Learning to be a skilled optical scientist or engineer; the 29 decision process

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What is "scientific thinking"?
How best to teach it?

copies of slides to be available

See--Price, Kim, Burkholder, Fritz, and Wieman, *A Detailed Characterization of the Expert Problem-Solving Process in Science and Engineering: Guidance for Teaching and Assessment,* CBE- Life Sciences Ed. Aug. 2021.
Supported by HHMI.

Talk outline

I. Introduction. Fundamental principle of learning from research. Authentic problem-solving skill as ultimate goal.

II. Research on expert problem solving– discovered a set of decisions-to-be- made (29).

III. Learning & teaching problem solving. Making these decisions.

* Freeman et al, active learning metanalysis, PNAS 2014, https://www.pnas.org/content/111/23/8410

Rethinking education, how learning happens

old/current model

knowledge

soaks in, varies with brain

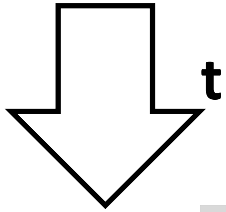
focus on:

- selecting best brains
- knowledge soup

new research-based view

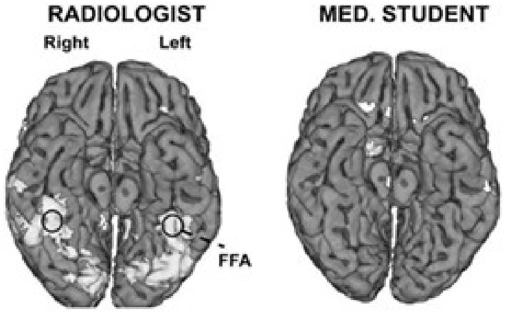
brain changeable

~ same



transformation

Change neurons by intense thinking.
Improved capabilities.



fMRI-- interpreting x-ray image

Brain research--enhancing relevant neuron connections—like muscle development. Intensity & type of exercise critical.

A. Ericsson et al. Process of developing of any expertise. (chess, music, soccer,...)
"Deliberate practice". Level of expertise determined by amount of D. P.

1. Identify key subskills (cognitive or physical) of the expertise
2. Intently practice to master each subskill, with guiding feedback to improve.
3. Intently practice combination of subskills.
4. repeat, repeat, increasing challenge. (rewiring brain better and better)

Brain learns what it practices intently.

Explains most sci. & eng ed research results:

- Typical sci ed research (many labels)– replace listening to lecture with practice predicting & explaining on conceptual questions. Get feedback (peers & instructor).
- Improve on doing conceptual questions, little else.

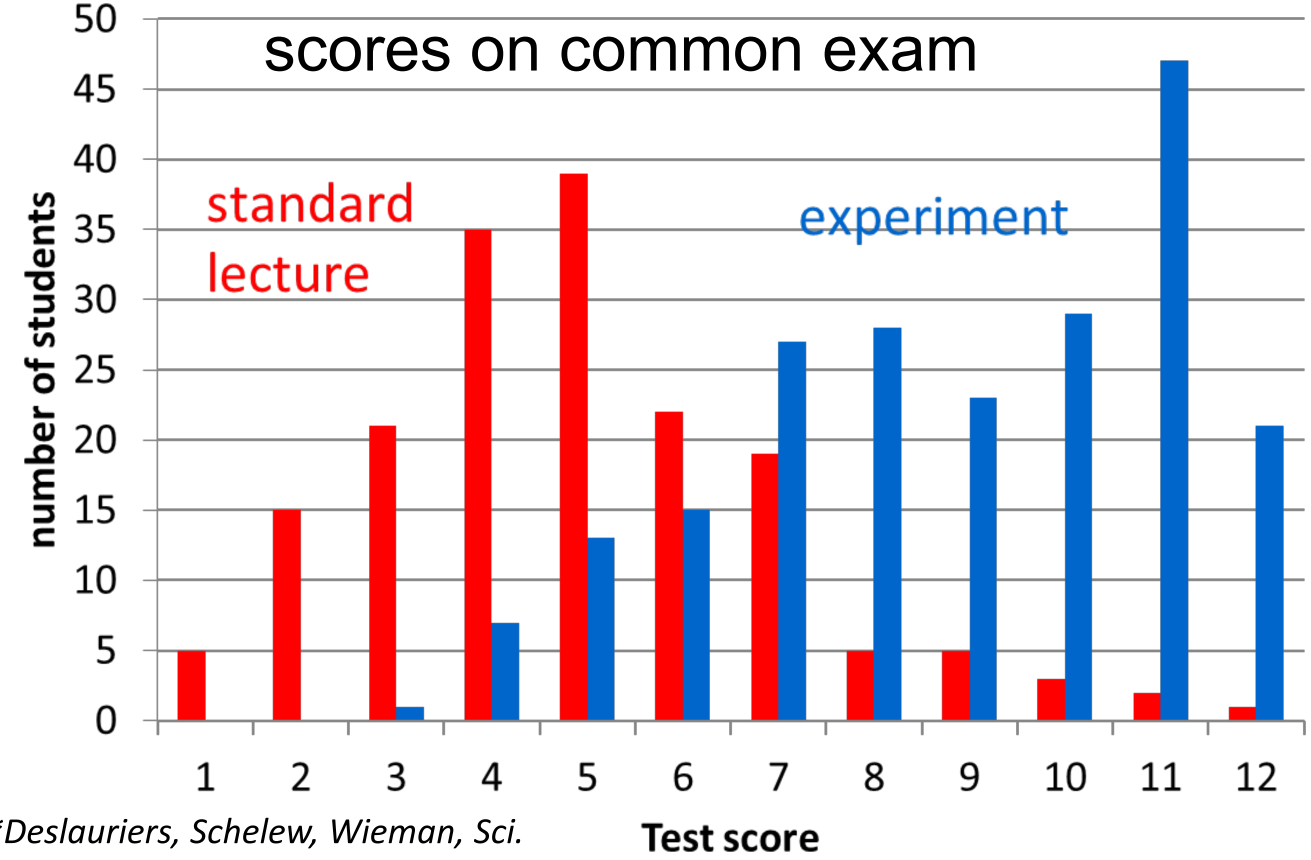
- My group, practice and improvement on wider range of questions in courses
  (physics 1 through grad courses)

e.g. Learning in large intro physics class*

Comparing the learning in two ~identical sections.

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

Experiment–- new physics Ph. D. trained in practice-with-feedback teaching method. Students answer questions.



Big difference in learning for entire distribution!

General course design and implementation--
Jones, Madison, Wieman, (2015). ***Transforming a 4th-year modern optics course using a deliberate practice framework****. Phys. Rev. ST Phys. Educ,11(2), 020108.*

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

But what does a good scientist do? (the thinking to be taught and learned)

Problem solving!

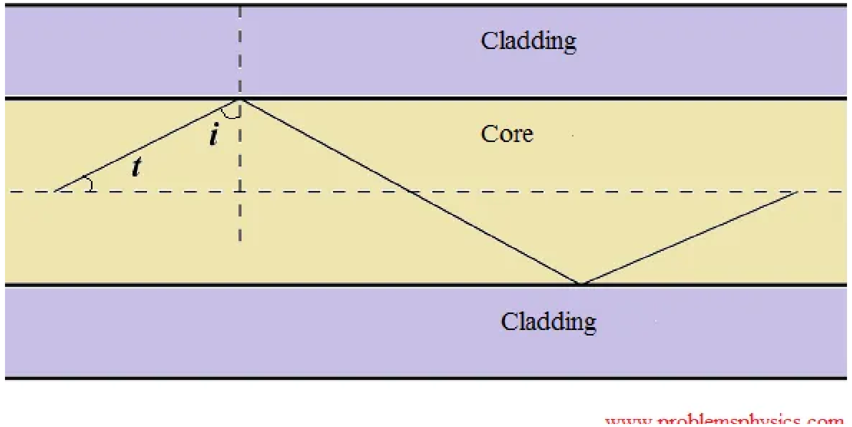
NOT textbook problems. Authentic ("real") problems.

Typical optics textbook problems

Q.1 Which of the following is the correct formula for focal point calculation?

1.F= I + O ,   2. 1/F = I x 1/O ,   3. F = 1 x 1/O,   4. 1/F = 1/I + 1/O

Q. 2 You have a concave mirror and a candle. The candle is 14.7cm tall, and the image is 21.9cm tall. What is the magnification of the mirror?



Q. 3 In the optical fiber shown, the core has a refractive index equal to 1.5 and a cladding of refractive index of 1.4.

a) What is the speed of light inside the core?

b) What is the critical angle at the core-cladding interface?

c) What is the maximum angle t that the rays leaving the source of light should make with the axis of the fiber so that light stays in the fiber?

Typical authentic optics problems:

P. 1. How can you double the output power from your dye laser (with a budget of $6000)?

P. 2. How can you increase the bandwidth of a long-distance optical fiber by 50%?

Complex, no obvious solution. Solution method? What information is needed? How to find the information? Plan for solving? ... None covered by textbook problems.

Learning to solve <u>authentic</u> ("real") problems.

Do lots of homework or old exam problems? Follow recipes?
(learn procedures, solve textbook problems, NOT solve real problems)

Trial and error in research lab?
typical, but not efficient. Rest of talk– doing better.

What should be practiced and learned to become a good sci. & eng. problem solver? (“optics expert”)

I struggled with this for many years advising physics phd students.

Many did well in courses, but then struggle with research problems in lab.
Why? What missing? How to help?

Talk outline

I. Introduction. Fundamental principle of learning- research. Expertise involves solving authentic problems.

II. Research on expert problem solving– the set of decisions-to-be- made (29).

III. Learning & teaching problem solving. Making these decisions.

Wieman group research on expert scientific problem solving ~ last 7 years.

Detailed interviews with ~ 50 successful scientists and engineers on how they solved a significant problem in their careers.

A “typical” research problem.

Focus on choices and reasons. Looking for patterns and differences.
Needed research team with wide range of expertise: science, engineering, medicine.

Identified a decision in interview either by:

a) explicitly stated in interview as step in solving process
b) made choice of actions between alternatives

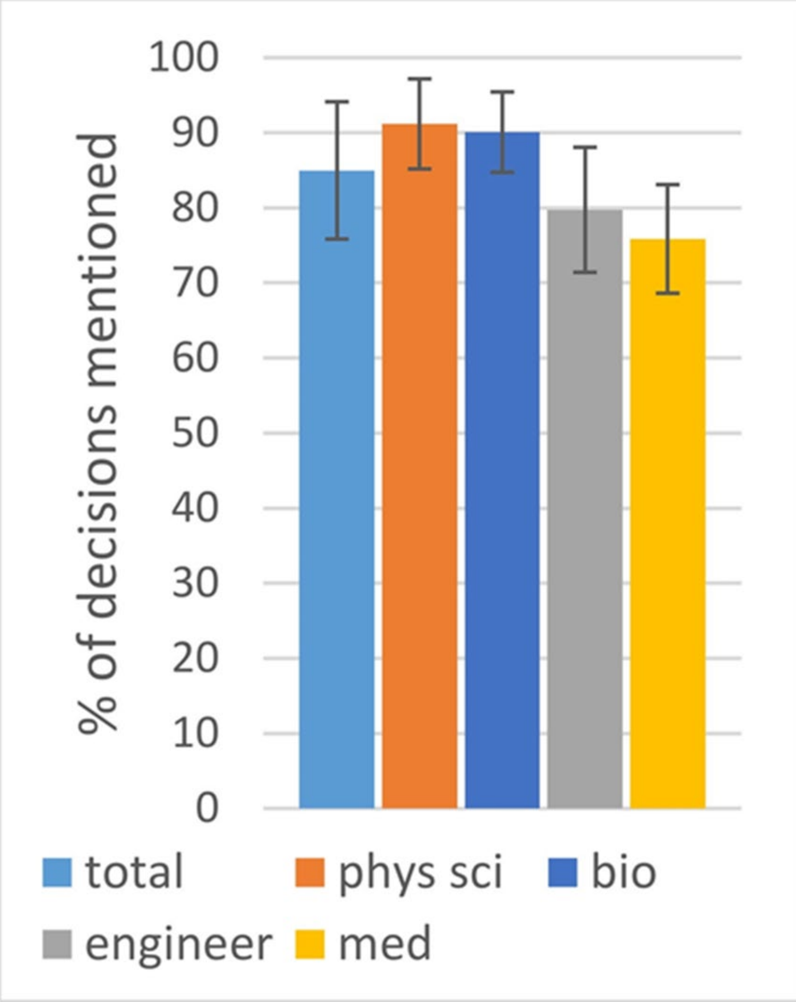
Tested if any steps in problem-solving process not explained by decisions.

Price, Kim, Burkholder, Fritz, and Wieman, *A Detailed Characterization of the Expert Problem-Solving Process in Science and Engineering: Guidance for Teaching and Assessment*, CBE- Life Sciences Ed. Aug. 2021.

Finding– could characterize process of all 50 sci & engs in terms of the decisions they made.*

<u>Surprising discovery! All made the same 29 decisions. e.g.</u>

- ***What is important in field?***
- ***How well does it fit my expertise and capabilities (equipment etc.)***
- ***What important underlying features or concepts apply?***
- ***What approximations or simplifications are justified?***
- ***What information is needed to solve the problem?***
- ***Plan for how to get information needed?***
- ***What to prioritize?***
- **...**
- ***How believable is the data?***
- ***What can & cannot conclude from it?***
- ***How to test possible failures/errors in solution? ...***
- ***How to best communicate results to community?***



*A. Price, Kim, Burkholder, Fritz, Wieman, *A Detailed Characterization of the Expert Problem-Solving Process in Science and Engineering: Guidance for Teaching and Assessment,* CBE-Life Sci. Educ. Just out.

“Decisions”– a choice between options with limited information.

- **What important underlying features or concepts apply?** (and what info irrelevant)
- **What approximations or simplifications are justified?**
- **What information is needed to solve the problem and how best to get it? What to prioritize?**
- **How believable is the data?**
- **etc.**

If have complete information, is just a procedure. (all textbook, HW,, and exam problems)

= Educated guess. But always uses relevant disciplinary knowledge.

Discipline independent problem-solving skill (“critical thinking”) is oxymoron.

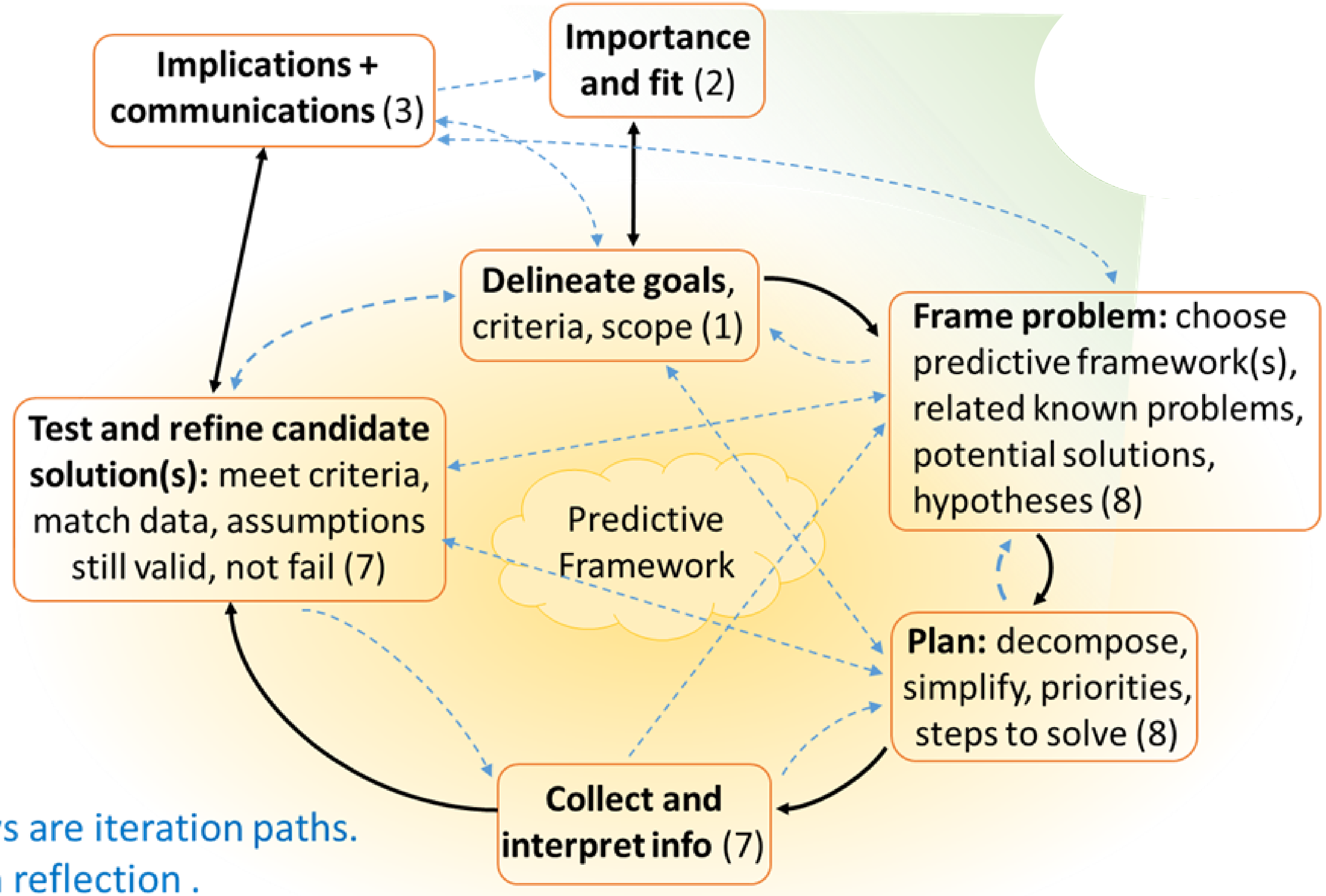
Recognizing and applying relevant information always required.

Knowledge called upon organized in form of “predictive frameworks”.
= mental models with only the required features and connected by mechanism.
Predict result of changing variable.

Sometimes one obvious PF. Often unclear– test & modify.

Categories of the 29 Science Problem Solving Decisions

(Slightly time ordered according to black arrows but involve extensive iteration)



Blue arrows are iteration paths.
Depend on reflection .

What problem solving decisions being practiced and learned in a typical optics course?

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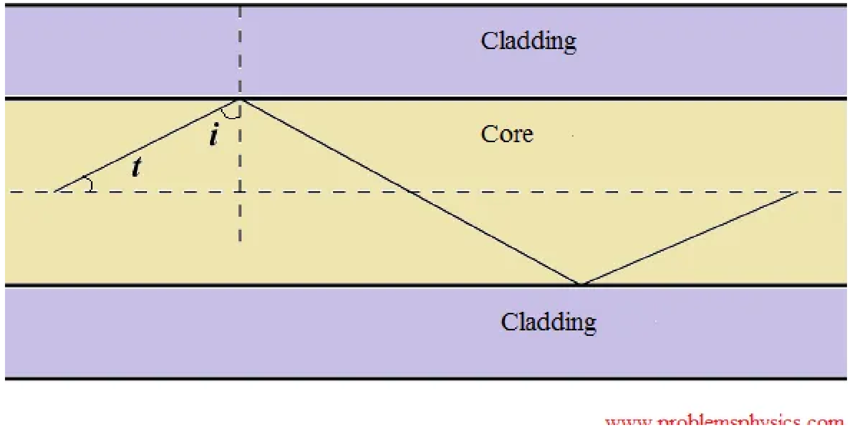

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Solving requires making almost none of the 29 decisions. Almost everything given. Teaching information and procedures– **not** real problem solving.

Talk outline

I. Introduction.

II. Research on expert problem solving– discovered a set of decisions-to-be-made (29).

III. Learning & teaching expert problem solving. Deliberate practice at making these 29 decisions in realistic contexts. Teacher/coach providing regular feedback.

IV. Better measurement of expertise. Identify areas for improvement in courses, programs, and students.

Template for teaching (or measuring) skilled problem-solving.

1. Give realistic problem scenario. Engineering: part to be designed to meet a need. Science, meaningful question to be answered, explain or control some process. Relevant, irrelevant, incomplete information given.

Problem first, information needed to solve provided as needed.

2. "What are important features?" "What info needed to solve and why?" A useful option: provide trial flawed solution, ask them to decide good and bad features.
3. Continue through making preferred subset of decisions. Often starting more general (What features important?) then narrowing down to probe specific knowledge (If feature A was changed, how would decision change?).
4. Provide additional information, as requested or as needed by learner, see how they use it.

Use for teaching:

a) ***In class-- Students work in groups of 3-4, making and justifying decisions. Instructor monitoring, answering questions, and providing feedback at suitable intervals.***

b) ***In research/design lab. Explicitly identify decisions to be made, have learners make, get feedback. Appropriate level. Reflection!*** (what worked? what didn't? why? how improve?)

Wieman group ongoing work– Creating **decision-based-problem-solving assessments** in multiple fields of science, engineering, and medicine.
(same template as for teaching activities, but student does alone)

Tested with variety of student populations and skilled practitioners in discipline.

Results:

a) Clear consensus response of skilled practitioners as to what decision and why. Confirms that each discipline has a well-established process for making all these decisions.
b) Students who successfully complete undergraduate courses and programs in relevant discipline **not** like skilled practitioners. Miss critical features and planning steps.
c) Students not all bad. Courses or experiences (work or research) where practiced decisions has impact.

List of problem-solving decisions (from Price et al.) pg 1

A. Importance and fit and delineate goals.

1) What is **important in field**?

What are important questions or problems? Where is the field heading? Are there advances in the field that open new possibilities?

2) Opportunity **fits solver's expertise**?

If and where are there gaps/opportunities to solve in field? Given experts' unique perspectives and capabilities, are there opportunities particularly accessible to them? (could involve challenging the status quo, questioning assumptions in the field)

3) **Goals, criteria, constraints**?

What are the goals for this problem? Possible considerations include:

a. What are the goals, design criteria, or requirements of the problem or its solution?

b. What is the scope of the problem?

c. What constraints are there on the solution?

d. What will be the criteria on which the solution is evaluated?

List of problem-solving decisions (from Price et al.) pg 2

B. Frame problem. These decisions lead to a more concrete formulation of the solution process and potential solutions.

4) What are **important underlying features or concepts** that apply, and which available information is relevant to solving?
(When appropriate) Create/find a suitable abstract representation of core ideas and information Examples: physics – equation representing process involved, chemistry – bond diagrams/potential energy surfaces

5) Which potential **predictive frameworks/models to use**? (decide among possible predictive frameworks or create framework) This includes deciding on the appropriate level of mechanism and structure that the framework needs to embody to be most useful for the problem at hand.

6) How to **narrow down the problem**? Involves formulating **specific questions and hypotheses**.

7) **Related problems**?
What are related problems or work seen before, and what aspects of their solutions might be useful in the present context? (may involve reviewing literature and/or reflecting on experience)

8) What are **potential solutions**?
Based on experience and fitting some criteria for solution they have for a problem having general features identified.

9) Is problem **plausibly solvable**? And is it worth pursuing given the difficulties, constraints, and uncertainties?

List of problem-solving decisions (from Price et al.) pg 3

C. Plan process for solving. These decisions establish the specifics needed to solve the problem.

10) **What approximations or simplifications to make?** How to simplify the problem to make it easier to solve? How to justify?

11) How to **decompose** the problem into more tractable sub-problems? (Independently solvable pieces with own sub-goals.)

12) Which are areas of **most difficulty and/or uncertainty** in plan of solving?
Including, what are acceptable levels of uncertainty with which to proceed at various stages?

13) What **information is needed** to solve the problem?
What will be sufficient to test and distinguish between potential solutions?

14) **Priorities.** What to prioritize among competing considerations? What to do first and how to obtain needed resources? Considerations could include: What's most important? Most difficult? Addressing uncertainties? Easiest? Constraints (time, materials, etc.)? Cost? Optimization and trade-offs? Availability of resources? (facilities/materials, funding sources, personnel)

15) Specific **plan** for getting information?
a. What are the general requirements and what approach to pursue? (often decided early in process as part of framing)
b. How to obtain needed information? (This could involve many discipline and problem-specific investigation possibilities such as: designing and conducting experiments, making observations, talking to experts, consulting the literature, doing calculations, building models, or using simulations.)
c. What are **achievable milestones**, and what are metrics for evaluating progress?
d. What **possible alternative outcomes** and paths may arise during p. s. process, and what would be paths to follow for the different outcomes?

List of problem-solving decisions (from Price et al.) pg 4

<u>D. Interpret information and choose solution(s).</u> Includes deciding how to analyze, organize, and draw conclusions from info.

16) **Calculations and data analysis**. Decide what calculations and data analysis are needed? Then decide to carry those out.

17) **Represent and organize information**. Best way to represent and organize available information to provide clarity and insights? (usually specialized & technical representations related to key features)

18) **How believable** is information? Is information valid, reliable, and believable (includes recognizing potential biases)?

19) Compare to predictions. As new information comes in, particularly from experiments or calculations, how does it **compare with expected results** (of predictive framework)?

20) Any significant **anomalies?** If a result is different than expected, how should you follow up? Could involve deciding:
a. Does potential anomaly fit within acceptable range of predictive framework(s) (given limitations of framework and assumptions)?
b. Is potential anomaly an unusual statistical variation, or relevant data? Is it within acceptable levels of uncertainty?

21) What are **appropriate conclusions** based on the data? (involves making conclusions and deciding if they're justified)

22) What is the **best solution**? Involves evaluating and refining candidate solutions throughout problem-solving process. Not always narrowed down to a single solution. May include deciding:
a. Which of multiple candidate solutions are consistent with all available information and which can be rejected?
b. What refinements need to be made to candidate solutions?

List of problem-solving decisions (from Price et al.) pg 5

E. Reflect. Reflection decisions occur throughout the process and include deciding whether assumptions are justified, whether additional information is needed, how well the solution approach is working, and if potential and final solutions are adequate.

23) **Assumptions + simplifications appropriate?**
Are previous decisions about simplifications and predictive frameworks still appropriate?
a. Do the assumptions and simplifications made look appropriate considering new information? (reflect on assumptions)
b. Does predictive framework need to be modified? (Reflect on predictive framework.)

24) Is **additional** knowledge/**information needed**? (Based on ongoing review of one's state of knowledge.) Could involve:
a. Is solver's relevant knowledge sufficient?
b. Is more information needed and if so, what?
c. Does some information need to be checked? (e.g. need to repeat experiment or check a different source?)

25) How well **is the problem-solving approach working**, and does it need to be modified, including do the goals need to be modified? (Reflect on strategy by evaluating progress toward solution)

26) How adequate is the chosen solution? (Reflect on solution) Includes ongoing reflection on potential solutions, as well as final reflection after selecting preferred solution. Can include:
a. Decide by exploring **possible failure modes and limitations** – "try to break" solution.
b. Does it "make sense" and pass discipline-specific tests for solutions of this type of problem?
c. Does it completely **meet the goals/criteria**?

List of problem-solving decisions (from Price et al.) pg 6

F. Implications and communication

These are decisions about the broader implications of the work, and how to communicate results most effectively.

27) **Broader implications?**

What are the broader implications of the results, including over what range of contexts does the solution apply?
What outstanding problems in field might it solve?
What novel predictions can it enable?
How and why might this be seen as interesting to a broader community?

28) Audience. What is the **audience for communication** of work, and what are their important characteristics?

29) **Presentation.** What is the best way to present the work to have it understood, and its correctness and importance be appreciated? How to make a compelling story of the work?

Conclusion

Research on the nature of expertise and how it is acquired **+** research on decisions involved in sci & eng problem-solving = how to learn & teach sci & eng (optics) more quickly and effectively.

Students do deliberate practice making the specific problem-solving decisions used by scientists and engineers.

Refs. (copy of slides available by request)

Price, Kim, Burkholder, Fritz, and Wieman, A Detailed Characterization of the Expert Problem-Solving Process in Science and Engineering: Guidance for Teaching and Assessment, CBE- Life Sciences Ed. Aug. 2021.

Holmes, N.G., Keep, B., & Wieman, C.E. (2020). Developing scientific decision making by structuring and supporting student agency. Phys. Rev. Phys. Educ, 16(1). https://doi.org/10.1103/PhysRevPhysEducRes.16.010109

Jones, D.J., Madison, K.W., Wieman, C. (2015). Transforming a fourth-year modern optics course using a deliberate practice framework. Phys. Rev. ST Phys. Educ,11(2), 020108.

Wieman, C. (2019). Expertise in university teaching & the implications for teaching effectiveness, evaluation & training. Dædalus, MIT Press, 148(4), 47-78. https://doi.org/10.1162/daed_a_01760

<u>Non-decision themes many experts noted as important to success in their field.</u>

- Ongoing skill and knowledge development

  a. Regularly review the literature, which does involve making decisions as to which is important.

  b. Learn relevant new knowledge (ideas and technology, from literature, conferences, colleagues, etc.)

  c. Acquiring experience and associated intuition to improve problem-solving.

- Interpersonal, teamwork.

Includes navigating collaborations, team management, patient interactions, communication skills, etc., particularly as how these apply in the context of the various types of problem-solving processes.

- Efficiency-- Time management including learning to complete certain common tasks efficiently and accurately.

- Attitude--Perseverance, dealing with stress, confidence in decisions, etc.

1. Which decisions are most important to learn?

Carl answer--

E. Reflection decisions. Reflection decisions occur throughout and include deciding if assumptions are justified, whether additional information is needed, how well the solution approach is working, and if potential and final solutions are adequate.

Why most important?

These are the error correction. Improve all the others.

"I see a mistake I was making (possibly because of new information).
I see a better approach to use, or a way to simplify the problem.
I can see why that conclusion might be wrong. "

In exploring new areas of science or engin, you will never be perfect--
Need proper balance of courage in decisions to try *but* willingness and ability to change.

2. Which decisions are most difficult to learn?

My opinion– reflection decisions also the most difficult.
Requires recognizing what you don’t know, conclusions you decided on that were wrong.
Requires lots of experience to use for comparison. Also, recognition of your fallibility.

Learn by regularly and explicitly practicing.

- Dedicated time each day, each week.
- Interaction/collaboration with others helps. Brings in new perspectives and possible approaches.

How can a student learn on their own to make the other decisions?

Recognize as things to be improved upon through practice.
Practice wherever possible, reflect on outcome.

Explicitly think about decisions made in your research. Reflect on what they were and how they turned out. How could have been better?
Schedule time to go through list. (Every two weeks? Every 6 months?)

When learning material in courses, think
"How and where would I use this in problem solving decisions?"
"Where would it be useful/apply, where would it not apply, and what is criteria for deciding?"