

CHAPTER 2  
DESIGN OF THE STUDY**Rationale.**

Improving the higher-order thinking skills of individuals is, indeed, an immense and, so far, largely unsolved task. The overall review of the current state of problem-solving research and educational practice demonstrates how limited the educators' achievements are. Why is that? On the one hand, there appear to be serious inconsistencies and gaps in the literature devoted to understanding the mental mechanisms of problem solving and teaching problem-solving skills in physics. On the other hand, there is a fairly universal consensus among the educators that the common instructional methods, as well as available curriculum materials, are utterly inadequate. One cannot help but find a direct connection here. Below, I will discuss the deficiencies in existing research and their implications on practice.

Defining a *problem* seems to be the very first step to understanding problem solving. My review shows that several key findings emerge from the literature:

- for instructional and research purposes, it is essential to distinguish between *problems* and *exercises*;
- the distinction between problems and exercises is well-agreed upon among physics educators;
- the available curriculum materials (primarily, textbooks) do not provide an adequate amount of *problems* to support teaching problem-solving skills; mostly, the textbooks contain tasks that should be considered exercises.

The heavy dominance of exercises in the textbooks leads to apparent confusion on the part of many researchers and practitioners who work on improving problem-solving skills. The negative aspects of such situation can be outlined.

First, it hinders the quality of cognitive research on problem-solving. Many authors used trivial tasks in their studies, thus conducting, in effect, research in *exercise*-solving. The results of such research can do (and have done) little to improve problem-solving instruction. Of course, teaching the students to solve "standard" tasks is also a pedagogical challenge. However, it is, in my opinion, quite a different one from teaching problem-solving skills. In the studies described in the literature, the distinction seems to be lost. Second, the overall quality and effectiveness of curricular materials suffers: the students do not feel the need to study the text carefully, if a quick look at the equation sheet allows them to solve most of the end-of-chapter tasks effortlessly.

The third – and main – concern emerges from the first two: the quality of teaching suffers. Clearly, it is impossible to teach problem-solving skills effectively without making the students apply those skills.

Researchers – and practitioners – have repeatedly reported their frustration with the students' reluctance to follow the expert-like strategies even after having been explicitly taught such strategies. The reasons for such frustration can be traced to the shortcomings in the methodology used by researchers.

The research on physics misconceptions has yielded a rich collection of reliable data. The existence of misconceptions is well established; the most common ones have been, with some variations, catalogued by many researchers, and the instructional difficulties in correcting the misconceptions have been well recorded in the studies involving students of different ages and different countries.

However, this research is, in my view, unjustifiably disjointed from problem-solving research. For instance, researchers, in general, appear to think of a misconception as a belief that is firmly embedded in the student's brain before the instruction; such belief may (or may not) be corrected through explicit instruction on the topic. This view, while adequate in many respects, does little to link the existence of misconceptions to the individual's problem-solving abilities.

In particular, the fundamental differences in the cognitive nature of the pre- and post-instruction misconceptions have been largely unexplored. To me, it seems reasonable to view the pre-instruction misconceptions as *naïve beliefs* merely reflecting a non-scientific, "common-sense" view of the world.

However, the *post*-instruction misconceptions can be considered differently. In most studies, they are diagnosed in the same way as the pre-instruction ones: by administering a series of tests that include the questions based on certain laws and principles of physics. Incorrect answers given by the student, supposedly, indicate the lack of understanding and, implicitly, the existence of erroneous beliefs – misconceptions.

However, after the students *have studied* physics, the inability to apply the *familiar* laws and principles to an *unfamiliar* situation presented can be logically considered a *failure to solve a problem*.

Researchers have, indeed, found the connection between one's success on the post-instruction conceptual tests and the results on problem-solving tasks, which is the main reason tests like the Mechanics Baseline Test are considered valid and useful educational tools. However, to my knowledge, no serious analysis of such connection from the cognitive point of view has been conducted in the literature.

The “expert-novice” research provides the theoretical foundation for developing problem-solving instruction principles. However, the lack of clarity in defining a problem (as opposed to an exercise) has rendered many studies far less useful than they could have been. In fact, failure to distinguish explicitly between *problems* and *exercises* leads to difficulties in defining *experts* and *novices*. In the existing studies, the “expert-novice” distinction has been drawn in two major ways.

Some researchers (Larkin *et al*, 1980; Chi, Feltovich, & Glazer, 1981) think of “experts” as individuals with large experience in the field: physics professors, graduate students, etc. Novices, in this view, are the students with little experience: high school students, college freshmen, etc.

I would challenge the validity of all such studies<sup>1</sup> on the following grounds. The ultimate definition of a problem-solving expert is “an individual who is successful at solving problems.” Utilizing the rigorous definition of a problem, we can say that an expert is “an individual who is successful at solving challenging tasks requiring the application of known principles in unknown situations.” While physics professors and graduate students may, indeed, be experts according to this definition, they never *had a chance to prove it* in these studies! Why is that? The reason is strikingly simple: when the authors attempted to find differences in “expert” and “novice” approaches, they, naturally, offered them the *same* tasks to solve.

What happened? I invite the reader to consider an example from the world of sports.

Imagine that you want to see the difference between the jumping techniques of a world-class high-jumper (personal record 2.40 m) and a middle-school varsity athlete (personal record 1.60 m). The dominant style of high-jumping involves a complex technique of gliding over the plank face up, so that the back and then the legs of an athlete glide smoothly over the plank.

Of course, you would expect the world-class athlete (the “expert”) to have mastered this technique much better than a middle-school “novice.” Imagine that you want to conduct research to see the specific shortcomings of the “novice.” To do that, you ask both jumpers to clear a certain height and observe their movements.

The key question is: *what* height? Of course, you cannot choose, say, 2.30 m – because the novice will simply go *under* the plank and hit the mat without really demonstrating his jumping technique, whereas the expert would clear the height, although with some difficulty. Should you choose, then, 1.50 m? The “novice” would clear the plank, which would take some effort, and the faults of his technique will be easy to observe. What about the “expert”? Most likely, he would just use his strength and body height to push himself upward slightly and simply *step over* the plank. This time, it is the expert who is failing to demonstrate his “real” jumping technique – and, again, the research goal is not achieved. However, this “1.50 m” scenario is, figuratively speaking, exactly what the “expert-novice” researchers played out by offering the *same* tasks to both experienced and inexperienced individuals.

The “novices” usually found the tasks to be challenging – and were thus engaged in *problem-solving*. However, the tasks were quite trivial for the “experts” who approached them as *exercises*. As a result, the findings of such studies may not be distinguishing between “expert problem-solvers” and “novice problem-solvers”: rather, they show the differences between the problem-solving approaches and the exercises-solving ones. Such research, by the way, may be quite helpful in sharpening the “problem-exercise” dichotomy in terms of the cognitive processes involved in solving these two types of tasks – but this is *not* how research results have been interpreted.

The “jumping” example makes it clear that, in order to see the differences in problem-solving approaches, the “experts” and the “novices” should have been offered “different planks to clear” – in other words, *different* tasks to solve, the tasks that prove challenging for all *within the context of their prior knowledge* – which means, of course, using different tasks for the more experienced solvers (so-called “experts”) and the less experienced ones (“novices”). This approach, however, raises another possible concern: to what extent are the observed differences in approaches determined by the cognitive differences between the individuals, and to what extent are they just the product of differences between specific tasks?

Such concern is addressed in the studies that used the solvers of similar backgrounds (de Jong & Fergusson-Hessler, 1986, 1991; Finegold & Mass, 1985). Instead of using the “expert-novice” terminology,

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<sup>1</sup> Let us call them “professor-student” studies.

the authors talk about their subjects as “more successful and less successful problem-solvers” or as “good students and bad students.” I consider the findings of these studies more useful. However, it is not clear from the articles describing these studies that their methods were informed by any concerns about the validity of the “professor-student” studies – rather, the reasons appear to be purely logistical. Correspondingly, the interpretation of the results often converges with the findings of the “professor-student” studies. The reason, to me, is the same: the tasks offered may not have been challenging enough for the “good” students, thus causing the same methodological problem as in the “professor-student” studies.

The main distinctions between “experts” and “novices” have been found to be in the following areas:

- knowledge of problem situations;
- knowledge structure and prevalent use of particular types of knowledge;
- presence and use of problem-solving schemata.

I would not suggest that all these findings be ignored. However, the evidence supporting them is less direct than the authors may claim, and their usefulness in teaching problem-solving skills is limited, as evident from the literature. I, personally, find it difficult to clearly separate *declarative knowledge from procedural knowledge*; as described in many articles, they seem to be intertwined. Also, the *schemata*, as defined in the literature, appear to be more of an exercise-solving tool than a problem-solving one.

All these inconsistencies may be hindering the quality of instruction based on the findings of the “cognition of solving” studies. However, part of the blame may lie with the methodology of the “teach to solve” studies, as well.

Several key conclusions emerge from my review of the “teach to solve” literature. First, there appear to be two camps of authors that lack a common understanding of the term “problem.” The “cookbook” authors tend to present examples of what should properly be considered *exercises*, not problems. The “thinking skills” authors appear to use more sophisticated examples of tasks, the ones that can properly be called *problems*.<sup>2</sup>

Second – not surprisingly – is that the cookbook solving strategies presented are *only* fit to solve the cookbook tasks – that is, *exercises*. The more general strategies offered by the “thinking skills” authors appear to be more useful in solving real *problems* – but, importantly, not very useful in solving exercises. The evidence lies in the description of examples and strategies described in the “position papers” and also in the modest success of the intervention studies.

Third, most of the articles – written by *both* camps – are *not based on empirical research*. Unlike the “Cognition of Solving” works, they tend to be “position papers” or theoretical exercises, rarely backed by anything other than anecdotal evidence.

Fourth, and most important: In the relatively few cases where the empirical studies were actually conducted, the rate of success in teaching problem-solving skills is quite limited. Several studies report, with frustration, the students’ consistent reluctance to use the expert strategies in solving the tasks. To me, the obvious reason is that the more sophisticated expert strategies tend to increase the cognitive load on the solver and are, therefore, naturally rejected unless the solver is *forced* to use such strategies due to the failure of the novice ones. The latter can only be achieved if the tasks are sufficiently challenging, of course.

Also, when positive results *are* reported, they tend to be either very *narrow* (the improvement is shown on the topic in which the students had been thoroughly tutored) or *indirect* (the students show more of the skills deemed “expert” by the authors – but do not necessarily show improvement in solving problems) or possibly *invalid*. Validity concerns are several: for instance, in most cases, the tasks used are too trivial (*exercises*); the number of participants is often very small; also, the researchers often teach both the treatment and the control group themselves, etc.

Based on this critique, I would like to propose an alternative theoretical approach to describing the cognitive aspects of problem-solving.

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<sup>2</sup> Given the background of the participants.

The BARK theory: bisociation and rigid knowledge as two salient components of problem-solving in physics.

I propose dichotomizing problem-solving skills into *rigid knowledge* and *bisociation*. This dichotomy mirrors the one between problems and exercises and, I believe, provides a useful framework for approaching problem-solving research and practice.

Rigid knowledge is defined as the knowledge of *the facts* (such as the formula for Coulomb's law or the charge of the electron) and *the standard procedures* (such as resolving a vector into components or solving a quadratic equation). It combines the declarative (factual) and procedural knowledge as described in the literature.

Bisociation on the other hand, is a skill of relating the existing rigid knowledge and the unfamiliar situation described in the task. Its nature is quite complex; one of my research goals is to identify at least some component skills of bisociation. Some of them (described in the literature) are: situational knowledge, self-monitoring, and intellectual persistence; I aimed to identify some other skills in this research project. To visualize the BARK (**B**isociation **A**nd **R**igid **K**nowledge) dichotomy, consider two metaphors far removed from physics.

First, think of carpentry. If problem-solving is similar to house-building, then rigid knowledge is the carpenter's toolbox: to build a house, one must have all necessary tools (declarative knowledge) and know how to use them (procedural knowledge). However, the toolbox does not make a good carpenter – an apprentice, maybe. Besides the toolbox, a good carpenter also has the skills of choosing the right tool and procedure depending on the task at hand.

Another metaphor comes from the world of sport: in basketball, regular competitions are held in the “free-throw event” where the participants shoot the free throws until they miss. It is well known that the world-record holders in this event are *not* the top basketball players in the world. Rather, they are obscure individuals who have been *exercising* their free-throw skills for a long time – but lack the ability to solve *problems* on the court.

In my opinion, the proposed BARK dichotomy can prove useful in providing a new perspective that helps link together the strands of literature discussed above and addresses the inconsistencies found in current research. It can be used to describe the processes involving both quantitative and qualitative problems, thus providing a unifying view of the two, currently divorced, bodies of research: misconceptions (where the qualitative questions are usually used as probing tools) and problem-solving (where the quantitative tasks are used).

For instance, in most studies, the presence of post-instruction misconceptions is usually detected through the incorrect answers to the diagnostic test questions. In many common diagnostic tests, after having been taught Newton's laws and then asked to compare the forces acting on two colliding objects, many students still failed to connect Newton's 3<sup>rd</sup> law with the situation and claimed that a heavier object of the two exerts a greater force. Within my framework, such failure to connect the known principle and the unknown situation can be interpreted as the student's lack of bisociation skills.

Many results of the “expert-novice” studies can also be usefully interpreted using the BARK approach. More successful problem-solvers are more likely to plan a solution, to have better situational knowledge, to have better self-monitoring abilities, etc. – all these skills fall in the realm of bisociation. Also, several “professor-student” studies reported the use of “forward” strategies by the “experts” and the use of “backward” strategies by the “novices” – which can be reasonably interpreted as the “rigid knowledge-based” and “bisociation-based” approaches, due to a different relative difficulty of the tasks for “experts” and “novices.”

Also, the main difference between the “cookbook” and the “thinking skills” teaching methods can be clearly explained in the terms that I propose: the former only teach *rigid knowledge*, whereas the latter attempt to teach *bisociation* skills. In fact, the tasks can be classified as *exercises* and *problems* along the same lines. Solving a *problem* requires the use of bisociation: a complex process of analyzing an unfamiliar situation, recognizing the connection with the familiar ones, identifying and retrieving the relevant rigid knowledge – perhaps, after a few failures<sup>3</sup>. If the task at hand only requires facility with the standard procedures in order to be solved, it only draws on the solver's rigid knowledge and should be considered an *exercise*.

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<sup>3</sup> Researchers stress that solving a problem is not necessarily a “smooth” process (Crane, 1969, 1970; Fuller, 1982; Lawson & Wollman, 1995).

Imparting rigid knowledge and teaching *exercise*-solving skills is not that hard – but teaching *problem*-solving is different. Every math or science teacher has heard complaints like “I knew all the concepts, equations and formulas – *but I had no idea which one to apply*” or, notoriously, “How can you give us this problem? *We have never solved anything like that before!*” To me, such complaints are a tell-tale sign that a student may be competent in solving *exercises*, but lacks the *problem*-solving skill of relating the principles and formulas to an unfamiliar problem situation – in other words, lacks the *bisociation* skill. Additionally, breaking down the incredibly complex skill of problem-solving into no more than two major components allows for a relatively straightforward research design that can yield convincing, direct and valid results. Once the existence of these two salient components of problem-solving is reliably established, further studies may be conducted to refine the understanding of the components of the two major skills, develop techniques of diagnosing the presence of these skills in individuals and to devise instructional strategies aiming to improve the lacking skills. My study is, of course, only a small first step on this path. In the next section, I will discuss the methodology of the study, informed by the literature analysis and my proposed theoretical framework.