Liquid crystals: a new topic in physics for undergraduates

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Abstract
This paper presents a teaching module about liquid crystals. Since liquid crystals are linked to everyday student experiences and are also a topic of current scientific research, they are an excellent candidate for a modern topic to be introduced into education. We show that liquid crystals can provide a pathway through several fields of physics such as thermodynamics, optics and electromagnetism. We discuss what students should learn about liquid crystals and what physical concepts they should know before considering them. In the presentation of the teaching module, which consists of a lecture and experimental work in a chemistry and physics laboratory, we focus on experiments on phase transitions, polarization of light, double refraction and colours. A pilot evaluation of the module was performed among pre-service primary school teachers who have no special preference for natural sciences. The evaluation shows that the module is very efficient in transferring knowledge. A prior study showed that the informally obtained pre-knowledge on liquid crystals of the first-year students from several different fields of study was negligible. Since social science students are the least interested in natural sciences, it can be expected that students in any study programme will on average achieve at least as good qualitative knowledge of phenomena related to liquid crystals as the group involved in the pilot study.

(Some figures may appear in colour only in the online journal)

1. Introduction
For physicists, physics is a permanent inspiration for new discoveries. However, non-physicists often consider physics to be a boring and ‘old’ discipline, detached from everyday life. The public often fails to realize the implications of research for everyday applications, so it often considers academic research to be a waste of financial resources. But research is tightly connected to development, even if it is not strongly focused towards applications. This can be best illustrated by the well-known statement that ‘the light bulb was not discovered by optimizing a candle’ [1, 2]. The apparent irrelevance of physics for everyday life is often
caused by the choice of topics taught during lectures, which are usually ‘old’ from the point of view of young students, since even the fundamentals of modern physics are more than a hundred years old [3]. In addition, traditional teaching very often considers idealized examples and, worst of all, present experiments as ‘proof’ for theoretical explanations.

Physics education research has pointed out several of these problems and physics education in general has advanced tremendously in the last 20 years [4]. But topics that introduce a part of frontier research into the classroom, showing students that physics is not a ‘dead’ subject, are still extremely rare.

In this paper, we present a topic, liquid crystals, which is one of the rare examples where such a transfer is possible. The community occupied by liquid crystal research numbers several thousand researchers. We all experience the consequences of research on liquid crystals every day; every mobile phone, every portable computer and almost every television screen is based on technology using liquid crystals.

The physics of liquid crystals is not very simple, but there are several concepts that can be understood by non-physics students, especially if the teaching approach is based on gaining practical experience with liquid crystals. In addition, for advanced levels of physics students, liquid crystals may serve as a clear illustration of several concepts, especially in thermodynamics and optics.

A serious interest from researchers for the introduction of liquid crystals into various levels of education was first demonstrated at the International Liquid Crystal Conference (ILCC) in Krakow, Poland, in 2010. ILCC is a biennial event gathering more than 800 researchers studying liquid crystals from a variety of aspects. In Krakow, one of four sections running in parallel was called Liquid Crystals in Education. The audience unexpectedly filled the auditorium and after lectures lengthy discussions were held [5]. A similar story was seen at the education section at the European Conference on Liquid Crystals in Maribor, Slovenia, in 2011, and at ILCC in Mainz, Germany, in 2012.

At present, some of the physics of liquid crystals is usually briefly mentioned in various courses at university level, but there is no systematic consideration from the educational perspective about the importance of various concepts and teaching methods. To the best of our knowledge, no example of a model teaching unit exists. In this contribution, we report on a teaching module on liquid crystals, which is appropriate for undergraduate-level non-physicists. The module can be extended to laboratory work at more advanced levels. Most of the module can also be used in courses related to thermodynamics and optics as demonstration experiments or laboratory work accompanied by more rigorous measurements and calculations, which are not considered in detail in this paper.

The paper is organized as follows. In section 2, we consider the prerequisites for the introduction of a new modern topic into education. Before designing a module we had to consider several points, not necessarily in the same order as quoted here. What outcomes do we expect from the teaching module? Which concepts should students understand and be able to apply after the module? Where in the curriculum should the topic be placed, or equivalently, what do students need to know to be able to construct new knowledge about liquid crystals? Which teaching methods are most appropriate for the teaching module? And finally, do we have all the materials such as experiments, pictures, equipment and facilities to support the teaching module? In section 3, we report the pilot evaluation study of the teaching module, which was performed in 2011. In section 4, we conclude and discuss several opportunities that the new teaching module offers to physics education research, in addition to the new knowledge itself.
2. Teaching module

When we consider a new topic that is part of contemporary research with applications that are encountered every day, and we want to adapt it for teaching purposes, searching the literature is not much help. A thorough literature search did not show any theoretical frameworks for this topic. One can find theoretical frameworks for various approaches to teaching, and discussions about student motivation and their understanding of various concepts. We have found a few examples of the introduction of new topics, such as the introduction of semiconductors into secondary schools or the introduction of more advanced concepts with respect to friction only [6, 7]. There are also examples of the introduction of quantum mechanics concepts into high school [8–11]. All the authors reported similar problems with respect to existing theories and results in physics and science education research; they had to build the units mostly from personal knowledge, experience and considerations. On the other hand, several approaches for analytical derivation of already-treated concepts, and several suggestions for demonstrations and laboratory experiments for teaching purposes are published in every issue of pedagogical journals such as this one. This simply means that the physics community is very interested in the improvement of teaching itself, but the motivation of the researchers, being also lecturers, lies more in the area of developing new experiments than in thorough study of their impact. Therefore, many teaching materials for any topic, old, modern or new, are available, but one further step is usually needed towards a coherent teaching module.

With the above-mentioned problems in mind, we begin with a brief discussion of what liquid crystals are and then give a short overview of the existing literature regarding the introduction of liquid crystals into teaching. Then we focus on the teaching module: we define our goals, consider the pre-knowledge on which the module should be built and finally describe details for the module.

2.1. What are liquid crystals?

Liquid crystals are materials that have at least one additional phase between liquid and solid. This phase is called the liquid crystalline phase and it has properties from both the liquid and crystalline phases: (a) it flows like a liquid, or more fundamentally, there is no long-range order in at least one of the directions, and (b) it is anisotropic, which is a property of crystals, or, again, more fundamentally, there exists a long-range order in at least one of the directions. Liquid crystal is the name for a material that exhibits at least one liquid crystalline phase [12].

Liquid crystalline phases differ in their way of long-range ordering. The simplest type of ordering is in the nematic phase, the properties of which are used in a liquid crystalline screen. The molecular order in the crystalline phase is shown schematically in figure 1(a), in the nematic liquid crystalline phase in figure 1(b) and in the isotropic liquid phase in figure 1(c).
One can see that, in the liquid crystalline phase, there exists some orientational order of long molecular axes. Such a material is anisotropic; the physical properties along the average long molecular axis obviously being different from the properties in the direction perpendicular to it. There are several liquid crystal phases made of molecules having rather extravagant shapes. However, we shall limit our discussion to the simplest case of a nematic liquid crystal made of rod-like molecules without any loss of generality of the phenomena studied within the teaching module.

When liquid crystal molecules are close to surfaces, the surfaces in general tend to prefer some orientation of long molecular axes. Using a special surface treatment one can achieve a well-defined orientation of long molecular axes at the surface, for example, in the direction parallel to the surface or perpendicular to it. In liquid crystal cells, which are used in liquid crystal displays (LCDs), surfaces are usually such that they anchor the molecules by their long molecular axes in the direction parallel to the surface. Orientations of molecules at the top and bottom surfaces are perpendicular. Molecules between the surfaces tend to arrange with their long axis being parallel; however, due to the surface anchoring their orientation rotates through the cell (figure 2(a)). Because in the anisotropic materials the speed of light depends on the direction of light propagation and on the direction of light polarization, liquid crystals organized in such a special way rotate the direction of light polarization. If such a cell is put between crossed polarizers whose transmission directions coincide with the direction of surface anchoring, then the cell transmits light [12, 13].

Liquid crystals are also extremely useful in discussing different competing effects that determine the molecular arrangement. Application of an external magnetic or electric field changes the structure in the liquid crystal cell, because the electric or magnetic torque tends to arrange molecules in the direction parallel or perpendicular to the external field, depending on the molecular properties. Rotation of molecules in the external field changes the optical transmission properties of the cell. This is a basis of how LCDs work: with the field on (figure 2(b)), light is not transmitted through the cell and the cell is seen to be dark; with the field off (figure 2(a)), light is transmitted through the cell and the cell is seen to be bright.

Because of their unique physical properties, several authors have already considered the introduction of liquid crystals into undergraduate university study. A mechanical model of a three-dimensional presentation of liquid crystals phases is presented in [14]. The historical development of liquid crystal research and application is given in [15]. In [16], the same
authors point out that liquid crystals are an excellent material to connect some elementary physics with technology and other scientific disciplines.

The procedures to synthesize cholesteric liquid crystals (nematic liquid crystals in which the average orientation of long molecular axes spirals in space) in a school laboratory at undergraduate university level are given in [17, 18], together with the methods to test the elementary physical properties of liquid crystals. In the appendix of [18], an experiment to determine the refractive indices of a liquid crystal is discussed [19]. The anisotropic absorption of polarized light in liquid crystals is presented.

Liquid crystals that are appropriate for educational purposes are thermotropic; their properties change with temperature. The colour of cholesteric liquid crystals changes if temperature increases or decreases, so they can be used as thermometers [20]. They are also sensitive to pressure. Reference [21] contains worksheets for an experiment in which students discover the sensitivity of cholesteric liquid crystal mixtures on pressure and temperature. In [22], a simple experimental setup is presented by which students can detect and record light spectra, study and test the concept of Bragg reflection and measure the anisotropy of a refractive index in a cholesteric liquid crystal.

A series of simple experiments that can be shown during lectures and can bring the science of liquid crystals closer to students are described in [23]. The experiments are used to introduce the concepts of optics, such as light propagation, polarization of light, scattering of light and optical anisotropy. Liquid crystal can also be used to describe light transmission through polarizers [24]. When an external field is applied to a cell, a threshold value is required to rotate molecules in the direction preferred by the field. This effect is called the Freedericksz transition and an experiment for the advanced physics laboratory at the undergraduate level is presented in [25].

The procedure to prepare a surface-oriented liquid crystal cell is given in [26], where the procedure to synthesize a nematic liquid crystal 4-methoxybenzylidene-4′-n-butylaniline (MBBA) is provided as well. Several experiments that illustrate the optical properties of liquid crystals are shown. One learns how to design a cell in which molecules are uniformly oriented and what is observed if this cell is studied under the polarizing microscope. A detailed description of phase transitions between the liquid, liquid crystal and crystal phases is given. Exercises are interesting for undergraduate students, because they synthesize the substance which they use for other experiments, e.g. measurements of the refractive indices.

There are several advanced papers that give advice on the inclusion of liquid crystals in university in both undergraduate or graduate levels. An experiment for the advanced undergraduate laboratory on magnetic birefringence in liquid crystals is presented in [27]; measurements of order and biaxiality are addressed in [28]. In [29], defects in nematic liquid crystals are studied at using Physics Applets [30]. Liquid crystals are not only used in displays, but also in switches. In [31], a liquid crystal spatial light modulator is built and used for a dynamic manipulation of a laser beam.

2.2. What should students learn about liquid crystals?

When discussing the introduction of a new topic into education, the team should be aware of their goals. We decided that the aim of the teaching module is to explain how LCDs work and what role liquid crystals have in its operation. Basic understanding of LCDs should be a part of a general public knowledge, because LCDs are an important example of a link between academic research and applications. If non-physics students meet such an example at least once during their studies, they might not consider academic research that has no immediate specific application to be obsolete.
According to our opinion students should obtain and understand the following specific concepts:

- they should be able to recognize and identify the object of interest—the pixel—on an enlarged screen;
- they should be aware of the fact that liquid crystals are a special phase of matter having very special properties;
- they should become familiar with the following concepts: anisotropy, double refraction and birefringence;
- they should be aware of the fact that liquid crystals must be ordered if we want to exploit their special properties;
- they should know that liquid crystals are easily manipulated by external stimuli such as an electric field; and finally
- they should link the concepts mentioned above in a consistent picture of pixel operation.

After setting the goals, the next steps are (a) to consider the knowledge required before students start the module, (b) to position the topic in the curriculum, otherwise teachers will probably not adopt it and (c) to choose the methods that will be most successful in cultivating the new knowledge.

2.3. Which basic physics concepts should students know before considering liquid crystals?

As liquid crystals are materials that form a special liquid crystalline phase, students should be familiar with the concept of phases and they should know that phase transitions occur at an exact temperature. The next important concept is the speed of light in a transparent medium, its relation to the index of refraction and Snell’s law. Students should also know that materials electrically polarize in an external electric field and that material polarization is a consequence of structural changes of a material in the electric field.

Consideration of the required preliminary knowledge also gave some hints about the placement of the topic on liquid crystals in the curriculum. Liquid crystals can provide a motivational pathway through several topics in physics.

- When teaching thermodynamics or, more specifically, phases and phase transitions, an additional phase can be shown using liquid crystals, since the appearance of liquid crystals in their liquid crystalline phase is significantly different from their solid or liquid states. This is not the case for other materials; for example, a ferromagnetic material or a superconductor looks exactly the same when the phase transition to the ferromagnetic or superconductive phase appears at the transition temperature. The phase transition has to be deduced from other properties.
- When Snell’s law is introduced and prisms are discussed, a rainbow is often added as an interesting phenomenon that is observed because the speed of light depends on its wavelength. A similar phenomenon, i.e. a dependence of the speed of light on light polarization, can be discussed by the phenomenon of double refraction.
- One picture element (pixel) is formed by confining LC between two conducting plates. One pixel is thus a capacitor with a dielectric material (liquid crystal) between the plates. When voltage is applied to the cell surfaces (capacitor plates), the material between the plates polarizes. Electric polarization leads to changes in the structural properties of the materials, in this case to the reorientation of molecules, which affects the transmission of light through the cell. Thus, an LC pixel can be used to consider electric polarization of other materials that can change structurally due to the reorientation of molecules.
2.4. What do students already know about liquid crystals?

Since we use liquid crystals in everyday life, we were interested in just how much students already know about them. We used a liquid crystal questionnaire (LCQ) to test informally obtained pre-knowledge about liquid crystals for the first-year students at various study programmes at the Faculty of Education at the University of Ljubljana in the study year 2009/10 [32]. Since we were considering the first-year pre-service primary school students as a potential group for testing the module about liquid crystals (a pilot study group), we decided to repeat the study with the pre-service primary school students from the Faculty of Education, other students from the Faculty of Education and students of different faculties of the University of Ljubljana (a general group) at the beginning of the study year 2010/11. The LCQ also includes the question about students' achievement in the final examination at the end of high school, which gives data about the assessment of the intellectual level of the first-year students at different representative study programmes in order to estimate the equivalence of the potential pilot group and a general group. The results of the study performed on a more general and wider sample of 1121 students from different faculties of the Ljubljana University shows that general student pre-knowledge about liquid crystals is practically negligible (table 1), although male students showed statistically significant better achievement in the LCQ. This fact is in agreement with the findings of Haeussler and Hoffmann [33], who argue that male students are more interested in technology and the application of science than female students.

The difference between students from the Faculty of Education and those from faculties where the main study field is science and technology is in motivation for natural sciences. Students in the study fields connected to natural sciences and technology have greater interest in these subjects and therefore it was expected that their achievements in the LCQ would be greater. Indeed, there are statistically important differences in achievements in the LCQ between the students of natural sciences and technology and those who study social sciences and humanities (see table 2).

The bottom line of the study is: at the end of secondary school (or the beginning of university study), informally obtained knowledge of liquid crystals for the pre-service teacher...
Table 2. Achievements in the LCQ regarding the field of study and the natural sciences fields.

| Field of study                  | Percentage of students | Number of achieved points out of 8 | SD  | t     | p   |
|--------------------------------|------------------------|-----------------------------------|-----|-------|-----|
| Natural sciences or technology  | 41.7                   | 2.5                               | 1.6 |       |     |
| Social sciences or humanities  | 58.3                   | 1.4                               | 1.6 | 12.712| 0.000|

students (these students present a pilot study group for the teaching module presented in the following section) does not on average differ from that of students from different faculties: in both samples a lack of knowledge about liquid crystals was detected.

2.5. The teaching module

The teaching module provides the basic knowledge about liquid crystals that we assessed to be necessary for understanding liquid crystals and LCD technology for a general citizen having at least a slight interest in science and technology. To choose the methods for the teaching intervention, we had to take into account that liquid crystals are a new topic for students and should be introduced from the very beginning. Due to several concepts that must be introduced and the structure of understanding that students have to build without any pre-knowledge, we decided to use a combination of a traditional lecture and several demonstration experiments, where most of the fundamental concepts and properties are introduced; a chemistry laboratory, where students synthesize a liquid crystal; and a physics laboratory, where they use their own product from the chemistry laboratory to study its various physical properties using an active learning approach. The laboratory work allows students to construct and to comprehend several new ideas that are all linked together in the application, a liquid crystalline display. The estimated time for each part is 90 min.

2.5.1. Lecture. The lecture provides fundamental information about liquid crystals, about their properties and how they are used in applications. After the lecture students should be able to

- list some products based on liquid crystal technology;
- identify the additional liquid crystalline phase and phase transition;
- describe and illustrate the structure of liquid crystals on a microscopic level;
- test the properties of liquid crystals, which are important for applications: birefringence, resulting from the orientational ordering of molecules;
- test the above-mentioned properties of an unknown substance;
- explain the effect of an electric field on molecular orientation;
- explain how LCDs work;
- know that liquid crystals are also found in nature and that they are present in living organisms.

In addition, a short part of the lecture introduces polarizers and their properties, since most of the students have not heard of the concept of polarization and polarizers during their previous education.

The lecture starts with a magnification of an LC screen as a motivation; it is explained that at the end of the module students will be able to understand how the display works. The lecture continues with a description and a demonstration of the new, liquid crystalline, phase, the macroscopic appearance of which is similar to an opaque liquid. All three phases (crystalline, liquid crystalline and isotropic liquid) are shown while heating the sample. The
microscopic structures of all three phases are presented by cartoons and the orientational order is introduced. The molecular shape which allows for the orientational ordering is discussed. The concept of light propagation in an anisotropic material is introduced and double refraction is shown using a wedge liquid crystalline cell. Colours of an anisotropic material (scotch tape) between crossed polarizers are demonstrated and explained.

In LCDs, the electric properties of molecules are very important so the effect of the electric field on the molecular orientation is discussed as well. Molecules are described as induced electric dipoles that are rotated by the external electric field. Because the anisotropic properties depend on the structure of the liquid crystal in the cell, the transmission depends on the applied electric field. This leads to the structure of a pixel and how LCDs work.

At the end of the lecture some interesting facts are mentioned, such as liquid crystals being a part of spider threads and cell membranes in living organisms.

2.5.2. Laboratory work in chemistry: synthesis of the liquid crystal MBBA. The aims of the laboratory work in chemistry are as follows.

- Students are able to synthesize the liquid crystal MBBA.
- Students realize that the product of the synthesis is useful for the experiments showing the basic properties of liquid crystals.

Students synthesize the liquid crystal MBBA in a school laboratory from 4′-n-butylaniline and 4-methoxybenzaldehyde [34, 35]. Due to safety reasons, the synthesis has to be carried out in the fume hood.

2.5.3. Laboratory work in physics. Four experiments are performed during the laboratory work in physics. They provide students with personal experiences and allow them to investigate the most important liquid crystalline properties.

Experiment 1. An additional phase and phase transition

Aims.

- Students to know that the liquid crystalline state is one of the states of matter.
- Students to be able to describe the difference between the melting temperature and the clearing temperature.
- Students to be able to measure these two temperatures and use them as a measure of the success of the synthesis; if both temperatures are close to those given in the published data, the synthesis is successful.

Students use a water bath to heat the test tube with a frozen liquid crystal MBBA. They measure the temperature of water assuming that the small sample of the liquid crystal has the same temperature as the bath. They observe how the appearance of the substance changes (figure 3) while heating the water bath. They measure the melting temperature at which the sample begins to melt and the clearing temperature at which the milky appearance of the sample starts to disappear.

Experiment 2. Polarization

Aims.

- Students to know what polarizers are and how they affect unpolarized light.
- Students to know how light propagates through the system of two polarizers.
- Students to be able to test if the light is polarized and in which direction it is polarized by using the polarizer with a known polarizing direction.
- Students to be able to test if the substance is optically anisotropic by using two polarizers.
Figure 3. The phases of the liquid crystal MBBA: (a) solid, (b) opaque liquid crystalline and (c) clear isotropic liquid.

Figure 4. Various materials between crossed polarizers: (a) an isotropic drop of water, (b) a piece of scotch tape, (c) a transparent CD box and (d) cellophane.

Students use two polarizers and compare the transmitted light intensity as a function of the angle between the polarizer axes. By this activity they learn how to use a polarizer as an analyser. They also verify that the reflected light is partially polarized. Students observe various transparent materials placed between crossed polarizers and find that light cannot be transmitted when isotropic materials like water or glass are placed between the crossed polarizers. When anisotropic material such as a scotch tape, cellophane or a CD box is placed between the crossed polarizers, light is transmitted. Colours are also often observed (figure 4). The activity provides an experience that is later used for observations of liquid crystals in a cell.

Experiment 3. Double refraction

Aims.

• Students to know that birefringence is an important property of matter in the liquid crystalline state.
• Students to be able to make a planar wedge cell and find an area where liquid crystal is ordered enough that the laser beam splits into two separate beams; the beams are observed as two light spots on a remote screen.
• Students to know how to check light polarization in a beam by a polarizer.

Students manufacture a wedge cell from a microscope slide, a cover glass, a foil for food wrapping or a tape and the liquid crystal MBBA [35]. Special attention is given to the rubbing of the microscope and cover glass, which enables anchoring of the liquid crystal molecules.
Figure 5. Finding the polarization direction of beams transmitted through the LC wedge cell. The arrow on the polarizer marks the polarizing direction of the polarizer. The polarizer transmits (a) both beams, (b) only the extraordinary beam and (c) only the ordinary beam. Polarization of the ordinary beam is perpendicular to the polarization of the extraordinary beam. Two small arrows marking the light spots are used as a guide to the eye.

Figure 6. A planar cell with non-ordered molecules of MBBA under a polarizing microscope. The polarizers are perpendicular (left) and parallel (right).

Students direct the light on the wedge cell (they use a laser pointer as the light source) and find the area of the cell where the laser beam splits into two beams. By rotating the polarizer between the cell and the screen, they verify light polarization in the beams (figure 5). Then, students heat the wedge cell with the hair-dryer and observe the collapse of the two bright spots into one at the phase transition to the isotropic liquid.

Experiment 4. Colours

Aims.

• Students to be able to fabricate a planar cell, i.e. a cell with parallel glass surfaces.
• Students to know that liquid crystals are optically anisotropic and that light is transmitted if a cell filled with liquid crystal in its liquid crystalline phase is placed between two crossed polarizers; they should know that under such circumstances colours may also appear when the sample is illuminated by white light.
• Students to know that the colours observed under perpendicular and parallel polarizers are complementary.
• Students to be able to mechanically order molecules in a planar cell.

Students manufacture a planar cell filled with the liquid crystal MBBA from a microscope slide, a cover glass and foil for food wrapping or a tape [35]. They observe the planar cell under a polarizing microscope (a school microscope with \( M = 40 \) or 100 and two crossed polarizing foils). Then they rotate the polarizing foils and observe how colours change (see figure 6). This experiment also illustrates the concept of complementary colours [36]. Afterwards, students heat the cell and observe colour changes. An experiment where molecules are ordered is performed next. Students make micro notches on a microscope slide by rubbing it with velvet.
soaked in alcohol. Molecules orient with their long axes parallel to the surface and the rubbing direction. A similar process is used in the fabrication of LCDs. They observe the cell with the ordered liquid crystal under the polarizing microscope.

Finally, the cell is heated by a hair-dryer and students observe the phase transition that appears as a dark front moving through the sample ending in a dark image when the liquid crystal between crossed polarizers is in the isotropic phase. The laboratory work is concluded by a discussion of how one pixel in the LCD works, relating the changes of the liquid crystalline structure due to the electric field to the transmission rate of the pixel. At this point the fact that colour filters are responsible for the colours of each part of the pixel is also emphasized.

3. Pilot evaluation of the teaching module

The aim of our study was the development of a teaching module for non-physics students, which could also be implemented for high-school students. Our goal was to give future primary school teachers basic knowledge about liquid crystals, so that they will be able to answer the potential questions of younger students when they are teachers themselves. Therefore, the teaching module described in the previous section was preliminarily tested by a group of 90 first-year students enrolled in a four-year university programme for primary school teachers at the Faculty of Education (University of Ljubljana, Slovenia) in the school year 2010/11.

In this section, we present the evaluation of the module as regards the efficiency of the teaching intervention—which concepts do students assimilate and comprehend and to what extent?

3.1. Methods

3.1.1. Participants. First-year pre-service teachers (future primary-school teachers) were chosen to test the teaching module. They were chosen because their pre-knowledge about liquid crystals is just as negligible as the pre-knowledge of students from other faculties and study programmes (see section 2.4). In addition, the pre-service teachers do not have any special interest in natural sciences, but they have to be as scientifically literate as everyone else who has finished high school. And most importantly, the pre-service primary school teachers form the only homogeneous group that has physics included in the study programme and is, at least approximately, large enough to allow for a quantitative study. In the group of 90, six were male and 84 were female students. They were on average 20.1 years old (SD = 1.6 years). On average, they achieved 19.7 points out of 34 (SD = 3.6) in the final examination at the end of the secondary school. The average achievement in the final examination in Slovenia was 19.5 points out of 34 and a total of 8842 candidates attended the final examinations in spring 2010. The studied group consisted of a predominantly rural population with mixed socio-economic status.

3.1.2. Data collection and evaluation. The data collection took place through a pre-test; classroom observations of the group work; worksheets; and tests, in spring 2011. The pre-test had 28 short questions. The first part (seven questions) was related to general data about a student: gender, age, secondary school, final examination, residence stratum and motivation for science subjects. The second part (19 questions) was related to liquid crystals, their existence, properties and microscopic structure. The pre-test was applied at the beginning of lecture related to liquid crystals. Those students who did not attend the lecture filled in the pre-test before the beginning of the compulsory laboratory work in chemistry.
Table 3. Student achievement in tests.

| Test        | Average number of points achieved (max) | SD  | Percentage of achieved points |
|-------------|----------------------------------------|-----|-------------------------------|
| Pre-test    | 6.0 (25)                               | 2.9 | 24.0                          |
| Test 1      | 14.0 (20.5)                            | 2.4 | 68.1                          |
| Test 2      | 14.0 (22)                              | 2.6 | 63.5                          |

The worksheet for the laboratory work in chemistry includes a procedure to synthesize liquid crystal MBBA, a reaction scheme, observations and conclusions regarding the synthesis and questions from chemistry related to liquid crystals and the laboratory work.

The worksheet for the laboratory work in physics presents the properties of polarizing foils and optically anisotropic materials and experiments with the liquid crystal MBBA.

Test 1 includes 17 short questions related to the knowledge obtained during the lecture and laboratory work. Test 1 was held immediately after the end of the physics laboratory (in May 2011).

Test 2 was a part of an examination held four weeks later (June 2011). It has 17 questions that, again, cover the contents of the lecture and laboratory work. Questions on test 2 were similar to those on the pre-test and test 1.

The study provided an extensive set of data, but in this paper we will focus only on students’ comprehension of new concepts.

3.2. Results and discussion

The results of the pre-test show that 94.4% of students had already heard of liquid crystals. The percentage is so high because we were testing students’ informally obtained knowledge about liquid crystals as a part of the study (see section 2.4) held at the beginning of the academic year.

Since lectures are not compulsory only 37 students attended the lecture. 150 students attended compulsory laboratories. They worked on the synthesis a week after the lectures and another week later on experiments with liquid crystals at the physics laboratory. Students worked in groups of three or four in the chemistry laboratory and in pairs in the physics laboratory. However, all data (tests and worksheets) were collected for only 90 students; therefore, we present only their achievements.

All the groups made the synthesis successfully, which was confirmed by measuring the melting and clearing temperatures of the synthesized liquid crystal MBBA. On average, 63.3% of worksheets were correctly filled in (SD = 13.0%).

All the experiments described in section 2.5.3 were successfully carried out in the physics laboratory. The only difference was that students did not prepare the wedge cell by themselves. Due to the lack of time cells were prepared in advance. On average, 84% of worksheets included correct answers to questions and observations (SD = 9%).

In the pre-test students on average achieved 24.0% of the available points. Their achievements show that their prior knowledge about liquid crystals was limited, as expected. In test 1, which was held immediately after the physics laboratory, students on average achieved 68.1% (see table 3). Test 2 was a part of a regular examination in physics. In test 2, students on average achieved only 63.5% of the available points. The reduced performance in test 2 can be explained by the research on memory and retention, which suggests that many standard educational practices, such as examinations and a great emphasis on the final examination, which encourages studying by cramming, are likely to lead to enhanced short-term performance at the price of poor long-term retention [37].
Figure 7. Distribution of the percentage of students versus percentage of achieved points in tests. Black: pre-test; white: test 1; grey: test 2.

Figure 7 shows the distribution of students versus the points achieved on the pre-test, test 1 and test 2. The percentage of students who achieved higher scores in tests 1 and 2 than in the pre-test is evident. The expected level of knowledge about liquid crystals is highest immediately after the activities. From figure 7, it is seen that most students achieved less than 50% of available points in the pre-test. In test 1, most of the students achieved over 50%. It is clearly seen that the percentage of students achieving a higher percentage of points in test 2 is lower than in test 1, when the impressions of the laboratory work were still fresh in mind.

A comparison of the percentage of correct answers on selected questions from the pre-test, test 1 and test 2 (table 4) shows further details of students’ comprehension. Questions on tests were not always exactly the same, but they covered the same subjects. The results show that the percentage of students who answered correctly is higher in tests 1 and 2 than in the pre-test, which demonstrates the efficiency of the teaching module.

In test 1, 73% of students correctly answered that liquid crystals are a state of matter. The percentage of students who answered this question correctly in test 2 is smaller. It seems that the deeply rooted misconception about the existence of only three states of matter prevailed after some period of time over new concepts met only during teaching about liquid crystals.

As many as 93% of students stated at least one product with liquid crystals in test 2. The percentage of students who correctly underlined all three properties of liquid crystals which are important for their applications, i.e. colours, birefringence and electric properties, was highest in test 2.

In both tests, approximately 60% of students agreed with the statement that liquid crystals also exist in living organisms and 80% knew that double refraction can be observed in anisotropic materials.

Liquid crystals are liquid in the liquid crystalline state was a statement with which 76% of students agreed in both tests.

In test 2, 88% of students knew that an electric field has an effect on liquid crystal molecules.

The biggest jump in knowledge was detected in the question related to the propagation of light in a birefringent material. In test 1, 98% of students correctly sketched that the laser beam splits into two beams in birefringent materials. However, the percentage of students who assimilated this was lower, i.e. only 58%. The concept is very difficult and students did not have any preliminary knowledge about it. However, experiments were straightforward in showing that a single light beam splits into two, which is consistent with the phrase ‘double refraction’.
Table 4. The percentage of correct answers per question on the pre-test and tests.

| Question                                                                 | Percentage of students who answered correctly |
|--------------------------------------------------------------------------|----------------------------------------------|
|                                                                           | Pre-test | Test 1 | Test 2 |
| Liquid crystals are a state of matter.                                    | 16       | 73     | 61     |
| Write down a product with liquid crystals.                                | 38       | 86     | 93     |
| Which properties are most important for the application of liquid crystals? You can choose more than one property. | 34       | 76     | 87     |
| Substances with liquid crystalline properties appear in living organisms. | 18       | 61     | 60     |
| Double refraction can be observed in the anisotropic materials.          | 18       | 81     | 82     |
| Liquid crystals are solid in the liquid crystalline state.                | 43       | 76     | 76     |
| Electric field can influence the orientation of the liquid crystal molecules. | 49       | 67     | 88     |
| Draw the light propagation from air to water and from air to the birefringent material. | 2        | 98     | 58     |
| Draw the distribution of molecules in liquid crystals.                    | 39       | 100    | 73     |

Finally, 100% of students sketched the distribution of molecules in the liquid crystalline state correctly in test 1, while the percentage was reduced to 73% in test 2. The result is certainly again influenced by the laboratory work, where the reasons for the anisotropic properties based on the microscopic structure were discussed in detail.

The results of tests 1 and 2 show that fresh impressions from the laboratory faded away by test 2. This is expected for rather uninterested students who, unfortunately, are rather common on this specific study programme. Nevertheless, the results offer an interesting starting point for more extensive research on retention with respect to interest in different physics phenomena.

4. Discussion and conclusions

Liquid crystals are materials that flow like liquids and have the physical properties of solid crystals. They are quite common both in nature and technology, where they are used in laptops, mobile phones, mp4-players, etc. At the same time liquid crystals are an important topic in current scientific research. Liquid crystals are therefore a topic which fulfils two major conditions for being relevant and motivating for students. Because of that we have designed a teaching module of three parts: lecture, chemistry laboratory and physics laboratory. The aim of the module is to give students general knowledge about liquid crystals, their properties and the principles of how LCDs work.

The lecture provides basic knowledge about liquid crystals and their properties. With the laboratory work students strengthen and expand their knowledge. They synthesize liquid crystal MBBA, use their own product, i.e. MBBA, in experiments where they observe and
discuss an additional phase transition, the properties of optically anisotropic materials in general, double refraction and colours observed in liquid crystalline cells.

The module was tested on a sample of 90 first-year, mostly female, students in the study programme for teachers for the lower grades of elementary school in the academic year 2010/11. These pre-service teachers have no preference for natural sciences. The module is feasible in practice and knowledge obtained from the teaching module was confirmed by the results of the tests. Students on average achieved 68.1% in test 1 immediately after the activities and 63.5% in test 2, which was a part of an examination a month later. The achievements show a significant increase in knowledge about liquid crystals, since in the pre-test students achieved on average only 24.0%. By comparing the results of the pre-test, test 1 and test 2, one can conclude that the teaching module was appropriately designed and it allows for the development of concepts related to liquid crystals. We estimate that the results obtained are rather good as students started from almost non-existing pre-knowledge (table 4).

Can the results of the study for this specific group be generalized to a general population of first-year university students? The group consisted of future primary school teachers, mostly female, and it is not obvious that one can make general assumptions based on the results obtained for them.

Based on the results of the research described in section 2.4, the informally gained knowledge at the end of secondary school for the pre-service teachers and the students from different faculties on average does not differ: in both samples the lack of knowledge about liquid crystals was detected. So we can conclude that students who are interested in natural sciences and technology would assimilate at least as much knowledge about liquid crystals from the teaching module as the pre-service teachers did. Since the results of prior knowledge show statistically significant differences between the knowledge of male and female students, one may even dare to conclude that the male students would achieve better results on testing of the module than female students. One can therefore safely conclude that a general audience would achieve at least as good results as the group of students involved in this study. It must be stressed that we have designed the module in which students acquire new knowledge relevant to liquid crystals and their applications, as confirmed by its implementation and evaluation. The module can also be used as a teaching module for more specialized physics courses. Of course, there are still open issues that we intend to explore. Since we know that the module is appropriate for students who are not motivated in science, we will work on adaptation of the module for students motivated in natural sciences. The module presented in this paper can be readily used on introductory physics courses, and with appropriate modifications it can also be used at lower levels of education.

Evaluation of the model raised several questions that need to be addressed in the future. How do practical experiences influence knowledge about liquid crystals? How does a new learning environment influence this knowledge? How do the chosen teaching methods influence the study process? However, the whole study and its evaluation show that it is worth the effort to develop new modules on topics related to current scientific research and everyday technology.

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