UNIVERSITY OF LJUBLJANA
FACULTY OF MATHEMATICS AND PHYSICS
DEPARTMENT OF PHYSICS

Maja Poklinek

**Analyzing patterns in experts' approaches
to solving experimental problems**

Master's Thesis

ADVISER: prof. Gorazd Planinšič
COADVISER: prof. Eugenia Etkina

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Abstract

Investigative Science Learning Environment (ISLE) is a learning system, developed based on the history and philosophy of physics and observations of the work of scientists constructing new knowledge. It engages students in learning physics through processes that physicists use in their work. The processes form the so-called ISLE cycle – a logical progression of different steps from observation to testing. Research in this thesis investigates whether the physicists do indeed use the elements of ISLE while solving problems and also follow the logic of the ISLE cycle. We approached this issue with an experimental problem that was sufficiently novel to the experts so that they could employ the reasoning that they commonly use in their work. This research project is a comparison of four different case studies. Three case studies were conducted with pairs of expert scientists and one was conducted with students, who were videotaped while solving the same problem from geometrical optics. With the help of different graphical representations of the problem solving processes of the subjects we showed that not only scientists, but also students follow the transitions of the steps present in the ISLE cycle, although the experts were considerably stronger than the students. In addition, we observed that the students' problem solving approach in time became more similar to the one of scientists. It is possible that the logic of the ISLE cycle does not only come from the practice of scientists, but is a natural, inner way to approach this type of problems which easily transfers to solving similar problems.

Keywords: experts – novices, pair problem solving, Investigative Science Learning Environment (ISLE), ISLE cycle, light cone experiment, scientists, think aloud method, case study

Povzetek

Investigative Science Learning Environment (ISLE) je učni sistem, razvit na podlagi zgodovine in filozofije fizike ter opazovanj znanstvenikov pri gradnji novega znanja. Učence vključuje v učenje fizike skozi procese, ki jih fiziki uporabljajo pri svojem delu. Ti procesi tvorijo t.i. cikel ISLE, ki je logično zaporedje korakov od opazovanja do testiranja hipotez. V tej nalogi raziskujem, če znanstveniki pri reševanju eksperimentalnih problemov dejansko uporabljajo elemente cikla ISLE ter če sledijo njegovi logiki. K temu smo pristopili z eksperimentalnim problemom, ki ja zadosti nov, da lahko eksperti uporabljajo podobne procese, kot če bi se z njim srečali pri svojem delu. Ta raziskovalni projekt je primerjava štirih različnih študij primera, izmed katerih so bile tri študije izvedene z opazovanjem znanstvenikov – ekspertov, v eni študiji pa smo opazovali par študentov. Sodelujoče smo snemali, medtem ko so reševali isti problem iz geometrijske optike. S pomočjo različnih grafičnih upodobitev smo pokazali, da ne samo znanstveniki, ampak tudi študentje sledijo prehodom med koraki, ki so prisotni v ciklu ISLE, četudi so bili znanstveniki občutno močnejši od študentov. Dodatno smo opazili, da je pristop študentov s časom postal bolj podoben pristopu znanstvenikov. Možno je, da logika cikla ISLE ne pride le iz prakse znanstvenikov, ampak je naraven, notranji način, kako pristopiti k problemu takšnega tipa, ki zlahka prehaja na reševanje podobnih problemov.

Ključne besede: eksperti – novinci, reševanje problemov v paru, poučevalska strategija ISLE – Investigative Science Learning Environment, cikel ISLE, eksperiment svetlobni stožec, znanstveniki, metoda “think aloud” ali “misli naglas”, študija primera

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1

Introduction

In today's modern world, science and technology are developing much faster than in the past. All the time we are bombarded with new information and have to accommodate to new development. In order to get new knowledge it is important to know how to learn, how to distinguish important ideas from non-important and how to detect non-scientific information. Knowing “how” exceeds knowing “what”, or we could say that at this moment procedural knowledge is more important than factual knowledge. What an average person today needs are knowledge, skills and abilities to obtain new knowledge and solve different kind of problems.

As teachers, we are preparing young minds for their future lives, therefore it is important that we help them develop procedural knowledge. One possible teaching approach that enables students to enhance their problem solving abilities is ISLE – investigative Science Learning Environment [1]. It is an experiment-based approach that enables students to learn science and to think as scientists through repeated cycles of observations, pattern recognition, invention of explanations, and testing these explanations in new experiments.

If we want to help students to learn to think like scientists, it is necessary to know how scientists really think. In my master's thesis I explore how today's scientists actually think when they are challenged with an experimental problem, similar to those that we also use with students while teaching them through ISLE.

Problem solving could be not only a linear structure of some steps like cooking, but a complicated sequence of steps, like a web. My goal was to find patterns in scientists' thought process and compare them with the way students think when they encounter exactly the same problem. Additionally, I wished to compare these patterns with the way of thinking already encouraged by the teachers using ISLE.

1.1 Motivation

1.1.1 Motivation for the research

Physics education is gradually moving from the traditional method of instruction to more interactive approaches. One such approach is ISLE, a learning system that engages students in learning physics through processes that physicists use in their work. The processes form so-called ISLE cycle – a logical progression from the observation of phenomena to pattern recognition, then to the invention of explanations and the subsequent experimental testing of the explanations. The elements of the ISLE cycle has been developed based on the history and philosophy of physics and observations of the work of scientists constructing new knowledge. There is a plethora of curriculum materials that have been developed using this approach to learning and the materials were found to produce substantial learning gains in different student populations. What is missing in ISLE development and research is the evidence that physicists do indeed use the elements of the ISLE cycle and its logic not only while constructing new knowledge but also when solving problems involving the application of the existing knowledge

As ISLE is mostly used in physics courses, the beginning motivation was to see if expert physicists actually follow the ISLE cycle when faced with an experiment the outcome of which they cannot explain immediately. The necessary step here was an extensive analysis of the physicists' thought process. Such analysis is best obtained through a case study. The ISLE cycle is modeled after scientific approach and there are sciences other than physics, so the idea was to conduct the same research also with scientists from other fields to find similarities and/or differences in different scientists' approaches.

A good teacher is one that knows how to listen to her students and to learn from them. Although the focus of this research was to study scientists, as a future teacher I should also learn how to learn from students. That is why I conducted the same case study with a pair of physics students that had never met with this kind of problems in a physics class before. I wanted to see how the students, left on their own, solve the same problems and how their approach differs from the experts' approaches.

With several case studies I hoped to get some ideas about how science education could be improved so that students can learn to think as science experts. This research has limited results, being based on a few case studies, but the purpose was more to develop a method for further research than being widely applicable in school right away. This work is expected to offer a good basis and an inspiration for a further research, not only in the physics education but also in other sciences.

1.1.2 The light cone problem

For best comparison of the results all subjects under investigation should have solved problem in as similar circumstances as possible. The best way was that they all have been exposed to the same experiment that needed to meet certain requirements. The problem of the light cone meets all these:

- It has an appropriate difficulty. It is difficult enough so that it is a challenge for expert physicists. At the same time, the phenomenon can be explained by

using only basic physics, as we wish to show the same experiment to students and scientists from other fields.

- The experiment should be new, so that participating experts and students never have met with the observed phenomenon before.
- The possible testing experiments are easy and quick to perform, which is needed due to time and available material restrictions of the research. It is often enough just to move or rotate certain objects and the outcomes are instantly visible.

The phenomenon of the light cone is interesting and new to physicists. It is not simple to explain, however the only physics knowledge needed for solving it is Snell's law and the knowledge of total internal reflection, topics that are both taught in secondary school.

1.2 Research Questions

Having studied how the ISLE method is conducted in a classroom and having already pictured the research of scientists and students solving problem of the light cone, I shaped the following set of research questions:

- How do expert scientists solve the problem of the light cone?
- How closely does their solving pattern match with the ISLE cycle?
- What are the similarities and differences in problem solving approaches by different types of scientists: experimental physicists, theoretical physicists and pharmacists?
- What are the similarities and differences in problem solving approaches by scientists and by a pair of students?

1.3 Overview of the Thesis

In the 2nd chapter I first describe the ISLE method and the research regarding ISLE implementation in a classroom setting. Later in the same chapter I outline the existing research about how experts solve problems. I also describe the methodology I used and add the description of the light cone experiment.

In the 3rd chapter I describe my research from the planning and selecting participants to analyzing the results.

In the 4th chapter I focus on the results of each case study. After separate results follows the comparison of all the results with some comments.

In the last, 5th chapter I present the study results and suggest possible implications this work may have on instruction.

2

Literature Review

2.1 Introduction

The process of problem solving can be a very complex procedure due to complexity of our brains, which we do not fully understand. Consequently, the knowledge and research about problem solving are diverse. In this chapter I will focus on the existing literature that discusses how expert scientists solve problems. There is a lack of research in this area, especially that focusing on experimental problems, similar to the experiment I have conducted in my project. From the existing literature I will try to pull out the information about the approach experts use to solve problems that can be useful for my study. I will also quote the literature that compares expert and novice problem solving, considering that I am conducting the same case study also with a pair of students. In the second section of this chapter I will present the environment in which students at school can learn science through solving experimental problems. Later on I will present the existing literature on the methods I used in the investigation. At the end of this chapter I will describe the light cone problem used in this research.

2.2 Expertise in problem solving

2.2.1 Expertise and expert-novice comparison

The knowledge of how expert scientist think is of great importance, not only for deeper understanding of science, but also for the development of science education. Research on scientific thinking in science education is often based on introspections about what science is, the interviews with scientists, historical data and the prescriptive accounts of science. Each of these approaches lacks the detailed components of the actual cognitive processes underlying reasoning in science. [2]

Science takes place in a social context, since most scientists work on problems in groups, rather than alone. For that reason making generalizations of how scientists reason from research on individuals could be problematic. Scientific reasoning was mostly explored in individuals and therefore the social aspect of science was ignored. This is especially important when we investigate the aspects of science relevant to science education. [2]

Dunbar describes two approaches of how to determine the cognitive processes underlying reasoning in science. The first one is to bring scientists into the laboratory and to give them scientific problems to work on. The second is to investigate real

scientists as they work on their own problems. In both ways we can uncover thinking and reasoning strategies that enable new discoveries. [2]

Chi also writes about two approaches of how characteristics of experts, that are not necessarily scientists. First one was to study truly exceptional experts with the goal of understanding how they perform in their domain of expertise. There are many ways of determining whether one person is an expert. We can choose people from history or presence on the basis of their well-established discoveries. We can also choose scientists, whose breakthroughs are still debated. A second research approach to expertise is to compare experts to novices. This approach assumes that expertise is a level of proficiency that novices can achieve. [3] For example in a study of physics problem solving the researchers regarded the postgraduate students as the expert group and the rest of students as novices. The criteria of who is an expert was chosen extrinsically to the data of this research. In this case the postgraduate students had the highest score and fastest solution times. [4] Another expert-novices study was focused on categorization and representation of physics problems. Using a sorting procedure they also regarded the PhD students from physics department as an expert group and novices were undergraduates who had just completed a semester of mechanics. [5] There is also an example of study of information problem solving. Again PhD students from a field of Educational Technology were an expert group. All of them were in their final year. The novices in this case were Psychology freshmen. [6]

On the basis of the research up to that point Chi also writes about some ways in which experts excel and about some of their shortcomings. When solving a problem, experts come up with the best solution. They can detect some of the features that novices can't. For example the experts are able to detect important patterns. Experts spend a lot of time analyzing a problem qualitatively. They are better in detecting errors in their solving and the status of their own comprehension. They choose the solving strategy better. Experts are also more opportunistic users of the resources than novices. The cognitive effort with scientists is smaller when retrieving knowledge and execution of their skills is more automatic. However there are cases in which experts do not surpass novices. The expertise could be domain-limited. They can also have too much confidence in their capabilities when solving a problem from their own domain. Experts in some situations also fail to recall the surface features and overlook the details when they are glossing over the problem. Sometimes experts have trouble adapting to changes in problems, when changes are so great that don't apply in their regular routine. In some of these cases novices adapt faster. [3] However when they are asked to step out of their specialization, for example historians reading a text they had never seen, they can rely on more general problem solving. [7] Chi in her work describes the expertise in general, however there are different types of expertise. We can speak about adaptive expertise when the expert has the ability to adapt so that his solving addresses new situations. These are often situations when some knowledge is lacking. The opposite is the routine expertise, that is not adaptive to changes. [7] Expertise in scientific reasoning consists of both domain-specific and domain-general skills. A simple model to predict domain-generality of these skills is based on the distinctions between procedural and declarative knowledge. [8] In a familiar environment, people can behave quite effectively with just procedural knowledge, without understanding. [9] Expertise qualitatively depends on each domain. But it is also clear from studies across domains that the images of problem solving strongly depends on the nature of the problem that experts are asked to solve. [7]

2.2.2 Studying real scientists

The research described in the previous section studied expertise in general. In this section I will focus on studies where established scientists were considered. Dunbar, for example, spent a great deal of time in eight molecular biology and immunology laboratories. He discovered that a many findings were unexpected. For example, in one laboratory over a 9-month period 52% of all findings were unexpected. A finding was been coded as unexpected if the outcome of the experiment did not match with a prediction by the scientists. Approximately 54% of unexpected findings were attributed to unknown origins, 30% to methodological problems, 8% to a mistake, and 8% to a new mechanism. In every case an unexpected finding received considerable attention, especially the ones that were inconsistent with the scientists' current hypotheses.

Dunbar also studied the analogies that scientists frequently used. The analogy is used when a scientists builds on a problem that has been solved when she/he needs to solve a new problem. Dunbar grouped the use of analogies into four classes: when scientists formulated a hypothesis, design an experiment, fix an experiment, or explain a result. An interesting finding is that after a meeting scientists have very little memory of how they generated a new concept or solved a problem at a meeting that was recorded. Their memory was short particularly regarding the analogies that they made. [2]

Although science is a "group enterprise" where knowledge and reasoning are distributed over many scientists, very little is known about the nature of the thinking and reasoning that groups of scientists use. The distributed reasoning is when more than one person is involved in the reasoning procedure. For example if two scientists are working together, one can propose a hypothesis and another one is thinking how to test it. They found out that more than a half of the reasoning at a meeting is distributed. This indicated that distributed reasoning is an important component of today's science. [2]

From his findings Dunbar wrote a set of rules for science education. Educators should pay attention to unexpected findings, engage in analogic reasoning in both formulating hypotheses and solving research problems, use distant analogies as explanatory devices, engage students in distributed reasoning and make sure that the educators' current goal is not blocking them from considering alternate theories or ways of conducting experiments. [2]

Lawson in his work listed some examples from science. He found out that all of the examples suggest that at the main part of doing science lies in the "If... and... then... And/But... Therefore..." pattern of hypothetico-deductive reasoning. Therefore this study suggested that whole scientific research is guided by a general hypothetico-deductive method. [10]

2.3 Investigative Science Learning Environment (ISLE)

One of the major challenges in instruction is to invent new ways of assessing creative thinking and problem solving. An increasing number of investigators have become interested in approaches to instruction that enable the students to acquire relevant knowledge through solving complex and authentic problems. [11] One of these approaches is ISLE, the Investigative Science Learning Environment, that puts a student in the role of a scientist. This environment helps students learn physics by engag-

ing in processes that mirror the activities of physicists when they construct and apply knowledge. With ISLE, students can improve their conceptual understanding, problem-solving ability, and their use of various scientific abilities, for example how to form a hypothesis, make prediction or how to construct testing experiments. [1]

2.3.1 ISLE in a classroom

ISLE is an experiment-based approach to learning in which students learn physics through scientific processes. These processes form the so-called ISLE cycle – a logical progression of different steps from observation to testing. The basic construction of this cycle is shown in Figure 2.1. At the beginning of each conceptual unit, students first observe carefully selected physical phenomena. Students do not make any predictions about the outcomes of these experiments, but mainly look at it with “open eyes”. With the help of the instructor they collect relevant data about the chosen phenomena and look for patterns in these data. Then they construct ideas – hypotheses that could explain their observations. When appropriate, students are encouraged to suggest multiple hypotheses to explain a single phenomenon or a set of relevant phenomena. A hypothesis is any idea about the possible cause or mechanism, and the teacher allows students to freely express their ideas. In fact, all explanations are treated equally important before they are subjected to the testing procedures. [1]

Students then have to come up with experiments that will test each of the hypotheses. They design the experiments and predict the outcomes of the testing experiments on the basis of their explanations. Doing this they use sentences as this one: “If this hypothesis is true, and we do such and such, such and such should happen...” So their cognitive processes include hypothetico-deductive reasoning, frequent with scientists. [10] Students learn that a hypothesis can only be rejected, but never proved.

After conducting testing experiments, they make judgments about the correctness of each explanation under test. If the outcome of the testing experiment does not match the prediction based on the hypothesis, they check if they made any invalid assumptions while predicting the outcome of the testing experiment or while designing or performing the testing experiment before rejecting the hypothesis itself. If they made some false assumptions, they try to correct them and repeat the process. Otherwise, they can reject the hypothesis. If all hypotheses are rejected, they try to propose a different explanation directly or carry out more observational experiments to form new hypotheses.

If the outcomes of the testing experiments match the predictions based on the hypothesis under tests, the experiments do not disprove the hypothesis. In this case the students keep the hypothesis and try to make more testing experiments that would disprove it. The more testing experiments a hypothesis “survives”, the more confidence they gain in it. When they are confident enough, they think about how could we apply new-gained knowledge in our lives. [1]

Figure 2.1 The ISLE cycle [12]

All the way students work in groups, sharing ideas, explaining and convincing each other, as scientists do in their work. During this course students are active participants in all parts of their learning. They observe, seek patterns, think up ideas, draw pictures, predict, design and perform experiments, make and check assumptions and evaluate the testing experiment results. During whole cycle they use multiple representations: they learn to draw a picture of the apparatus, record data in a table, draw a graph and look for patterns in these graphs, etc. The instructor sometimes gives them hints about the use of representations. For example, a teacher may suggest the use of free-body diagrams to help students see a pattern in the data. [1] Students can then acquire a habit of automatic diagrams use [13] Use the different representations coincides with qualitatively and quantitatively reasoning about the phenomena. These procedures are also commonly used by scientists. [1]

Acquisition of abilities is not instantaneous, but can be a very long process. With ISLE students need to conduct several cycles of investigations to gain competence in the application of scientific abilities. One research shows that the improvement may be visible five to eight weeks of work, depending on the particular ability. [14]

2.3.2 ISLE is open-minded

ISLE is different from many traditional approaches, in which students' original ideas are often excluded, by a simple reason that the instructor knows that they are incorrect or inconvenient. ISLE is open-minded in a way that accepts all student ideas and treats them all with the same seriousness, since all the "good" and "bad" hypothesis are tested. Strike, Posner and others argued that a student will be able to adopt new ideas if he experiences something that contradicts to his prior idea and it is thus dissatisfied with them. [15] This experience can happen if the idea is tested.

From the aspect of accepting all students' ideas, ISLE instruction does not only differ from traditional, but also from some reformed approaches to physics instruction. [1]

2.4 Research methods

In this section I will present some of the research methods I used in the investigation for this thesis. My goal is to analyze the patterns in problem solving of scientists and students. Problem solving processes are complicated and their analysis demands several techniques. I've made use of several literature-based research methods to plan experiments, collect data, and analyze reasoning of students and experts. The most prominently used techniques in this study were case study [16], think aloud protocol [17], video analysis [18] and timelines [19]. I will present some literature on each of these methodologies.

2.4.1 Case study

A case study is the study of the particularity and complexity of a single case, coming to understand its activity within important circumstances. Although it examines only one case, it can provide reliable information about the broader class. [16, 20]

Despite the small sample, the case study can be extensive and the analysis can take a lot of time. Miles and Matthew describe assembling of qualitative data into traditional narratives as a source of burdensome and unrewarding activity. [21] Yin later describes three ways in which the problems of the case study analysis can be reduced. First he suggests distinguishing note-taking from narrative-writing, as constructing readable narratives for certain data elements can be very time-consuming. The second technique is tabulating meaningful events. The difficulties occur when investigators use categories that are too small and too numerous. Similarly many case studies are coded with the naïve assumption that anything might be relevant, so one ought to observe and code everything. Instead, the analysis should be focused on meaningful events in a case study. To know what is meaningful we first need to know what we are looking for, so the main questions of the case study do need to be constructed beforehand. A third technique is building explanations and it is relevant where case studies attempt to explain a phenomenon. [22]

There is a common misunderstanding that case study research is most useful for generating hypotheses, whereas hypothesis testing and theory building are best carried out by other methods later in the process. [20] K. M. Eisenhardt describes the process of theory building from a case study research. The process should start with defining research questions and then selecting cases by non-random theoretical sampling. Multiple data collection methods should combine qualitative and quantitative data. She writes that use of multiple investigators builds confidence in the findings and increases the chance of surprising results. Data collection and analysis, including field notes should overlap. Analyzing data is the main and most difficult part of building a theory from case studies. The process ends with shaping hypotheses, comparison with literature and reaching closure. [23].

2.4.2 Think Aloud Protocol

We speak about the think aloud protocol (TAP) when people are asked to think aloud while solving a problem, which enables analysis of resulting verbal protocols. This method can be used in psychological and educational research on cognitive processes. [17]

In the literature, TAP is described under different names: verbal reports, concurrent verbal protocols, retrospective verbal protocols, after think aloud and verbal protocols. [24] Literature separates two kinds of think aloud protocols. If subjects verbalize their thoughts during decision making, the technique is called *concurrent TAP*. Verbalization can also occur after the decision making. In this case we talk about *retrospective TAP*. Both have their advantages and disadvantages. In a study of the human decision making process, concurrent TAP provided more insights into separate decision-making steps. However, in the retrospective protocol, more statements about the final choice were provided. [25]

The TAP has already been used with goal to develop a theory about problem solving. [26] The focus of this study was on the differences between novices and advanced problem solvers while solving problems from thermodynamics. Preece, Rogers and Sharp comment that it is difficult to think out loud when the task becomes difficult. [27] A possible solution to avoid some silence is that two people work together and talk to each other. [24]

Because of its metacognitive nature, Think aloud pair problem solving (TAPPS) can not only be used as a research method, but also as an educational strategy. It focuses the attention on thinking of both persons. [28] Metacognition is a person's cognition about their own cognition, [29] which is present when students are explaining to each other their way of thinking. Research of Pate and Miller investigated whether TAPPS could improve students' problem solving success by focusing their attention on their own thinking. They came to the conclusion that the metacognitive nature of the TAPPS strategy does not improve problem-solving success when secondary-level career and technical education students do not possess enough domain-specific knowledge. They also recommend TAPPS as a formative assessment tool for checking students thinking and understanding of technical information for problem solving. [28]

However, research shows that metacognitive reasoning in the form of detection of used strategies is strongly connected with problem solving success. Detection and reflection of their own cognitive processes, which was most frequent with students and mature adults, improves the results. [30]

Someren, Barnard and Sandberg also write for TAP to be used to investigate differences in problem solving abilities between people, differences in difficulty between tasks, effects of instruction and other factors that affect problem solving. They see the TAP as a method to validate or construct theories of cognitive processes, in particular of problem solving. [17]

2.4.3 Video analysis

Video as data collection method is gaining popularity in educational and social science research. Videorecording can capture a great deal of details of interaction: talking, gestures, eye gaze, etc. It enables multiple observations of a single event that can be analyzed in detail. In self-reporting, it can occur that what is being reported does not match with the previous actions of a person. Videotaping eliminates this problem by enabling the researchers to re-watch the scene. Besides this, video allows a detailed investigation of reasons and consequences for various critical events. [31]

As any other method, videorecording has some disadvantages. The equipment needed is expensive and video analysis is very time-consuming, up to 10 times the duration of the videotape. Furthermore, completely relying on the transcription too early

can eliminate the benefits of the video because the video contains a lot of information and the transcript only captures some of it. [31]

The approach for video analysis can be divided into two groups: inductive and deductive approaches. The inductive approach is applied when the researcher has broad questions in mind but no strong orienting theory. In this case the repeated viewings are recommended by multiple viewers who should reach an agreement on major events, transitions and themes. [32]

When the researcher has a strong theory and clear research questions, a deductive approach is more suitable. In this case, systematically sampling from the videotape to examine specific research questions is involved. [32] For example, a study examined how a teacher uses gestures in explaining mathematics to middle school students. Researchers already had a hypothesis that gestures are more prominent and important in introducing new topics. They selected only the needed video clips and developed a coding system to categorize the facts and calculate the frequencies of events. The same coding was then used in further research to investigate future samples. [33]

Besides all this, the videorecording has a very strong ethical dilemma when the persons are recognizable from the presented material. [31] Although video data are non-anonymous, confidentiality can be kept in many ways. One such option is restricting access to the video and to the personal information such as the names of the participants or the names of the schools in which data were collected. Participants should be fully informed about the purposes and risks. They should participate voluntarily and be allowed to comfortably withdraw their participation anytime during a study without penalty. They should be informed about their rights to privacy and confidentiality. It is essential that the research purpose, the participants' rights, the potential benefits and the risks of participating are described so that the participants can easily understand them. They are described in a document, called informed consent form (ICF), that, besides informing, also protects the interests of both the researcher and the subject. [34]

2.4.4 Timelines

A timeline is a linear graphical visualization of events over time. [19] It usually contains a long bar labeled with time alongside itself and events labeled on points where they would have happened. [35]

Timelines are used in science education, for example to illustrate the students' use of different steps while solving a problem. [36] An example of such a timeline is shown in Figure 2.2.

2.5 Light cone experiment

Here I provide an example of an experimental problem, that can be used in the ISLE framework, the so-called light cone experiment. With this experiment, students can apply the concepts of geometrical optics that they have already acquired to analyze a complex phenomenon. [37] I will describe the instructions to set up the experiment and list the additional equipment needed for making basic testing experiments. At the end I will reveal the basic explanation of the cone formation.

Figure 2.2 A timeline, displaying students activities while problem solving [36]

2.5.1 Setting up the basic experiment

The equipment needed for making the basic experiment is:

- Transparent glass or plastic fish tank filled with water. A few drops of milk or glow in the dark color should be added to the water to make light beams visible.
- A laser pointer.
- White paper.

Observations need to be made in a darkened room. The white paper should be put under the fish tank, and both the paper and the bottom of the tank should be dry. The laser should point vertically down towards the water surface so that the beam hits the aquarium bottom with paper underneath. The setting is sketched in Figure 2.3. For a longer presentation I recommend a stand for the laser pointer, so that you can put it exactly vertical. A clothespin to keep the button on the laser pressed so that you don't have to hold it the whole time also comes in handy.

Figure 2.3 The setting of the light cone experiment. Laser points vertically down towards the water surface. The cone of light is formed in the milky water.

2.5.2 Other equipment

The article also suggests some possible explanations of the phenomenon that students may come up with and corresponding testing experiments. For conducting these experiments the additional equipment are needed: chalk, dry sponge, additional paper, fine sand paper, additional container to pour in the water from the tank, a thick slab of transparent plastic, a liquid with the same index of refraction as plastic. We can come close to this index of refraction with saturated water-sugar solution. [37]

2.5.3 The basic explanation

Here I provide the basic explanation of the cone phenomenon. For the deeper analysis we would need to take into consideration the properties of the light source, of the light scattering material, quality of walls of the fish tank (polished or rough surfaces), etc. However I describe only a simple explanation from ray optics, which is suitable for a high-school level.

We assume that the laser beam on the paper scatters in all directions. We also assume the refraction index of the liquid in the tank is lower than the refraction index of the material of the tank wall ($n_{glass} > n_{liquid}$). There is a thin layer of air between the paper and the bottom of the tank. After the light scatters on the paper, it re-enters the tank, where it refracts twice, first on the air-glass interface and then at the glass-liquid boundary. The fact that some light is always reflected on the boundary between two media is here neglected. The double refraction is schematically shown in Figure 2.4.

The heart of this explanation is that rays, scattered on the paper, that are parallel to the air-glass boundary are refracted into the glass at the critical angle. All other rays refract at smaller angles inside the cone. The cone angle is determined by rays that undergo refraction twice, first from air to glass at the critical angle α_{gl} and second from glass to water at angle α_{liquid} . [37]

Figure 2.4 Basic analysis of the light cone formation. The notation α_{gl} on the picture is used for the critical angle although the respective schematic ray has $\alpha_{air} < 90^\circ$. [37]

The critical angle at air-glass boundary is given by the equation:

$$\sin \alpha_{gl} = n_{glass}$$

For the refraction on the glass-water boundary we can write the Snell's law:

$$\frac{\sin \alpha_{liquid}}{\sin \alpha_{gl}} = \frac{n_{glass}}{n_{liquid}}$$

By combining the previous two equations we can express the sine of the apex angle of the cone observed in water as

$$\sin \alpha_{liquid} = \frac{n_{air}}{n_{liquid}}$$

From the expression for the cone angle α_{liquid} , we can see that this angle is determined only by the index of refraction of liquid (in this case water) and the index of refraction of the medium between the paper and the tank (in this case air). Notable, it does not depend on the tank wall material or its thickness. [37]

If we use the values for refractive index of water: $n_{liquid} = 1.33$ and of air: $n_{air} = 1$, we get $\alpha_{liquid} = 48.7^\circ$. The total angle at cone apex is twice as large, which is 97.5° .

2.6 Summary

The needs of the workplace and the condition for the development are the people with knowledge, ideas, skills and abilities to critically separate scientific from non-scientific and to know how to observe the world around them. Besides this people should know how to solve every-days problems, get new knowledge and technological ideas. By gaining skills of a scientist peoples' attributes will approach all these needs. Educational systems play a big role in shaping young minds, so they should provide an environment in which students could learn the scientific reasoning. If we want the student to learn to think as scientists, we must first know how expert scientist actually think and reason. For this reason multiple research has been done by interviewing, historical data, observation of scientist at their workplace, etc. to get a step closer to understanding the cognitive processes of scientists. Science is mostly a social event, in which scientists formulate hypotheses, design, predict, perform and explain experiments. All the way they are using hypothetico-deductive reasoning and make different presentations of their work. Scientists pay attention to unexpected findings, engage in analogical reasoning when forming hypotheses and solving research problems, use distant analogies as an explanatory device. Also the scientists are not perfect in all views. Even to them it happens sometimes that their current goal is preventing them from considering alternate theories or different ways of conducting experiments.

All this knowledge can be applied in our curriculum that is building on educational approaches that encourage scientific reasoning. One such approach is ISLE, the Investigative Science Learning Environment. ISLE helps students learn physics by engaging in processes that mirror the activities of physicists when they construct and apply knowledge. With ISLE students can improve their conceptual understanding, problem-solving ability, and their use of various scientific abilities, for example how to form a hypothesis, to make prediction or how to design testing experiments. ISLE is an open-minded social environment, different from traditional and also some reformed approaches. It requires time and patience for ability or skill to develop.

This thesis' research also studies scientists and aims to unpack the processes they go through when solving an experimental problem. A mind of a scientist is complex and requires complex analysis. For this reason several techniques were used to conduct research described below. These were case studies, video analysis, think aloud protocol, and the timeline graphs. The center of this research was solving a problem of the light cone by science experts. Light cone experiment is simple to make, but complex and new enough so that even scientists could spend considerable time explaining it.

3

Research

3.1 Introduction

This work is unique and original, not only with the idea and approach, but also in the way of analysis. I will present how the research and its findings developed from the initial idea. We did not select all the participants at once and the coding system was being ironed over till the end, even long after we already have had some interesting results. The program I used luckily enabled changes in the transcription so that corresponding graphs were easily produced. In this chapter I will share a brief description of the research progression. Then I will describe the way we selected participants, how we planned the research, the coding and finally the graphical representations that gave us a better insight in processes that scientists use when solving experimental problem of this kind. Some of these graphs present a unique way of presenting data in clear way.

3.2 Research progression

It all begun with the initial idea of prof. Etkina and Planinšič to study how expert physicists solve problems, used in ISLE. More of this the reader can find in chapter 1.1. We had our idea and an appropriate experiment that physicists could solve while we would study them. My idea was not to include only physicists but also other scientists who possess enough knowledge of physics that they are able to solve the problem. I suggested pharmacists because of my previous experience in the study of pharmacy. We had to choose the methods and set the beginning coding system, on the basis of which the videotaping was planned. The first two case studies were conducted with a pair of expert pharmacists and a pair of expert physicists, one of which was a meteorologist and the other was astronomer. We coded both pairs solving problems and the initial results were in favor of our initial hypotheses. Good initial results were an inspiration and a driving force to conduct the research with students and another pair of theoretical physicists who rarely do experimental work. From the beginning till the end of this research I was developing graphical representations that would enable us to have a simple comparison of all four case-studies. I came up with graphs of transitions between steps and graphs for simultaneous use of different steps that I later describe in section 3.6.3. These graphs provided us with better understanding of the complexity of cognitive processes that scientists and students use while solving problems.

3.3 Choosing the method

We decided that each case study should be done with a pair of scientists. There were many reasons for this kind of decisions. Here I will list the ones that seem most important:

- When conducting the think aloud method, the moments of silence can occur, for example when the task becomes difficult. [27] A possible solution to avoid this silence is that two people work together and talk to each other. [24]
- If two people work together, we thought that there would be less tension for each of them than in the case of individual solving, because they would not be the only ones at the focus of attention.
- In ISLE students also work in groups [1]. For that reason we wanted to look at the process from the group problem solving point of view so that we could compare it with the way ISLE is implemented.
- Science is a social enterprise [2] and scientists often work in groups at their workplace. We were interested in the way real scientist cooperate with each other.

We decided to work with pairs, not with larger groups, because with larger groups it is possible for one person to become passive, or that he or she at some stage does not express her opinion because the other two are having a conversation.

We needed science experts. In our case these were scientists that for many years have actively worked in science. For that reason we chose to study university professors. The reason was that in Slovenia, one needs a great deal of scientific publications at the national and international level to become a professor. Each of the chosen participants had at least 20 years of scientific publishing. As professors they were also interested in our research and willing to participate, because they teach as well.

The first case was a pair of pharmacy professors. The second case was an astronomer and a meteorologist, both professors at a physics department. Later in this work I will call these two “experimental physicists”, although astronomy and meteorology are not typical experimental disciplines. Unfortunately due to time restriction we did not conduct the research with “pure” experimentalists, but it would be interesting to see how scientists that often deal with practical experiments, deal also with this problem. The third case were two pure theoretical physicists, who at their workplace mostly develop the mathematical aspects of a theory and rarely engage in experimental work. The fourth case was a pair of physics students at their last year of second Bologna cycle. They are both successful students, two of the best students from their cohort and both decided to continue on the physics PhD program. Their knowledge of physics is extensive, but before this research they have never met with a kind of problem where they would need to explain a physics phenomenon. In their study of physics they were taught in a very traditional way. We cannot say that it is the knowledge of physics laws and formulas that separates them from scientists. The main difference between them is years of experience in actual research. I called the groups of scientists the expert groups and the group of physics students the novices.

Experts in our research were all males and the students were a mixed group of a male and a female.

3.4 Videotaping plan

3.4.1 Goals

Besides the main research questions which I described in section 1.2, we wanted to extract as much information as possible from the process of problem solving that took place. I made a list of things that could be seen from the video records:

- How careful is their observation of the initial observational experiment (OE), for example how many phenomena they notice?
- How much time do they need for thinking/reasoning at a particular stage (initial reasoning about the phenomenon; proposing hypotheses, designing testing experiments (TE), performing TE, etc.)?
- What is the sequence of using particular stages (for example do they first propose several TE and then conduct them or do they plan, test and make a judgment about it one at the time)?
- Do they attempt to conduct TE to prove or reject their hypothesis?
- When planning TE do they think about possible outcomes (do they try to connect outcomes with different hypotheses or only with the one they test)?
- When conducting testing experiment do they think about possible outcomes (do they try to connect outcomes with different hypotheses or only with the one they test)?
- How are their hypotheses connected with their previous knowledge?
- How is their planning of TE connected with their previous knowledge?
- In what cases do they try to reject the hypothesis without planning and performing any testing experiment?
- How careful is their planning of TE?
- Do they change/modify/improve their TE during the process of conducting the experiments?
- How many different hypotheses do they formulate?
- Do they fix to one hypothesis which they think is the best and try to test mostly this one?
- In what circumstances do they use different representations?
- What are differences between both persons in all items listed above?
- How do they cooperate (for example, are ideas of one of them dominant or are they equivalent)
- What are psychological characteristics of both experts (for example: shyness, introversion, inferiority, courage, positive attitude, motivation, impulsiveness, complacency...)?

3.4.2 The scene setup

The responsible researchers for the time of videorecording were prof. Planinšič and I. According to ICF, we are the only two who can have the access to the videos and also the only two who are present at the videoing. Thus in the following text in this chapter by “we” I mean prof. Planinšič and myself.

We use two independent video cameras at different positions, one above the table and one in front of it. The first one has the main part of the table and both participants in its focus. It records what the participants are drawing or writing, how they are moving other objects on the table, where they are turning and what kind of gestures they are making. The second camera is focused on the experiment and the participants’ faces, so that it’s possible to tell where they are looking. Both cameras record sound and we have a Dictaphone on the table as a backup. The setting is illustrated on 3.1.

Figure 3.1 The setting of the scene. On the table is the experimental setup, two stacks of white paper, two pens and Dictaphone. One video-camera is positioned above the table and the other in front of it. Participants sit at the table.

The filming is in a room in which we have a lot of different equipment that can be used by participants for conducting testing experiments.

3.4.3 Initial instructions to participants

When inviting physicists to this research, we provided them with an informed consent form (ICF), an English translated version of which can be found in the Appendix A. The whole plan for our video-recording was done with consideration of the ICF.

The participants receive small gifts, including a pen and a protractor. The latter is not immediately visible, so that it doesn’t apply that they should measure anything. We all sign an ICF. I turn on both cameras and dicta-phone. On the table we have the experimental set up, two pens and two stacks of white paper. I tell them that they can freely use the papers if they wish, and that they will be used after the filming as an additional research resource. I tell them that the experiment that we will show them might have an interesting result. Their job is to explain the phenomenon that seems interesting or surprising to them. They should explain it in the same way that

they would explain something surprising that they encounter in their laboratory. To students I say that they should imagine that they are two scientists, working in a laboratory and give them exactly the same instructions. I tell them that they should explain the result so well that they have enough confidence in their explanation. I tell them that if they need any sort of additional equipment, they should just ask for it. I tell them that if they have any questions, they can ask now. During solving the questions should be minimized.

I explain the setup of the experiment in this way: we have here a glass aquarium. Inside is water that contains few droplets of milk, only to make the path of light in water visible and doesn't influence the essence of any visible phenomenon. Under the aquarium is a piece of paper and here we have a green laser pointer. I will now turn on the laser and leave you on your own.

Finally, I turn on the laser and let the participants observe on their own.

3.4.4 During the solving

We do not interfere in the solving process. If they ask us, we bring them additional equipment. The only circumstances in which we are allowed to speak are following:

- If we feel that participants would like to do something, but don't have the equipment. In this case we say: "If you need anything, just ask for it."
- If we feel that they forgot that they can make additional experiments, we remind them only once.
- If we feel that a participant is having an important idea, but we don't understand his explanation. In this case we say: "I didn't understand the explanation, could you repeat it?"
- If we feel that they need more or less bright room, we ask if we darken the room or turn the light on.
- If we don't have the equipment for the testing experiment they want to perform, we can propose another testing experiment for which we have the equipment, that is analogous to the experiment they thought of.
- If they are wondering about the value of some constants, for example the refraction index of glass, we can tell them.
- If they wish to use the computer to find some information, we can allow it and help them to find information that they are looking for.
- If they are wondering about some laws of physics, for example the Snell's law, we can explain it to them.
- Whenever they ask us a question related to the experiment setup or some additional information

3.4.5 When they say this is it

When they say that they are sure that they explained everything, I ask them to illustrate their final explanation and explain it once again. I tell them that they were solving very well. If they did not come up with the right explanation, I do not tell them. Instead I congratulate them and say, that their thinking was very good and even we do not have a 100% sure explanation. However if their explanation matches with ours, we can tell them that they explained it in the same way as we and that we think this is the correct explanation.

3.5 Coding

Coding was performed directly from the video-recording. I went through the video and marked all the steps that were a part of the actual solving. In transcriptions I marked some other things as well, for example my interventions, but I did not include any of things that were not a part of their solving into further analysis. My main goal was to compare expert solving pattern with the ISLE cycle. For this reason I specifically marked the steps of the ISLE cycle. Additionally, I marked the use of multiple representations, that are not directly marked as a separate step, but are prominently used by students throughout the whole cycle. The steps that I couldn't categorize as any of these steps I put under the category "Other".

We checked the reliability of the method by two persons independently coding a part of the transcript. We concluded that the method was very robust, because both persons mostly coded the same steps. There was some disagreement, that resulted in a wide discussion in which we came to the same opinion. We mostly widened or changed the definitions of some steps and added another category – "other". We regard this kind of coding very objective, if only the criteria is well defined.

The coding itself was the most time-consuming part of this study. I coded the data from each case-study for approximately two weeks and went through videotapes and transcripts several times. It is possible that one can still disagree regarding naming a certain step, but due to the amount of data in the resulting representations the importance of naming a single step is negligible.

At each step I wrote one or more names of a step, because some steps could fit in more than one category and also because two people in some moment could perform of talk about two different things. I also marked the phenomenon and hypothesis that a step is concerning. In the second column I wrote the explanations about what is which hypothesis or some other comment of the participants' activity, so that the reader can get deeper understanding of the solving and to make the following analysis easier. In the third column I wrote the exact words that participants used when they were in a step. From this third column we can see the activities of both persons, that I later in this thesis represent in the timelines graphs.

3.5.1 Criteria for marking steps

"Observing" is when they are watching an experiment as a whole without predicting the outcome. During the observation they often list the phenomena they observe, without describing and focusing the observation on the details of a single phenomenon. It is not necessary that they observe only the initial experiment (the light cone exper-

iment), but they can also observe some experiments that they conduct during their solving. **Accidental observation** is when they are doing and focusing on one thing and accidentally notice something else that seems surprising to them. This can be another phenomenon or that the phenomenon they already saw somehow changes. For example, when they lift up the aquarium to see if the angle of the main reflected beam changes or not, they notice that the initial cone disappears.

“Recognizing patterns” is when they are observing the details of a single phenomenon, e.g. the sharpness of the cone, seeing if it is axially symmetric or not, etc. It is also when they are finding the dependencies between different quantities. For example: they shine a laser at different angles and watch how the cone angle disappears. Before doing this they make no prediction on the basis of their previous hypothesis about how the dependency should look like. They also have no hypothesis that they would try to disprove by doing this. They before however can make a prediction that is based solely on their intuition. Sometimes the distinguishing between the observation from finding patterns is subjective, for example when they are quietly watching at the aquarium. It can be hard to know if they are looking just at the details of a single phenomenon or at the experiment as a whole.

“Forming hypotheses” is when they form an explanation of a certain phenomenon, sometimes also when they explain an outcome of a certain testing experiment – in this case we have overlapping of hypothesis and judgment. It is not necessary that the hypothesis contains the whole mechanism for the phenomenon, it can contain only a part of it, for example the sentence: “I think that the paper under the aquarium is responsible for spreading the light in different angles.” does not explain the whole cone formation, but I do mark it as a hypothesis for the cone formation. I marked the qualitative modifications of the same hypothesis as different ones. For example “The cone is formed on the air-glass surface.” is a modification of the hypothesis: “The light spreads on the paper, but then something cuts off some angles.”

“Designing experiment” is when they say how they would perform the testing experiment. That can be before performing a testing experiment or while performing it. For example when they think about the improvements in the testing experiment that they are performing. Experimental design occurs also when they are planning the numeric calculation of some properties of the phenomenon, knowing that they will measure it afterwards, for example when they say: “Let’s calculate the angle and then we will measure and see if this could be correct.” I marked a design of the experiment also when one of the subjects was giving instructions about how he or she should perform the experiment.

“Predicting the outcome” is when they say anything that would indicate that they are thinking about the experiment’s outcome, that they have not seen yet. Sometimes they don’t say anything but from the following words it is clear that in their minds they had the prediction about the outcome, before they saw the outcome. In this case I mark also as a prediction a step during which I conclude that they made a prediction. Selection of the time when I think they made a quiet prediction can be very subjective. Most predictions are **qualitative**. That is when they predict whether

a certain phenomenon will be visible or how will it change, without predicting numeric values of certain phenomenon's properties. In the contrast the **quantitative prediction** is when they calculate the numeric values of the phenomenon's properties, that they want to measure afterwards.

“Performing testing experiment” is when they perform an extra experiment or measurement, when they use the theory or they just reason to disprove a certain hypothesis. When they are performing the experiment or measurement, the testing experiment performing lasts from when they start moving objects for making an experiment, until they finish reading the results. I also mark the step as testing experiment if they are disproving the hypothesis, that they haven't said out loud yet, but one of them probably thought about it.

“Judging the outcome” can come only after the experiment has been already done or while it is being done. It is whenever they talk about the possible reason for that kind of outcome or partial outcomes of a single experiment. Judging the outcome is also whenever they are comparing the outcome with the prediction based on a hypothesis, for example it is enough if they say: “the outcome should not be like this” or: “Yes, this is it” (when they after the experiment performing think that their hypothesis is correct). Another case when I mark a step as judging the outcome is when they are drawing a conclusion from the testing experiment in the form of a new hypothesis. In this case I mark the same step as both, forming hypothesis and Judging the outcome. If they are using a result of an experiment to reject or validate a hypothesis that they formed long after the experiment has been done, this is not a judgment.

“Making or checking assumptions” Making assumptions and checking assumptions are two different things, but I put them in the same coding, because in all cases participants make very little explicit assumptions and also very rarely explicitly say that they are checking/thinking about whether they assumed too much. The assumption is also when they are assuming that a certain physics law can be used in some circumstances, where there might be other things included that could change the validity of the law. For example saying that the intensity of the cone in water falls with square of the distance is an assumption because the light also scatters on the milk droplets and this statement would need some thinking over.

“Using multiple representations” is whenever they draw or write on the paper or on the white-board.

“Other” is used for all the steps that are a part of their solving but cannot be categorized in any category from above. Here I will list only some of these steps. “Other” is when they are analyzing a phenomenon in detail, considering all the knowledge and different testing experiments that they already made. It is also when they are summing up, describing or making list of what they have already done or seen. It is when they are making conclusions about a hypothesis regarding many testing experiments. It is when they are finding different data or think of possible applications of a phenomenon. It is also when they are using a result of an experiment to reject or validate a hypoth-

esis that they formed long after the experiment has been done, it is a sort of looking back. It is also when they are making a scientific question, for example, when they explicitly ask themselves: “But what forms the cone?”. It is also when it is seen that they are thinking very hard, but don’t tell what. It is also when one of the scientists explains the other one his previous actions or thoughts. Last but not least, “other” is also when they are planning what to do next.

3.6 Graphical representations

This research turned out to produce a lot of data from extensive coding. It was a challenge to present all this data in a clear and intuitive way. In some previous research where a solving process was represented, they used the timeline graphs [36, 38, 39]. As the others, we also wanted to see the complexity of their solving and the use of steps in time that can be nicely seen from the timelines. However, I wanted to show more than just the use of different categories in time. For that reason I designed two different coloring of steps that I will describe shortly. We saw some patterns from the timeline graphs, that matched with patterns from ISLE cycle, but it is hard to see the frequency of certain transition or which steps are mostly used simultaneously. The last thing is important for example for the use of multiple representations. I was interested with which steps the use of multiple representations is very frequent. I designed two more graphical representations from which these kind of information is easy to see. Miha Cančula wrote a program that takes the transcriptions from a formatted file and outputs these graphs. [40] Here I will describe all different representations that I used and explain what kind of information we can extrapolate from them.

3.6.1 Timeline with steps colored by hypothesis

In the light cone experiment, the light cone itself seems to me the most interesting phenomenon. With all experts and the pair of students it turned out that they also spent most of the time analyzing the cone. To better represent how they solved the problem of the light cone, I decided to color the steps in the timeline that are connected with a certain hypothesis regarding the cone. Every hypothesis, connected with the cone phenomenon has its own color and the other steps are colored gray. When a certain step is connected with more than one hypothesis, the rectangle on the graph is colored with more than one color. From these graphs can be seen when their solving is focused on which hypothesis. It is possible to determine how many times they test the same hypothesis, how many hypotheses they form at once, how big a part of their solving they dedicate to the cone, and so on. An example of this kind of coloring is in Figure 3.2.

Figure 3.2 An example of a timeline with steps coloured by hypothesis

3.6.2 Timeline with steps colored by person

The social aspect of science is very important. The ways scientists and students interact with each other and complement each other can be seen from the timeline graphs where the rectangles are colored by the person speaking or doing something important as a part of a certain step. From these graphs we can see how and when each person is active. All steps in which only person A is active are represented by red color, all steps in which person B is active are blue, and steps when both are active are purple. If we compare these timeline with the one colored by hypothesis, we can see in what way both participants are active within a single hypothesis. An example of this kind of graph is seen in Figure 3.3.

Figure 3.3 An example of a timeline with steps coloured by person

3.6.3 Graph of transitions between steps

I defined transitions between steps in the way of looking at the circumstances at the beginning of a step. On the next two figures, 3.4 and 3.5 I have sketched the definition of transitions into step A on two hypothetical timelines. A transition into step A is marked from each step that was occurring at the moment at which step A started. If there was no activity at the moment when step A started, then the transition into step A is marked from one or more steps that ended last before the step A started. Transition is not just a connection between the two steps it also has direction. In the figures 3.4 and 3.5, only transitions towards step A are marked. It is important to establish what exactly constitutes a transition, so that one can interpret the graphs of transitions, described in the following lines.

Figure 3.4 An illustration of what I defined as a transition into step A in the case when there was some activity when the step A started. Step E started at the same time as step A, so there is no transition between these two steps. The only two steps that were occurring at the time when A started, were B and C. I count both of these two paths as transitions into step A.

Figure 3.5 An illustration of what I defined as a transition into step A in the case when there was no activity when the step A started. At the time that A started, there was no marked activity. The last step that occurred before step A started was step B. I mark the path from B towards A as a transition.

Figure 3.6 shows an example of a graph of transitions between steps that I made for all groups. Transitions between two steps are shown with arrows. The size of each arrow and the thickness of the line are proportional to the number of times the

transition between the two steps occurs during the whole process of problem solving. The actual thickness of a line on the graph is a sum of thicknesses of the lines that go in both directions. Another feature on these graphs is that the surface area of the circles for each category is proportional to the proportion of time that experts or students spend on certain step. Note that the surface area of the circles is normalized, so they reflect the proportion of time spent at each step, while the line thickness has an absolute scale. Solving with a larger number of transition will therefore produce graphs with thicker lines on average. The most important thing is that the dynamics of problem solving, in the form of frequency of different step sequences, can be seen from these graphs.

Figure 3.6 An example of a graph of transitions between steps

3.6.4 Graph of simultaneous use of different steps

In some cases we are not only interested in the transitions between steps but also in the simultaneous use of different steps. The overlapping of the use of multiple representations with other steps is just one of many examples. The strong simultaneous use of a hypotheses and judgments for example indicates that the participants acquire many ideas from the outcomes of testing experiments, which could be an interesting point in itself.

I designed graphs that show the number of times that steps from two different categories are used together. The thickness of the lines that connect two steps is proportional to the number of times that these two categories of steps overlap in time. The surface area of the circle is again proportional to the portion of time a certain type of step was used. The example of this type of graphical representation is shown in Figure 3.7.

Figure 3.7 An example of a graph of simultaneous use of different steps

4

Findings

In this chapter I introduce the findings of each case study separately. For each pair I describe the general solving, considering also the graphical representations of the solution process. I select some of the participants' statements that are interesting either because they depict some characteristics of their problem solving approach or their psychological characteristics. I also focus on the instance of a critical moment when the participants developed the idea for the final explanation. These instances are specially important because from them we can learn in what kind of circumstances we should encourage the students to think about possible explanations. Different graphs for each problem solving process are shown at the end of each section.

4.1 Pharmacists

4.1.1 General description of their solving

Pharmacists showed a lot of enthusiasm to participate in this study. It looked as if they really enjoyed solving the problem, and also at the end they said it was a great fun to them. At the beginning they were a bit skeptical about their knowledge of physics, because we told them that this was a physics problem. One of them also told me not to expect too much, because it is a long time since they did some serious physics. However during the problem solving their knowledge of physics was sufficient. They did not remember the physics laws in details but knew about the phenomena they encountered. For example they knew that light refracts when it goes from one media to another, but they did not remember Snell's law in detail. They knew that there are some sines of both angles in it, but did not know from where the angles were measured and if there were also the wavelengths in the formula. We explained to them the relation, because we were not studying their understanding of physics but the way in which they approached the problem. They could also easily check the information on the Internet or in some book if they were at their workplace. Another reason is that the students in class would solve this kind of problem if they already knew the formulas from previous lectures.

Although the problem was from physics, the hypotheses they made were connected to the field of their expertise. One of the hypotheses was that the reason for the spread of light was fluorescence. Although the fluorescence is a physical phenomenon, in general pharmacists very often meet with it, mostly because some drugs fluoresce. [41]

From the timeline graph 4.2 we see that most of the steps that lasted longer than

average are colored with purple. This means that in these steps both persons were actively participating. In the steps that lasted for a shorter time, person A was more active than person B, but the difference was small and we can say that both experts contributed a great part to their final solution. If we look at the graph colored by the active person, we can see that from the shorter steps there are only few steps colored purple. This is a feature of the coding, as the shorter steps were represented by a single thought that one of them said out loud. We can, however, observe quick exchanges of the two colors, which implies they were both active.

They dedicated the largest amount of time to performing of the testing experiments. They spent a little less, but still a lot of time on finding patterns, making judgments and on the “other” category. They also used quite some time for making hypotheses and using different representations. They spent little time observing and designing testing experiments. They spent least time on assumptions, which were also the step used the least.

In their solving in general, pharmacists were very systematic. Systematic patterns of sequences of experimental design, prediction, testing experiment performing, and judgment can be seen from the timeline graph in Figure 4.1. This sequence usually follows right after they form an explanation. After their initial observation they immediately formed a hypothesis. The reason was that the first phenomenon that they observed was the reflected beam besides the original one, and this phenomenon was simple for them to explain. However, a few minutes after this, when they noticed the cone that is a much more complex problem, observation was followed by pattern recognition and after this by a hypothesis. The third observation was an accidental one and was again followed by pattern recognition by person A that for the person B served as a testing experiment for a hypothesis he had before about the reflected beam. Again the observation was not so simple for them to explain, as before with two beams. From the transition graph in Figure 4.3 it can be seen that pattern recognition is mostly followed by hypothesis formation, although the hypothesis formation can occur in many different circumstances. It transitioned from all other steps categories, except from assumptions, which were used very rarely. Another step that was not followed by a hypothesis was making predictions. However the transition in the other direction, from hypotheses to predictions, is very frequent.

From Figure 4.1 it can be also seen that they mostly formed one hypothesis about the cone at a time, but at two occasions they also formed two, one right after another. In the first case the two hypotheses were not connected, but were two totally different hypotheses. In the second case each person formulated his own hypothesis as a result of disagreement between them.

If we look at the graph that shows simultaneous use of different steps, we see that they often make judgments while performing a testing experiment. So they are reading the results and explaining them at the same time. For example instead of saying: “I see the point in which the beam reflects and it is on the upper surface” (this would be just reading the result), they say: “Yes, from the lower surface. Oh, wait, it’s from both of them, although much less from the upper one, can you see two parallel beams?” – so they read the result and interpret it as a correctness of a hypothesis they are testing at the same time.

There is also a strong connection for simultaneous use of predictions and experiment design, because as I mentioned before, they design experiments and make predictions during a very short time interval. Interesting is the simultaneous use of judgments and

formation of hypotheses, which indicates that they with the testing experiments not only test the existing explanations, but also get the ideas to make new ones. So the results of testing experiments serve as opportunities for the formation of new hypotheses. We see that they use different representations together with forming hypotheses, performing testing experiment, judging about the outcome and the “other” category.

If we look again at the graph of transitions 4.3, we see that their problem solving is highly concentrated around finding patterns, hypothesizing, designing testing experiments, predicting outcomes, performing testing experiments and judging outcomes. More than in 1/2 of cases they make a prediction before conducting the testing experiment. They also perform several testing experiments for the same hypothesis, as can be seen from timeline 4.1. While designing experiments and making predictions they also used hypothetico-deductive reasoning.

If we compare the transition graphs with the ISLE cycle, we see that the transitions used in the ISLE cycle are also more frequent in their solving. The transitions in the ISLE cycle are:

- observing → finding patterns → forming hypotheses (with making assumptions) → predicting → performing testing experiment → judgment → reflections (That in this case were a part of the “other” category) and revisions of assumptions → more observational experiments
- reflections and revisions of assumptions → change hypotheses
- reflections and revisions of assumptions → change predictions

Pharmacists frequently leave out separate steps that are in ISLE. For example: a lot of times they go directly from hypothesis to experiment performing, leaving out the design and prediction or from a hypothesis to a prediction, leaving out the design. The reason for this could be that they are so excited about the outcomes of the testing experiments that they perform them as soon as they can. Their problem solving in general is more complex than the ISLE cycle. On the graph of transitions we can also see the transitions that seem irrational at the first glance, for example when they proceed directly from a prediction to the judgment. From the transcription however can be seen for example, that they don’t go from the prediction to judgment without performing testing experiment, but that a testing experiment and judgment happen simultaneously and on the graphs of transitions both connections are drawn: prediction → performing testing experiment and prediction → judgment. Besides the fact that most of the transitions in the ISLE cycle are frequent in pharmacists’ problem solving, the important outcome of this case study is that the solving of pharmacists follows the philosophy of the ISLE cycle, which is based on devising open-minded explanations about a physics phenomenon and testing these explanations.

4.1.2 Selected statements

Person A: **It is not fluorescence. If it had something to do with fluorescence, then the other color would be different.** This is showing the influence of knowledge from their own domain on their ideas. He had an idea but rejected it right away, using hypothetico-deductive reasoning.

Person B: **Regardless of the presence of the paper and the distance between**

the paper and glass, the intensity of the reflected beam is constant. In other words, reflection is bound only to the lower surface of the glass. The language he used was sophisticated. He is describing the dependencies of different variables to substantiate his hypothesis.

Person B: **That means we were wrong.** Person A: **That the glass has no effect.** They are reducing the possible causes of the phenomenon to come up with the correct explanation. They concluded that the glass wall has something to do with the cone after the laser beam reflects from paper in all directions. Here one can see how the idea for the final explanation was growing step by step.

4.1.3 The insight

Here I will shortly describe the occurrences of the “Aha! Moment” or an insight, a sudden break through that solves a problem. Although the experience of insight is sudden, it is a result of a series of brain processes and states, which suggests interventional opportunities for the facilitation of the insight. [42]

The pharmacists came up with the final idea for their explanation, using the following dialogue:

B: So glass has some effect. It obviously prevents some angles of propagation.

A: Yes, but where does it prevent them, do they not enter the glass, or exit? That about exiting would not hold according to the theory, but I’m not sure about the entering.

B: Shine at a very large angle, and we will see what happens. See, it all remains in the glass, it doesn’t go into the solution.

A: Of course, it’s logical. Now that you were shining into the glass, there was a total reflection, but it only occurs when the outgoing angle is equal to 90 degrees, while here it’s only 45 degrees. What if we try looking at it this way, what... (points the laser into the glass from the side) Look, now we have more than 45 degrees, but it is still... Look what is interesting. As far as I remember, if you have like this (thinks that the incident angle in the air and the angle in the water should be the same) Oh, of course not, because we have different media outside and inside. If we had the same medium, the angles would be the same, but here they aren’t. Maybe it’s connected to this, yes of course!

Person B gave the idea about shining one laser beam inside the glass of the aquarium bottom. He wanted to show that the beam does not enter the water if the beam in the glass is too horizontal. From his idea, person A got the idea about shining into the glass from the air in the same way and see if beams at all angles are entering the glass. He expected the beam in the air and water to be parallel. The surprising outcome gave him the idea about the final explanation in which the angles of the beams that are in air then change the directions in the water.

4.1.4 Conclusion

Although they were solving the problem from a foreign scientific domain, pharmacists were very successful in their solving. Their final explanation was the same as the one we consider to be the best and they also substantiated it very well. In a little bit more than a half an hour they solved the problem in a systematic but a complex way. They frequently used the sort of transitions that are being used in ISLE. This confirmed my hypothesis that experts like Pharmacists, even though their domain of expertise is not physics, while solving experimental problems of that kind, follow the ISLE cycle that is a general scientific approach to solving this type of problems. After their solving they told us that also at their workplace they often meet a certain phenomenon that they want to explain. In these situations they usually do not approach these problems alone but with their co-workers. They both agreed that also in this case they would not have solved this problem so well if they were solving alone. I also showed before how they both contributed to the insight.

4.1.5 Different graphs

Figure 4.1 Pharmacists – timeline with steps coloured by hypothesis

Figure 4.2 Pharmacists – timeline with steps coloured by person

Figure 4.3 Pharmacists – graph of transitions

Figure 4.4 Pharmacists – graph of simultaneous use of different steps

4.2 Experimental physicists

4.2.1 General description of their solving

Experimental physicists seemed honored to participate in this study. Their knowledge of physics is extensive so they had no problems whatsoever with the physics laws or equations. Furthermore, it looked as if they did not expect the problem to be solved with only simple geometric optics, so they analyzed the phenomenon of cone from many possible views of physics. They thought about the wave optics, for example the Mie scattering or about the possible birefringence of the glass. The extensive knowledge of physics seemed to hinder the ability to solve simple problems as they kept looking for some “high physics” in the phenomenon. However they came up with a well substantiated solution, that was the same as we considered to be the best.

In their solving I noticed several things that I can connect with the fact that one of them was a meteorologist and the other was an astrophysicist. Meteorologist mentioned the Mie scattering that is used in atmospheric sciences. Mie scattering occurs when the particles in the atmosphere are the same size as the wavelengths being scattered. [43] Astrophysicist also estimated distances and tried to find connections between them. In astrophysics the estimation of distances is very important, since astrophysicists usually deal with such distances that they can only estimate.

From the timeline graph in Figure 4.6 we can see how nicely they cooperated with each-other. For the same reason as before with pharmacists in the shorter steps their activity is mostly individual, but in the longer steps they cooperate often. The exception was during the time 14.25 – 16.41, when they were using multiple representations while making a quantitative prediction. In this step only the astrophysicist was calculating. It is possible that the meteorologist followed his thought process and let the astrophysicist to calculate in peace. We cannot say that any of the experts was significantly more active than the other because blue and red are quite equally represented on the timelines. Even more, by comparing timelines in Figure 4.6 and in Figure 4.5, we can see how much they cooperated inside the testing procedure of every single hypothesis. Now and from this point on with a “testing procedure” I mean all steps connected with testing experiments: designing testing experiments, predicting outcomes, performing testing experiments and judging outcomes.

During their first observation they both noticed the cone and agreed that it is an interesting phenomenon. They also dedicated a major part of their solving to the cone. While solving they noticed some other interesting phenomena, but they did not dedicate them much attention. Their whole solving lasted for approx. 50 minutes. From the transition graph in Figure 4.7 one can see that the larger amount of time was spent on performing testing experiments and the other categories were quite evenly distributed in time. Assumptions and observation again lasted for the least time.

From Figure 4.8 we can see the frequency of simultaneous use of different steps. The judgments and hypotheses frequently overlap. The reason is that also for physicists the outcomes of testing experiments are a source of new hypotheses. This can be also seen in Figure 4.7, where hypotheses are formed mostly after testing experiment performing, but often also after judgments, observation and finding patterns. Design is frequently used with prediction, prediction with experiment performing and experiment performing with judgment. So two steps that usually follow one another, are many times going on simultaneously. In this case we have also some simultaneous use of observation and forming hypotheses. This is mostly because one of the experts is still observing and the

other is forming hypotheses. They use multiple representations together with forming hypotheses, making predictions or with performing testing experiments.

Their solving had a very similar pattern of transitions as the one of pharmacists. It is interesting to see how they stick to a certain hypothesis and make testing experiments several times before rejecting it. In Figure 4.5 we can see the systematic patterns of sequences of experiment design, prediction, testing experiment performing, and judgment. Hypothesis is usually not followed by an experiment design, but mostly by a direct experiment performing. It is interesting that the experiment design transits from all other categories, except of observation. They obviously got these ideas for testing experiments in many other circumstances, however the strongest transition into experiment design is from making judgments. From judgments, they go to all other steps, except to observation, and there is no single dominant path that leads from judgments. This means that with the outcomes of the experiments, they get the ideas about many other things. Besides the ideas for new hypotheses they think about how to improve the testing experiments.

If we look again at the graph of transitions in Figure 4.7, we see that their solving (as before with pharmacists) is highly concentrated around finding patterns, hypothesizing, designing testing experiments, predicting outcomes, performing testing experiments and judging outcomes. They frequently make a prediction, before conducting a testing experiment. Looking only on the transition graph could be misleading, because it looks as if they have made a prediction in only a third of cases, since three almost equally strong paths are leading to testing experiments. However the paths from prediction and the paths from experiment design are mostly the same transitions, marked twice because of the overlapping of design and prediction. So prediction is made in approx. one half of cases.

We can compare their solving pattern with the transitions in the ISLE cycle. Experimental physicists frequently follow the transitions from the ISLE cycle. In many times they leave out separate steps. For example: a lot of times they go directly from hypothesizing to experiment performing, leaving out the design and prediction or from a hypothesis to a prediction, leaving out the design. Their solving in general is much more complex than ISLE cycle. In their solving they made a lot of transitions between steps, so almost every two steps are connected in the web in Figure 4.7. Most of the connections also go in both directions. The reason for this is the complexity of their solving that is in every moment based on different circumstances.

Reflections and revisions of assumptions are in our cases in two categories, of which one is “others”- reflections and the other one is “assumptions” – revision of assumptions. Taking this into consideration, we can see the connections on the graph that correspond to the transition between the judgment and reflections and revisions. However, these connections are not so strong as those, concentrated around testing experiments, also because they rarely make explicit assumptions and they often leave out the reflections and revisions of assumptions and go directly from judgment to experiment design or hypothesis. These last two connections are on the other hand very strong.

Taking everything into consideration, the solving of experimental physicists was based on forming open-minded explanations, that needed to be tested. When a hypothesis turned out to be false, they overthrew it and leaned on the other existing hypotheses or they formed new ones. On this basis we can say that their solving follows ISLE philosophy.

4.2.2 Selected statements

Person B: **If you swim underwater, then you have the same story, if you look sideways, you see a bright spot above you** – They are not looking only for the patterns in the experiment, but also in their memory, in other known situations. They want to adjust the known explanations of a certain phenomenon to the new situation.

Person B: **If I stood here on the head, it would be similar to having hot air here and the road here. Going to a lighter medium, you get total reflection, yes.** – They are making analogies

Person B: **Approximately the glass thickness is the tolerance. If you have more air in between, the cone is not visible.** – They are looking for connections among different things, to get the hint about the explanation.

Person B: **B: But wait, there is no water here, so we have excluded water totally.** – They reduced the problem by excluding some variables. In this case they saw that the cone is formed already inside the glass.

4.2.3 The insight

There was no instant moment in which they would figure out the final explanation. They came to it step by step. First they thought that in the glass the light is in all directions and it totally reflects back at some angles. They wanted to see, if this is true. They noticed the cone inside the glass and started to think whether the layer of air could have any influence on the cone:

A: What if we took one thick pane of glass? Thick pane, and look at it from the side?

A: Yes, there is definitely no light in all directions in the glass. A little bit of cone is visible.

B: I can see the cone, yes.

A: This may be because the glass also has imperfections. A little light is visible, but the glass itself, apart from the cone, is dark.

B: But wait, there is no water here, so we have excluded water totally.

A: So light cannot go at any angle from the paper into glass.

B: Yes, this is the decisive thing here. Now, why does it happen... Glass is denser than that micro air below it. Here we said goodbye to the simple explanation of glue paper. It seems strange to be that the layer of air had any influence.

B: But it does. It can't be too thick.

A: Yes, but look, if you press it with a finder, this is direct contact with the paper. There is no air there.

They tried to find out if the air influences the cone by getting rid of it. This was the next step:

A: There is almost no cone.

B: Now you're on the scotch tape. Now I'm moving it again.

A: Yes, now there is a cone.

A: So that layer of air is important, right?

B: Yes. The paper has to have some air inside.

Now they have reduced the problem in this way, that the final hypothesis was on the hand:

A: There is no air between the scotch tape and glass, right? We can ignore that.

B: There probably isn't, only glue. Molecules of glue are much smaller than the wavelength of light.

A: So we have a diffuse reflection at the interface, that is right next to the glass, so we can say that scotch tape is part of the glass?

B: Yes, of course.

A: Then there is no cone, but if we have diffuse reflection on a rough paper, with some air between, we get the cone.

B: This now explains everything. The story is like this (He draws the layer of air, the beams and edge of the cone in the glass.) When it enters the glass, even though it goes sideways like so, it still enters the glass. And because it enters at some angle, it means, that it confines the cone.

B: Now let's calculate if this is correct.

4.2.4 Conclusion

Experimental physicists conducted the experiments with a lot of skill. By testing several hypotheses, of which most of them turned out to be wrong, they managed to reduce the problem so much that the final hypothesis came to them naturally. They cooperated nicely with each-other and both agreed that they could not have solved the problem so quickly if they would be solving it alone. They mostly followed the logic of ISLE and also their solving was mainly concentrated around testing experiments. The problem of light cone is complex and they broke it into smaller bits, which were easier to analyze. They also made a very good argument for their final explanation.

4.2.5 Different graphs

Figure 4.5 Experimental physicists – timeline with steps coloured by hypothesis

Figure 4.6 Experimental physicists – timeline with steps coloured by person

Figure 4.7 Experimental physicists – graph of transitions

Figure 4.8 Experimental physicists – graph of simultaneous use of different steps

4.3 Theoretical physicists

4.3.1 General description of their solving

Theoretical physicists gave us an interesting insight into solving approach of physicists, who at their workplace conduct almost no real practical experiments, but still work in the field of science for many years. We predicted that they would use testing experiments more in the form of hypothetical or imaginary experiments instead of practical testing experiments. One cannot see this from the graphs, because all kinds of testing experiments belong to the same category, but it can be nicely seen from the transcription. The testing experiment for them is many times just reasoning about the correctness of the hypothesis, for example A reasoning about his hypothesis: “The total reflection hypothesis could be overthrown if the refraction index in glass was lower than that of water. Then there would be no total reflection. Otherwise, we probably have total reflection.”

When theoreticians came in the classroom, the first thing they asked us was why we chose them. It seemed odd to them, that we invited them to solve an experimental problem, since they are theoreticians. I told them that we wanted to find out how non-experimental scientist solve experimental problems. Maybe this is the reason why one of them right after he observed the cone, told us the hypothesis about it. This was even before he would tell us, that he speaks about the cone. One possibility is also that he misjudged the problem and thought it must be very simple, since it could be used for educational purposes. This other explanation seems likely, because we observed that also the pharmacists go directly from observation to a hypothesis when the observed phenomenon was simple enough to explain. It is interesting that there were absolutely no transitions from observing to finding patterns. The reason could be that during their problem solving they didn't encounter a phenomenon that would for them seem non-trivial enough.

From the graph in Figure 4.10 we see that they cooperate with each other very often, even during steps that last for shorter times. Also the idea for the final explanation was developed as a result of their conversation.

They dedicated their whole problem solving time to the cone, although they noticed some other phenomena, like multiple reflections and crystallized sugar particles. After observing the phenomenon they immediately formed a hypothesis and performed a few testing experiments, of which results agreed with the hypothesis. The interesting part was that at that moment one of the scientists said: “I think there's nothing else to do here. ” It looked as if he wanted to finish solving, because he was sure about their explanation. Another person was a little bit more skeptical and suggested another testing experiment, which overthrew the hypothesis. This is a very illustrative example of how skepticism of a single person in a group of scientist can bring better results. The cooperation of two scientists in this case was needed for getting to a better final explanation.

Another, rather unexpected thing was that at the end when they had an insight of the final explanation, they did not perform any new practical experiments to test it. They just used theoretical knowledge that the middle glass layer only translates the outgoing beam, but does not change the angle. Another way for judging about the correctness of their final hypothesis was that they compared the outcomes of previous testing experiment with the predictions that would have been made based on this new hypothesis. The conclusion of this is that experts besides testing their ideas, sometimes

also look back and try to find consistencies with these new hypotheses in within their previous work.

From Figure 4.11 can be seen that their solving is concentrated around hypothesis, experiment design, prediction, experiment performing, judgment and the category “other”. It is rather interesting that the category “other” mostly comes after experiment performing or judgment, since it represents many different things. In this case they used the category “other” for:

- application of showing this experiment somewhere else (In this case it always follows judgment)
- data search
- setting questions
- finding consistencies in within previous work
- describing the mechanism in detail (while drawing)

They did not observe much, and also didn’t spend much time for finding patterns. They spent a lot of time performing testing experiments, among which these were mostly thought testing experiments. They also made many statements that we put into the category other and into multiple representations. From Figure 4.12 we can see that they used multiple representations together with forming hypotheses, performing a testing experiment, making judgments and “other”. There was also often simultaneous use of design and prediction.

Their solving was based on the testing experiments, although these are mostly thought experiments or the use of theory. Within the testing procedure the transitions are directed from the hypothesis towards design, prediction, performing testing experiment and judgment, the sequence consistent with the ISLE cycle. They mostly went from the hypothesis directly to the testing experiment. The reason is exactly this that they perform little practical testing experiments, but mostly thought experiments and consistency checks. I marked predictions and design only before practical testing experiments, where there was an indication of their use.

To conclude, I would say that theoreticians follow the logic of ISLE, however they do it in a different way than experimentalists, they do it with thought experiments, finding consistencies in within previous work and describing the mechanism in detail and with this kind of testing probably there are also fewer predictions. It is interesting that even though they meet with little practical experiments at their workplace, they still perform practical testing experiments or test their ideas in a different way.

4.3.2 Selected statements

Person A: **Yes, if the glass had the same index as water the light would go straight. If you use water with a lower index, it refracts away from the perpendicular, and you get a larger angle. This is it.** – He is checking if the new hypotheses are consistent with their previous solving.

Person B: **No, no, we are theoretical physicists. (They laugh)** – After they calculated the angle and wanted to see if the angle matches with the prediction, I

offered them a protractor. One of them commented that they do not need it, because they are theoretical physicists.

Person A: **If we modified the angle like this... You know, now I'm trying to simulate the rays from the lit patch. See, it goes to some maximal angle. We simulate the lit patch and watch how the rays spread.** In these sentences we can find the connection with their field of work, since theoretical physicists in their work also make a lot of simulations. Here they can simulate a path of only one among the beams inside the diffuse reflection from the paper.

4.3.3 The insight

The insight was not momentary but happened gradually. The first step that led them on the right path was a result of the following testing experiment. The idea to perform it came from the person A.

A: You know what, let's check this idea with total reflection experimentally. Let's take the laser out and turn it like this and light the tank from below. Then we have no diffuse reflection, so let's see what happens.

A: If we modified the angle like this... You know, now I'm trying to simulate the rays from the lit patch. See, it goes to some maximal angle. We simulate the lit patch and watch how the rays spread. (A tries to find a stand for the tank, so it could be lifted)

A: Look what I'm thinking. Now we have incidence at right angle. Now I'm changing the angle. Now I have a really big angle. Do you see the angle in water is the same? It's converging towards some angle.

They probably saw an experiment where the angle of incidence goes from 0° to 90° , but refracted angle cannot be bigger than some critical angle of total reflection. It is possible that person B connected this with that experiment, because he very quickly responded with comment that the total reflection would occur, if the beam came from above and reflect, so he got the idea that the mechanism of the phenomenon they observe is not total reflection, but the angle is the critical angle. This was a second thing that led them in the right direction:

B: This is the angle of total reflection, no? Except that total reflection would occur, if the beam came from above and reflect. From this we can calculate the index of refraction.

B wants to calculate whether the explanation of reverse total reflection on the water-glass boundary agrees with the outcome of the experiment with saturated sugar solution. He finds out that it does not agree, but it would agree if the refractive index of glass would be smaller than that of water. In that moment he gets the idea that he can consider the air and water instead of glass and water, because the air has smaller refractive index than water.

B: Look, in my opinion the explanation is just that the refractive index of this glass is smaller than that of water. We have total reflection, because the liquid is denser than the surrounding glass. We saw greater effect, when we put a denser liquid in, this was the saturated sugar solution.

A: Where did you hear about a glass with lower index of refraction than water?

B: Nowhere, but...or maybe we have to consider the refractive index of air. Yes, of course!

A: Of course, because the glass is only there for translation.

Taking everything into consideration, we can say that both experts gradually contributed to the circumstances in which the insight happened. The first step was an unexpected result of the testing experiment, that led them in the right direction. After some calculating and thinking over, the final idea was born.

4.3.4 Conclusion

Theoretical physicists approached the problem in the way of coming up with different ideas and testing them whether with a practical experiment or just a thought experiment. They followed the logic of ISLE and came up with a solution that in our opinion is the best one. Although they perform very little actual experiments at their workplace, the scientific skills that they possess enabled them to solve problem in a relatively short time.

4.3.5 Different graphs

Figure 4.9 Theoretical physicists – timeline with steps coloured by hypothesis

Figure 4.10 Theoretical physicists – timeline with steps coloured by person

Figure 4.11 Theoretical physicists – graph of transitions

Figure 4.12 Theoretical physicists – graph of simultaneous use of different steps

4.4 Physics students

We conducted the same study with a pair of physics students, a male and a female. They were both students of second Bologna cycle in the last year of their study. They are both very successful and are among the best students in their generation. Their knowledge of physics laws and theories can be compared to that of expert physicists and definitely exceeds the one of expert pharmacists. The thing that makes them novices in our example is lack of experience in conducting science. The educational system at their faculty is also quite traditional, where the teacher speaks and students listen. They had only one laboratory subject where they were actively involved, but even there they followed “cookbook” recipes. I have invited them to the research to get a better image of the effect of both, physics knowledge and ability to conduct research, on the problem solving success. I expected that the solving of students would differ from the one of experts, who are used to do science. I expected also that the students would use more time to solve the problem.

4.4.1 General description of their solving

When I showed them the experiment, students noticed the cone and also incident and reflected beam. They immediately formed a hypothesis that one beam is reflected. Before making an explanation for the cone, however they first found some patterns connected with it. It looks like the harder problems demand finding patterns before making a hypothesis. They took a lot of time and observed a lot of different phenomena, however they dedicated the majority of their time to the cone.

It is interesting that they planned their solving steps a lot. For example, male saying: “I think we should draw the case and see where we get the cone.” It seems that students are used to do multiple representations, since in our school classes we were often encouraged to draw diagrams or sketches at the beginning of solving a physics problem. There is a study that shows that students do spontaneously use a lot of multiple representations when solving physics problems. [39] From Figure 4.17 we see that they use different representations with many different categories: finding patterns, forming hypotheses, etc. They solved the problem in a very similar way as scientists did. They spent a lot of time performing testing experiments, but very little time on assumptions.

It is surprising that they perform so many testing experiments and have so many hypotheses, which can be seen in Figure 4.14. Another interesting thing is that one of them had a hypothesis and tested it, but told the hypothesis to the other only after the testing procedure. The steps connected with this hypothesis are yellow-colored in the figure.

From Figure 4.15 one can see that they do cooperate throughout the solving as there are many purple parts, but the person that is active in red colored steps, the male student, is somewhat dominant. If we look for example at the time from 50:00 -60:00 on the graph, we can see that there are a lot of red parts, but very little blue and purple parts, which means that he is doing most of the talking. However the female contributed a lot to the solving, she was the one who noticed the cone and also accidentally observed that the cone disappeared when they lifted up the aquarium.

The most important thing was that she was first to realize that the hypothesis that they had from the very beginning could not be correct. It is possible that she was a

little bit shy and did not want to say anything or that she was not sure about it. I noticed that she also did not have much confidence in her own abilities. Once when there was some quiet time, she even said to him: “You think this through a little bit.” Additionally there were some instances that he did not accept her ideas about the hypothesis they had being wrong, although she repeated her reasoning several times.

It is interesting that the solving pattern, shown in Figure 4.16, contains a lot of elements from the ISLE cycle, although the students have never met with ISLE before. Their solving pattern is concentrated around testing experiments, which includes experiment design, prediction, experiment performing and judgment, since the arrows that connect these steps are thickest. Most of the time they go from an observation directly to the formation of a hypothesis, without finding patterns. In none of these examples they formed a hypothesis for the light cone existence, but usually dealt with phenomena like reflections and simple refractions. However, after observing the cone and another interesting phenomenon that were not so simple to explain, they began searching for patterns right after observing each of these two phenomena. Their solving as a whole is similar to ISLE cycle, however there are some differences, for example a lot of those connections that in ISLE go in one-way, they use it in both ways, for example: finding patterns $\leftrightarrow$ forming hypotheses or experiment performing $\leftrightarrow$ predicting.

They took a lot of time and observed many different phenomena, however they dedicated the majority of their time to the cone.

The category “other” in this case is often used for planning their solving, searching consistencies in within their previous solving and asking themselves the questions, for example: “But why the cone?”

A very interesting observation is that in the first half of their solving they also performed testing experiments, but there were not so many transitions present between designing, predicting, performing experiment and judging the outcome. The testing procedure looks rather random. In the second half however, their whole solving pattern changes so that the transitions inside the testing procedure are more frequent. The comparison of the first and second half of their solving can be seen in Figure 4.13. The possible reasons for this change in approach are described in section 4.5.

Figure 4.13 Students: a comparison of used transitions in the first half (0-41 min) – left and the second half (41-92 min) – right of their solving

4.4.2 Selected statements

Female student **It could also be because of something...I don't know.** She has ideas but she does not express them. She is careful that she says only things that she is confident in.

Male student: **What now? Will we still bother with all these...? You can see laser even here, for example.** They are not determined in what they would investigate. Their goal is not clear at the beginning.

4.4.3 The insight

Although the female noticed that their original hypothesis does not agree with the theory, they did not overthrow the hypothesis yet. They did this, when they wanted to calculate the angle and they did not succeed to get any cone angle that would be smaller than 90 degrees. Their reaction after this was:

A: Wait, are we figuring out that there should be no cone?

B: Yes.

A: This is quite bad.

Later on they figured out that the reflection from the paper is not completely spherically symmetrical, but they get less brightness with more horizontal angles. The idea about the paper making the cone was developed when they were asking themselves what the cause for the cone could be, and was not a result of some experiment outcome as many other ideas, that scientists have. They described this as the cone with soft boundaries. When they were lifting up the aquarium, trying to see if the angle changes, the male realized that they could have forgotten to take the air layer into consideration. They tested this idea and concluded that there is considerable layer of air in between the paper and aquarium. They just perfected their hypothesis, by explaining why the border of the cone becomes sharp after the double refraction through the glass wall.

4.4.4 Conclusion

The students surprised us in many ways. Not only that they came up with a reasonable solution, in their final explanation they also took into account some additional parameters. They took into consideration that the light is not uniformly reflected in all directions from the paper and that the amount of transmitted light inside a beam through glass depends on the angle of the beam hitting the glass. They spent more time solving the problem than scientists, but also they noticed and explained more different phenomena. Even their solving in the first half of the time had many similarities with ISLE cycle.

4.4.5 Different graphs

Figure 4.14 Students – timeline with steps coloured by hypothesis

Figure 4.15 Students – timeline with steps coloured by person

Figure 4.16 Students – graph of transitions

Figure 4.17 Students – graph of simultaneous use of different steps

4.5 Comparison of results

4.5.1 Similarities among different experts

From figures 4.18 and 4.19 one can see that all of the subjects (except students in the first half of their work) have a lot of similarities in their problem solving approach:

- Dominant directions are: designing experiments $\rightarrow$ predicting $\rightarrow$ performing experiments $\rightarrow$ making judgments.
- In all cases there are many transitions in the direction: making judgments $\rightarrow$ exp. design.
- They have strong bidirectional exchange: hypothesizing $\leftrightarrow$ performing experiments.
- Also strong is bidirectional exchange: designing experiments $\leftrightarrow$ performing experiments. With experimental physicists there are considerable more transitions in the direction of performing experiments.
- For all experts there is notable simultaneous occurrence of designing experiments and predicting.
- All of them simultaneously form hypotheses and make judgments. With theoretical physicists this overlapping is not as strong as in other two cases, but it still exists.
- They all spend most time on performing testing experiments, very little time on assumptions and some more but still little time on observation.

We can also look at timeline graphs. Observation is concentrated mostly at the at the beginning of the problem solving. For experimental physicists and theoretical physicists there is also a short observation period near the end. They all had several hypotheses for the cone. They all tested certain hypotheses four or more times.

4.5.2 Differences among experts

Examining all the transitions graphs, one can find a several differences among different pairs of experts. Here I will list only some most obvious, interesting or most important ones.

- Theoretical physicists spent much less time searching for patterns than the other two groups, but more time on the category other.
- Theoretical physicists have more pronounced transition between category other and hypothesizing compared to pharmacists and experimental physicists.
- Time spent for Experiment design was smallest for pharmacists and larger for the other two groups.
- Theoretical physicists spent significantly more time on producing different representations than the other two groups.

Figure 4.18 A comparison of the transition graphs for solving of all four cases.

- Theoretical physicists did not identify any patterns right after observation, but others did. Also in other cases it turned out that after observation participants search for patterns if the problem is hard. On the other hand, if the phenomenon is simple for them to explain, they will form an explanation immediately after observing it. It could be that the theoretical physicists perceived the problem as simpler than it really was.
- For pharmacists the observation is most often followed by finding patterns but never by “other”, as it was sometimes followed with both pairs of physicists.
- For theoretical physicists judgments are often followed by “other” and never by making hypotheses while for other two groups judgments are often followed by making hypotheses and (to a lesser extent than with theoretical physicists) also by “other”.
- Pharmacists and experimental physicists have notable simultaneous occurrence of Judgment and Hypothesis while for theoreticians this is very weak.
- Simultaneous use of judgments and performing testing experiments is most com-

Figure 4.19 A comparison of the simultaneous use of different steps in solving of all four cases.

mon with pharmacists, less with experimental physicists and the least with theoretical physicists. Pharmacists also spent more time overall making judgments and theoretical physicists the least time.

- The transitions hypothesizing $\rightarrow$ designing experiments $\rightarrow$ performing experiments $\rightarrow$ making judgments are all more one-way directed with pharmacists and experimental physicists than with theoretical physicists, where there are considerably more transitions also in other direction.

Considering all the similarities and differences I can conclude that all experts are devising and testing the hypotheses in a way that is similar to ISLE cycle. It is interesting that the solving approach of pharmacists and experimental physicists is more similar to ISLE than the approach of theoretical physicists. The former is a great indicator that for solving this type of problems, what matters is not only pure knowledge of physics laws and concepts, but mostly the ability to conduct research. I would dear to say that pharmacists are more than other two groups used to solving experimental problems, as they often perform different experiments at their work, as they told us

after the think aloud session. At their work they sometimes also meet with a surprising result and try to explain it. Pharmacists spent the least time to come up with a well grounded solution. Experimental physicists in their work also derive from natural phenomena, but work of theoreticians on the other hand derives from the theory.

4.5.3 Comparison between students and experts

The solving pattern of students is similar to those of scientists. If we compare the transition graphs in Figure 4.18 we can see that all the lines are thicker. The reason is that students solved the problem for considerably longer time than experts and consequently made more transitions overall. Their solving pattern is also very much concentrated around performing testing experiments, as with pharmacists and experimental physicists. On the other hand the transitions that were used most often by theoreticians are also present with students. These are judgment $\rightarrow$ other $\leftrightarrow$ forming hypotheses. These transitions however are in comparison with other transitions not so common with students as with theoretical physicists, but still more than with experimental physicists and pharmacists. If we assume that the solving pattern of theoretical physicists is representative for most of the theoreticians and if we assume that the solving patterns of pharmacists and experimental physicists are representative for all experimentalists, then we could say that the solving pattern of students is somewhere in between these two different patterns, which is very interesting.

The female was more shy than the male, so he was dominant in their solving. I did not detect such strong dominance in any other case. One possible explanation is that students are more careful when expressing themselves, and another one is that females in general are more careful expressing themselves. Even both explanations might be true.

Another, probably the most important observation of this work is that the approach of the students considerably changes in time. I split the solving of students on two halves and drew transition graphs for each part of their solving. This can be seen in Figure 4.20.

Figure 4.20 Students: a comparison of used transitions in the first half (0-41 min) – left and the second half (41-92 min) – right of their solving

In the first part students spent significant fraction of time on finding patterns and observation. In the second part this fraction of time decreased by increasing the fraction

Figure 4.21 Pharmacists: a comparison of used transitions in the first half (0-17 min) – left and the second half of their solving (17-34 min) – right

Figure 4.22 Experimental physicists: a comparison of used transitions in the first half (0-25 min) – left and the second half of their solving (25-51 min) – right

of time spent mostly on performing testing experiments, predicting and judging the outcomes. In the first part they had a hypothesis for the cone that seemed reasonable to them and they were pretty sure about it, almost without testing it. They also saw other phenomena and tried to explain them, so the experiments, predictions, judgments, etc. are also for other phenomena besides the cone. At the end of first part they noticed the hole in their explanation and then they started to solve more like scientist. Their solving pattern also became more similar to ISLE cycle. Closer look at the timeline graph shows that students spend significant and continuous time on finding Patterns during last minutes of the first half of their work. During this time they did not spend any time on Experiment design but they made some Judgments and Analysis. That was when they started to realize that their hypothesis is wrong. This caused a major difference in their solving. Perhaps that was why afterwards they were testing so much, because they saw that not necessarily everything that seems logical is true.

I also split the solving of scientists in two parts to see if there are also similar differences between the two parts. With scientists there is no obvious difference between

Figure 4.23 Theoretical physicists: a comparison of used transitions in the first half (0-21 min) – left and the second half of their solving (21-42 min) – right

approaches in the first and the second half of their solving. This can be seen in Figures 4.21, 4.22 and 4.23.

Solving of students lasted longer than solving of different experts, so the students also made more transitions between different steps. For this reason the both halves of students' solving look more "ordered" than separate halves of experts' solving. Still, we can see that the solving patterns of experts are concentrated in the lower-right part of the transition graphs, around testing experiments. Even though that the solving pattern of students, who had very little experience with similar problems, becomes more similar to the ISLE cycle in the second half of their solving, scientists already start with this kind of approach. We thus believe that the ISLE cycle is something scientists spontaneously learn to use with years of experience of solving problems, because this kind of approach is effective.

4.5.4 Comparison of the testing procedure

Since testing hypotheses is the main part of ISLE philosophy, I will focus mostly on the lower-right part of transition graphs, the testing procedure. The testing procedure consists of designing experiments, predicting the outcomes, performing experiments and making judgments. Looking at Figure 4.18 we can compare several things, related to testing experiments:

- For experts experiment design is mostly triggered by hypotheses and judgments. For students it is mostly triggered by finding patterns in the beginning of the first half of their work.
- The transition experiment performing → experiment design is strong with students and also with experts. With students and experimental physicists this was mostly improving experiments with trial and error method. With theoretical physicists this transition was sometimes more than just an improvement. They first made a reasoning testing experiment and then started to design a practical one. Once they just wanted to expand the testing experiment, which was also more than just an improvement.

- For experts experiment performing is mostly the result of making hypotheses, predictions and experiment design. For students in the first half of their work the experiment performing is also many times the result of the category “other” but in the second half of their work it becomes the result of experimental design and prediction, similar to experts. The fact that in the first part of their solving students were doing some testing experiments, but not in the same way as scientists is a very interesting part. They of course had to design testing experiments before making it, but they didn’t say anything before actual performing. They weren’t talking much at the beginning, maybe they were held back. They also didn’t cooperate much, as the female was very quiet. They were both very careful about what they say. In some moment they started to whisper and I asked them to speak what is on their minds. The female said that it is nothing, just as if she didn’t want to come up with wrong ideas.
- All of them spent large and approximately equal fractions of time on experiment performing. Students spent relatively less time on experiment performing in the first half of their work but increased this share, to the same level as experts in the second half of their work. Maybe the proportion of time spent on experiment performing combined with characteristic transitions to it from predictions, hypotheses and/or from experimental design, can be an indicator for expert behavior.

5

Conclusion

5.1 Answering the research questions

I sum up the most important findings regarding each research question.

- **How do expert scientists solve the problem of the light cone?**

They solve the problem by forming several hypotheses regarding the observations they conduct and subsequently testing them. They usually come up with one or a few hypotheses at a time, and test them, sometimes even more than one at a time. During testing they often get ideas for new hypotheses. These are not necessarily completely new, but can be only a slight modification of the previous ones. They do not only design and perform new testing experiments, but also check the consistency of the new hypotheses with the outcomes of previous testing experiments. They use steps such as observing, finding patterns, hypothesizing, predicting about the outcome, performing testing experiments, and so on. Many times a testing experiment is just a thought experiment or the use of previous knowledge that can discard a certain hypothesis. They make very little explicit assumptions and also rarely check the assumptions that they made. Together with different steps or as a separate step they use multiple representations. They draw sketches, beam diagrams and formulas. They often perform more than one step at a time. Sometimes both participants perform two different steps at the same time, but sometimes also one thought can be interpreted as different steps. Experts cooperate most of the time and complement each other.

- **How closely does their solving pattern match with ISLE cycle?**

Comparing the transition graphs with the ISLE cycle, we saw that the transitions used ISLE cycle are also more frequent in the solving of experts. The solving pattern of experts is much more complex. Experts frequently leave out separate steps that are in ISLE, for example going directly from designing experiment to performing experiment, leaving out the prediction. They also make some unexpected transitions, for example going from making predictions directly to formulating new hypotheses. On the whole we judge that ISLE is a simplified but a realistic model of problem solving by experts. The most important finding is that experts do form several hypotheses and subsequently test them, which means that physicists and all other scientists not only use the elements of the ISLE cycle while constructing solving problems, but also follow the logic of the ISLE cycle.

- **What are the similarities and differences between solving by different kinds of scientists?**

Theoretical physicists spent less time on searching for patterns than the other two groups, but more time on the category other. They have also more pronounced transition between category other and hypothesizing compared to pharmacists and experimental physicists. It is logical that they form hypotheses right after the “other”, since one of the things “other” is used for is setting scientific questions. Time spent for Experiment design was smallest for pharmacists and larger for the other two groups. The reason could be that pharmacists performed simpler testing experiments, for example, throwing paper in the water, looking from different angles, etc. Theoreticians spent significantly more time on producing different representations than the other two groups. This part was expected, since theoretical physicists also at their workplace work mostly with formulas. This is a nice example of how experts implement some habits from their domain, such as theoretical physics in problems from other domains, such as experimental problems. Theoreticians also did not identify any patterns right after observation, but others did. In other cases it turned out that after observation participants search for patterns if the problem is hard. On the other hand, if the phenomenon is simple for them to explain, they will form an explanation immediately after observing it. It could be that the theoretical physicists perceived the problem as more simple than it really was.

It is interesting that the solving approach of pharmacists and experimental physicists is very similar, while the approach of theoretical physicists is noticeably different. This is a great indicator that for approach of solving these kind of problems, what matters is not just pure knowledge of physics laws and concepts, but the habits of mind developed during research.

- **What are the similarities and differences between solving by scientists and by a pair of students?**

It was a surprise for us that the solving pattern of students was on average very similar to the solving pattern of experts. It is interesting that their solving had strong similarities with all of the experts. On one hand they made a lot of transitions inside the testing procedure, as experimental physicists and pharmacists, and on the other hand they made the same connections with the “other” category, that were strongly present with theoreticians.

Contrary to the expectation that solving patterns of experts should be more similar to the ISLE cycle than the solving pattern of students we found that the students are rather similar to the experts. Although we observed that solving of students in the first half of their solving differs a lot from the approach of scientists and also from the ISLE cycle, we saw that in the second half the process became more similar to the approach of scientists, which is also closer to the ISLE cycle. Scientists on the other hand already started with this approach.

We also observed, that students did not cooperate and complement each other as much as scientists did.

5.2 Implications for instruction

We speculate that the ISLE cycle can be spontaneously learned through experience in solving similar problems. For that reason we believe that a teacher should provide the opportunities for students to learn physics by working with experimental problems that allow the students to devise and test multiple ideas.

Not only when conducting ISLE method, but in every science lesson teacher should be open to students ideas and should not reject them right away. Experts also sometimes make incorrect hypotheses but then they test those hypotheses and reject them if necessary. Similarly, students should test their ideas, either with performing practical testing experiments or using thought experiments or checking for consistency with their previous knowledge. However before actually performing testing experiments they should carefully plan them and most importantly – make predictions about the outcomes based on the ideas under test. Experts always make a prediction that is based on a hypothesis that they are testing. Students should make predictions that are based on the ideas they are testing, in other words, they should not make blind predictions.

On the other hand, scientists do not make predictions before observational experiments, but look at the experiment with “open” eyes. This could be an indicator that the method predict $\rightarrow$ observe $\rightarrow$ explain (POE) should not be used at the beginning of a conceptual unit, where students have no sufficient knowledge to make reasonable and not blind predictions. POE on the other hand is a good tool for testing already gained knowledge in the middle of a unit or at the end of it.

5.3 Future research

This work offers a good basis for future research. We did not observe real experimentalists, so I think this could be an interesting thing to do in the future, as they are supposed to be the biggest experts in solving experimental problems. We also couldn't get any female expert, which would be an interesting thing to do in the future. We observed some gender differences with students, so it would be interesting to see if similar gender differences appear with scientists. Since we observed that the solving approach of students changes during the time of solving, I wish we could observe students during longer periods when they solve many similar problems to see how their approach changes during such time interval as a year, for example. Last but not least, now that we have a tools and experience for conducting similar research, we could investigate how different parameters affect the solving, for example, the nature of the problem, years of experience, number of people in group, participants' gender, the initial instructions, etc.

5.4 Summary of the thesis

Teaching of physics to students of all ages has slowly progressed from traditional lectures, where a teacher talks and students listen, to more interactive methods. These newer methods encourage scientific reasoning in students. One such method is ISLE, the “Investigative Science Learning Environment”. In this research we wanted to find out how experts reason and act while solving experimental problems. Once we knew

this, we wished to compare their solving with logic of ISLE.

The research described in this thesis took place in the form of four case studies. In each case, we videotaped a pair of scientists and filmed them while they were solving an experimental problem in optics. We used pairs because we could analyze their thought processes from communication between them. The scientists were shown an experiment from geometrical optics, and they were asked to identify an interesting phenomenon and explain it. We offered any help or equipment they needed for their explanation. Their whole conversation while solving the problem was captured on the tape. We observed a pair of pharmacists, a meteorologist and an astronomer, and two theoretical physicists, who were the next case. For comparison, we conducted the same case study with a pair of physics students. We wanted to compare the results and find similarities and differences between different case studies.

We analyzed videos of experts and from their communication determined which steps they were performing. We plotted this data on the timeline graphs that show use of certain step category in time. We saw that experts displayed a high level of cooperation, with the students however one person was dominant. We saw that in all cases participants made several testing experiments for each hypothesis and sometimes tested more than one hypothesis at once. As soon as the experts had a hypothesis, they wanted to test it. First they designed a testing experiment and made a prediction about the outcome based on the hypothesis under test. They made predictions mostly before actually performing the experiment. After conducting the experiment or when they already had some results, they made a judgment about the outcome. In this part they were mostly thinking about how the outcome of the testing experiment affected the hypotheses under test.

Timeline graphs were useful for identifying patterns in sequences, but it was very difficult to compare different graphs. That's why I developed transition graphs, a representations that shows how common some of the transitions between steps are. From this representations we saw that experts' solving pattern is concentrated around formulating hypotheses, designing testing experiments, performing them and judging about the results. Transition graphs for all observed experts turned out to be very similar. The sequences used in ISLE cycle were dominant with the experts. We found that problem solving by expert scientists closely matches the ISLE cycle. Of course, there are some differences. The actual solving is more complex, which is rather expected. Scientists make some unexpected transitions, such as going from making predictions directly to formulating new hypotheses. On the whole, however, we judge that ISLE is a simplified but good model of problem solving by experts.

An interesting thing is that students also solved the problem in a very similar way as the scientists. However, students showed some different patterns. A very interesting observation, which might be the most significant result of our research, is the change in the approach of students over time. In the first half of their solving, the transition graph looks rather random, with no clear signs of a cycle. However, when we separately analyzed the first and the second half of students' work, we noticed clear difference between them. The transition graph of the second half is very similar to those of experts.

Our hypothesis is that immediately after seeing the experiments, the two students thought the problem is trivial, and attempted to solve it quickly. When they failed that, they attempted a more productive approach, which is closer to the ISLE cycle. All the scientists, on the other hand, started with this approach. We thus believe that

the ISLE cycle is something scientists spontaneously learn to use because it is effective for solving problems.

There are several implications that follow from our analysis. The most important is in my opinion that students need to learn to test their ideas, as scientists do. Students should make predictions regarding the outcome of experiments, however these should not be blind guesses but statements based on specific ideas under test.

6

Povzetek v slovenskem jeziku

6.1 Uvod

Poučevanje fizike na vseh ravneh se počasi odmika od tradicionalnega načina poučevanja, kjer učitelj govori in učenci poslušajo. V uporabo prihajajo nove poučevalske metode, ki vzpodbujajo interakcijo in v ospredje postavljajo učenčevo aktivnost ter razvoj znanstvenega mišljenja. Ena izmed teh novih poučevalskih strategij je ISLE (Investigative Science Learning Environment) [1]. ISLE sloni na experimentih, ob katerih se učenci naučijo fiziko skozi ponavljajoče se cikle opazovanj, iskanja vzorcev, tvorjenja razlag ter nadaljnega testiranja teh razlag z izvedbo dodatnih – testnih eksperimentov. Zaporedje vseh teh procesov tvori t.i. cikel ISLE, prikazan na Sliki 6.1.

Slika 6.1 Cikel ISLE [12]

Elementi cikla ISLE so bili razviti na podlagi zgodovine in filozofije fizike ter na podlagi opazovanja dela znanstvenikov. V razvoju metode ISLE manjka potrditev, da današnji fiziki ne le uporabljajo elemente cikla ISLE ob gradnji novega znanja, ampak tudi, da si ti koraki sledijo v zaporedju, podobno, kot je to v ciklu ISLE. Moja naloga je bila raziskati, kako razmišljajo znanstveniki ob reševanju eksperimentalnih problemov, podobnih kot tisti s katerimi se srečajo učenci med izvajanjem metode ISLE.

6.2 Opis raziskave

Raziskava, opisana v tej nalogi, je bila narejena v obliki štirih študij primera [16]. V vsaki izmed študij smo opazovali par znanstvenikov – ekspertov, medtem ko rešuje eksperimentalni problem. Vsakemu paru smo pokazali eksperimentalni problem iz optike, v katerem sta sodelujoča morala sama najti zanimiv pojav in ga razložiti. Pare smo opazovali zato, da smo lahko iz njunega pogovora izluščili pomembne informacije o njunem razmišljanju. Sodelujoča smo prosili, naj poskusita govoriti čim več tistega, kar razmišljata, tako da vsaka izmed študij primera temelji na tehniki “think aloud”. V tej tehniki preiskovanec skuša razmišljati na glas, s pomočjo česar so analizirani preiskovančevi miselni procesi. [17] Celotno reševanje smo posneli s kamero, da smo lahko kasneje analizirali videoposnetke. [18]

6.2.1 Eksperimentalni problem

V vsaki študiji primera smo sodelujoča soočili z eksperimentom “Svetlobni stožec” [37]. Za postavitve osnovnega eksperimenta potrebujemo steklen ali plastičen akvarij, napolnjen z motno vodo, ročni laser in list belega papirja. Postavitev je prikazana na Sliki 6.2. Eksperiment mora biti izveden v zatemnjenem prostoru.

Slika 6.2 Osnovna postavitve eksperimenta “svetlobni stožec”. Laserski žarek je usmerjen vertikalno navzdol proti dnu akvarija. V motni vodi se svetloba širi v obliki stožca.

Ta eksperiment je bil primeren za našo raziskavo predvsem zato, ker je dovolj netrivialen, da reševanje tudi od znanstvenikov zahteva precej časa in truda, hkrati pa za razlago obstoja in oblike svetlobnega stožca zadostuje srednješolsko znanje geometrijske optike. Za globljo analizo bi bilo treba upoštevati še lastnosti vira svetlobe, lastnosti papirja, itd., a bom na tem mestu navedla le osnovno razlago.

Predpostavimo lahko, da papir siplje laserski žarek v vse smeri. Prav tako lahko predpostavimo, da je lomni količnik stene akvarija, ki je v našem primeru steklen, večji od lomnega količnika vode v akvariju ($n_{steklo} > n_{voda}$). Pomembno je dejstvo, da je med plastjo papirja in stekla še tanka plast zraka. Potem, ko se svetloba siplje na papirju, ponovno vstopi v akvarij, pri čemer se dvakrat lomi, najprej na meji zrak-steklo in

nato še na meji steklo-voda. Pri tem smo zanemarili dejstvo, da se za vsaki izmed mej nekaj svetlobe tudi odbije. Dvojni lom je shematsko prikazan na sliki 6.3.

Bistvo te razlage je, da se na papirju sipani žarki, ko so vzporedni z mejo zrak-steklo, lomijo v steklo pod kritičnim kotom totalnega odboja. Vsi ostali žarki se lomijo v steklo pod manjšimi koti znotraj stožca. Kot stožca je torej določen z žarki, ki se dvakrat lomijo, najprej iz zraka v steklo pod kritičnim kotom α_{st} in nato še iz stekla v vodo pod kotom α_{voda} . [37]

Slika 6.3 Osnovna analiza mehanizma nastanka stožca. Zapis α_{st} na sliki je uporabljen za kritični kot totalnega odboja, četudi ima na sliki pripadajoči žarek v zraku vrednost $\alpha_{zrak} < 90^\circ$. [37]

Če upoštevamo enačbo za kot totalnega odboja na meji zrak-steklo ter lomni zakon na meji steklo-voda, pridemo do enostavnega izraza za kot v vodi:

$$\sin \alpha_{voda} = \frac{n_{zrak}}{n_{voda}}$$

Izraz za α_{voda} je torej odvisen le od lomnega količnika vode in zraka. Izraz je po drugi strani neodvisen od lomnega količnika materiala, iz katerega je narejeno dno akvarija, in prav tako od debeline dna. [37]

Če upoštevamo lomna količnika vode in zraka: $n_{voda} = 1.33$ in $n_{zrak} = 1$, dobimo $\alpha_{voda} = 48.7^\circ$. Kot pri vrhu stožca je dvakrat tolikšen, kar je 97.5° .

6.2.2 Sodelujoči v raziskavi

V vsakem primeru smo opazovali par znanstvenikov oz. študentov. Razlogov za to je več:

- Med izvajanjem metode “think aloud” lahko večkrat pride do trenutkov tišine, npr. ko problem postane pretežek. [27] Če imamo par dveh ljudi, ki sodelujeta pri reševanju, se je možno izogniti takšnim trenutkom. [24]
- Pri izvajanju metode ISLE učenci vedno delajo v skupinah. [1] Zato smo se odločili, da bomo gledali na postopek reševanja z zornega kota skupinskega dela. Tako smo namreč rezultate lažje primerjali z načinom izvajanja metode ISLE.

- Znanstveniki tudi na svojih delovnih mestih pogosto delajo v skupinah. [2] Ker je sodelovanje med znanstveniki pomembno, nas je zanimal tudi način, na katerega znanstveniki sodelujejo med seboj.

Odločili smo se za pare, ne pa za večje skupine, kjer je možno, da postane ena oseba pasivna, npr. ker se ostali dve pogovarjata. K raziskavi smo povabili eksperte v znanosti. To so znanstveniki, ki že več let aktivno sodelujejo pri raziskovanju. Vsak izmed sodelujočih ekspertov ima za seboj že vsaj 20 let znanstvenih objav. Prvi primer je bil par profesorjev farmacije. Drugi primer sta bila astronom in meteorolog, prav tako oba profesorja na univerzi. Četudi astronom in meteorolog nista tipična eksperimentarna fizika, sem jo v temu delu označila kot takšna, za boljše ločevanje od para teoretičnih fizikov, ki sta naslednji primer. Tudi teoretika sta bila univerzitetna profesorja, ki se pri svojem delu le redko srečujeta s praktičnimi eksperimenti. Za primerjavo smo opazovali še par študentov fizike v zadnjem letniku 2. bolonjske stopnje. Oba študenta sta med najuspešnejšimi študenti v generaciji. Prav tako oba nameravata nadaljevati študij na doktorskem programu. Njuno znanje fizike je precej obširno, tako da ne moremo reči, da ju to ločuje od ekspertov. Glavna razlika med študenti in eksperti je v letih izkušenj na področju raziskovalnega dela. Vključeni eksperti so bili sami moški, medtem ko sta bila v paru študentov moški in ženska.

6.2.3 Raziskovalna vprašanja

S primerjavo štirih študij primera smo želeli odgovoriti na naslednji set raziskovalnih vprašanj:

- Kako znanstveniki rešujejo problem svetlobnega stožca?
- Kako dobro se njihovo reševanje ujema s ciklom ISLE?
- Kakšne so podobnosti in razlike med reševanji različnih znanstvenikov: eksperimentalnih fizikov, teoretičnih fizikov ter farmacevtov?
- Kakšne so podobnosti in razlike med reševanji ekspertov in študentov fizike?

6.2.4 Potek raziskave

Ob povabilu smo sodelujočim poslali tudi izjavo o sodelovanju v raziskavi, katere angleški prevod lahko bralec najde v Dodatku A. Celotna raziskava je bila narejena v skladu s to izjavo, ki smo jo vsi podpisali tik pred snemanjem. Odgovorna raziskovalca za čas snemanja sva bila prof. Planinšič in jaz. Postavitev snemanja je prikazana na Sliki 6.4.

Preden sem pokazala eksperiment, sem sodelujočim razložila njuno nalogo, ki je v eksperimenti najti pojav ter ga razložiti na takšen način, kot če bi se z njim srečal pri svojem delu. Študentom sem rekla, naj si predstavljata, da sta znanstvenika na svojem delovnem mestu. V vseh primerih sem poudarila, da morata pojav razložiti do takšne mere, da sta dovolj prepričana v njuno razlago. Povedala sem jima tudi, da jima lahko kadarkoli pomagamo s kakšno dodatno opremo, če jo potrebujeta za izvedbo morebitnih dodatnih eksperimentov. Razložila sem jima še postavitev eksperimenta, nato sem prižgala laser, onadva pa sta pričela z reševanjem.

Slika 6.4 Postavitev snemanja. Na mizi je postavljen eksperiment, dva kupa belih listov, dve pisali in snemalnik zvoka. Ena izmed kamer je nameščena nad mizo, druga pa pred njo. Sodelujoča sedita za mizo.

Med reševanjem je bilo dovoljeno minimalno vmešavanje naju s prof. Planinšičem, kot npr. vzpodbujanje h govorjenju v trenutkih tišine. Drugi pogost primer je opozarjanje, da lahko dobita dodatno opremo, če se nama je zdelo da sta jo sodelujoča potrebovala, a tega nista povedala naglas. Reševanje se je zaključilo, ko sta sodelujoča ocenila, da sta dovolj prepričana v njuno razlago, da lahko zaključita.

6.2.5 Analiza videoposnetkov

Videoposnetki so omogočili podrobno analizo reševanja. Počasi sem šla skozi videoposnetek in označila vse korake, ki so bili del reševanja. Ker je bil cilj primerjati vzorec reševanja s ciklom ISLE, sem se posebej osredotočila na korake, označene v ciklu ISLE. Dodatno sem označila rabo različnih upodobitev, ki v ciklu ISLE sicer niso označene kot posamezni korak, ampak jih študenti vestno uporabljajo skozi ves cikel. Korake, ki jih nisem mogla označiti kot nobenega izmed teh korakov, sem dodala v kategorijo "other".

Koraki, ki sem jih označila so naštetih spodaj. Zapisane definicije so tu zelo ohlapne, saj so v njih le povzeti dejanski kriteriji.

- **Opazovanje** je, ko gledata na eksperiment kot celoto in iščeta zanimive pojave.
- **Iskanje vzorcev** je, kadar opazujeta podrobnosti določenega pojava ali iščeta odvisnosti med različnimi spremenljivkami.
- **Tvorjenje hipotez** je, ko tvorita razlago mehanizna pojava ali razlago podrobnosti pojava.
- **Načrtovanje eksperimenta** je, kadar govorita o tem, kako bi izvedla določen testni eksperiment.
- **Napoved izida** je, kadar kakorkoli nakažeta razmišljanje o možnem izidu testnega eksperimenta, ki ga še nista videla.

- **Izvedba testnega eksperimenta** je, kadar izvajata praktičen eksperiment, s katerim želita preveriti veljavnost določene hipoteze. Lahko izvajata tudi miselni eksperiment ali pa hipotezo želita ovreči z njunim znanjem oz. teorijo.
- **Presoja izida** je kadar razmišljata o že videnem izidu ali delnem izidu testnega eksperimenta, če to razmišljata kmalu po izvedbi ali med izvedbo.
- **Privzetki** so kadar eksplicitno privzemata svari, za katere ne bi smela biti prepričana, da držijo. Ta kategorija je uporabljena tudi kadar preverjata, če sta privzela kaj napačnega.
- **Raba različnih upodobitev** je kadarkoli rišeta ali pišeta na papir ali tablo.
- **Drugo** je vse ostalo, kar je del njunega reševanja, a ne spada v katero izmed zgornjih kategorij.

Podatke iz transkripcij smo grafično prikazali na več načinov. Časovnice [19] prikazujejo rabo posameznih korakov tekom reševanja. Posamezne korake na teh grafih smo obarvali na dva možna načina: glede na osebo, ki je aktivna znotraj posameznega koraka in glede na hipotezo, s katero je posamezni korak povezan. Za lažjo primerjavo med posameznimi študijami smo oblikovali grafe prehodov med posameznimi koraki, prikazane na Sliki 6.7. Da smo videli, katere korake sodelujoči uporabljajo hkrati, smo dodatno oblikovali še grafe simultane rabe posameznih korakov. Nekatere grafične upodobitve so prikazane v naslednjem poglavju.

6.3 Rezultati

Časovnice so nam omogočile vpogled v to, kako eksperti sodelujejo med seboj. Primer takšnega sodelovanja za farmacevte je prikazan na Sliki 6.5. Vidimo, da je precej delov vijoličnih, izmed modre in rdeče barve prav tako nobena ne izrazito prevladuje. Oba farmacevta sta torej prispevala precejšen del h končni rešitvi. Za ostale eksperte so grafi podobni.

Slika 6.5 Farmacevti – časovnica s koraki, pobarvanimi glede na osebo, ki je aktivna znotraj koraka. V rdečih predelih je aktivna le oseba A, v modrih le oseba B, v vijoličnih predelih pa obe osebi sodelujeta.

Poleg medsebojnega sodelovanja lahko na časovnicah opazimo tudi vzorce rabe različnih korakov. Opazimo lahko, da si koraki pogosto sledijo v vrstnem redu od opazovanja, do prepoznavanja vzorcev, postavljanja hipotez, načrtovanja testnega poskusa, itd. Progresija korakov navzdol je še lepše vidna na Sliki 6.6, kjer dodatno vidimo zaporedje korakov, povezanih z določeno hipotezo. Ko tvorita določeno hipotezo, jo večinoma želita testirati. Pred dejansko izvedbo testnega eksperimenta pa eksperiment načrtujeta in ponavadi pred izvedbo poskusa na podlagi hipoteze, ki jo testirata še napovesta izid eksperimenta. Vidno je tudi, da včasih tako tvorita kot tudi testirata več hipotez naenkrat. S primerjavo obeh vrst časovnic lahko vidimo, da se oba eksperta izmenjujeta in sodelujeta tudi znotraj testnega postopka ene hipoteze. Kot testni postopek štejem vse korake, povezane s testnim eksperimentom: načrtovanje, napoved, izvedba ter presoja.

S časovnicami dobimo informacije o nekaterih ponavljajočih se vzorcih v rabi določenih korakov, težko pa je videti frekvenco teh vzorcev in tudi primerjava med študijami je zahtevna. Grafi prehodov, prikazani na Sliki 6.7 omogočajo lažji vpogled v dinamiko reševanja ter omogočajo enostavno primerjavo. Na teh grafih so ploščine krogov sorazmerne z deležem celotnega časa reševanja, ki ga sodelujoča namenita za določen korak. Debeline puščic in črt pa so sorazmerne z dejanskim številom prehodov med posameznima dvema korakoma. Dejanska debelina je vsota debelin za število prehodov

Slika 6.6 Farmacevti – časovnica s koraki, pobarvanimi glede na hipotezo, na katero se navezuje določen korak. Če se kakšen korak navezuje na več kot eno hipotezo, je pobarvan z večimi različnimi barvami. Sivi predeli se ne navezujejo na nobeno hipotezo.

v vsako izmed smeri. Koraki si v smeri urinega kazalca sledijo kot v ciklu ISLE, tako da je tudi primerjava s tem ciklom lažja.

Iz primerjave grafov za eksperte vidimo, da so prevladujoči prehodi: **načrtovanje eksperimenta** → **napoved izida** → **izvedba eksperimenta** → **presoja o izidu**. V vseh primerih je močan tudi prehod **presoja o izidu** → **načrtovanje**. Močni prehodi v obe smeri so: **tvorjenje hipotez** ↔ **izvedba eksperimenta** ter **načrtovanje eksperimenta** ↔ **izvedba eksperimenta**.

Vsi veliko časa namenijo izvedbi testnih eksperimentov, zelo malo na privzetkih ter nekoliko več, ampak še vedno malo časa namenijo opazovanju.

Vidimo tudi, da se graf prehodov za teoretične fizike precej razlikuje od grafov prehodov za eksperimentalne fizike in farmacevte. Teoretiki npr. precej manjši delež časa porabijo za iskanje vzorcev, ampak večji delež časa za različne upodobitve ter za korake, ki smo jih označili kot “drugo”. Tudi prehodi **tvorjenje hipoteze** → **načrtovanje eksperimenta** → **napoved izida** → **izvedba eksperimenta** → **presoja o izidu**, so pri teoretikih bolj dvosmerni, kot pri farmacevtih in eksperimentalnih fizikih.

Te in še veliko več drugih podobnosti ter razlik kaže, da je pristop farmacevtov in eksperimentalnih fizikov nekoliko bolj poboben ciklu ISLE kot pristop teoretičnih fizikov. Prejšnje kaže tudi na to, da za pristop k tovrstnim problemom ni pomembno le znanje fizikalnih zakonov ter konceptov, ampak predvsem sposobnost reševanja eksperimentalnih problemov. Farmacevta sta verjetno izmed vseh treh skupin najbolj vajena reševati eksperimentalne probleme, saj sta po reševanju povedala, da se tudi pri delu kdaj srečata s kakšnim pojavom, ki ga ne znata takoj razložiti. Farmacevta sta za rešitev problema svetlobnega stožca potrebovala tudi od vseh najmanj časa. Eksperimentalni fiziki pri svojem delu prav tako izhajajo iz opazovanj naravnih pojavov, medtem ko delo teoretikov izhaja iz teorije.

V naspreotju s pričakovanjem, da bi naj bil vzorec reševanja pri ekspertih bolj

Slika 6.7 Primerjava grafov prehodov za vse štiri primere

podoben ciklu ISLE kot vzorec reševanja študentov, tudi pri študentih najdemo enake vzorce v reševanju. Na eni strani sta študenta naredila velik delež vseh prehodov med koraki znotraj testnega postopka, kot eksperimentalna fizika in farmaceuta, po drugi strani pa je tudi pri študentih prisotne iste močne povezave s kategorijo “drugo” kot pri teoretikih, le da pri študentih niso tako močno izražene.

Morda najbolj pomemben rezultat te raziskave je opažena močna sprememba pristopa v času reševanja pri študentih. Reševanje študentov sem razdelila na dva enaka časovna dela in opazila, da je pristop v drugi polovici veliko bolj podoben pristopu ekspertov, kar je prikazano na Sliki 6.8. Hkrati je vzorec reševanja v drugem delu bolj podoben ciklu ISLE kot v prvem delu.

Slika 6.8 Študenti – primerjava grafov prehodov za prvo polovico reševanja (0-41 min) – levo, in za drugo polovico reševanja (41-92 min) – desno

Podobno razdelitev na dva enaka časovna intervala sem naredila tudi za eksperte, kjer tako močne razlike v pristopu nisem opazila.

6.4 Zaključek

Videli smo, da je vzorec reševanja pri znanstvenikih zelo podoben ciklu ISLE. Seveda je tudi precej razlik. Dejansko reševanje je bolj kompleksno, kar je bilo za pričakovati. Znanstveniki včasih tudi nepričakovano prehajajo med posameznimi koraki, npr. tvorijo novo hipotezo direktno po napovedi o izidu testnega eksperimenta. Gledano v celoti menimo, da je cikel ISLE poenostavljen, ampak še vedno dober model reševanja eksperimentalnih problemov pri ekspertih. Že samo dejstvo, da hipoteze testirajo, da napačne hipoteze testirajo večkrat, dokler jih ne ovržejo, se ujema s filozofijo metode ISLE.

Opažena sprememba pristopa v reševanju študentov je zelo zanimiva. Naša hipoteza je, da sta študenta najprej mislila, da je problem stožca trivialen, zato sta ga želela rešiti na hitro. Ko sta ugotovila, da je bilo njuno reševanje neuspešno – da njuna začetna razlaga ne drži, sta poskusila bolj produktiven pristop, ki je prav tako bližje ciklu ISLE. Znanstveniki, ki so vajeni reševati takšne probleme, pa so že pričeli s takšnim pristopom. Domnevamo, da je ISLE cikel nekaj, česar se znanstveniki spontano naučijo ali privadijo uporabljati, ker je bolj učinkovit za reševanje problemov.

Iz teh ugotovitev smo prišli do nekaterih praktičnih napotkov za učitelje. Učitelj bi naj učencem nudil priložnosti, da se učijo fiziko skozi eksperimentalne probleme, ki učencem omogočajo tvorjenje in testiranje različnih idej. Ne samo pri izvajanju metode ISLE, ampak znotraj vsake običajne ure bi naj bil učitelj odprt idejam študentom, ne da jih zavrača. Tudi eksperti imajo včasih napačno hipotezo, ki jo testirajo in tudi ovržejo, če je to potrebno. Prav tako bi naj učenci svoje ideje testirali. Pred dejansko izvedbo testnih eksperimentov pa bi naredili napoved o izidu. Pomembno je, da ta napoved ni slepa, ampak sloni na hipotezi, ki jo testirajo.

Appendix A

Statements of participation in the research

A.1 Statement of free and conscious consent for participation in study (for experts)

You are invited to participate in a study to determine how experts from various areas solve science problems. The data gathered with this research will form the basis of the undersigned master's student's thesis. We have invited experts that have worked actively in their area of scientific research for several years.

In the case of your participation you will be solving a problem paired with a colleague who will be participating the same way as you. First you will be shown a simple experiment, and then you and your colleague will attempt to explain it. Your conversation during the solving will give us valuable data about how experts approach experimental problems. We should stress that we are more interested in the process of solving than the actual solution to the problem. Your conversation will be recorded, so that we can later extract the important information.

The study, including the showing of a simple experiment and your solving the problem, should not take longer than two hours.

Your consent for participation can be withdrawn at any time without penalty. We guarantee that the videos, as well as any other data gathered in this study, will be used only for research purposes. Your personal information along with the videos will only be accessible to persons running this study. Your personal identity will not be revealed during or after the research.

All questions related to the study can be addressed to the responsible persons:

Student: Maja Poklinek, bachelor of Physics (UN)

E-mail address: maja.poklinek@gmail.com Phone: 040 980 045

Advisor: prof. dr. Gorazd Planinšič, professor of Physics

E-mail address: gorazd.planinsic@fmf.uni-lj.si

I, _____, confirm that I am informed about the procedure and conditions of the research, and consent to my participation in the research.

Date and signature of the participant:

Date and signature of responsible persons:

A.2 Statement of free and conscious consent for participation in study (for students)

You are invited to participate in a study to determine how students solve science problems. The data gathered with this research will form the basis of the undersigned master's student's thesis.

In the case of your participation you will be solving a problem paired with a colleague who will be participating the same way as you. First you will be shown a simple experiment, and then you and your colleague will attempt to explain it. Your conversation during the solving will give us valuable data about how students approach experimental problems. We should stress that we are more interested in the process of solving than the actual solution to the problem. Your conversation will be recorded, so that we can later extract the important information.

The study, including the showing of a simple experiment and your solving the problem, should not take longer than two hours.

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I, _____, confirm that I am informed about the procedure and conditions of the research, and consent to my participation in the research.

Date and signature of the participant:

Date and signature of responsible persons:

Appendix B

Transcription for pharmacists

Time in video track (min.sec)	Step in ISLE cycle	Description	Exact words they say (English translation)
15.14 – 15.54	Observation [P1]	A: P1: notices a second beam (in addition to the original laser beam) B: he sees as if the original beam is split in two parallel beams (he sees incident and reflected beam from the bottom of the aquarium)	A: I can see another thin beam besides the original one. B: I think that the original beam is split in two parallel beams. I don't know, if this is an optical illusion.
15.54 – 15.56	Formulation of hypothesis [P1, H1]	A: H1: One light beam is reflected	A: The other one could be reflected.
15.56 – 15.59	Prediction [P1, H1]	A: If H1 is correct and we change the incident angle of laser beam, then the angle between the two observed beams should increase. (they use hypothetico-deductive reasoning)	A: If we change the angle, we will see if this is...
15.59 – 16.01	Performing testing experiment, judgment [P1, H1]	Angle between the two beams increased $\Rightarrow$ H1 is correct	A: Yes, so it really is a reflection.
16.01 – 16.24	Formulation of hypothesis (Why do we see 2 beams even if incident beam is vertical?) [P1, H2, H3]	B: H2: Glass surface is not perfectly flat, therefore we still see 2 beams even if the incident beam is vertical A: H3: Glass surface is horizontal and flat but the laser beam was not perfectly vertical.	B: One possibility is that the lower glass surface is not flat. A: It could be horizontal, but the laser beam was not perfectly vertical.

16.25 – 16.26	Formulation of hypothesis (Where does the light beam reflect from?) [P1, H4]	A: H4: Light beam does not reflect from the paper.	A: Does it reflect from the paper? Probably not.
16.26 – 16.38	Testing experiment [P1, H4]	A: He removes the paper. Reflected beam remains visible.	A: We can try to take the paper away... and the phenomenon stays approximately the same.
16.38 – 16.42	Formulation of hypothesis (where does the light beam reflect from?) [P1, H5, H6], judgment	A: H5: Light beam reflects from the inner / outer surface of the glass wall. A: H6: Light beam reflects from both surfaces.	A: So, most probably it is reflected from the glass surface. Is it from the inner or the outer surface... It could also be from both.
16.42 – 16.51	Testing experiment (Reasoning about H6, while observing the phenomenon), judgment [P1, H6]	A: Reasoning: if H6 is true then we should see two parallel outgoing beams. Since we see only one outgoing beam, the beam reflects from one surface only.	A: It is not from both. If it were reflected from both, there would be two parallel beams, so it is only from one.
16.51 – 17.06	Observation [P1, P0]	B: Reflected beam is less bright than the incident beam so this means not all light get reflected, some light also scatters. They focus attention on the scattered light. A: P0: The light scatters at certain angles. There is pretty sharp boundary.	B: The reflected one is weaker, so not everything reflects, but some part also scatters. A: But also at certain angles, actually there is a pretty sharp boundary.
17.09 – 17.51	Recognizing patterns [P0]	They are observing how the cone angle depends on the angle of incident beam. It seems that the cone angle does not change.	A: We can change this angle and we will see... Does the angle of the cone change? B: I think not, but I will try with a paper (he closes the paper so that the paper edge is parallel to the cone edge. Subject A meanwhile changes the angle of incident beam.). It stays parallel. I should take more precise measurement, but on a hunch I would say that it is parallel all the time.

17.51 18.09	–	Formulation of hypothesis [P0, H7, H8]	A: H7: The formation of the cone angle is related with the upper and lower surface of the glass wall. A: H8: It could be fluorescence.	A: This could be related to the upper-lower surface. A: It is not fluorescence...
18.02 18.09	–	Testing experiment (reasoning) [H8]	They have the hypothesis and they are rejecting it right away using hypothetico-deductive reasoning. They are using the initial observational experiment as data to reject this hypothesis. Reasoning: The color of the scattered light is the same as the color of the original laser light. If it had something to do with fluorescence, then the other color would be different. H8 is correct.	A: ...If it had something to do with fluorescence, then the other color would be different.
18.19 18.26	–	Recognizing patterns [P0]	A: The cone is truncated (<i>the top point is not visible</i>).	A: The cone top is truncated.
18.26 18.38	–	Formulation of hypothesis [P0, H9]	1. H9: The effect of light scattering (<i>in cone</i>) is connected with the lower surface of the glass bottom.	A: That would indicate that it is the lower surface. B: Yes, because now we see that it would come exactly on lower surface (With hands he shows that the left and right edge of the cone would come together exactly on the lower surface.)
18.38 19.08	–	Design of the experiment [P0, H9]	B: Wants to see what happens inside the glass wall. In order to see it better he moves the tank to the edge of the table. He would probably like to see the cone in the glass to show that the light scatters on the lower surface of the glass.	B: It would be ideal if this (shows on the table) would be glass at least in this area (in front of the front edge of the aquarium), that that thing below would be nicely visible. A: That we would display what is going on inside the glass wall? B: Yes. If we could move the whole thing to the edge of the table...
18.45 18.48	–	Prediction [P0, H9]	They predict that if there was no table under aquarium, the light cone inside the glass would be visible.	B: ... that that thing below would be nicely visible.
19.02 19.17	–	Performing testing experiment [P0, H9]	He moves the aquarium partly over the the table, so that the beam still hits the table, but they could look upwards what is happening inside glass.	B: What happens? A: Aha...

19.17 – 19.21	Accidental observation [P0]	A: Accidentally notices that the cone disappears when the bottom is no longer touching the table	A: Did the cone disappear? B: Yes, the cone disappeared.
19.21 – 19.37	Recognizing patterns, performing testing experiment [P1, H5, H6]	They are trying to see the results of the testing experiment (18.38 – 19.17): B: Observes the reflected beam, that can be seen, even when the bottom is no longer touching the table.	B: While the reflection remains and it is nicely visible that it is from the lower surface.
19.37 – 19.42	My intermezzo	I ask them to speak louder.	
19.42 – 19.53	Recognizing patterns, performing testing experiment [P1, H5, H6]	They are trying to see the results of the testing experiment (18.38 – 19.17): B sees that the beam is reflected from the bottom surface of the glass wall. Subject A doesn't see light in the glass, but notices a small spot on the bottom surface of the glass wall.	A: I don't see any light inside the glass. A: I see a small spot if I look from the bottom...
19.53 – 19.56	Making assumptions [P1]		A: but I would see that even if I looked from the upper...
19.56 – 21.00	Recognizing patterns [P1, P0]	They are observing gradual appearance of the cone, when beam crosses the edge of the table.	A: I see the beam, interruption, then a spot and then probably mirror image of the beam. B: Let's do so, that it would just be on this wooden surface. Then we would probably see exactly... A: Aha, now a cone appears. Oh, it appears gradually, just at the edge of the table!
21.00 – 21.01	Formulation of hypothesis, judgment [P0, H10]	H10: The supporting surface (<i>on which the tank is resting</i>) is necessary for the cone formation.	A: So, the supporting surface is actually... (he doesn't finish his statement, but it can be seen what he means).
20.59 – 21.01	Design of the experiment [P0, H10]		A: I will try with a paper...
21.01 – 21.05	Prediction [P0, H10]	He predicts that the cone will appear, if the supporting surface is necessary for the cone formation.	A: ... if also the paper makes the cone.
21.04 – 21.07	Testing experiment + judgment [P0, H10]	A: They place the tank so that part of it is leaning over the edge of the table. They aim laser at the place on the bottom where there is no table below (<i>no cone visible</i>). They place/press the paper on the spot where laser beam hits the bottom. The light cone appears.	A: I will try with a paper, if also the paper makes the cone. Yes, now there is a cone, now there isn't. B: It does.

21.07 – 21.13	Judgment [P0, H10]		B: So, right when it reaches a non-transparent, non-translucent surface...
21.13 – 21.41	Using different representations, Other [P0]	A: After his speech on the right, he begins drawing the sketch and explaining at the same time. Light comes vertically to the dull surface where it scatters in all directions. He draws the scattered rays in all directions. He draws that the light scatters in all directions in the glass. He doesn't draw the air layer between the paper and glass.	A: It would be probably best if we begun drawing a scheme of what could be happening. A: Let's say that the beam reaches the table or paper, the surface which scatters light in all directions.
21.41 – 21.59	Formulation of hypothesis, using different representations [P0, H11, H12]	B: H11: Light doesn't scatter in all directions, but only to a specific angle. A: H12: Light does scatter in all directions, but beams that are at too large angle, cannot enter the liquid, but they totally reflect at boundary glass-liquid. (Meanwhile he supplements the sketch.)	B: But it doesn't scatter in all directions. A: No, it probably does scatter in all directions, but the beams at too large angle totally reflect back. (he explains enthusiastically)
21.59 – 22.03	Prediction [P0, H12]	B: If H12 were true, we would see the light inside the glass while looking sideways.	B: But if that was true, wouldn't we see here anything happening?
22.03 – 22.18	Testing experiment [P0, H12]	He puts the paper on a side of the aquarium to see if any light comes out of the glass. We don't see any light.	B: But if that was true, wouldn't we see here anything happening? Because this way (He puts the paper on one side of the aquarium and watches if the paper will become green-colored of the light.) we don't get anything, nothing comes out.
22.18 – 22.27	Formulation of hypothesis [P0, H13], judgment	A: H13: Light at certain angles doesn't even enter the glass, but totally reflects back.	A: Then maybe something doesn't even enter glass, but it reflects from the lower...
22.27 – 22.53	Testing experiment [P0, H13]	A: Reasoning: Total reflection can be present only when incident light is traveling within the more optically dense medium towards the less optically dense medium. So H13 cannot be true. They are not completely sure that H13 doesn't stand, because in praxis we can see a reflection in a window, although there is no total reflection. They suspect that the right explanation has something to do with this.	A: How does this go... From optically more dense to optically less dense there could be a total reflection. The other way around cannot. But yes, the cone must be connected with this in some way.

22.53 – 23.04	Judgment [P0, H13]		A: But yes, the cone must be connected with this in some way.
23.20 – 23.23	Design of the experiment [P0, H10, H11, H12, H13]	Subject A is planing moving the paper up and down from the aquarium bottom.	A: What if you move the paper up and down?
23.23 – 23.25	Prediction [P0, H10, H11, H12, H13]	Subject A asks himself whether anything changes if we move the paper slowly away from the aquarium bottom. If the cone originates on the paper, the bottom of the cone should expand when the paper is further away from the glass.	A: Does anything change?
23.37 – 23.45	Performing testing experiment [P0, H10, H11, H12, H13]	B moves down the paper.	B: Yes, right when I move it away, the cone disappears.
23.45 – 23.53	Prediction [P0, H10, H11, H12, H13]	If the cone originates on the paper, the bottom of the cone should expand when the paper is further away from the glass.	A: Does the truncated top of the cone increase?
23.53 – 24.11	Testing experiment [P0, H10, H11, H12, H13]	B: He sees that that the top of the cone would be on the paper, if we lengthened the edges.	B: Yes, it actually goes to the paper...
23.56 – 24.11	Judgment [P0, H10, H11, H12, H13]		B: ...so it reflects off the paper. A: Yes, so the top of the cone is at the paper.
24.11 – 24.42	Recognizing patterns [P0]	B: The angle of the cone does not change when we move the paper further away. A: The intensity of light inside the cone almost doesn't change when moving paper a little (1 cm) away. A: The cone is the most sharp when the paper is right besides the glass.	B: While the angle itself does not change. A: And neither does light intensity in some point inside the cone change much. A: But the sharpness of the cone edge diminishes slightly (says while moving the paper downward).

24.42 24.54	–	Formulation of hypothesis (Why is the cone the most sharp near the top.) [P0, H14]	B: H14: The sharpness of the cone is falling downside up because of light scattering.	B: This is likely, because then light is reflected or scattered when going back (meaning back up away from the paper).
24.54 25.41	–	Other	They ask for refraction index for glass, water and air, wave length of light.	
25.41 25.59	–	Testing experiment [P1, H5, H6]	B: Intensity of reflected beam (P1) is independent on position of paper underneath the aquarium. H5 stands.	B: Regardless of the presence of the paper and the distance between the paper and glass, the intensity of the reflected beam is constant.
25.59 26.13	–	Formulation of hypothesis, judgment [P1, H15]	B: H15: It is only reflected from the lower surface.	B: In other words, reflection is bound only to the lower surface of the glass. A: Though we can't conclude that it only reflects from the lower surface.
26.13 26.21	–	Prediction, experiment design [P1, H15]	Obviously he predicts that there will be angle between incident and reflected beam, and from the top of this angle they will be able to see, from which surface the beam is being reflected. (if it is truncated or not)	A: But we can determine that from the top of the angle. If we focus on the reflected beam instead of the cone, we can try...
26.18 26.53	–	Performing testing experiment, judgment [P1, H15, H6]	A: If we shine from the side, we will see from which layer it is reflected. After a good look they notice another beam, parallel to the main one, with a much lower intensity. Judging by the cone shape they conclude light is reflected from both surfaces, although it is mostly from the lower one. H15 is wrong, H6 stands.	A: But we can determine that from the top of the angle. If we focus on the reflected beam instead of the cone, we can try... (shines the laser from the side). Yes, from the lower surface. Oh, wait, it's from both of them, although much less from the upper one, can you see two parallel beams?
26.56 26.58	–	Prediction [P1, H6]	If H6 holds, we should see 4 beams where the two reflected beams are again reflected from the side wall of the aquarium.	A: So there should be 4 beams...
26.53 27.07	–	Testing experiment [P1, H6]	No such beams are detected. They come up with possible explanations for this result: A: some of the four reflected beams overlap B: twice-reflected beams are too weak to notice.	B: It's nicely visible here too. A: Oh, after it reflects also from the side wall. So there should be 4 beams, except if two maybe combine again. B: Question is, aren't then the other two too weak to notice?

26.58 – 27.24	Judgment [P1, H6]	B: Light reflects from both surfaces. A: The reflection from the lower surface is stronger	A: ...except if two maybe combine again. B: Question is, aren't then the other two too weak to notice? B: So reflection is, as should be, from both surfaces. A: And stronger on the lower one, which is somewhat logical.
27.21 – 28.10	Recognizing patterns [P1]	A: Reflection occurs not only at the critical angle, but also at very steep angles. A: Observes how reflected beam intensity changes with the incident beam angle. A: They observe what the critical angle of reflection is – where the intensity of the reflected beam is equal to the intensity of the incident beam on the boundary water-glass. This happens gradually while increasing the angle.	A: But reflection occurs even though we are not at the critical angle. Even at a very steep angle we get a reflection. Does the reflected beam intensity increase with the angle? B: No. A: At a certain critical angle there should be a total reflection (varies the angle). B: Aha, here it is. A: Does the reflected beam intensity gradually increase? B: I think it's gradual, but it's barely noticeable at the start, then somewhere here it starts to increase.
28.10 – 28.44	Other [P1, P0]	A: We have a bunch of phenomena: Two reflections from two surfaces, scattering on the paper and reflection of the scattered light. That's why some of it is missing .	A: There's a bunch of phenomena here. We have reflection, scattering on the paper and then reflection of the scattered light back. That's why some of it is missing, or rather the scattered light is in a cone shape. We have two reflections, the intensity varies with the angle.
29.00 – 29.13	Testing experiment, judgment [P0, H12, H13]	Paper scatters light in all direction. (Makes a Testing experiment, if he sees a dot on the paper, looking from all angles)	A: The scattered light goes in all direction, including towards me, because I see the dot (on the paper).
28.44 – 29.38	Formulation of hypothesis (Why the cone angle is constant) [P0, H12]	A: Again H12: (adds to the sketch on paper 1) Paper scatters light in all direction. At a certain angle a total reflection occurs at the glass-water interface.	B: I want to know especially why the cone angle is always constant. A: I think at a certain angle it reflects back. The scattered light goes in all direction, including towards me, because I see the dot (on the paper). When it goes up, at a certain angle total reflection occurs, and there is no light there.

29.38 – 29.51	Testing experiment (reasoning) [P0, H12]	A: Wonders what the outgoing angle would be when the incident one is critical.	A: At what incident angle does total reflection occur? Is it at the angle where the outgoing angle would be 90 degrees?
29.51 – 30.18	Design of experiment, Prediction [P0, H12]	B: Let's see of the edge of the cone is at the same angle as the total reflection angle at glass-water interface. Prediction: The total reflection angle will be equal to the cone angle.	B: Let's try again and draw what the cone angle is. Then we can try moving the laser again to see if if we get total reflection at the same angle as the cone angle. This would be a good piece of information.
30.18 – 32.14	Testing experiment (if the angle of the cone is connected with the critical angle of total reflection) [P0, H12]	They measure only the cone angle. They decide it is around 45 degrees. B: Writes down “+- 45 degrees” on paper 3 at 32:13.	B: I see that it is 45 degrees. Is it? A: Yes, it is.
32.15 – 32.20	Judgment [P0, H12]		B: It is actually very close to the right angle. Now, is this a coincidence or not...
32.20 – 34.01	Intermezzo by professor	Professor writes down and sketches Snell's law of refraction and the angle of total reflection.	
34.01 – 34.45	Testing experiment (reasoning) and using different representations, judgment [P0, H12]	A: If total reflection were the reason, we would still get all angles in the water. H12 is wrong. He draws a sketch on the board. It is probably something related to the light entering the glass.	A: This means that my previous explanation is incorrect (draws a sketch, where light spreads into the glass in all directions and some totally reflects from the glass-water interface), because total reflection would only occur where this angle (cone angle) would be 90 degrees, so there would be no cone. The explanation must be something related to the lower surface and how light enters the glass.

34.48 – 35.00	Experiment design, other [P0, H12]	B noticed that the angle is close to 90 degrees and is asking himself if this is just the coincidence or is it exactly 90 degrees. - We will categorize this as “other”.	B: Regarding the angles themselves I want to know if it's a coincidence, that it's so close... (doesn't finish the sentence). A: We can calculate that, since we have the formula and information about refraction indexes.
35.00 – 37.03	Other, finding patterns [P0], [P1]	A: They try to calculate the ratio of sines of incident and outgoing angles at the glass-water interface. They think about how beams are reflected.	A: Right, but we have no incident or refracted angles, because it's all perpendicular. Anyway, let's see... B: This one is incident (downwards), this one is going back (cone edge). A: But if this one is vertical, then the sine is zero.
37.03 – 38.26	Other and multiple representations [P0, H13]	A: Would it be possible to connect P0 with the lower surface? He draws a sketch with the paper drawn lower, so a layer of air is visible. He draws beams reflected from the paper in all directions. A: They use the theory, that there is no critical angle at the air-glass interface. He has second thoughts, because in practice some light is always reflected from glass surfaces, like windows.	A: Could something be done with the lower surface? Say here is the glass and here is the paper, scattering in all directions (draws). And what happens now? Is here (at the air-glass interface) also a critical angle? Theoretically no, at any incident angle... According to the equation there isn't, but in practice there is. If you look at the glass very sideways, you don't see what's behind it, but what's in front. Except this isn't a phenomenon that would radically change at a certain angle.
38.52 – 39.45	Testing experiment [P0, H12]	A: Let's light up the paper from below. The same cone appears. Changing the laser angle (incident angle of the beam falling on paper) has no effect on the cone. (He did not tell the prediction of this experiment loudly, but he probably predicted that there will be a cone visible). He doesn't tell, but he is probably testing H12, because light is transmitted through paper in all angles, like reflected light. With this he sees, that the cone can be formed by the light reflected from paper.	A: OK, I know, we can light up the paper from below. (They perform the experiment). A: Here, the same cone appears, with the same angle and truncated top. I'll try changing the laser angle. If I do this, the cone doesn't change.

39.45 40.07	–	Formulation of hypothesis [P0, H16]	B: H16: Walls of the tank have no effect, everything depends on the paper on which a cone appears.	B: Question is, what effect does the glass wall have, or is it all depending only on the surface that poorly transmits light?
40.07 40.15	–	Prediction, experiment design [P0, H16]	A: He predicted, that there will be a cone visible in the water if the paper makes the cone. We can see this from his words when he sees the result of the testing experiment.	A: Let's try to put the paper inside (puts the paper into the water).
40.15 42.01	–	Testing experiment [P0, H16]	A: They put the paper into the water and observe whether a cone appears when pointing a laser on the paper. They want to see the cone, because this would solve the problem. For some time, subject B think he sees it. But there is no cone, so H16 does not hold. Glass has an effect as well.	A: No, there is no cone. B: Yes, I think there is. A: Except it's not the same cone, it's not as sharp and it's considerably wider. Is it the same? B: Yes, it is exactly the same. That means we were wrong. A: That the glass has no effect. (They put the paper on the bottom) B: No, there is no cone. So glass has some effect. It obviously prevents some angles of propagation.
40.58 41.05	–	Judgment [P0, H16]		B: That means we were wrong A: That the glass has no effect.
41.48 42.01	–	Judgment [P0, H16]		B: So glass has some effect. It obviously prevents some angles of propagation.
42.01 42.11	–	Formulation of hypothesis [P0, H17]	A: H17: Some of the beams do not enter the glass.	A: Yes, but where does it prevent them, do they not enter the glass, or exit? That about exiting would not hold according to the theory, but I'm not sure about the entering.
42.11 42.17	–	Experiment design [P0, H12]		B: Shine at a very large angle.
42.17 42.18	–	Prediction [P0, H12]		B: ...and we will see what happens.
42.18 43.02	–	Testing experiment [P0, H12]	B: They shine the laser through the glass sideways (so the beam is almost horizontal in the glass) and try to see the angle at which light enters the water from the glass. Instead, they see that light remains in the glass. (does the light enter water from glass, when incident angle is very big)	B: Shine at a very large angle, and we will see what happens. See, it all remains in the glass, it doesn't go into the solution.

43.02 – 43.21	Judgment [P0, H12]	A: This happens because of total reflection. Explains, once more, that total reflection does not explain the cone, as we would get all angles.	A: Of course, it's logical. Now that you were shining into the glass, there was a total reflection (on the glass-water interface). But it only occurs when the outgoing angle is equal to 90 degrees, while here it's only 45 degrees.
43.21 – 43.25	Experiment design, prediction [P0, H13, H17]		A: What if we try looking at it this way, what...
43.25 – 44.08	Testing experiment + judgment [P0, H13, H17]	A: They look at what happens if they shine into the water tank through a glass wall. He sees that the beam is at a different angle in water than in air. From his speech can be seen that he had already predicted that when incident angle will be more than 45, something (probably the beam in the water.) will not be visible any more. He also predicted that the angles in the air and the water will be the same.	A: What if we try looking at it this way, what... (points the laser into the glass from the side) A: Look, now we have more that 45 degrees, but it is still... A: Look what is interesting. As far as I remember, if you have like this (thinks that the incident angle in the air and the angle in the water should be the same)
44.08 – 44.16	Other, judgment [P0]	A: They use theory: If the same medium is on both sides, light exists the glass at the same angle I enters. (draws a sketch). Because in our case the medium is not the same, the angles aren't the same either.	A: Oh, of course not, because we have different media outside and inside. If we had the same medium, the angles would be the same, but here they aren't.
44.16 – 44.21	Formulation of hypothesis [P0, H18]	A: H18: The cone is connected with the fact that light exits the glass at a different angle than it enters. No matter how large or small the incident angle is, the angle in water is always smaller. The unpredicted outcome of the testing experiment leads them in the right direction.	A: Maybe it's connected to this, yes of course!
44.21 – 44.50	Testing experiment [P0, H18]	A: Shines the laser at the glass (as at 43:23 – 44:08) and varies the angle. The reflected angle in water is never more than approximately 45 degrees. H18 stands. He makes no prediction, because he already made the same experiment (for different reason) in time (43.23 – 44.08) and already knew the outcome.	A: Yes, look, this angle is never greater than 45 degrees, it can't be. Because this is not dependent on the index of refraction of glass, only of water and air.

44.34 – 44.50	Judgment [P0, H18]		A: ...it can't be. Because this is not dependent on the index of refraction of glass, only of water and air.
44.51 – 44.59	Other		B: What is the refraction index of the air? A: Of water is 1.33.
44.59 – 44.59	Experiment design, prediction [P0, H18]		A: If we calculate this and if it comes exactly 45 degrees...
44.59 – 46.25	Quantitative prediction [P0, H18], multiple representations	A: The ratio of the sines depends on indexes of refraction of water and air, but not glass between them. (uses the theory). He writes down the law of refraction. They calculate the angle of refraction in water for the incident angle of 90 degrees. They use Snell's law. The result is 48 degrees, which is close to 45 degrees.	A: Sine of what is 1.33? B: Of 1/1.33... A: Yes, I don't know if I did it right, we can see that after we calculate. A: It is 48 degrees.
46.25 – 46.37	Judgment [P0, H18]	B: The difference could be because we do not have exact values for refractive indexes. A: The difference could be because we didn't measure accurately.	B: But, if we used completely accurate figures, we would come to 45 degrees. A: Or a completely accurate measurement. We did not measure completely accurately.
46.37 – 46.38	Experiment design [P0, H18]		A: We can measure again...
46.38 – 46.40	Prediction [P0, H18]	He predicts that maybe the repeated measurement's result will be 48 degrees.	A: ...and we will see, maybe it is 48 degrees.
46.44 – 47.54	Performing quantitative testing experiment [P0, H18]	They measure the angle again and check for inaccuracies. The angle is the same as before.	A: I see that it is less than 45 degrees. B: It is close to 50 degrees. A: I see it is less than 45 degrees.
47.54 – 48.30	Judgment [P0, H18]	They decide that the error is in the data or the measurement, so it is close enough (assumption!) to conclude this mechanism causes the cone to appear – that H18 holds.	B: This could be. I doubt it is a coincidence that it is so close. A: Yes, and here we actually saw (points the laser through the glass into the water again) that you cannot get a greater angle at any incident angle. B: So, it is the air-water transition.

49.25 – 51.51	They draw a scheme of their explanation (after prof. Planinšič asks them to, not on their own)	<p>They draw a schematic drawing with the right explanation. They are sure enough that they explained it correctly so that they can finish.</p> <p>They connect their explanation with the observation that the top of the cone is truncated.</p> <p>They connect their explanation with the outcome of testing experiment in time interval (23.04 – 24.11).</p>	<p>A: Here we can already see the cone is truncated, because the beams exit at different points.</p> <p>A: Oh, and this is what we previously observed, that by lowering the paper only the top if the cone is moving downward.</p> <p>B: The virtual top, because it is not there below the water.</p> <p>A: If we had dust particles in the air between the paper and the glass, we would notice it there too... Wait, no, not below, because it goes from the paper in all directions.</p> <p>B: Yes, so now we've explained ti.</p>
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