

HOW TO BECOME A SUCCESSFUL PHYSICIST



An apprentice (right) glues parts of a double bass under the watchful eye of a teacher (left) at the Swiss School of Violin Making in Brienz on 5 June 1969. (Image from Photopress Archiv/Keystone/Bridgeman Images.)



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All scientists and engineers solve research problems by calling on relevant knowledge to make a series of common, critical decisions.

Physics graduate students may find it confusing and intimidating to figure out how to become a successful physicist. The good ones they see apparently know an enormous amount of stuff and come up with solutions before the student even understands the problem. Advisers can find it similarly difficult to figure out how to best guide their graduate students to become good physicists and may wonder, “What do I need to teach them, and how should I do that?” Although students have demonstrated success in physics courses, they often struggle when given a research problem. What is the source of their difficulties, and how can one best help them improve?

This article is intended to help students, advisers, and teachers understand what is needed to become a skilled physicist and what is the most efficient and effective way to reach that goal. The solutions to those problems can benefit all students and advisers in science. They are based on cognitive-science results of studies on the general acquisition of expertise and my current research group’s extensive work on expertise in science and how it is learned. That interest grew out of my own struggles with advising PhD students in my atomic-physics group.

The primary characteristic of a successful physicist is being a good problem solver. Real physics problems are those pursued in research. Solving such problems involves a far more complex set of mental processes than are needed for even the most difficult textbook problem. Unlike real problems, textbook problems provide all the information needed and have a single well-defined path to a solution.

“Solving” is defined as everything a physicist does in their research, from selecting a suitable problem, to carrying out the lengthy process of obtaining results, to finally presenting those results and their implications to the community. That definition, however, is too broad to be useful. Becoming a good physics problem solver is typically learned through trial and error, but that method of learning is quite inefficient for such a complex task. There are just too many errors that can be

made during the problem-solving involved in physics research.

Cognitive-science research shows that people improve learning efficiency by practicing the set of specific cognitive tasks required for their area of expertise.¹ Although that approach is based on learning research, it is uncoincidentally quite similar to the ideal master-apprentice method for traditionally teaching a craft (see figure 1). The master decomposes the craft into a set of specific subskills, gives the apprentice a set of increasingly challenging tasks to practice each one, and intersperses feedback

on how to improve. The apprentice practices each subskill to a reasonable mastery and then uses them together to produce the desired product. In the case of physics problem-solving, my research team and I have identified the necessary subskills as a set of problem-solving decisions.

Much of the past research on scientific problem-solving has looked at expert-novice differences, usually in how they organized their knowledge to solve puzzles and simple textbook problems. That work looks at only a small fraction of the true process. There are many anecdotal descriptions of problem-solving methods in math and science.² Nearly every introductory physics textbook has its own problem-solving method, but little evidence has shown whether those methods are correct, complete, or effective for learning to solve authentic problems.

Decisions decisions

My research group interviewed some 50 skilled scientists and engineers (“experts”), including physicists, on how they solved authentic problems in their discipline. We analyzed the interviews in terms of the decisions made during the solving process. Decisions were defined as instances when an expert selected between competing alternatives before taking some action. To my surprise, we found that the same set of 29 decisions

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occurred over and over (see the box on page 50). Nearly all of them showed up in every interview, and they essentially defined the problem-solving process.³

The decisions were always made with limited information. To reach their decisions, the experts answered such questions as the following: “What information is needed to solve this problem?” “What assumptions and simplifications are appropriate?” “What is the most difficult or uncertain aspect of my solution plan?” If complete information was available, then the steps to follow were just procedures that required little thought and so were seen as relatively unimportant. With limited information, the decisions can never be certain; rather, they are educated guesses or judgments, albeit highly informed ones. The problem-solving skill was in the quality of the judgments. The experts often noted that research breakthroughs came from recognizing the significance of some additional information that other researchers had overlooked.

Whereas the decisions the experts needed to make were common to all disciplines, how they came to each decision was not. When making any of those decisions, the experts called on specific disciplinary knowledge and experience. Most of the relevant knowledge was common in a discipline and different across disciplines. Experts who solved interdisciplinary problems still called on an established body of knowledge in essentially the same way, although it spanned more than one academic discipline.

Knowing what information to apply and how to apply it was essential to making every decision well. Meaningful learning of the knowledge in a discipline, therefore, must include mastering how to make good decisions with that knowledge. That means that knowledge-free problem-solving is a meaningless concept.

We found that all the experts organized their disciplinary knowledge in a way that was optimized for making decisions. We describe that knowledge-organization structure as a “predictive framework.” Such frameworks are mental models that embody all the key features relevant to the problem and their relationships via an underlying mechanism. The frameworks are used to predict the behavior of the system being modeled when any of the variables are changed. As our experts explained to us, when they made decisions, they continually ran thought experiments using the frameworks.

An early and repeated decision in the problem-solving process was to determine which predictive framework was most suitable to the problem (decisions 5 and 23; see the box on page 50 for this and the other decisions mentioned throughout this article). The complexity of the model and mechanism was selected to match the needs of the problem.

Consider, for example, a physicist

working on a research problem involving laser cooling. A predictive framework they might initially adopt would include the momentum of the light, the mass and momentum of atoms, the conversion between the two forms of momentum because of light scattering, and the dependence of the scattering rate on the frequency of the light and the Doppler shift. As they carried out experiments and collected data, they might decide that the data were reliable (decision 18) but inconsistent with the predictions of the framework (decision 19). That may lead them to modify their predictive framework by, for example, adding the AC Stark effect and its spatial variation across the laser beam.

The set of decisions

The list of decisions is organized into somewhat arbitrary categories represented in figure 2 and in more detail in the box on page 50. It roughly corresponds to the order in which they appear during the solving process. No one, however, follows such a simple, time-ordered process. Based on new information and reflection, experts frequently jump to a different step in the process and revise earlier decisions, conclusions, and plans.

Few physicists will be surprised to see the decisions on the list. What is more notable is that a finite list of 29 seems sufficient to characterize the entire problem-solving process across all sciences and engineering. They provide a much more specific guide as to what is important to master to become a successful physicist or, for that matter, any flavor of scientist or engineer.

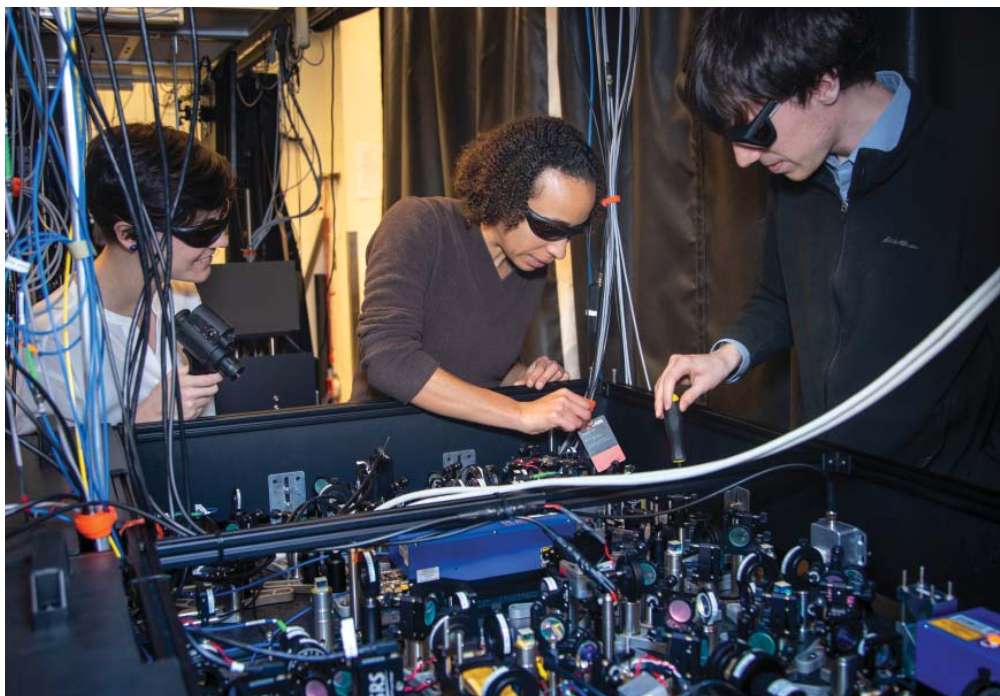


FIGURE 1. MONIKA SCHLEIER-SMITH (center) works in her cold-atom lab with students Emily Davis (left) and Eric Cooper (right). Experts in various building and craft occupations have taught the necessary trade skills to apprentices by giving them an increasingly complicated set of tasks to complete followed by regular feedback. Such an approach is also one of the best ways for students to learn to be successful physicists, according to cognitive-psychology research. (Courtesy of Dawn Harmer.)

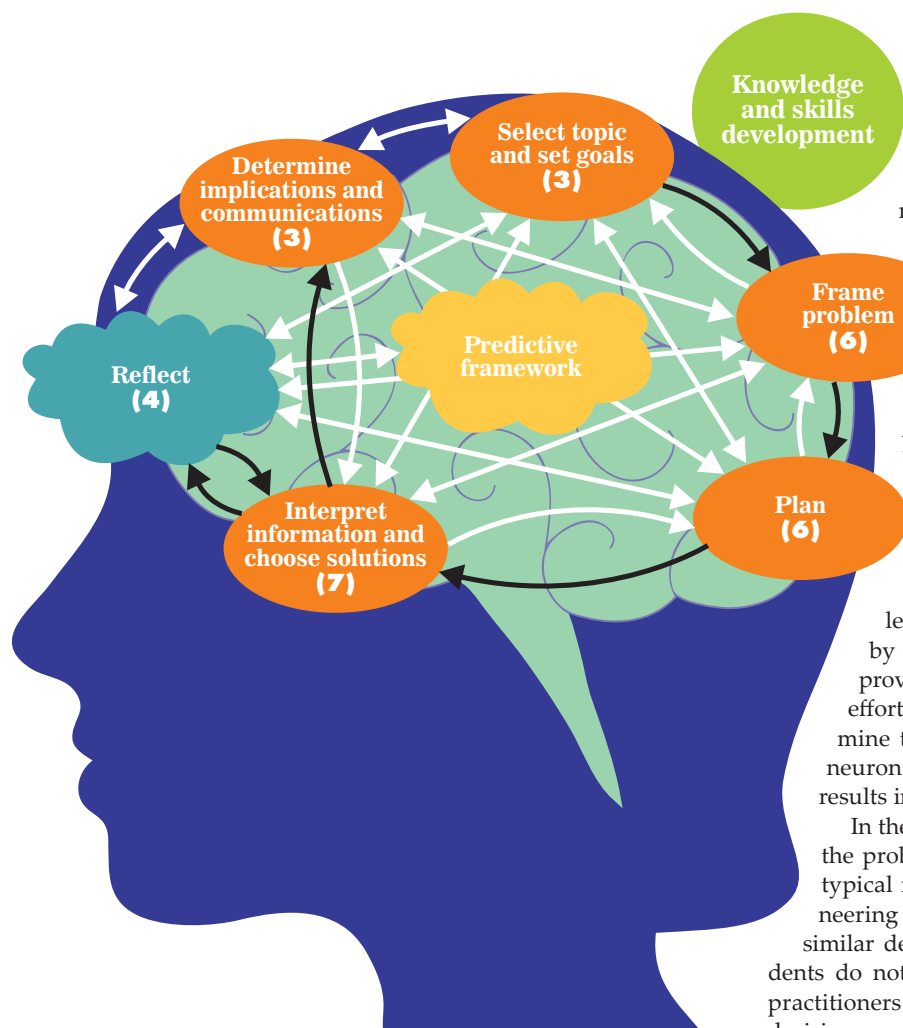


FIGURE 2. SOLVING PHYSICS PROBLEMS. The black arrows represent a hypothetical but unrealistic order of decision making that begins with selecting a research direction and identifying goals for the project. The white arrows represent more realistic iteration paths. Decisions are grouped into categories for presentation purposes; the parentheticals indicate the number of decisions that need to be made in each category. Although both knowledge and skills development are not decisions per se, based on interviews with physics experts about how they solve problems, the two are commonly mentioned themes. (Adapted from ref. 3.)

In addition to the decisions, which were our focus, the experts volunteered common areas of general skills they saw as important elements of expertise in their fields.

Stay up to date in the field by learning relevant new knowledge, ideas, and technology from literature, conferences, and colleagues.

Develop intuition and experience to improve problem-solving.

Enhance interpersonal and teamwork skills—for example, how to navigate collaborations, manage a team, and strengthen communication—particularly as they apply in the context of the different problem-solving processes.

Improve one's efficiency by practicing time management, including learning to complete certain common tasks efficiently and accurately.

Cultivate an attitude, or motivation, which includes persevering in the task despite obstacles, dealing with stress, and having confidence in decisions.

Becoming a highly skilled physicist requires developing those common skills and learning to make decisions well.

The cognitive psychologist K. Anders Ericsson and collaborators have demonstrated the process by which people become experts in many disciplines,¹ and my group has applied those ideas to teaching physics.^{4,5} The level of mastery is primarily determined by the amount of what Ericsson has labeled “deliberate practice.” It entails identifying the specific subskills involved for expertise in the discipline, usually by a good teacher or coach. The learner intensively practices those specific subskills individually and then in combination. That practice is interleaved with frequent targeted feedback, typically by a teacher or coach, and reflection on how to improve. The focus, intensity, and extent of the mental effort is critically important. Those factors likely determine the extent to which the desired changes in the neuronal connections in the brain are achieved, which results in improved capabilities.

In the case of physics, the subskills to be mastered are the problem-solving decisions. We have found that for typical realistic problems in any given science or engineering discipline, skilled practitioners tend to make similar decisions with similar justifications, whereas students do not.⁶ The mismatch between students and skilled practitioners is understandable if one notes how few of the decisions are required, and hence practiced, in solving the typical textbook or exam problems encountered in courses (see figure 3). That also explains the puzzle that originally got me interested in physics-education research some decades ago. Namely, why is there so little correlation between students’ performance in their physics courses and their ability to do physics research?

Deliberate practice in the research setting

Research always involves problem-solving, and decisions arise naturally. When conducting research, the learner should explicitly focus on the decisions from the list, think about which ones are encountered during the research process, and practice making those decisions. Then they should reflect on how and why they made each decision they did and how subsequent results indicate how each one could have been improved. They should also seek out the adviser or more experienced members of the research group to discuss their process for making those decisions and get feedback on it.

The adviser should also encourage the student to carry out that type of practice by identifying when a specific decision needs to be made and challenging them to make it. The adviser may then discuss the student’s choices and justifications and point out what aspects were good and what could be improved. That process is a much more effective educational experience than simply telling the student what the decision should be.⁷ But speaking from extensive personal experience, I know that human nature strongly inclines a person in an advisory position to instead make the decision and tell the student. It may be more efficient in the short term for advancing the research,

THE NATURE OF PHYSICS PROBLEM-SOLVING

Below are 29 sets of questions that students and physicists need to ask themselves during the research process. The answers at each step allow them to make the 29 decisions needed to solve a physics problem. (Adapted from reference 3.)

A. SELECTION AND PLANNING

1. What is important in the field? Where is the field heading? Are there advances in the field that open new possibilities?

2. Are there opportunities that fit the physicist's expertise? Are there gaps in the field that need solving or opportunities to challenge the status quo and question assumptions in the field? Given experts' capabilities, are there opportunities particularly accessible to them?

3. What are the goals, design criteria, or requirements of the problem solution? What is the scope of the problem? What will be the criteria on which the solution is evaluated?

4. What are the important underlying features or concepts that apply? Which available information is relevant to solving the problem and why? To better identify the important information, create a suitable representation of core ideas.

5. Which predictive frameworks should be used? Decide on the appropriate level of mechanism and structure that the framework needs to be most useful for the problem at hand.

6. How can the problem be narrowed? Formulate specific questions and hypotheses to make the problem more tractable.

7. What are related problems or work that have been seen before? What aspects of their problem-solving process and solutions might be useful?

8. What are some potential solutions? (This decision is based on experience and the results of decisions 3 and 4.)

9. Is the problem plausibly solvable? Is the solution worth pursuing given the difficulties, constraints, risks, and uncertainties?

Decisions 10–15 establish the specifics needed to solve the problem.

10. What approximations or simplifications are appropriate?

11. How can the research problem be decomposed into subproblems? Subproblems are independently solvable pieces with their own subgoals.

12. Which areas of a problem are particularly difficult or uncertain in the solving process? What are acceptable levels of uncertainty with which to proceed at various stages?

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

14. Which among the many competing considerations should be prioritized? Considerations could include the following: What are the most important or most difficult? What are the time, materials, and cost constraints?

15. How can necessary information be obtained? Options include designing and conducting experiments, making observations, talking to experts, consulting the literature, performing calculations, building models, and using simulations. Plans also involve setting milestones and metrics for evaluating progress and considering possible alternative outcomes and paths that may arise during the problem-solving process.

B. ANALYSIS AND CONCLUSIONS

16. Which calculations and data analysis should be done? How should they be carried out?

17. What is the best way to represent and organize available information to provide clarity and insights?

18. Is information valid, reliable, and believable? Is the interpretation unbiased?

19. How does information compare with predictions? As new information is collected, how does it compare with expected results based on the predictive framework?

20. If a result is different from expected, how should one follow up? Does a potential anomaly fit within the acceptable range of predictive frameworks, given their limitations and underlying assumptions and approximations?

21. What are appropriate, justifiable conclusions based on the data?

22. What is the best solution from the candidate solutions? To narrow down the list, decide which of those solutions are consistent with all available information, and which can be rejected. Determine what refinements need to be made to the candidate solutions. For this decision, which should be made repeatedly throughout the problem-solving process, the candidate list need not be narrowed down to a single solution.

23. Are previous decisions about simplifications and predictive frameworks still appropriate in light of new information? Does the chosen predictive framework need to be modified?

24. Is the physicist's relevant knowledge and the current information they have sufficient? Is more information needed, and if so, what is it? Does some information need to be verified?

25. How well is the problem-solving approach working? Does it need to be modified? A physicist should reflect on their strategy by evaluating progress toward the solution and possibly revising their goals.

26. How good is the chosen solution? After selecting one from the candidate solutions and reflecting on it, does it make sense and pass discipline-specific tests for solutions to the problem? How might it fail?

Decisions 27–29 are about the significance of the work and how to communicate the results.

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

28. Who is the audience for the work? What are the audience's important characteristics?

29. What is the best way to present the work to have it understood and to have its correctness and importance appreciated? How can a compelling story be made of the work?

but that approach is far less effective educationally and for producing skilled researchers in the long run.

An adviser typically trains new research students by giving them small projects to work on, usually a piece of the group's larger research agenda. The decisions list provides guidance on what sorts of projects are likely to be the most educationally beneficial. Ericsson's work has shown the importance of having practice tasks that are just above the student's ability so they can finish those tasks only with intense effort. To be effective, therefore, practice projects should have neither too few nor too simple decisions for the student to make, nor should the projects have decisions that are of such complexity that the student finds them impossible.

The downside of the research environment is that the nature and pace of the work can make it difficult for the student to practice the full set of decisions, particularly the repeated practice and improvement at making a particular decision. Although decisions 16–26 will come up frequently and repeatedly during research, many of the earlier ones appear less often, and some need to be made without consulting the student. For example, many of the problem-definition and planning decisions occur when the adviser develops proposals to fund the work and hire students and postdocs.

To address that weakness, the student (or postdoc) and adviser should seek out opportunities to review those previous decisions and how they were made. Whenever possible, the adviser should challenge the student to think of alternatives and then discuss why those alternatives would usually not be as good. Of course, if the student comes up with an improvement, so much the better. Additionally, the student could apply for graduate fellowships, such as from NSF's Graduate Research Fellowship Program, that require them to write a research proposal, which should include making and justifying those first decisions.

Deliberate learning in the classroom

In the typical physics course, students practice and learn to make very few problem-solving decisions. Seldom are any encountered in a lecture, and only two or three of the 29 decisions are called for in doing typical homework or non-project-based laboratory courses. In a lecture, the outcomes of the decisions are presented, usually without the student ever recognizing that the decision needed to be made.

With good teaching, however, most of the decisions can be made an explicit part of course activities. For example, students in introductory physics,⁴ advanced undergraduate,⁵ and advanced graduate⁸ courses can work through authentic problems in class. Those problems are simpler than most research problems, but they involve many more decisions than standard textbook problems. In solving authentic problems in class, students make and justify many of the decisions explicitly in consultation with their peers and get regular feedback and guidance from the instructor (see figure 3). Similarly, solving homework or exam problems can involve explicitly justifying various decision choices. Of course, including all 29 decisions is impractical, but the instructor can select those they find particularly important in the context.

At their best, courses do have an advantage over the research setting: Thoughtful instructors have the freedom to assign problems that give students practice in making various

decisions, including the repeated practice of making particularly important decisions. My personal preference in undergraduate courses is to make every problem solution include identifying important features (decision 4), determining what information is needed (decision 13), planning the solution process (decision 15), and evaluating potential solutions (decision 26). Problems can be varied to probe other decisions and call on a variety of physics knowledge. Courses have the disadvantage of the decisions always being more artificial than in the research setting, but that issue can be minimized with careful thought, usually by ignoring the textbook!

For students to make decisions, they must learn a substantial amount of physics knowledge. The best way to learn that knowledge is to witness its importance when it's used to make the problem-solving decisions. The traditional practice is for the instructor to teach physics knowledge to the students and then later give them problems so that they can practice using that knowledge. A much more effective approach is to give them a meaningful problem to struggle with first and then provide them with the knowledge they need to figure it out.⁹ When information is presented as useful for solving certain kinds of problems, the brain stores that information so that it is readily accessed and applied when needed to solve novel related problems.

Whereas most of the 29 decisions are applicable for problem-solving at every level of a physics education, a few are only appropriate for advanced graduate students and postdocs. Deciding on the state of the field (decision 1), the broader implications of the research results (decision 27), the audience (decision 28), and the most effective way to present research results (decision 29) all require extensive exposure to current research and attitudes in the field. Most of the other decisions are suitable for every level of student to practice, but the physics topics and knowledge necessary to make them needs to be appropriate to the course and level of the student. That specific physics knowledge is usually set by the problem context.

A student in a graduate class can practice making such decisions even when the decisions are not part of the curriculum. Every new physics concept and calculational technique the graduate student sees was originally the solution to an authentic physics problem. They can ask themselves what decisions called for that solution? How was the problem framed (decisions 4 and 5)? What approximations were used (decision 10)? Where would the solution method apply and not apply (decisions 25 and 26)? Discussing such questions with peers and usually the instructor will benefit their learning.

In deciding how to use the instructional time, teachers should remember that the body of physics knowledge learned in school will always be a small fraction of the knowledge needed in a physics career. The skill of making good problem-solving decisions, however, will always remain essential.

Most important and difficult

To be a successful physicist requires mastering how to make all 29 decisions, but the reflection decisions (decisions 23–26) are arguably the most difficult to learn. They require students to examine their own thinking, which is challenging for three reasons. First, having that kind of perspective on one's own thinking is just difficult. Talking through the ideas with others can help. Second, a good physicist tends to be consumed with

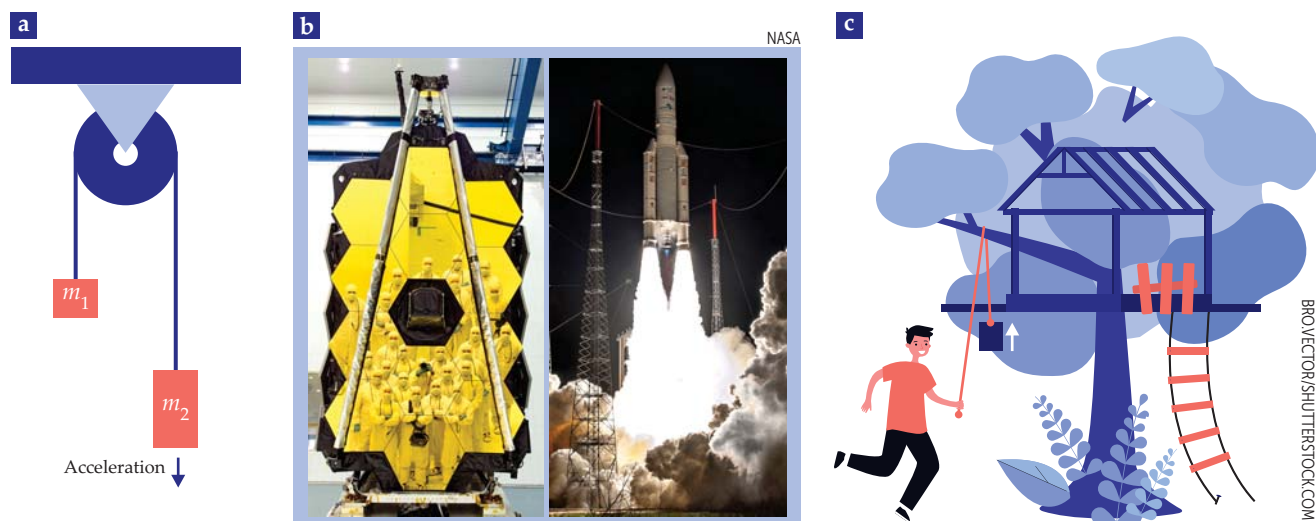


FIGURE 3. TEXTBOOK PHYSICS PROBLEMS—including this one (a) to calculate the acceleration of m_2 , assuming a massless pulley and rope—don't require much decision making and often lack any context that motivates a student to solve them. (b) Real-world physics problems, such as determining the requirements necessary for a rocket to launch the *James Webb Space Telescope*, are societally relevant. Yet they can be too difficult because of the many complex decisions that must be made. (c) An example of an authentic but skill-appropriate physics problem calls for a student to calculate the weight that can be pulled up to a treehouse using a rope over a branch and to decide whether it's worth the time and money to buy a pulley for the job. Authentic problems are designed to include many decisions and be more relevant but still need to be approachable for those with limited knowledge and decision-making skills.

the immediate challenge of the work—for example, how to improve the vacuum, how to reduce the jitter in the detector trigger, or how to create faster code for evaluating that complex integral. Shifting mental gears to put those thoughts aside and think more broadly is hard. I find it helpful to schedule blocks of time in my week to think about those reflective decisions.

The third and probably most serious difficulty in making good reflective decisions is confirmation bias. It's a well-established psychological tendency for humans, once they have decided on an answer that they think is correct, to be strongly prepossessed toward maintaining that belief. Confirmation bias causes them to suppress thinking about alternatives and interpret all new evidence in a way that confirms their belief. I suspect most of the serious errors in physics have been the result of such bias. Students (and scientists in general) should practice fighting against it when making reflective decisions.

Despite the difficulty in learning them, the reflection decisions are also the most important. They are the error-correction decisions of the problem-solving process and allow students to catch when they have made a poor decision and fix it. Frequently, corrections happen when new information becomes available or the relevance of overlooked information is recognized, such as why an assumption that was made does not apply. An adviser should have their students explicitly practice decisions 25 and 26, test their solutions, and try to come up with the ways their decisions could fail, including alternative conclusions that are not the findings that they were hoping for. Thinking of such failure modes is something that even many experienced physicists are not very good at, but our research has shown that it can be readily learned with practice.

The set of decisions for how to become a good physics problem solver also provides a good framework for measuring a person's strengths and weaknesses in solving authentic physics

problems. I am sure many advisers are like I was: Although I knew a student was failing to solve the research problems I gave them to work on, I didn't know why or how I could help them improve.

My group has now developed tests in several areas of science and engineering based on those problem-solving decisions. We give the student a realistic scenario and then ask them to make and justify a representative subset of the decisions. We then compare their responses with those of experts in the field. Typically, students are quite poor at making those decisions despite having successfully completed courses that covered the relevant knowledge. But the more experience they have had in doing authentic problem-solving, the more expert-like they tend to be in their decisions. If properly taught, the skills are quite learnable.

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