, Wieman, Sci. Mag. May 13, ‘11*
Clear improvement for entire student population. Engagement 85% vs 45%. Experimental class covered less, 11/12 topics (but still scored higher on #12).
Converting a successful advanced optics course (4th year) from lecture to practicing thinking like physicist (highly mathematical)

David Jones, Kirk Madison, Wieman

in review, preprints available arXiv??
Lossy ("real life" or damped) Resonators

\[ U_{n+1} = r e^{i\phi} U_n \]

so...

\[ U_1 = U_0 r e^{i\phi} \]

\[ U_2 = U_0 r^2 e^{i2\phi} \]

\[ \vdots \]

To find total field in cavity:

\[ U_T = U_0 + U_1 + U_2 + U_3 \ldots \]

\[ = U_0 + U_0 r e^{i\phi} + U_0 r^2 e^{i2\phi} + \ldots \]

\[ = U_0 + U_0 r e^{i\phi} + h^2 U_0 r^2 e^{i2\phi} + \ldots \]

\[ = \frac{U_0}{1-h} \]

Amplitude of the field in one round trip is reduced by:

- absorption on mirrors
- leakage
- scattering

Lump all of these effects into one factor = "r"

- on each round trip

\[ |U_{n+1}| = r |U_n| \]

- still have a longitudinal round trip phase

\[ \phi = 2kd = \frac{4\pi}{\lambda} d \]

Total field in cavity traveling to the right:

\[ U_T = \frac{U_0}{1-re^{i\phi}} \]
3) Consider this optical setup

Laser with tunable frequency

\[ U = U_0 + U_1 + U_2 + \ldots \]

where \[ U_{n+1} = r e^{i2kd} U_n \]

3a) Explain what this second expression means:
3b) What is the meaning of the terms \( U_n \) and \( U_{n+1} \) ?
3c) What is \( U_0 \) in terms of \( r_1, r_2, t_1, \) and \( U_{\text{laser}} \) ?
3d) What is \( r \) in terms of \( r_1 \) and \( r_2 \) ?
3e) Suppose there was a loss inducing optical element inside the cavity with a field transmission coefficient of \( t_{\text{loss}} \). What would \( r \) be in terms of \( t_{\text{loss}}, r_1 \) and \( r_2 \) ? What if \( t_{\text{loss}} \) were complex?
3e) What is the effect of changing the index of refraction of the material between the mirrors? Is this equivalent to changing the distance between the mirrors? Why or why not?
3f) What is the effect of changing the wavelength of the input laser field? Is this equivalent to changing the distance between the mirrors? Why or why not?
3g) Evaluate the infinite sum for the field and derive an expression for the intensity

\[ \text{Hint} \quad 1 + a + a^2 + a^3 \ldots = \frac{1}{1-a} \]
TABLE II. Progression through sequential stages of a typical class period. Each action of students and instructors is described in detail within text.

<table>
<thead>
<tr>
<th>Actions</th>
<th>Time (min)</th>
<th>Students</th>
<th>Instructors/TA(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparation</td>
<td>—</td>
<td>Complete targeted reading and pre-class online quizzes</td>
<td>Formulate/review activities</td>
</tr>
<tr>
<td>Introduction</td>
<td>2-3</td>
<td>Listen/ask questions</td>
<td>Introduce goals of day</td>
</tr>
<tr>
<td>Activity</td>
<td>10-15</td>
<td>Group work on activities</td>
<td>Circulate in classroom, answer questions and assess students</td>
</tr>
<tr>
<td>Feedback</td>
<td>5-15</td>
<td>Listen/ask questions, provide solutions and reasoning when called on</td>
<td>Facilitate whole class discussion, provide feedback to class</td>
</tr>
<tr>
<td>Activity</td>
<td>:</td>
<td>:</td>
<td>:</td>
</tr>
<tr>
<td>Feedback</td>
<td>:</td>
<td>:</td>
<td>:</td>
</tr>
<tr>
<td>…repeat as needed…</td>
<td>:</td>
<td>:</td>
<td>:</td>
</tr>
<tr>
<td>Conclusion</td>
<td>2-3</td>
<td>Hand in in-class work</td>
<td>Wrap up</td>
</tr>
</tbody>
</table>
Exam scores--nearly identical (isomorphic) final exam problems

**mathematical solutions, problems from new contexts**

- **practice & feedback 2nd instructor, N = 81**
- **practice & feedback 1st instructor, N = 31**
- **1 standard deviation improvement**
- **taught by lecture, 1st instructor, 3rd year practice, N = 52**
But, learning in-class just the beginning. Practice and feedback on thinking like physicist on homework and exams equally important.
Expertise practiced and assessed with typical HW & exam problems.

- Provide all information needed, and only that information, to solve the problem
- Say what to neglect
- Not ask for argument for why answer reasonable
- Only call for use of one representation
- *Possible* to solve quickly and easily by plugging into equation/procedure

- concepts and mental models + selection criteria
- recognizing relevant & irrelevant information
- what information is needed to solve
- How I know this conclusion correct (or not)
- model development, testing, and use
- moving between specialized representations (graphs, equations, physical motions, etc.)
Perceptions about science

Novice

Content: isolated pieces of information to be memorized.

Handed down by an authority. Unrelated to world.

Problem solving: following memorized recipes.

Expert

Content: coherent structure of concepts.

Describes nature, established by experiment.


measure student perceptions, 7 min. survey. Pre-post intro physics course ⇒ more novice than before

chem. & bio as bad

*adapted from D. Hammer
Applying your expertise in the classroom. Designing practice tasks and providing ongoing feedback.

More fun, students more engaged, learn more.

slides (+30 extras) available

Good References:
S. Ambrose et. al. “How Learning works”
Colvin, “Talent is over-rated”

cwsei.ubc.ca-- resources, references, effective clicker use booklet and videos
~ 30 extras below
U. Cal. San Diego, Computer Science
Failure & drop rates– *Beth Simon et al., 2012*

<table>
<thead>
<tr>
<th>Course</th>
<th>Standard Instruction</th>
<th>Peer Instruction</th>
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</thead>
<tbody>
<tr>
<td>CS1*</td>
<td>24%</td>
<td>10%</td>
</tr>
<tr>
<td>CS1.5</td>
<td>25%</td>
<td>11%</td>
</tr>
<tr>
<td>Theory*</td>
<td>25%</td>
<td>6%</td>
</tr>
<tr>
<td>Arch*</td>
<td>16%</td>
<td>3%</td>
</tr>
<tr>
<td>Average*</td>
<td>20%</td>
<td>7%</td>
</tr>
</tbody>
</table>
Research on Motivation—
(essential & complex- depends on background)

Enhancing motivation to learn

a. Relevant/interesting to learner (meaningful context--)

b. Sense that can master subject and how to master
   **Ability innate** --student or teacher/parent, —self fulfilling prophecy of failure. Challenge causes giving up/encouraging to quit.
   **Ability developed through effort**— challenge causes greater effort & more success.

c. Sense of personal control/choice
If time, some new, yet-to-be-published work on introductory instructional labs

I. Cognitive task analysis of experimental physics research versus cognitive tasks in instructional lab

II. Data on learning impact of Stanford intro labs

III. Spectacular new results from Holmes and Bonn teaching quantitative critical thinking in intro lab by explicit practice of expert thinking.
Cognitive tasks involved in experimental physics research (table-top)

1. Establishing research goal: What are the goal(s) and question(s) of the research? Deciding if the goal is interesting, timely, consistent with constraints (time, funding, ...)

2. Defining criteria for suitable evidence. What variables important, what data needed.


4. Experimental design:
   a. Exploration of many possible preliminary designs (requires clear definition of the optimum depth of analysis of the alternative designs)
   b. Analyzing relevant variables that may lead to systematic errors
   c. Finalizing the design, taking into account construction details and performance requirements of each component. Often requires bringing in additional expertise.
   d. Developing detailed data acquisition strategy: How much, what parameter ranges, what order, additional checks, ...? Necessary precision and accuracy. Estimation use of time and money. (Revise after apparatus constructed and tested.)
5. Construction and testing of apparatus:  
   a. Deciding who should build the various parts and on what schedule.  
   b. Developing criteria and test procedures for evaluation of components.  
   c. Testing performance of individual components and complete apparatus.  
   d. Trouble shooting of apparatus.  
   e. Modify design as needed. Revisit data acquisition strategy, modify as needed.

6. Collect experimental data.

7. Analyzing data:  
   a. Model the data mathematically with suitable approximations.  
   b. Choose statistical analysis methods & calculate statistical uncertainty.  
   c. Determining systematic uncertainties.

8. Evaluating results:  
   a. Checking the results, when they come out differently than expected.  
   b. Testing data that is as expected. Skepticism. Tests against experimenter biases.

9. Analyzing implications. What ideas confirmed? Possible new theoretical or experimental directions?  

10. Presenting the work:  
   a. Follow standard data display procedures, or as needed, develop new procedures.  
   b. Written and verbal: convey context and significance; clearly and in appropriate style describe apparatus, procedures, and conclusions.

1 Requires extensive expertise in the research field. 2 Requires extensive experience with the relevant equipment.
**Cognitive tasks in standard introductory instructional lab?**

Given-- research question-- “Measure g”
Given-- data to collect-- “period and length of pendulum”
Given-- feasibility analysis
Given-- apparatus design
Given-- construction
Given-- components already built and tested
*Get to collect data!
Given-- analysis methods
*Get to decide statistical uncertainty, and tinker with systematics (not real without early analysis stages)
Given-- what correct answer is, what instructor wants to see.
Given-- format for write up, data tables, and graphs.
Given-- significance and context, clarity of presentation and argument-- irrelevant
Recent unpublished results. Learning in 1\textsuperscript{st} year labs.

I. Mechanics & E & M. Goal-- Support content mastery of course. Quite standard, Many copied or adapted (UW, UICU,...) 1/3 students take, 1/3 exam questions on lab related topics. 
\rightarrow \textbf{Impact on final exam scores 0.1, 0.3 \% \pm 1\% !!}
\textbf{not practicing expert thinking, not achieving learning.}

II. Doing better: Natasha Holmes and Doug Bonn UBC--
Basic cognitive tasks/decisions involved in quantitative critical thinking. Examine data, compare with other data or model, make decision. Act on decision. Practice repeatedly with feedback over many weeks.

Compare with group doing same lab experiments, standard way. 40 !! times more likely to recognize disagreement explain limitations in at theoretical model!
Large differences year later, different course.
3. Evidence from the Classroom

~ 1000 research studies undergrad science & eng. (few from math)
- consistently show greater learning
- lower failure rates
- benefits all, but at-risk most (*smaller data set*)

a few examples—
- learning from course
- failure and drop rates
- learning in classroom

all sciences & eng. similar.
PNAS Freeman, et. al.
recent massive meta-analysis
Measuring conceptual mastery

- Force Concept Inventory- basic concepts of force and motion

Apply like physicist in simple real world applications?

Test at start and end of the semester--
What % learned? (100’s of courses/yr)

On average learn <30% of concepts did not already know.
Lecturer quality, class size, institution,...doesn't matter!

R. Hake, “…A six-thousand-student survey…” AJP 66, 64-74 (’98).

Fraction of unknown basic concepts learned

Average learned/course
16 traditional Lecture courses

improved methods
Best results in classes ~200
Emphasis on motivating students
Providing engaging activities and talking in class
Failing half as many
“Student-centered” instruction

Aren’t you just coddling the students?

Like coddling basketball players by having them run up and down court, instead of sitting listening?

Serious learning is inherently hard work
Solving hard problems, justifying answers—much harder, much more effort than just listening.

But also more rewarding (if understand value & what accomplished)—motivation
Design of Activities

TABLE I. Design considerations used for this course transformation

- Each activity was motivated either verbally by the instructor or in the written preamble.
- Mathematical models were tied to phenomena, and “real-life” examples were employed.
- Prior course material was included wherever possible to maximize continuity.
- Questions were ordered from least to most difficult to optimize engagement.
- Activities were designed so that continuous work did not exceed 15 minutes and at least two class feedback sessions could occur over the full class period.
- Activities included some work that was judged to be just beyond what the students were capable of, so as to optimally prepare them for the feedback period.
- Long/elaborate algebraic manipulations in activities were minimized so students could focus on underlying physical phenomena.
- “Bonus” questions were included to challenge the most advanced students.
IV. Making effective research-based teaching the norm

Universities determine STEM learning of K-12 teachers and their model for teaching—so have to fix first.

Why demonstrably more effective teaching methods not being widely adopted in Higher Ed. STEM?

Incentives are against at all levels—fac., dept, admin. Research productivity only thing measured and rewarded. So diverting even small amount of time is bad.

CW poll--No major institution collects data on the teaching methods used by its faculty.
Necessary (and probably sufficient) 1st step—have good way to evaluate teaching quality

Requirements:
• measures what leads to most learning
• equally valid/fair for use in all courses
• shows how to improve, & measures when do
• is practical to use on annual basis

method that currently dominates--student evaluations, fails badly on first three

Better way—thoroughly characterize all the practices and decisions used in teaching a course. Determine extent of use of research-based methods.

better proxy for what matters
helps faculty, helps institution
The Teaching Practices Inventory: A New Tool for Characterizing College and University Teaching in Mathematics and Science

Carl Wieman* and Sarah Gilbert†

~10 min or less to complete:
• instructive to fill out
• document good things you (ind. & coll.) are doing
• shows what instructor could do to improve
• documents improvement
Effective teaching practices, ETP, scores various math and science departments at UBC before and after for dept that made serious effort to improve teaching.
2 simple immediately applicable findings from research on learning. Apply in every course.

1. expertise and homework design

2. reducing demands on short term memory
Perfection in class is not enough!

_Not enough hours_

- Activities that prepare them to learn from class (targeted pre-class readings and quizzes)
- Activities to learn much more after class
  - good homework—-
    - builds on class
    - explicit practice of all aspects of expertise
    - requires reasonable time
    - reasonable feedback
2. **Limits on short-term working memory** -- best established, most ignored result from cog. science

Working memory capacity **VERY LIMITED**!
*(remember & process 5-7 distinct new items)*

**MUCH less than in typical lecture**

Mr Anderson, May I be excused? My brain is full.

*slides to be provided*
Reducing unnecessary demands on working memory improves learning.

- jargon, use figures, analogies, pre-class reading
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.
Use of Educational Technology

**Danger!**
Far too often used for its own sake! *(electronic lecture)* Evidence shows little value.

**Opportunity**
Valuable tool *if* used to supporting principles of effective teaching and learning.

Extend instructor capabilities. Examples shown.

- Assessment  (pre-class reading, online HW, clickers)
- Feedback  (more informed and useful using above, enhanced communication tools)
- Novel instructional capabilities (PHET simulations)
- Novel student activities (simulation based problems)
Components of effective teaching/learning apply to all levels, all settings

1. Motivation

2. Connect with and build on prior thinking

3. Apply what is known about memory
   a. short term limitations
   b. achieving long term retention (Bjork)

   retrieval and application-- repeated & spaced in time (test early and often, cumulative)

4. Explicit authentic practice of expert thinking.
   Extended & strenuous
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

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

- Actual Majors who were originally intended phys majors
- Survived as Majors who were NOT originally intended phys majors

CLASS Overall Score (measured at start of 1st term of college physics)

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

Percent of Students

Novice  Expert
What is the role of the teacher?

“Cognitive coach”
• Designs tasks that practice the specific components, of “expert thinking”.
• Motivate learner to put in LOTS of effort
• Evaluates performance, provides timely specific feedback. Recognize and address particular difficulties (inappropriate mental models, ...)
• repeat, repeat, ...-- always appropriate challenge

Implies what is needed to teach well: expertise, understanding how develops in people, common difficulties, effective tasks and feedback, effective motivation.
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.
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
Retention curves measured in Bus’s Sch’l course. UBC physics data on factual material, also rapid drop but pedagogy dependent. (in prog.)
Comparison of teaching methods: identical sections (270 each), intro physics. (Deslauriers, Schewlew, submitted for pub)

---

**I**

Experienced highly rated instructor-- trad. lecture

wk 1-11

very well measured-- identical

**II**

Very experienced highly rated instructor-- trad. lecture

wk 1-11

Wk 12-- experiment
Two sections the same before experiment. (different personalities, same teaching method)

<table>
<thead>
<tr>
<th></th>
<th>Control Section</th>
<th>Experiment Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Students enrolled</td>
<td>267</td>
<td>271</td>
</tr>
<tr>
<td>Conceptual mastery (wk 10)</td>
<td>47±1%</td>
<td>47±1%</td>
</tr>
<tr>
<td>Mean CLASS (start of term)</td>
<td>63±1%</td>
<td>65±1%</td>
</tr>
<tr>
<td>Agreement with physicist</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Midterm 1 score</td>
<td>59±1%</td>
<td>59±1%</td>
</tr>
<tr>
<td>Mean Midterm 2 score</td>
<td>51±1%</td>
<td>53±1%</td>
</tr>
<tr>
<td>Attendance before</td>
<td>55±3%</td>
<td>57±2%</td>
</tr>
<tr>
<td>Engagement before</td>
<td>45±5%</td>
<td>45±5%</td>
</tr>
</tbody>
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Comparison of teaching methods: identical sections (270 each), intro physics. (Deslauriers, Schewlew, submitted for pub)

I
Experienced highly rated instructor--trad. lecture

wk 1-11

identical on everything diagnostics, midterms, attendance, engagement

Wk 12-- competition

elect-mag waves
inexperienced instructor research based teaching

wk 13 common exam on EM waves

II
Very experienced highly rated instructor--trad. lecture

wk 1-11

elect-mag waves
regular instructor intently prepared lecture
<table>
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<th></th>
<th>control</th>
<th>experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Attendance</td>
<td>53(3) %</td>
<td>75(5)%</td>
</tr>
<tr>
<td>3. Engagement</td>
<td>45(5) %</td>
<td>85(5)%</td>
</tr>
</tbody>
</table>
Survey of student opinions-- transformed section

“Q1. I really enjoyed the interactive teaching technique during the three lectures on E&M waves.”

Not unusual for SEI transformed courses
Measuring student (dis)engagement. Erin Lane
Watch random sample group (10-15 students). Check against list of disengagement behaviors each 2 min.

example of data from earth science course
New paradigm on learning complex tasks (e.g. science, math, & engineering)

old view, current teaching

knowledge

soaks in, variable

new view

transform via suitable “exercise”
(lecture teaching) Strengths & Weaknesses

Works well for basic knowledge, prepared brain:

- **bad, avoid**
- **good, seek**

Easy to test. \(\Rightarrow\) Effective feedback on results.
Information needed to survive \(\Rightarrow\) intuition on teaching

But problems with approach if learning:
- involves complex analysis or judgment
- organize large amount of information
- ability to learn new information and apply

Complex learning-- different.
Major advances past 1-2 decades in cognitive psychology and brain research are guiding principles for achieving learning of complex expertise.
Why so hard to give up lecturing? (speculation)

1. tradition
2. Brain has no perspective to detect changes in self. “Same, just more knowledge”
3. Incentives not to change—research is closely tracked, educational outcomes and teaching practices not.

Psychology research and our physics ed studies
Learners/experts cannot remember or believe previously held misunderstandings!
Changing educational culture in major research university science departments necessary first step for science education overall

- Departmental level
  ⇒ scientific approach to teaching, all undergrad courses = learning goals, measures, tested best practices
  Dissemination and duplication.

All materials, assessment tools, etc to be available on web
Characteristics of expert tutors*  
(Which can be duplicated in classroom?)

**Motivation major focus** (context, pique curiosity,...)  
Never praise person-- limited praise, all for process

Understands what students do and do not know.  
⇒ timely, specific, interactive feedback

Almost never tell students anything-- pose questions.

Mostly students answering questions and explaining.

Asking right questions so students challenged but can figure out.  Systematic progression.

Let students make mistakes, then discover and fix.

Require reflection: how solved, explain, generalize, etc.

*Lepper and Woolverton pg 135 in Improving Academic Performance
“What do I do with the weakest students? Are they just hopeless from the beginning, or is there anything I can do to make a difference?”

many papers showing things that do not work

Here-- Demonstration of how to transform lowest performing students into medium and high.

Intervened with bottom 20-25% of students after midterm 1.

a. very selective physics program 2nd yr course
b. general interest intro climate science course
What did the intervention look like?

Email after M1—“Concerned about your performance. 1) Want to meet and discuss”; or 2) 4 specific pieces of advice on studying. [on syllabus]

Meetings—“How did you study for midterm 1?” “mostly just looked over stuff, tried to memorize book & notes”

Give small number of specific things to do:
1. test yourself as review the homework problems and solutions.
2. test yourself as study the learning goals for the course given with the syllabus.
3. actively (explain to other) the assigned reading for the course.
4. Phys only. Go to weekly (optional) problem solving sessions.
Intro climate Science course (S. Harris and E. Lane)

The scatter plot shows the relationship between Midterm 1 and Midterm 2 scores for different intervention groups:

- **No intervention** (represented by diamonds)
- **Email only** (represented by black dots)
- **Email & Meeting** (represented by black squares)

The right side of the plot is labeled as 'intervention' and the left side as 'no intervention'.
- End of 2\textsuperscript{nd} yr Modern physics course (very selective and demanding, N=67)

- Intro climate science course. Very broad range of students. (N=185)

bottom 1/4 \textbf{averaged +19\% improvement on midterm 2!}

Averaged +30\% improvement on midterm 2!
Bunch of survey and interview analysis end of term.

⇒ students changed how they studied

(but did not think this would work in most courses,
⇒ doing well on exams more about figuring out instructor than understanding the material)

Instructor can make a dramatic difference in the performance of low performing students with small but appropriately targeted intervention to improve study habits.
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
Many new efforts to improve undergrad stem education (partial list)

1. **College and Univ association** initiatives (AAU, APLU) + many individual universities
2. **Science professional societies**
3. **Philanthropic Foundations**
4. **New reports** — PCAST, NRC (~april)
5. **Industry**— WH Jobs Council, Business Higher Ed Forum
6. **Government**— NSF, Ed $$, and more
7. ....
Fixing the system

but...need higher content mastery, new model for science & teaching

Higher ed

K-12 teachers

everyone

STEM teaching & teacher preparation

STEM higher Ed
Largely ignored, first step
Lose half intended STEM majors
Prof Societies have important role.