What we talk about when we talk about physics problem solving

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Introduction

I am a second-year cognitive science major, and as a student who has completed my physical science distributive requirements, I will likely never again come across Gauss’s law. So why do I feel that the time and effort I devoted to solving Gauss’s law problems was worth it? Partly, I inherently enjoy the learning process and the new perspective on the physical world I have acquired by understanding electromagnetism. But I was also inspired by the ways in which physics problems train the mind in effective problem-solving strategies. (Of course I was—I am a cognitive science major!) Two themes emerged as I reflected on this realization. First, physics problems serve as useful toy models for more complex problems outside of physics, training us in broadly transferable problem-solving skills. Second, the physics problem-solving process invites us to reflect on our unique cognitive and affective processes. These themes are interconnected and complimentary. An improved metacognitive understanding of our minds facilitates solving progressively more complex problems, and the act of solving increasingly difficult problems provides further insight into our minds. In what follows, Professor Zosia Krusberg and I consider nine general lessons offered by the physics problem-solving process.

Nine Lessons

1. Physics problems often initially strike us as impossible to solve, leading to a great deal of stress. We struggle to make sense of the wording of the problem, to visualize the system, to discern relevant and irrelevant information, and to identify applicable physical principles.
However, after solving countless physics problems that initially appeared overwhelming, we begin to develop a sense of confidence in our problem-solving abilities, both within and beyond the physics classroom. Indeed, when we come across real-world problems that initially feel overwhelming, **physics problem solving can teach us not to let first impressions of a problem daunt us.** After all, in the context of problem solving, perhaps one of the least useful states is being overwhelmed: it turns off our sense of focus and curiosity, disabling two of our main skills for solving problems in the world.

2. Once we have convinced ourselves that a problem is solvable, we need to decide how to begin our solution. In physics, there are a number of effective steps to get the problem-solving process started, including drawing a simple visual representation of the system, labeling relevant physical variables, and identifying the objective of the problem. These methods work because **successful problem solving begins with a clear picture of the problem.** Such strategies can be effective outside the physics classroom as well. For instance, we often describe complex, real-world problems quite broadly, like “the problem of climate change” or “the problem of Covid-19,” but in order to begin to address such immense problems, it is critical that we understand what specific aspects of these problems that we are trying to confront. In that way, we can focus our awareness and attention and begin to take action.

3. Physics problems also teach us that **the problem-solving process can be simplified by the productive use of assumptions.** In physics, acknowledging assumptions included either implicitly or explicitly in the problem statement, as well as assumptions invoked to simplify and constrain the problem, is an essential problem-solving strategy. I developed the habit of stating my assumptions explicitly early in the problem-solving process, noting whether I could safely assume that dissipative forces could be neglected, whether there were no other charges close enough to affect the system, and so on, which made the process of determining what physical principles to invoke

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1 A wonderful example of what can be accomplished when someone is not overwhelmed by a problem is the story of the American mathematician George Dantzig. As a graduate student, Dantzig once arrived late to a statistics lecture, and assumed that the two problems written on the board were homework problems. When he handed in solutions to the problems a few days later, his professor informed him that he had just solved two previously unsolved statistics problems.
significantly easier. Our brains regularly make conscious and uncon-
scious assumptions in order to simplify our experience in the world. 
However, when faced with the task of solving real-world problems, it 
seems critical that we should be aware of and curious about our as-
sumptions, to be willing to challenge them, and to be open to letting 
them go.

4. While physics problem solving makes extensive use of assumptions and 
simplifications, the use of orders of approximation allows us to iden-
tify the most important factors contributing to a solution and provides 
us with a tool to determine whether we may have oversimplified the 
problem. For instance, if we want to determine the trajectory of a 
basketball launched toward a hoop, to find a first-order solution we 
may assume that the ball is a point particle in a vacuum. Then, to 
determine second-order corrections we may account for effects such as 
air resistance and the rotation of the ball. Then, and only if we are 
concerned with obtaining an answer to an extreme degree of precision, 
we may account for relativistic effects. So, the use of orders of 
approximation can simplify complex problems dramatically 
by offering a strategy to identify the most important factors 
contributing to a solution. Since it provides us with a way to cal-
culate the relative contributions of various terms to a solution, this 
technique also allows us to determine whether we have oversimplified 
the problem—if we initially made an assumption that neglected a fac-
tor whose contribution to the final answer is an order of magnitude 
larger than the factors we chose to take into consideration, something 
has clearly gone awry!

5. Once we have made sense of a problem, invoked assumptions, and 
verified that we have accounted for the most important factors con-
tributing to our solution, we need to identify the fundamental phys-
ical principles at play. One of the difficulties we might encounter in 
this process is that different physics problems may appear quite sim-
ilar based on their superficial features, yet may be solved using very 
different physics—and vice versa. For instance, in one version of a 
collision problem, mechanical energy may be conserved. In another, 
non-conservative forces may need to be considered. And in yet an-
other, relativistic effects may be non-negligible. In each case, a dif-
ferent physical law would be invoked to solve the problem. Clearly, 
a critical aspect of the problem-solving process is to differ-
entiate between fundamental principles and surface features of problems \[3, 4, 5\]. The skill of identifying fundamental principles when we are stuck on some surface features of a problem seems equally critical in the world outside of physics problem solving. Patients with the sniffles may all appear similar at first glance, however, in order to determine the proper treatment, it is critical that we establish whether they are suffering from allergies, a bacterial infection, or the flu.

6. **To move forward in the problem-solving process, we make use of heuristics—cognitive tools and techniques built up in the course of our experience with problem solving** \[6, 7\]. In physics, useful heuristics include such strategies as drawing new diagrams, comparing the problem to a similar one that we have solved in the past, and explaining the problem out loud (a technique I found particularly helpful in my own problem-solving process). Other heuristics prompt the unconscious mind to generate insight into the problem, such as brainstorming related concepts, taking a break from the problem, even sleeping. From both a cognitive science as well as a practical perspective, it is interesting that in the context of problem solving, relying entirely on the conscious mind through single-minded focus is sometimes not sufficient to arrive at a solution, and insights emerging from our unconscious mind can play an important role in the problem-solving process \[8, 9\]. The critical point is that our problem-solving toolbox consists of both domain-specific and domain-general heuristics that have proven to be helpful for us in our unique experience as problem solvers.

7. Although our focus thus far has been on our inner, individual problem-solving experience, there is no doubt that the diverse perspectives of other individuals enrich the problem-solving process \[10, 11, 12, 13, 14\]. The study groups that emerged in my physics classes frequently highlighted the limits of my understanding and the value of other people’s cognitive processes in solving the physics problems we had been assigned. When the groups functioned well, there was something magical about how we helped one another—the part of the problem I was stuck on was the part someone else understood and vice versa. These groups also exposed me to some of the inherent challenges of collaboration, such as keeping an open mind to other perspectives, making space for all individuals to be heard, and handling disagreements respectfully, all of which exist at grander scales.
in the world beyond the physics classroom. Indeed, the sciences are highly collaborative fields of study and practice. In research groups around the world, individuals come together every day to present lines of reasoning, listen critically, solicit and provide feedback, and use that feedback to deepen understanding. When we encounter obstacles, we turn to one another, since modern scientific problems demand combinations of skills and knowledge that no single individual possesses.

8. Once we have completed a problem, our solutions offer an excellent opportunity for reflection and introspection on our experience of the problem-solving process [15][16]. At the conclusion of a problem, we can look back on the path from problem statement to solution, making note of successful and unsuccessful strategies. We can also reflect on moments where we were stuck and experienced a sudden moment of insight—evidence of the work of the unconscious mind—making note of what preceded the insight. Was it a particular way we played with the problem? Was it how someone else described it? Was it a process in the unconscious mind that just needed time to work? This is also a great time to determine whether our solutions make intuitive and mathematical sense, which effectively constitutes a check of all the procedural steps leading to the solution—a nonsensical answer would be a red flag that, somewhere along the way, we made an error. In addition to performing these cognitive checks, we can also reflect on our affect during the problem-solving process [17]. We might note the feelings that emerged when we first encountered the problem, when problem-solving decisions brought us to a dead end, and when we had moments of insight and understanding. This can be a critical process to prepare ourselves for future problem-solving endeavors—after all, it is easier to accept feelings of standstill and frustration when we have a collection of experiences in which such feelings eventually lead to feelings of joy and satisfaction, which in turn can result in feelings of curiosity and excitement when encountering new problems.

9. Along the same lines, mistakes offer insight into our cognitive patterns and invite us to construct new and more effective ones [18]. By deliberately reflecting on feedback on graded assignments, we can assess whether we have a tendency to make certain types of errors: misinterpreting problem statements, excluding essential details on diagrams, carrying out incorrect mathematical operations, and so on. When we discover such cognitive patterns, we can
make internal or external reminders to warn us when we are about to repeat them, making us more effective problem solvers. Even mistakes that, at first glance, appear completely nonsensical sometimes can offer insight into how our minds are trying to integrate new concepts and problem-solving strategies [19]. Unsurprisingly, simply stating, “That was silly, I’ll never do that again”—as many of us do when confronted with evidence of our errors—is generally completely unhelpful and all but ensures that we will repeat them.

If, on the other hand, we take the errors seriously, we are offered a wonderful opportunity to examine and modify the dynamic processes in our minds.

For an interesting study on what happens when students don’t reflect on their errors, see Andrew Mason and Chandralekha Singh. Do advanced physics students learn from their mistakes without explicit intervention? American Journal of Physics, 78(7):760, 2010.
Conclusion

We have made the case that training in physics problem solving prepares us for the more challenging problems that we will come across in our lives. To begin, physics problem solving teaches us to approach problems with confidence, and to obtain a clear understanding of a problem and its context (Points 1, 2, 3, and 4). It is rare to find problems in other domains that allow us to so sharply hone our holistic understanding of a situation. Also, most problems that we encounter in our physics classes are at an unusual level of difficulty in that they are challenging enough to require sophisticated and broadly transferable problem-solving techniques, yet simple enough to be completely solvable (Points 5, 6, and 7). Furthermore, clear and prompt feedback on our physics problem solutions offers us the opportunity to reflect both on the state of our problem-solving skills and on the cognitive and affective processes involved in our unique experience solving problems (Points 8 and 9).

In conclusion, we would like to encourage physics teachers at all levels to make the case to their students that physics problem solving is a complex yet reasonably well-understood process and to provide explicit, formal instruction in problem solving. We would also like to invite students to look at their introductory physics courses as being about more than Newton’s laws, Maxwell’s equations, and the laws of thermodynamics, and instead as opportunities to develop effective problem-solving skills that may be of use far beyond the physics classroom, as well as invitations to explore the beautiful complexities of their minds.

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