The reform of laboratory exercises included in the basic physics courses at the University of Helsinki[1]

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The pedagogical principles of the reform of the laboratory exercises accomplished recently at the Physics Department of the University of Helsinki, are discussed in general and in the light of a few examples. The reasons for the reform, the results achieved at the present stage as well as future plans are reviewed.

1. The background

There are some traditional pedagogical problems in the laboratory exercises of physics. The clearest external indication has been the delay, of up to several years, from their intended schedule. The students have not been interested in the exercises, there has been no motivation.

Inquiries and other feedback have given support to this diagnosis. Among the major reasons mentioned have been the lack of connection between the exercises and the rest of the instruction, their schematic nature, which causes mechanical performance and copying of results, as well as the excessive work required for the reports, particularly, the thorough analysis the accuracy, the meaning of which has remained unclear for the students.

Attempts to develop the exercises have remained isolated, they have lacked coordination. Their accomplishment has been dependent on the spontaneity of the assistants, which certainly has not been encouraged by the prevailing nonappreciation of teaching merits in the Finnish universities.

The reform of the examination system in 1980 offered an opportunity for a thorough change. It was then believed that making the exercises a formal part of the courses required in the examination would make them less isolated and improve performance motivation. Planning was carried out in cooperation with the lecturers in order to tie the exercises more closely to the contents of the lectures.

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[1] In J. Laurén (ed.) Science education research in Finland. Yearbook 1987–1988. University of Jyväskylä. Institute for Educational Research. Publication series B. Theory into Practice **36**, 41–50.

However, motivation did not improve essentially. The situation remained the same, except that now the delay in doing the exercises made the statistics of physics studies look worse, since now no mark for the course was given until the exercises were completed. It was evident that the problems were deeper down and a change in the nature of the exercises was needed.

The Faculty of Science revised the examination requirements in autumn 1986. This offered a new opportunity for reorganization. In that situation it was possible to apply the pedagogical principles regarding the physicality of teaching, developed in connection with physics teacher education. In fact, those ideas had already been applied for two years in the so-called self-service demonstrations (SSD) (voluntary exercises for the students to repeat and study in depth the demonstrations shown in the lecture). The experiences from the SSD-laboratories, which had been very positive, could be utilized and a great number of the demonstrations and semiquantitative experiments developed for the SSD could be included in the new laboratory exercises.

2. Pedagogical principles

The attractiveness of physics instruction and, hence, Its success depends crucially on how well the teacher manages to link the build-up of an integral cognitive and methodological picture and the development of physical thinking to the details of the instruction. The possibilities of building up an integral picture and of teaching physical thinking have been analyzed extensively in connection with a special course for physics teachers (Kurki-Suonio & Kurki-Suonio 1987). Two simple schemes can be used as aids (Kurki-Suonio & Kurki-Suonio 1989, see also Kurki-Suonio et al. (1982, 15) and Kurki-Suonio et al. (1985, 9-10). By means of a scheme of logical processes it is easy to give sensible logical contents to the various teaching events. By means of a hierarchical level scheme of the cognitive structure of physics one can, in concept formation, consistently follow the natural experimental approach and avoid the gaps characteristic of the traditional theoretical approach.

When the experimental approach is applied in teaching, demonstrations and laboratory exercises become indispensable. One cannot learn to understand the meaning of quantities as concepts representing properties of natural objects and phenomena without actually personally perceiving the properties, that have to be represented by means of the quantities. Lectures then aim at laboratory instruction and the laboratory exercises no more remain isolated. On the other hand, since the theoretical instruction gives the demonstrations and laboratory exercises a logical and methodological content, the experimental instruction can form a chain starting from qualitative demonstrations and leading to more and more quantitative and systematic experiments, which in a natural way provide training in experimental research.

The motivation for experimental exercises is essentially based on the logical contents attached to them, which makes them meaningful from the point of view of the research method of physics. Both in demonstrations and laboratory exercises it is essential that the reason why they are performed is understood and clearly expressed. They can be classified according to their role in the concept formation and to the position that the reasoning involved takes in the scheme of logical processes, e.g. in the following way:

1.the recognition and visualization of a phenomenon,
2.the classification and identification of the phenomena,
3.becoming acquainted with a measuring method or equipment,
4.the experimental determination of the value of a quantity,
5.the determination or verification of an experimental law,
6.the use of a law as the basis of concept formation regarding a phenomenon and the determination of the quantity based on it,
7.the testing of a theoretical (quantity or law) prediction,
8.the determination of the' parameters of a model using experimental data,
9.the verification or study of the validity area of a theoretical model with a possible improvement of the law,
10.the presentation of the uses of a phenomenon,
11.the presentation of the applications of a theory.

The order of the list does not follow the order of quantification but rather the logical cyclic order of the method scheme, from the purely experimental through induction to theory and further through deductive reasoning back to the experimental. All these types have their roles in instruction either as demonstrations or as laboratory exercises. Using this list, one can give each experiment a purpose which provides the work with a logical content. An experiment in itself does not express its own logical meaning, the meaning must be given to it. The way, in which the experiment is done, presented and explained depends on the meaning given to it.

The theoretical lessons can be efficiently supported especially by exercises of the types 5-9. They elucidate the foundations of the concept formation and the role of the theories (Andersson et al. 1989). Naturally, it is possible to include several types of reasoning in the same exercise. The exercise becomes more interesting, when it contains at least one logical loop. characteristic of the physical method. and becomes thus in itself a miniature of the physical research method.

3. The structure of the exercises

3.1. *The accomplishment*

The link between the exercises and the lectures was created by writing the textbooks and laboratory instructions according to the same principles of the experimental approach, where the theoretical concept formation requires the support of experimental work. The exercises were planned so that they were based on the contents of the course as presented in the textbook, and the laboratory instructions were limited to short technical instructions. The exercises are also included in the examination material of the courses and questions connected with the exercises are presented both in the intermediate and the final examinations.

The exercises of each course were grouped into five packages, which are done during the course and in pace with the lectures. At present the packages have the following titles. Basic physics I (mechanics): 1) Basic measurements, 2) Dynamics of translational motion, 3) Conservation of momentum and angular momentum, 4) Conservation of energy and 5) Rigid body motion. Basic II (Electricity and magnetism): I) Introduction of the equipment, 2) Electrostatics, 3) Direct current circuits, 4) Magnetism and induction and 5) Alternating current circuits. Basic physics III (waves): I) Radiation protection and an introduction to wave phenomena, 2) Eigenoscillations and resonance, 3) Reflection, refraction and polarization of light, 4) Intensity of light, diffraction and geometrical optics and 5) Modern physics.

Each package consists of two or three main exercises and a flexible number of shorter exercises, especially repetitions or extensions and quantifications of lecture demonstrations. As a rule, the equipment needed in the exercises are introduced in connection with the lecture demonstrations.

In the main exercises of each package special emphasis was given to the types 5, 6 and 7 introduced in the previous section, which elucidate the principles of concept formation. By including these types in the same exercise it is possible to give, on a basic course level, an idea of the logics of physical research on a miniature scale.

Special attention has been given to the simplicity and clarity of the exercises, since most of the students have no background in experimental work. Particularly, the aim has been that the experimental data could be recorded easily - and rapidly and that the physical laws studied could be immediately represented in a graphical form, providing direct support to potential concept formation and an easy starting point for the evaluation of the results. On the other hand, there must be an opportunity for more accurate and sophisticated experimentation. One aspect in planning the exercises has therefore been that the same exercises should be applicable at various levels depending on the capabilities and interests of the student.

The exercises are done in small groups supervised by an assistant, and finally the results are analyzed and discussed together. No ordinary reports need to be written.

3.2. *Examples*

3.2.1. *Basic measurements: the law of the spring force*

The exercise contains two parts. In the first part. the dependence of the stretch of the spring on the acting force, $x = x(F)$. is studied. The (approximate) proportionality $x \sim F$ is verified. This shows that the ratio F/x is invariant. independent of the acting force (the weight $F = mg$). It can thus be introduced as a new quantity characteristic of the spring and named the spring constant

$k = F/x$ $(= mg/x)$. In the exercise the stretch is measured using four different weights and the data are presented graphically in the (x,m) -frame. To what extent the experimental points fall on a line drawn through origin is checked. From the slope of the line the spring constant k is calculated. The accuracy of the result is estimated from the error bars.

In the second part of the exercise. the validity of a dynamic prediction based on the previous result is tested by an independent measurement. The first part yielded as a result the law of the spring force $F = -kx$. where k is now a known constant. On the basis of the Newtonian mechanics it yields predictions concerning the motion of a body attached to the end of the spring. The simplest quantity to be tested is the period of the vertical motion of the body. The simple prediction is $T = 2\pi\sqrt{m/k}$, where m is the mass of the body.

By comparing the measured periods with the predicted value. one is led to discuss the reasons for deviations. It is then possible for the students to ponder together. how the model could be improved. The first natural question concerns the influence of the mass of the spring. The exercise can be continued by studying this question experimentally using different springs and weights. The textbook naturally gives the simple Newtonian answer for comparison.

Properly guided, this exercise demonstrates how concept formation is based on experimental laws. It shows the approximate nature of the law and how the area of usability of the quantity is connected to the validity area of the law.

It also demonstrates how a model (harmonic force) is defined by a law and how the model gives a basis for theoretical predictions. It also shows in an elementary form the relation of theoretical and experimental research and the need for improvements and generalizations in the research. For students with advanced abilities, the exercise can also be developed into the exploration of a different kind of force law and the predictions following from it.

3.2.2. *Electrostatics: the capacitor law*

In this exercise the dependence of the charge of a capacitor on the voltage, $Q = Q(U)$, is studied. Especially the (approximate) proportionality $Q \sim U$ (the capacitor law) is pointed out. According to this law, the ratio *Q/U* is invariant, independent of the voltage. This shows the experimental basis of the capacitance of a capacitor $C = Q/U$.

The charge of a capacitor is measured by a ballistic galvanometer. The galvanometer may be calibrated by uncharging some known charges through it, thus turning it into a charge meter. For the present, only the proportionality $C \sim U$ is tested and no calibration is needed.

This exercise contains several potential development prospects. The intention is to construct capacitors of different sizes and shapes, which may be filled with various dielectric materials. This would make it possible to study experimentally the law of dielectricity, according to which the ratio of the capacitances of an empty capacitor and a filled one is independent of the geometry of the capacitor. This would show the experimental background of the relative permittivity of the material.

3.2.3. *Waves: the law of refraction*

In this exercise, the law of refraction is verified. According to it, the sines of the angles of incidence and refraction of monochromatic light arriving at the boundary of two media (A,B) are proportional $\sin\alpha \sim \sin\beta$. Thus, the ratio of the sines is invariant, independent of the angle of incidence, and can be introduced as a new quantity, which defines the refractive ratio of the boundary, $\sin\alpha / \sin\beta = n_{AB}$.

Next, the "connective law" $n_{AB}n_{BC} = n_{AC}$, valid for the boundaries between three substances *A, B* and C, is verified. According to this law the refractive ratios of the boundaries can be interpreted as ratios of material-specific constants, the refractive indexes. The "unit substance" can in principle be selected arbitrarily. The vacuum is, no doubt, a natural choice. The refractive ratio of the boundary between the vacuum O and the material A thus defines the refractive index of the material A, $n_{OA} = n_A$, hence $n_{BC} = n_C/n_B$.

In addition to the refractive ratios and indexes, the invertability of the path of the light propagation and the total reflection are studied and the limiting angles of the total reflection are determined.

In group discussions, attention should be paid particularly to the fact that the wave model explains the observed experimental laws and yields a simple prediction for the refractive index as the ratio of velocities of light. On the other hand, also the particle model offers an explanation and gives its own prediction for the refractive index. This observation broadens the views and at the same time makes it clear that the ratio of the phase velocities is not a valid definition of the refractive index.

3.2.4 *The Gaussian lens equation*

In this exercise, image formation in a lens is explored. Especially it is verified that the quantity $a^{-1} + b^{-1}$ is (approximately) invariant, independent of the position of the object on the optical axis. Thus it is again noted how the definition of quantities is based on invariances. In this case the quantities defined are the dioptric power $D = a^{-1} + b^{-1}$ and the focal length $f = 1ID$, which are characteristic quantities for a lens (and the medium).

In the exercise, the distances a and b of the object and the image from the lens are measured. The experimental data are presented graphically in the ($1/a$, $1/b$) -frame and a straight line is fitted. From the graphical representation, conclusions on the validity and accuracy of the Gaussian lens equation are made and the focal length is determined. At the same time the dependence of the quality of the image on the position of the object is studied.

The discussion may be continued by pondering on the physical significance of the extrapolation of the line beyond the part determined experimentally as well as on possible subsequent predictions and the possibilities to test them.

4. The reception of the reform

The opinions of the students were inquired in December 1986 (after three months) by a questionnaire. They were almost unanimous that the reform was an improvement. Typical answers to the question "Benefits of the new system compared to the old one?" were: one learns better when working in pairs; there is better concentration on the main points; it is possible to do many kinds of different exercises; doing away with written reports is good because earlier they took up too much time compared to the gain; interest in physics is increasing. It was also noted that the threshold for starting the laboratory exercises had disappeared, no more "labophobia". As drawbacks students mentioned that the exercises are restricted to limited periods during the term, the exercises are done more superficially, writing abilities do not develop, and in a group it is easy to avoid doing anything.

Part of the criticism was due to the "flood" of students, which made it difficult to arrange sufficient working facilities. Although some so called old students, who had attended the lectures earlier, were expected, their great number was a surprise: during the first two terms, about one hundred old students per course completed the reformed exercises (in addition to an approximately equal number of regular students).

The development work has continued. Some of the exercises have been replaced with better ones, new ones have been developed for the more deficient packages. The aim is to provide a more versatile selection of exercises. Special attention is paid to exercises which could be performed at various levels of difficulty and would then be adaptable to different backgrounds and abilities. This is important for maintaining motivation.

In the beginning, the time needed for the measurements and calculations was overestimated. It turned out that when working in pairs the measurements were done much faster than alone. On the other hand, this may be partly due to the fact that the assistants did not completely grasp the new nature of the exercises. They tended to supervise the exercises according to the same traditional principles as they themselves had been supervised and taught with. This manifested itself as certain indifference in the supervision and as ignorance of the goals.

Because of the shortage of space and equipment it has been necessary to set up the apparatus of each package separately for each term. During the second term, it turned out that the qualitative exercises of one package had been omitted, because they were mentioned only in the table of contents of the written instructions. This shows that tradition dies out in less than six months. It will be possible to overcome these problems by educating the instructors (which aim also this text is meant to serve), and by providing more detailed instructions. Accurate instructions are essential also because most of the assistants are replaced every term.

The success of the exercises depends also on the cooperation of the lecturers. Some problems have occurred because the lecturers have not followed the same order or time-table. The printed lecture notes have, however, made this problem less crucial. Still, it may turn out that the lecturer is the weakest link in the reform. He or she has the task of preparing and motivating the students for the exercises by explaining the idea and the theory or by giving suitable problems. In order to do this properly he/she should thoroughly understand the pedagogical principles and aims of the laboratory exercises. All this presupposes that the lecturer understands teaching to be a privilege not just a duty.

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