Computer based instructional support during physics problem solving
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Chapter One

Theoretical background of problem-solving in physics

1.1 Introduction

1.1.1 Problem-solving in physics education
Problem-solving plays an important role in regular school practice in physics. After the teacher introduces the concepts, students apply these concepts in problems. Problems in this context follow some well-defined criteria: all information needed to solve the problem is given; a limited set of rules is needed to solve the problem; in many cases only one procedure leads to the right answer; and there is only one correct answer. This kind of problem is rather common in educational practice, but problem-solving in this approach is ‘dominated by recall, a relatively undemanding cognitive task’ (Osborne & Dillon, 2008; see also NiNa, 2006). The approach does have its merits, however, as many students can correctly solve the problems and teachers are convinced that they are doing a good job. Nevertheless, it turns out that students find it hard to apply their knowledge in more realistic situations in which the problem situation differs from the situations practised (Hobden, 1998; Taconis, 1995). In other words, their knowledge of scientific concepts and algorithms is tied too closely to the problem situations they have practised. They only know how to solve problems within a ‘limited solution space’ (Stadler, Duit & Benke, 2000).

In recent decades the national curricula committees involved in curriculum reform in many Western nations have stressed the need for problem-solving in science and mathematics teaching (Kultusministerkonferenz, 2005; National Research Council, 1995; NiNa, 2006). In their opinion, students need to learn how to solve problems and become skilled at analysing problem situations, to connect their prior knowledge to the new situations, to work out a proper solution plan, and to check and evaluate the solution found (Ministerie van Onderwijs en Wetenschappen, 1998). Secondary school should prepare students to continue their studies in higher education, where they are trained to become ‘knowledge workers’ who can provide leadership in institutions and companies that carry our future. Problem-solving skills are certainly required in these positions. For these future tasks, correctly applying standard solutions is less important than analysing problem situations and finding ways to solve problems. Complex calculations and solutions to
standard problems are increasingly in the hands of computer programs, which highly qualified workers use in their problem-solving tasks.

1.1.2 Problem-solving in the Dutch secondary school curriculum

Physics education in the Netherlands has changed since the educational reforms of 1998. Before 1998, lessons were dominated by teacher-led instruction on physics concepts and procedures and students had little time to work individually on problems during school time. Practice exercises had to be done as homework, and the teacher would discuss the answers to the problems in the next lesson. Most homework tasks were similar to the tasks done at school. This practice gives little effective problem-solving time. Hence Taconis’s claim (1995) that secondary school practice in the Netherlands emphasizes the learning of facts and procedures, and does not give special attention to the development of more general problem-solving strategies.

Some early initiatives were taken to improve the learning of more general problem-solving strategies. The use of the Systematische Probleem Aanpak [Systematic problem-solving approach] (SPA), developed in the 1970s and 1980s, showed positive effects in experiments under school practice conditions in mathematics (Van Streun, 1989) and physics (Van den Berg, 1983). Since the 1998 reforms, SPA has been introduced in some regular school textbooks, including those for physics (Middelink et al., 1998). This meant that it could be used to implement the most recent curriculum reform in the Netherlands.

Since the most recent curriculum reform of 1998 in Dutch secondary schools, called the ‘study house’ (Stuurgroep Tweede Fase Voortgezet Onderwijs, 1994, 1995), lessons in Dutch secondary schools can be characterized as follows:

• focusing on an active and independent role for students
• being aware of differences among students
• encouraging student thinking skills.

At first glance, improving problem-solving abilities fits in with these statements very well. Problem-solving requires students to be active and independent and to use their own approach to solve problems. As such it is a thinking skill which should certainly be encouraged. The new ‘study house’ system can thus create opportunities where students can learn to solve problems independently and thereby improve their strategic knowledge.

Today, however, regular school practice still involves a combination of brief instruction for the whole group, independent work, practical work and discussion of some of the completed problems (Tweede fase Adviespunt, 2005;
Dijsselbloem, 2008). During lessons, most of the students’ problems (homework) are not discussed with the class as a whole; instead students check their answers with the help of answer books containing model answers. This means that if students work out their homework problems, they themselves can choose whether to consult answers to the different questions and the model answers. In many cases, students make a first attempt at solving a problem, do not succeed, and then consult the model answer. This means that the aim – students solving problems independently – is not achieved. The instructive role of the teacher is largely replaced by the book with model answers. Nevertheless, while many students think that they know how to complete a standard exercise, they are not able to finish a new, unknown problem that requires them to apply their knowledge.

In addition, the physics textbooks used since the 1998 reforms still contain many closed problems designed to teach facts and procedures, while students are not often invited to try to solve new, less-structured problems (Ministerie van Onderwijs en Wetenschappen, 1998). Statements from secondary school students underline the lack of encouragement for more general problem-solving strategies (Leenheer, Simons & Zuylen, 1998). I often hear my students say ‘when doing homework, I understand the solution process as written down in the model answers, but when I have to do it myself the next time, I can’t complete the solution without help.’ Students think they understand how problems should be solved, but are not given enough experience of learning how to solve novel problems. In the study by Leenheer et al. (1998) students mention that sciences are especially hard to learn at school because these subjects need more explanation than what the teacher often provides.

Thus in regular school practice today, the development of problem-solving strategies is still hampered in two ways. The first is that books are provided with immediately accessible model answers which are used wrongly by the students and which therefore deny them sufficient problem-solving experience. The second is the minimal and in many cases late feedback from the teacher.

1.1.3 Research into problem-solving: a brief overview

This thesis will discuss the effects of the computer program Physhint, which supports students in problem-solving. The main goal of Physhint is to improve students’ ability to solve problems in new situations. A ‘problem’ is defined here as a situation that the student experiences as being different from the
initial situation. A problem is solved by a sequence of actions that reduces the difference between the initial situation and the goal (Newell & Simon, 1972). The problem is solved if such a sequence of actions has been found and the goal has been reached. In general, both the series of actions required and the goal can be well defined or there may be multiple correct solution paths and correct answers (closed versus open problems). The availability of the information needed to solve the problem can also influence the degree of openness of a problem. In this thesis, the definition of a problem is limited to problems with one clear answer, although there may be more than one solution path that can be used to arrive at that final answer. Research shows that if the problem situation is one that students are unfamiliar with, many of them find the problem more difficult and have difficulty finding the actions needed to arrive at the goal state (Stadler et al., 2000).

During the 1960s and 1970s, research on problem-solving involved laboratory tasks such as the Tower of Hanoi problem (a puzzle in which discs have to be moved between three pegs in accordance with certain rules in order to shift the tower from the first to the last peg), which was novel for participants (see Mayer, 1992). Such problems could be solved in a relatively short time, solutions were clearly defined and researchers could trace participants’ problem-solving steps. Researchers made the underlying assumption that the way to solve laboratory tasks such as the Tower of Hanoi captured the main properties of problems in other domains and that the cognitive processes underlying students’ attempts to solve simple problems were representative of the processes engaged in when solving problems in other domains. Thus researchers thought they could generalize from the solution processes of these general problems to problem-solving in other fields.

After the 1970s, researchers acknowledged that problem-solving processes differ across knowledge domains and across levels of expertise (e.g. Sternberg, 1995) and that, consequently, findings obtained in the laboratory could not necessarily be generalized to problem-solving situations outside the laboratory. Schoenfeld (1985) showed that in order to solve mathematics problems, experts and novices use the same episodes of orientation, analysis, plan-making, implementation and verification. However, experts take relatively more time to read and analyse problems and to ‘look back’, whereas novices devote most time to finding a solution plan and making calculations.

Problem-solving is not a linear process that proceeds from one step to another; it is a more cyclical process. A student may begin by considering a problem as a task to be carried out and engage in thought and activity to
understand it. The student attempts to make a plan and in the process may discover a need to understand the problem better. Or, once a plan has been formed, the student may attempt to carry it out and be unable to find a solution. If the student is unable to find a solution, the next activity may be to make a new plan, or go back to develop a new understanding of the problem, or pose a new – perhaps related – problem to work on.

In Figure 1.1, each of the arrows describes student activities in the process of solving physics problems. Problem-solving by experts or novices in physics cannot be captured by one-directional steps in problem-solving alone. Experts and students go to and fro in the problem-solving process, although this depends on the complexity of the problem as experienced by the students. Experts will solve a problem more systematically than novices do. Novices begin almost immediately by making a plan and carrying it out whereas experts first spend more time on understanding the problem (see Schoenfeld, 1992). Chi, Feltovich and Glaser (1981) investigated expert and novice behaviour in physics education. They showed how experts and novices differ in the organization of their knowledge when solving problems. Their findings show that experts represent physics problems according to the underlying principles, whereas novices base their representation on the problem’s surface features. When novices have to solve non-standard problems they do not succeed in formulating and working out an effective plan, in particular because they do not know how to analyse the problem situation from the point of view of its
underlying principles. This is probably because they were not taught how to do so and do not possess general problem-solving strategies to manage their own problem-solving actions (Taconis, 1995).

1.1.4 Can problem-solving be taught?
Problem-solving involves the process of orientation to a problem, schematizing the available information, working out a solution plan, and checking and evaluating the final answer. Untrained students seldom work in an organized way at novel problems that demand transfer of their knowledge (Larkin, McDermott, Simon & Simon, 1980; Chi et al., 1981). Science education does not emphasize systematic solving of novel problems and students are not trained to solve novel problems; most of the learning time is devoted to practising standard problems. Can problem-solving be taught, or are teachers right to leave this matter alone? It is not easy to improve student problem-solving skills in a systematic way. Polya’s teaching of problem-solving in mathematics (Polya, 1965) was directed at asking students to think aloud and giving students examples of think-aloud solution processes by experts. In his teaching he stressed the process of problem-solving and not the final result. Taking up this approach, Schoenfeld (1985) taught his students to ask themselves questions as an effective way to guide their thinking processes. He let students use the different problem-solving episodes by encouraging them to ask themselves how to solve problems and by providing them with examples. Mayer (2008) concludes from a review of research that problem-solving is best taught by training students in the use of components that play a role in problem-solving. The components he gives bear considerable resemblance to Schoenfeld’s episodes. Mayer (2008) asserts that effective practice in problem-solving should be given in a structured way, but not in a step-by-step procedure. He concludes that problem-solving programs are most effective when they focus on problem-solving not as a single intellectual ability but as a collection of smaller component skills. Mayer (2008) stresses that successful problem-solving training involves:

- specific problem-solving skills
- contextualized tasks that students are expected to perform in school
- practice in the process of problem-solving
- discussion of the problem-solving process
- teaching problem-solving before students have fully mastered content knowledge of a domain.
Mayer also stresses that problem-solving training should be provided in addition to developing domain-specific content knowledge. Students need to learn domain-specific problem-solving skills in order to become successful learners in physics.

This thesis seeks to work out and evaluate a method of instruction which both helps students to solve physics problems and teaches them to develop their problem-solving abilities and apply Schoenfeld’s problem-solving episodes: orientation, analysis, planning, control and reflection. The skills instruction that goes with these episodes can help students to solve problems more systematically. With the episodes, domain-specific knowledge can be offered that will be useful to structure and plan the solution to a problem. It is argued in this thesis that students are best taught problem-solving by offering them support and not teaching them directly how to solve problems. It is essential that students make their own choices in seeking instructional support during problem-solving. Problem-solving is not a step-by-step procedure that can be learnt by heart and carried out mechanically. Solving novel problems requires flexibility in planning and the ability to follow one’s own route to a solution. Instruction in the form of hints with the problem-solving episodes can offer support. Instruction in novel problems should be timely and in line with student problem-solving processes and the episodes they use in order to arrive at the goal state. Students’ understanding of the rationale behind the sequence of problem-solving episodes and the instructions that accompany them is considered a crucial factor in student learning; my expectation is that it will improve their problem-solving skills (Harskamp & Suhre, 2006).

1.2 Types of problems in physics education

Expressed most simply, problem-solving is ‘What you do when you don’t know what to do immediately’. A problem arises when students are confronted with a task that is non-routine and they set their mind to solving the task. This definition of a problem thus depends on who is solving it. A student’s level of experience with a given task will determine whether a particular example is simply an exercise or in fact a real problem. Hollingworth and McLoughlin (2001) suggest that it is familiarity, rather than difficulty or complexity, which distinguishes an exercise from a problem. Exercises can often be solved by an algorithm and by forward reasoning. By contrast, novel problems may require a cyclical, reflective approach for their solution.
Johnstone (1998) proposes a useful classification of problem types. If the data are given, the methods to apply familiar and the goals clear, students can apply their knowledge without much analysis and thought. These are characteristics of ‘structured problems’, which are in fact exercises allowing students to practise knowledge and skills that they can then apply with ease in future. These kinds of tasks are important for learning the basic concepts of the physics domain and for using physics formulae. For instance, if the teacher demonstrates how speed can be calculated using the formula \( s = v \cdot t \), if the distance covered and the time travelled are known, students can learn to solve the following kind of problem through practice. For example:

*Theo runs 8 km in 40 minutes at a constant pace. What is Theo’s speed in km/h?*

Through the demonstration of worked-out examples and practice of similar tasks, students can learn to use the formulae in this kind of routine task: calculating distance on the basis of speed and time or time on the basis of distance and speed.

If the data are given but the method is not strictly familiar or if students have to choose from different data, a non-routine problem arises. Students have to look for parallels between their acquired knowledge and the problem. The goal state (the correct answer) is clear, but there is more than one way to arrive at the answer. The aim of this kind of problem is to learn how to analyse a problem situation and decide what information is needed to solve it. The problems are semi-structured and the student has to analyse and select from the given information or to adapt known methods in order to go from the problem state to the goal state. For example, if students are taught how to calculate constant speed from distance and time, it will not be as easy for them to solve a problem where more variables are included than in the formula \( s = v \cdot t \). For instance:

*Diana travels from Amsterdam to Breukelen at a constant speed and arrives after 36 minutes. However, during the trip she was caught up in traffic for 6 minutes, during which the car travelled at an average speed of 20 km/hour. The distance from Amsterdam to Breukelen is 58 km. What was the average speed of the car when it was not caught up in traffic?*
This problem is not as easy to solve, not because the knowledge that should be applied (the formulae) is unknown, but because the situation is different from problem situations that have already been taught. For the student, the change from the initial state to the goal state will be more complicated because a new element is introduced into the problem situation – a short period with a different speed as the constant speed. The student can solve this problem by breaking it down into two separate problems (distance during congestion and distance during constant speed and time remaining) or by creating a new integrated formula:

\[ s \text{(constant)} = v \text{(constant)} \cdot t \text{(constant)} \Rightarrow 58 - (20 \cdot 6/60) = v \text{(constant)} \cdot (36 - 6) \]

Even more difficult for novice students with a basic knowledge of \( s = v \cdot t \) are problems in which two vehicles start from different places along the same road and move in opposite directions at different times and different speeds and students have to figure out where both vehicles meet. Students often use tables and step-by-step estimations instead of a formula to arrive at an answer (Harskamp & Suhre, 2006).

Johnstone (1998) also describes the characteristics of open problems where the goal is open-ended and the data are superfluous or the methods unfamiliar. These are unstructured problems. The aim of such problems is to prepare students for real-life situations in which the problem itself has to be further developed to turn it into a solvable problem and where there are many ways to solve a problem and several solutions. An example is:

**Find out which road to take from Utrecht to Paris tomorrow (regular weekday). You are travelling by car. Take into account the speed limits and expected traffic jams. You want to start at 8.00 a.m. and waste as little time as possible.**

Depending on their assumptions and reasoning, students will apply one solution which they consider to be sounder than another. In training students to solve problems, it is important to examine carefully what types of problems are presented. This research does not aim at giving students exercises needed to introduce new facts and procedures. Students need to become better problem solvers and to develop higher-level skills. This means they should also be supported to progress beyond the skills needed to solve routine exercises. After the introduction of new facts and procedures through routine exercises, students need to consider problems that are non-routine and novel, but that
also pose clear problem situations and goals. These semi-structured problems may or may not be real-life problems, but they are ones that will help the students to understand how to apply their knowledge in new situations.

Stadler et al. (2000) demonstrate that semi-structured problems are best for improving these higher-level skills in a school context. These problems require students to use their content knowledge in a problem setting that can be solved in a relatively short time. The unstructured problems often used in school physics projects take longer to solve. They require close monitoring and guidance by the teacher in order to motivate and support the actions students take in order to arrive at a satisfactory goal state (e.g., Williams, Stanisstreet, Spall, Boyes & Dickson, 2003).

1.3 Types of knowledge involved in solving problems and how they can be learned

Much research on problem-solving starts from the cognitive perspective (Anderson, 1995). According to this perspective, three types of knowledge play a role in problem-solving:

- declarative knowledge of physics concepts and facts
- procedural knowledge, such as how to apply formulae, and
- strategic knowledge needed to put the former two types of knowledge to work in a problem in order to generate a solution.

De Jong (1986) elaborates these types of knowledge in problem-solving as follows:

- declarative knowledge (knowing that and why): for example, knowing facts, principles, abstractions, rich cognitive schemes and overviews of a subject
- procedural knowledge (knowing how): for example, knowing how to apply algorithms such as the use of formulae
- strategic knowledge and meta-cognitive knowledge (knowing about knowing): reflection, monitoring, knowledge about what one knows and how to apply this in problem-solving.

Researchers in physics education agree about the influence of the quality and organization of subject knowledge (declarative and procedural knowledge) and about the differences in performance between good and poor problem solvers (Chi et al., 1981). The ‘chunks’ of knowledge used by experts are larger and richer than those of novice problem solvers. Expert problem solvers also show a better overview of and coherence between concepts and procedures which are
relevant for solving a problem. A comparison of experts and novices showed that these groups not only differ with respect to the quality of declarative (or procedural) knowledge. The way novices deal with a problem also differs from that of experts. When trying to solve a problem, novices almost immediately start working with a poorly defined plan, whereas experts take the time to analyse the problem and gather information before making and implementing a plan (Larkin & Reif, 1979; Chi et al., 1981; Sherin, 2001; Van Streun, 1983). Van Streun (1994) and Boekaerts (1997) show that this knowledge about how to solve a novel problem – strategic knowledge – is necessary. Strategic knowledge is needed to analyse and elaborate upon the problem situation in order to relate domain knowledge to the problem. Strategic knowledge enables students to recall their knowledge about concepts and procedures in a domain. By using strategic or meta-cognitive knowledge, students control, regulate and monitor their problem-solving process. Although some students fail to solve physics problems because their declarative and procedural knowledge basis is too small, the main reason for blockages in problem-solving seems to be a lack of strategic knowledge (Taconis, 1995).

1.3.1 Declarative knowledge
Strictly speaking, declarative knowledge is the knowledge of facts (Anderson, 1995). De Jong (1986) includes within declarative knowledge the knowledge of facts, principles, abstractions, rich cognitive schemes and overviews of a subject. In later work, De Jong and Ferguson-Hessler (1996) breaks down declarative knowledge into factual knowledge and conceptual knowledge. This subdivision is used to distinguish between the quality of different kinds of declarative knowledge and therefore the possibility of using it in problem-solving. If students have acquired some kind of factual knowledge, there is no guarantee that they can use this knowledge in a new contextual situation. Although facts, terms, calculation rules and algorithms can be memorized and reproduced easily, students have difficulties activating this knowledge in new contexts. If a problem has to be solved within a chapter of a book, the toolbox of knowledge available to solve a problem is much smaller than for a problem involving a mixed collection of problems covering three years of physics education. In the latter situation, students have to somehow relate their knowledge to unknown problem situations, which involves conceptual knowledge. Although we can distinguish this difference in the quality of declarative knowledge, I will simply use the term ‘declarative knowledge’ in the remainder of this thesis.
It appears that novices and experts have differently structured declarative knowledge within physics. This is the main reason why experts are better able to gain an overview of problems situated in unknown contexts and to relate them to their existing knowledge. Pellegino, Chudowsky and Glaser (2001) have stated that the most convincing examples of differences between the structures of subject knowledge of novices and experts have been found in physics. When given a mechanics situation, experts will describe it with the help of basic physics principles, as can be seen in Example 2 in Figure 1.2.

Explanations

Novice 1: This deals with blocks on an inclined plane.

Novice 5: Inclined plane problems, coefficient of friction.

Novice 6: Blocks on inclined planes with angles.

Explanation

Expert 2: Conservation of energy.

Expert 3: Work-theory theorem. They are all straightforward problems.

Expert 4: These can be done from energy considerations. Either you should know the principle of conservation of energy, or work is lost somewhere.

Figure 1.2: An example of sorting a selection of physics problems as done by novices and experts (Adapted from Chi et al., 1981; and Bransford, Brown & Cocking, 2000)

Each picture represents a diagram from a standard physics problem in an introductory physics textbook. The novices and experts in the study by Chi et al. (1981) were asked to categorize many such problems based on the similarity of the solution process. The explanations in Figure 1.2 show a marked contrast between the experts’ and novices’ categorization schemes. Novices tend to categorize physics problems as being solvable in a similar fashion if they ‘look the same’ (i.e. share the same surface features such as a block or a slope), whereas experts categorize problems according to the major principle (e.g. conservation of energy) that could be applied to solve the problems. An
example of the organization of knowledge structures by novices and experts is given by Chi, Glaser and Rees (1982) and can be found in Figure 1.3.

This example shows that the quality of declarative knowledge (i.e. to what extent do physics concepts guide the relationships in the knowledge structures) differs between experts and novices. This influences their analysis of problem situations. Experts can reduce the complexity of the problem situation and come to the heart of the problem more easily. They find a way to solve it more easily than novices, who are overwhelmed by the situation and its surface characteristics. Differences in what is known and how this is presented may lead to the different answers of novices and experts. Because of the well-structured knowledge base, experts do not need to search all the different items which might be related to the problem, but can directly activate that part of knowledge needed to solve the problem (Glaser, 1992; Larkin et al., 1980).

The examples above thus indicate that there are differences between students in the quality of declarative knowledge, depending on their level of expertise. This is confirmed by De Jong and Ferguson-Hessler (1996) who
studied the ways first-year university students categorize problems and concluded that the conceptual level of declarative knowledge differs.

Anderson (1995) presents a simple model of how instruction about declarative knowledge can be organized: the more often a learner encounters a fact, the higher the chance this fact will be remembered. For the broader area of concepts, exercise is expected to be a good way to develop knowledge of concepts for use in different situations. However, in education, students need to both develop scientific concepts and establish links between the different concepts within a subject. Such a network of concepts makes it easier to analyse problem situations and to reduce the chance of wrong solutions.

Many investigations have been carried out in recent decades into the development of declarative knowledge in the field of science education (see for example, Pfundt & Duit, 1991; Duit, 2009). When starting to learn about a phenomenon in school, students often already have their own intuitive or naive ideas about that phenomenon. In many cases, intuitive ideas or preconceptions do not correspond with physical descriptions. The students’ own ideas can then obstruct the acceptance of the scientific description of the item. Thus preconceptions can survive education and become misconceptions. The impact of this is evident in the large amount of literature about misconceptions in all domains of physics education (see for example, Wandersee, Mintzes & Novak, 1994; and the STCSE bibliography by Duit, 2009).

According to Van Genderen (1989), preconceptions can be so strong that education cannot really change the conceptual ideas of students. Others think more from the learners’ point of view and talk about alternative frameworks (Driver, 1983), or about an interpretation problem (Clement, 1982; Lijnse & Klaassen, 1995). Solomon (1983) suggests that students may preserve two different frameworks alongside one another for use in different situations: the school framework when they do physics in school and the private framework outside school.

Since the 1990s, many attempts have been made to explicitly change preconceptions (conceptual change). Using the Force Concept Inventory and the Mechanics Baseline Test, Hestenes, Wells & Swackhamer (1992), among others, tried to obtain an overview of student conceptions and made available clear tests to show students’ knowledge of concepts. Mazur’s Peer Instruction (1997) and similar instruction strategies used by Meltzer and Manivannan (1996) were shown to be effective. In peer instruction, talented and less-talented students discuss in collaboration possible solutions to conceptual physics problems. The idea is that this will clarify their preconceptions and thus change
their ideas more easily. Groups of students undergoing peer instruction showed results on conventional knowledge tests that are comparable to those of a control group, but showed significantly improved conceptual understanding (Mazur, 1997; Hake, 1998; Crouch & Mazur, 2001).

Another example of the positive effect of collaborative work is given by Kalman, Morris, Cottin and Gordon (1999), who asked two different groups of students to work out different concepts about the same phenomena. In the discussion afterwards, each group had to defend its concepts, thus creating a better understanding.

Instruction of concepts on an individual basis was worked out by Albecete and VanLehn (2000), who developed a computer program which gives students hints depending on their answers. The hints take into account possible misconceptions. Preliminary results revealed that the program had positive effects on the learning of physical concepts. Students learn that concepts can be presented in different ways, as well as that different concepts are related and that a problem can therefore be solved in different ways, depending on the representation.

1.3.2 Procedural knowledge

De Jong and Ferguson-Hessler (1996) give the following definition of procedural knowledge: ‘... procedural knowledge contains actions or manipulations that are valid within a domain. Procedural knowledge helps the problem solver make transitions from one problem state to another. It can have a specific, domain-bound (strong) character, or it can be more general (weak).’

Anderson (1995) also distinguishes between more general knowledge of procedures and techniques and more subject-specific knowledge of procedures. General knowledge of procedures may entail calculations, making drawings and sketching. In order to be able to use this knowledge in problem-solving, students need to know how to use it in specific situations in which it has been practised, as well as be able to use it quickly, when needed, on a more general operational level. When this occurs, the transfer of procedural knowledge has been achieved.

Procedural knowledge means knowing methods of manipulating a specific condition or technique for implementing a task. This may include the procedures used to perform a lab experiment or solve a standard science problem. Procedural knowledge is needed when handling declarative knowledge. It is quite different from declarative knowledge. It is possible to know all the relevant declarative knowledge without actually knowing how to
solve a problem. For example, this thesis considers calculations with forces. Within physics, forces are described with vectors that can represent both the size and direction of a force. Calculations with forces require knowledge of certain procedures with vectors which a student must possess in order to complete the calculations (De Jong, 1986).

Procedures are important for science and thus the learning of procedures is important. Many of the concepts students learn in science involve memorizing and following steps to find the correct answer to a problem. As the students learn to complete basic science procedures, they are immersed in the more general procedures they need to follow. These procedures serve as building blocks for the more complex procedures within problem-solving that students will need in the future. Marzano, Pickering and Arredondo (1997) suggest that there are three phases of acquiring procedural knowledge: a) construct models, b) shape and c) internalize.

In the construct model phase, a model of the process to be learned is displayed and the steps involved shown. An example is a series of exercises in which the equation \( s = v \cdot t \) must be applied. As the exercises are worked out, the steps should be discussed in a way that learners can comprehend. When working out the example and discussing or listing each step, learners have the model as a point of reference. Students can construct their own models and list their own steps in their own words, which will demonstrate their understanding of the process.

In the shape phase, the process originally followed is modified to make it better. Adjustments should be made to improve the process and make it more efficient to use. Some aspects may be added or dropped, depending on what makes the process comprehensible to the learner. Learners may come up with ways of making the problem easier to solve and want to add the steps they follow. In this phase it is important for the students to gain an understanding of the procedure they are performing. In our example, the student has to learn that \( s = v \cdot t \) also includes \( v = s / t \) and \( t = s / v \). Depending on which unknown variable the students have to calculate, they may use a variation of the basic formula.

In the internalize phase, learners need extensive practice in order to reach a level of ‘automaticity’ or ‘fluency’ (Marzano et al., 1997, p. 101). Certain skills need to be automatic, without learners having to think about what they are doing. Recognizing which basic operations are involved in the formula (substitution and division or multiplication) should become automatic, not
requiring much conscious thought. Other skills also need to become fluent, requiring a thought process but known well enough to be performed with ease.

1.3.3 Strategic knowledge

Strategic knowledge is concerned with general problem-solving procedures and meta-cognition (De Jong and Ferguson-Hessler, 1996). It is about how to apply declarative and procedural knowledge appropriately in a given problem situation and how to monitor one’s own solution process. When students solve a problem in practice, the three types of knowledge interact and are very hard to distinguish. However, when students are trained in problem-solving, they can be supported in the acquisition of the different types of knowledge. Traditional education emphasizes the development of declarative and procedural knowledge, but for problem-solving, strategic knowledge also needs to be developed.

Newell (1990) noted two layers of strategic knowledge: applying a strategy in order to handle a problem and the conscious monitoring of this strategy. The term meta-cognition is used for the process of selecting and monitoring a strategy, for the process of solving a problem (‘Is this a good heuristic to analyse a problem?’), as well as for more common activities such as reflection on and guidance of one’s own thinking (‘Is it a good idea to work out this problem now, or better to read part of the chapter first?’) (Pellegrino et al., 2001). In this thesis, the term strategic knowledge is used for both layers of strategic knowledge.

While solving and learning to solve problems, experts have been shown to notice the restrictions of their own knowledge, to know when to apply a certain procedure or rule, to assess the correctness of an answer or action, to plan in advance, and so on. The ability to self-regulate and to learn from their own experience enables experts to derive maximum benefit from their own work. Research into meta-cognition has shown that people monitoring their own problem-solving are better at recalling knowledge (Nelson, 1989). Students competent in problem-solving can be distinguished from weak students by their meta-cognitive strategies. Competent students can explain which strategies they have used to solve a problem and why, whereas weak students only monitor their own thinking irregularly and give incomplete explanations of their strategies (Chi, Bassok, Lewis, Reiman & Glaser, 1989; Chi & VanLehn, 1991).

Strategic knowledge such as monitoring one’s own progress, reflecting on one’s own strengths and weaknesses and correcting mistakes can be taught.
Bransford et al., (2000) emphasize that teaching such knowledge is best located within specific subjects because monitoring one’s own understanding is best related to domain-specific knowledge and expertise.

Learning strategic knowledge demands a different approach than learning declarative or procedural knowledge. Taconis, Ferguson-Hessler and Broekkamp (2001) analysed a number of articles published in highly reputable international journals between 1985 and 1995 that described experimental research into the effectiveness of a wide variety of teaching strategies for problem-solving in science education. Offering learners guidelines and criteria for judging their own problem-solving process and products, as well as immediate feedback, were found to be important prerequisites for the acquisition of problem-solving skills.

De Corte (2004) and Mayer (2008) state that several conditions must be met before the learning of strategic knowledge can take place. Firstly, the learner should play an active role. This does not mean that instructional support is not needed, but that there has to be a good balance between this support and student initiative. De Corte expects that if students are given interesting context problems that refer to real-life situations, they will be motivated to accept the task and make an active attempt to seek a solution.

Secondly, successful learning is expected if learning occurs in a wide variety of situations to develop both domain knowledge and strategic knowledge.

The third condition is that the learning environment should be embedded in a specific domain. De Corte and Mayer stress the importance of domain-specific problem-solving. It is not about applying a step-by-step general problem-solving procedure that holds for all problems, but about the joint application of declarative and procedural knowledge guided by strategic knowledge.

The fourth condition is that instructional support should be about the components of the problem-solving process and that support should gradually fade away during the practice of problem-solving. This should give students as much room as possible to develop their own problem-solving strategies (Renkl, Atkinson, Maier & Staley, 2002). The role of the teacher should be to provide indirect teaching, which means that the student takes the initiative when information is processed (see also Taconis et al., 2001). The teacher’s support should only provide full demonstrations and explanations if students cannot progress or do not know how to start. If instruction or hints are provided, they should be about aspects of the solution, such as specific instruction or hints about representing a problem if a student finds it hard to understand a problem.
description. It is essential that instruction is just-in-time. Students can ask questions or seek help and receive a rapid response to their specific questions instead of more generic explanations (Van Merriënboer, 1997; Kester, Lehnen, Van Gerven & Kirschner, 2006).

The fifth condition is about the need for explicit reflection on the students’ way of problem-solving. This is because reflection is not only an important part of strategic knowledge itself, but it also supports the development of strategic knowledge (Davis, 2003).

The sixth condition for the successful teaching of strategic knowledge is the amount of practice (Glaser & Bassok, 1989). This means that strategic knowledge is learned by doing and that students are given sufficient time and exercises to practise.

The seventh condition states that teaching should improve the learner’s self-efficacy. Experiencing correct problem-solving behaviour will increase learner confidence in their problem-solving abilities, thus giving them the idea that they can finish a problem next time, and motivating them to keep on trying. This in turn will increase student motivation, encouraging them to solve problems more effectively. Although this condition is only explicitly mentioned by Mayer (2008), it is also in line with the criteria mentioned by De Corte (2004).

As De Corte (2004) states and Mayer (2008) confirms, many of these guidelines still need to be validated in future studies.

The basis for a great deal of research into strategic knowledge as a major aspect of problem-solving can be found in the work of Polya (1945), who was the first to distinguish phases in the problem-solving process. Many variants were later worked out to better describe the strategic knowledge used in the problem-solving process. One variant was worked out in practice by Schoenfeld (1992), an important proponent of the problem-solving approach in which students take the initiative in building up their strategic knowledge. He investigated expert and novice problem-solving behaviour and, based on this research, distinguished five ‘episodes’ in the problem-solving process:

1. survey the problem (read, analyse)
2. activate student’s prior knowledge (explore)
3. make a plan (plan)
4. carry out the plan (implement)
5. check the answer (verify)

According to Schoenfeld (1992), by knowing and understanding these episodes, students have a general strategy to solve problems. By working out
problems according to the episodes, students do not have to follow a linear course, but spend time on all episodes.

Schoenfeld (1992) argued that strategic knowledge is improved when novices learn to work through the episodes more effectively. In his work he showed how secondary school science students can learn to apply these episodes by demonstrating the processes experts follow. Students should answer questions about the episodes, such as: Do I understand the problem? Do I know what answer I have to provide? Do I know which knowledge should be applied? and Do I have this knowledge? If students are accustomed to asking these questions, they will start asking them automatically in new situations. In this way students are taught conscious use of the episodes.

1.3.4 Summary

Three types of knowledge play a role in problem-solving in physics education: first, declarative knowledge of the physical facts, formulas and concepts; second, knowledge of procedures such as the application of formulas; and finally, strategic knowledge needed to put the former two types of knowledge to work so that a solution is generated. Strategic knowledge is also about the individual’s knowledge of their own knowledge and about the conscious guiding of one’s own problem-solving process (meta-cognitive knowledge).

Strategic knowledge is not best learned through direct instruction and worked examples because students then follow standard procedures which do not offer them the flexibility needed to solve new problems. Support based on systematic help might be more effective. Students who get stuck need to be given feedback on their own thinking, approach, knowledge and overview of the knowledge needed to solve a certain problem. The final goal is for students to be able to solve problems without help. This is best achieved if students, while monitoring their own work on solving problems, recognize how the support provided helps them later on.

Support given to students working on developing strategic knowledge must meet certain criteria. Students should be actively involved (active role) in a process of solving a variety of subject-specific exercises (practice counts). In this process the student should have support available on demand, targeting specific aspects of the problem-solving process. This summary of the criteria for developing strategic knowledge highlights the benefits of computer-supported instruction. Such support can be organized individually and be designed in such a way that students receive help at their own initiative at the moment they
think they need it. The following section discusses how a computer program can give help to improve strategic knowledge.

1.4 Computer-supported instruction to improve strategic knowledge

Aleven, Stahl, Schworm, Fischer and Wallace (2003) distinguish four different kinds of computer instruction programs that represent different points of view as to what kind of knowledge should be supported in order to improve problem-solving. The first type is the Intelligent Tutoring System (ITS). Examples are the ANDES program for physics problems (VanLehn, Siler, Murray, Yamauchi & Baggett, 2003) and the intelligent tutoring program for solving applied algebraic problems developed by Koedinger, Anderson, Hadley and Mark (1997). These programs teach students to use diagrams and formulas in solving problems. If the programs detect a mistake by the student, they offer feedback which can help the student to solve the problem. Instructional support is delivered during the solution process. The student has to follow the instructions. Although these tutoring programs certainly have advantages, they also have their limitations. One important limitation is their narrow approach to the problem-solving process. VanLehn and Koedinger’s programs are based on the well-known cognitive architecture ACT-R (Adaptive Control of Thought – Rational) theory (Anderson & Lebiere, 1998), which looks at the process of problem-solving as a number of production rules that students need to acquire. Students are trained in solving problems by being guided through a certain number of steps in the problem-solving process. The programs do not explicitly try to develop strategic knowledge so that students can acquire their own problem-solving strategies (Shute & Psotka, 1996), but are directed more at applying declarative and procedural knowledge to a specific problem. Students usually have no control over the instructional support these programs offer.

The second group are Computer Assisted Instruction (CAI) programs. Aleven et al. (2003) state that these programs are based on the principle of providing instruction with questions and giving feedback on answers, to which end they provide model answers. The support is given before and after the problem-solving process, which is assumed to be unique. Because the main goal of CAI is to improve students’ declarative and procedural knowledge, once again little instruction is directed at developing strategic knowledge.

The last two groups of programs mentioned by Aleven et al. do not offer clearly structured support to students, but allow them to find problem-solving strategies for themselves. Educational Hypermedia Systems (EHS) are web-based
programs which offer information from the World Wide Web relating to a student’s question. The student can use the information provided by a search engine to fulfil a task. In contrast to the first two examples, this group of programs leaves students almost completely free in the process of finding solutions and merely presents the web as a place to find information. EHS filters the information offered to students, but the value of the information flow is not checked, which may mean that students are also offered wrong or irrelevant information. This type of program is aimed at improving problem-solving skills such as problem analysis and searching for information. EHS uses open problems that need to be specified by the students. There may be many ways of solving these problems and more than one correct answer. The effectiveness of the instructional support in these programs is open to debate (Eklund & Sinclair, 2000; Surjono & Maltby, 2003).

The last program type mentioned by Aleven et al. (2003) is Project or Problem-Oriented Learning Environments (POLE). These programs are inspired by situated learning approaches, in which context problems are presented in computer simulations. Simulations present simplified reality, for instance, a simulation of gravity showing how fast a stone falls from a tower, with graphs to clarify the formula involved. The context problems are often complicated and the students need a high level of prior knowledge to work through the problems in the programs (De Jong & Van Joolingen, 1998). This type of program also aims to encourage strategic knowledge. Because of the open structure of the programs, they are often ineffective for novices, who tend to explore the possibilities of the simulation without forming hypotheses about the principles underlying the phenomena.

The study by Aleven et al. (2003) reviews the different types of knowledge to be learned when solving physics problems, and also suggests how programs that support the learning of problem-solving can be designed.

Both ITS and CAI are aimed at developing student knowledge of problem solving by providing standard solution procedures that can be used to solve certain types of problems. Intelligent tutor programs often allow more than one standard solution, determining from the student’s actions which solution path the student seems to be following. However, Aleven, McLaren, Roll & Koedinger (2004) indicated that even intelligent tutoring programs often fail to generate the intended use of extra help by the students.

In CAI, worked examples are often used for instruction, with fading of support during practice on analogous problems. Students receive feedback on their answers based on the solution procedures in the worked example. In both
ITS and CAI, students are supported in their learning before and after problem solving.

EHS and POLE, on the other hand, aim at developing strategic knowledge that will enable students to apply general problem-solving skills to analyse complex problem situations and apply their content knowledge of a domain. For novice problem-solvers, these types of program are often too open and poorly structured. There is little instruction to show how problems can be analysed and solutions planned and executed.

In computer environments with program control, the program decides both when instruction is presented and the content of this instruction (direct instruction). The procedure for solving problems is clear from the start. Examples can be found in tutoring programs for problem-solving such as those devised by Albecate and VanLehn (2000) or Koedinger et al. (1997). The supply of instruction is predictable and unambiguous. Fine-tuning of the instructions to overcome imperfections in non-standard but otherwise adequate solution methods is often not provided. An important drawback is that program control leads to programs that are effective only in cases where the solving of similar problems is being taught (see Owen & Sweller, 1985; Renkl, 2002).

The drawback of being unable to provide instruction that fits with adequate alternative problem-solving approaches does not apply to student-controlled computer environments (indirect instruction). In these environments students can be given control over whether and when to consult the information offered by the program and which instruction method to follow (Taconis et al., 2001). Instruction can be designed in a way that leaves room for the students to choose different solution methods (Mathan & Koedinger, 2005; Mestre, 2002; Reif, 1995; Teong, 2003). One reason for preferring student control in a computer program is that it gives students sufficient room to develop strategic knowledge that fits their way of learning (Reif, 1995). Students need to acquire a flexible problem-solving strategy with which to tackle different types of problems.

Examples of the effectiveness of student control of problem-solving abilities can be found in the research of Mathan and Koedinger (2005) and Mestre (2002). Mestre found positive effects on problem-solving when asking students to design problems based on concepts and contexts in a certain domain. When working our these tasks, students received clues during the process of combining different parts of the problems to be designed. Mathan and Koedinger (2005) created a model of the ‘intelligent novice’. When using
this model, students first work out problems without help. If they want to move on before solving a problem correctly, they are advised to accept help in finishing the first problem correctly. Users of this model learned faster and performed better on a conceptual understanding test and on a transfer test than a control group.

In the first two groups of programs, as indicated by the review of Aleven et al. (2003), the system gives instruction. The programs decide when to support the student. The last two groups of programs, as indicated by Aleven et al. (2003), give control of the support to the student, it being assumed that students know best when they need help. Thus, at first sight strategic knowledge seems best if supported by a student-controlled system which allows students to work on their own individual problem-solving strategies. However, when implementing student-controlled learning environments, we need to consider the disadvantages of this type of instruction; students need a certain level of content knowledge and strategic knowledge to take control of the problem-solving process. If the necessary knowledge is not present, the student needs to be supported in gaining this knowledge. This may take some form of system control because a novice finds it hard to tell what knowledge is needed to work on new problems (Clark & Mayer, 2002).

A combination of system-controlled and student-controlled instruction is probably most effective. On the one hand, students should be able to follow a well-structured line of problems using the instruction available and thus preventing failure. On the other hand, in order to develop strategic knowledge, a program needs to be open enough to create space for students to choose their own problem-solving strategies. A blend of student-controlled and system-controlled instruction is also proposed by proponents of instruction through worked examples. Instruction with worked examples is too limited and needs further improvement in order to support diverse problem solving. One way of doing this is by not providing worked examples at the start of the problem-solving process but to offer hints during the process (Reif, 1995) and worked examples (model answers) as feedback afterwards so that students can reflect on the solution they have chosen (Moreno, 2006).

Summary
Computer systems supporting students in solving problems have been designed for different purposes. Closed systems support students in learning declarative and procedural knowledge. These systems follow well-defined problem-solving processes and can show students where to go if they fail to
solve a problem. In contrast to this are the open computer systems, which overwhelm students with information from which they have to choose. This latter kind of program helps students to improve their strategic knowledge, but a minimum base of knowledge is needed to benefit from them.

To allow students with less knowledge to benefit from a system, the system should combine both positive points. In other words, it should be closed in terms of supplying students with information that fits the problem-solving process, but open in that it allows students to choose which of this information to use. This means that students should guide their own help. By offering a well-defined set of help, even if students are not skilled in the subject to be learned, they will not lose their way in a forest of information, but will still be able to find their way out and solve the problem.

We therefore need to ask when help should be offered to the students. This question will be addressed in the following section.

1.5 Timing of instructional support

An important question when designing instruction to develop problem-solving abilities is: ‘At which moment is support most effective for the development of strategic knowledge?’ Supporting students in this development can be accomplished by giving instructions or examples before the problem-solving process begins, during the problem-solving process or after the students have found a solution.

Supporting students in advance can be done with worked-out examples in which students are clearly instructed about how to solve types of problems before starting to work them out for themselves (Owen & Sweller, 1985; Renkl, 2002). When using worked-out examples before problem-solving, a student learns to solve one type of problem at a time. In some situations the worked-out examples are available both before the student works out similar problems and during problem-solving. When the student works out the similar problem step-by-step with less reliance on the worked-out examples, thus learning to solve problems independently, this decrease in scaffolded support is called ‘fading’ (see Renkl et al., 2002).

Van Gog (2006) investigated whether instruction should be process-oriented or product-oriented or should gradually change from the one to the other. Process-oriented worked-out examples involve help that points to arguments for a solution procedure, whereas product-oriented worked-out examples involve the solution procedure itself. Van Gog’s experiments showed
a significant extra learning effect when the use of worked-out examples gradually changed from process-oriented to product-oriented during the learning process. In this way, students are first given an opportunity to develop knowledge about solution procedures, and then to investigate possible solutions. They are no longer hampered by a lack of knowledge of the correct procedure.

The success of worked-out examples can be explained by the fact that more general knowledge about how to solve a certain type of problem gives the student more mental capacity for explicit knowledge needed to solve a particular problem. Worked-out examples showed good results in cases where the problems solved by students were similar to those worked out in the examples. However, in cases where the problems worked out by students were very different from those in the worked-out examples, the effect of worked-out examples disappeared, or was even negative (Kalyuga, Chandler, Tuovinen & Sweller, 2001; Renkl et al., 2002). If students need to learn how to solve different types of problems, worked-out examples in advance seem to be ineffective (Moreno, 2006).

The second option for timing support is during the problem-solving process (just-in-time). Examples can be found in different tutoring systems, which give students help according to their actions. If a student does not succeed in finishing a problem, or gives a wrong answer, the program provides a hint which should help the student to continue with the problem-solving process (Albecate & VanLehn, 2000; Koedinger et al., 1997). Tutoring systems are based on the principle that students learn by developing their own initiative and combining different parts of a solution when trying to solve a problem. By helping students when they are struggling, tutoring systems guide them through the solution process and thus develop their strategic knowledge. Some researchers claim efficiency for tutoring programs when students are tested using problems similar to the ones they have already practised (see also Corbett & Anderson, 2001). Two issues need to be addressed when using tutoring systems to develop problem-solving abilities. Firstly, many tutoring programs are based on one superior procedure to solve problems. However, not all students use the same procedure when solving applied problems. In other words, when using a tutoring program, students are forced to follow one procedure although they might be better off with another. The other drawback is that students might become dependent on the tutoring program, hampering them in learning to find their own way to an answer (Fox, 1993; Schoenfeld, 1992).
The third option for timing support is giving help *afterwards* – also called delayed feedback – by providing students with worked-out solutions (model answers). This allows students to check their answers and compare their solutions with the one provided by the program. Special types of feedback afterwards have been shown to be effective under certain conditions (Anderson, Corbett, Koedinger & Pelletier, 1995; Bloom, 1984; Mathan & Koedinger, 2005). Feedback can be effective when provided directly after solving a problem. However, if the delay is greater, it is not effective because students may have forgotten part or all of their solution method (Mathan & Koedinger, 2005). The main disadvantage of delayed feedback relates to the amount of time that elapses between solving the problem and receiving feedback.

**Summary**

When helping students to solve problems, support can be given before, during or after problem-solving. Strategic knowledge is best supported with just-in-time feedback. This means that help should be available the moment students need support to go on with solving a problem. By making help available during the problem-solving process the moment students need it, the mental block can be overcome, and the process can continue. However, just-in-time help also means evaluating the problem-solving process directly after finishing a problem. Support thus needs to be available during (help) and after (evaluation) the problem-solving process. The level of support should gradually fade away so that students do not become dependent on the help, but can develop their own problem-solving strategies.

**1.6 Summary and conclusions**

Learning to solve problems is an important skill in life which needs to be learned in school. Problem solving plays an important role in physics, and is used as a way to learn the subject. In school practice, it is used to test the level of students in a certain domain. Being a good problem solver thus means that students will succeed in science lessons at school.

Research into problem-solving can be described very well from the cognitive perspective. From this view, successful problem solvers need three kinds of knowledge: declarative (facts, formulas, principles, etc.), procedural (when and how to use declarative knowledge) and strategic knowledge (monitoring and reflecting on the problem-solving process). The body of research on problem-solving and learning to solve problems is extensive, but
the characteristics of physics make it interesting to do research into problem-solving in this subject. Compared with mathematics, for example, problem-solving in physics incorporates more contexts from daily life. But contexts are also what makes it difficult for students to solve physics problems; preconceptions can block the learning of scientifically correct concepts needed to solve these problems.

In addition to subject knowledge (declarative and procedural knowledge), the learning of strategic knowledge plays an important role in physics problem-solving. Strategic knowledge cannot be viewed separately from declarative and procedural knowledge; it involves working within a certain domain and thus relates to domain-specific declarative and procedural knowledge. School science emphasizes the learning of declarative and procedural knowledge, but neglects the learning of strategic knowledge despite its importance for the solving of physics problems. This thesis reports on investigations into the learning of strategic knowledge within physics.

Strategic knowledge can be improved by solving a variety of problems that give students the opportunity to exercise and develop their solution strategies. The problems to be solved should not be too simple (closed problems in which students only learn declarative and procedural knowledge) nor too difficult (open problems which cannot be solved by students with insufficient content knowledge). Support needs to be available just-in-time, and with the students themselves guiding the help process as much as possible. Help should gradually fade away in order to give students the opportunity to develop their own problem-solving strategies.

As an alternative to individual support from a teacher, problem-solving can be supported by a computer program which guides the student when solving problems. Help can be offered before, during or after problem-solving. The literature has shown that support for the development of strategic knowledge can best be offered just-in-time, which means during problem-solving, and directly after problem-solving by providing model answers, offering students the opportunity to check and evaluate the problem-solving process. Help should be indirect, that is, students guide their own support in order to develop their own problem-solving strategies.

A computer program with the above criteria can be implemented in present school practice. The program should not replace the teacher, but should be implemented at times when students work on problems independently. Teachers regularly guide a whole class, groups of students, or one individual student at a time. By working with a program that takes into account the many
individual wishes of different students, all students can be supported all of the time.

Research into the use of such a program will tell us whether students really can benefit from using it to improve their strategic knowledge compared with students who work out problems using a textbook. Research into problem-solving in the normal classroom is especially rare and could increase our knowledge of the practical implications of supporting problem-solving. The next chapter will describe the working out of the ideas mentioned in this chapter. I will also describe a preliminary study into the effectiveness of this kind of support using cards offering help to students in solving physics problems. The results were used to develop the computer program *Physhint*, which will be evaluated in the remainder of this thesis.