Evaluation of Students' Understanding the Uncertainties after A New Course "Search for Physics Laws"

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Abstract—The main goal of this paper is to present a new introductory laboratory course "Search for Physics Laws" and results of the evaluation of this course. It is known that a laboratory course is traditionally one of the most important components of university physics course. And it is supposed that after such course first-year engineering students learn what to do with experimental data. However, authors discovered that most students do not acquire the necessary skills. The presented laboratory physics course is based on the algorithm of systematic construction of skills for conducting an experimental research. The basic method used in the course is the graphical method of error analysis. This method could give students an intuitive understanding of an experimental situation, and it goes through all sessions. The evaluation of the first part of the course is based on responses to a written questionnaire administered to three groups of students: an experimental group (85 students) and two control groups (61 and 23 students). The results suggest that the organized in the new way laboratory sessions has been more successful in improving students' basic skills of error analysis.

Keywords—Systematic Construction of Mental Actions, Laboratory Course, Analysis of Experimental Data, Physics Law

1 Introduction

There are no doubts that a laboratory course is one of the most important components of university physics course. The ability to generate knowledge using experiments is a competence that students in engineering education have to learn [1]. Laboratory experiences play a central role in engineering education, developing hands-on skills, and bridging the gap between theory and practice [2].

The rapid development of technology has caused of the emergence of new types of laboratory works, for example, mono-user virtual labs, remote labs and multi-user virtual labs [3]. Despite of the variety of modern physics laboratory work types, the basic set of skills students have to acquire is the same for all of them: to create a scientific question or hypothesis, to design and conduct an experiment, to analyse the raw data, to evaluate and interpret obtained results [4].

The topics of measurement and error analysis are usually presented in the very first chapter of most textbooks about experiments in physics, and it is expected that as a result of experimental activity students learn how to appropriately interpret obtained data. Nevertheless, the results of tests showed that a lot of our students had marked difficulties in understanding even the basic ideas of error analysis.

The literature analysis revealed that our concerns about the current state of students' knowledge after traditional laboratory course of physics are not uncommon. It was noted in [5] that professors frequently frustrate at students' lack of understanding in these areas. Authors of [6] established that often students 'perform lab experiments in a plug-and-chug frame, procedurally completing each activity with little to no sensemaking'. The author of [7] has observed 'the tendency of students approaching the laboratory components in a rather mechanistic way instead of trying to understand the broader context of the laboratory exercise'.

2 Literature Review

The importance of laboratory practice in science studies at all levels of education is acknowledged by the educational research community, and the pedagogical value of the experiments in science teaching is well established [4]. As it was noticed in [8], there is a common thread that runs through most introductory physics laboratory courses. It is the fact that experimentation should involve analysing measurements. However, despite the fact that such courses often include the key information about carrying out the data analysis the students' understanding the concept of uncertainty is far away from the expected level.

There are several researches which point out ways of changing the situation. The negative but important result about effectiveness of a traditional physics laboratory course was described in [9]. The author interviewed experts, compiled a list of topics students have to know about experimental uncertainty, and checked if students really have this knowledge. The biggest amount of data was gathered at two universities, and it was expected that students from the first sample should show a better results than students from the second sample, because the topic of error analysis is emphasized much more in the first university physics laboratory works. However, the study revealed that students from both universities have difficulties with understanding of measurement uncertainty and comparison of obtained results [9].

A study about improving students' ability to analyse measurement results and uncertainty in the physics laboratory was presented in [6]. A whole introductory algebra-based physics course (lectures, homework assignments, discussion sections) was considerably modified for this purpose, and the traditional introductory laboratory was replaced by scientific community laboratory. Research questions were described in short paragraphs, and students had to design and carry out experiments working in small groups. At the end of a laboratory work each group presented their method, data, and analysis to the other groups. The author argues that after this course, students leave the laboratory with an understanding of the basic concepts of uncertainty analysis and are ready to learn the mathematical tools of uncertainty analysis in the second semester of physics course. Also, reassuring results was obtained by [10] in a school laboratory. The author asserts that students' inadequate views of experimental work in science could be changed in relatively short time.

As regards a cause of students' misconceptions and misunderstandings of error analysis, according to authors of [11], it is using *point paradigm* instead of *set paradigm*. The *point paradigm* is characterized by the notion that each experimental observation potentially yields the correct or 'true' value of the quantity being measured. Students with this paradigm believe that a single carefully performed observation is sufficient to establish the true value of the measured quantity. If there is a deviation from an expected result they consider it as environmental influence or a mistake made by the experimenter. The *set paradigm* is characterized by the notion that each observation provides partial information about the quantity being measured.

The authors of [12] analyzed the existing views on a concept of 'the result of a laboratory work', and found five classes of paradigms: the naive-point paradigm, point paradigm, syncretic paradigm, training-interval paradigm, and interval paradigm. The first of them can be described as 'the result of exactly performed single measurement is the true value'. In the authors' opinion, thinking within the naive-point paradigm should be considered as a rudiment for university students; before studying physics course the level of first-year university students corresponds to the level of the point paradigm. For the final level of the introductory laboratory physics course it is proposed to choose the level of the training-interval paradigm. The following principles were offered in [12] for achieving this educational goal: a) the basic principles of the training-interval paradigm should be formulated at the first session as deep as possible and vividly interpreted; b) it is necessary to strictly adhere to this system of views during next sessions; c) intuitively understandable interpretation should be given to all abstract mathematical concepts.

About designing a special course and a set of materials based on the probabilistic framework for measurement was reported in [8]. The course has been evaluated, and the authors claim that the new course considerably improves students' understanding of uncertainty.

We share the authors of [8] view on importance of using the set paradigm, however, experience prompts us an additional cause of students' failure in gaining skills for analyzing obtained experimental data — their unpreparedness for such activities.

3 Idea About Systematic Construction of Mental Actions

Traditionally, it is implied that for leaning basic skills for error analysis students just need to conform to well-defined instructions, i.e. self-dependent learning is expected from students. We believe it is quite possible that if physics laboratory course has four hours per week and the course lasts at least three semesters the best students acquire all required knowledge and skills. However, a common laboratory course for engineering majors at our university is much shorter, and we came to a conclusion that usually necessary skills do not develop as expected, and are fragmentary and unstable.

This situation can be changed by replacing 'hope for self-dependent learning' principle with 'systematic construction of skills' principle. This does not mean that we cast doubt on importance of self-dependent learning but as it will be shown below students definitely need more help in studying error analysis.

We have used Gal'perin's stepwise approach (see, for instance, [13]) as a working model for outlining the teaching-learning process, and designed an innovative laboratory physics course based on the theory of the gradual formation of mental actions. The main teaching goals of our course "Search for Physics Laws" are:

1. To build a set of basic skills for conducting an experimental research.
2. To form the idea that the main result of a laboratory work should be finding a physics law.

The first goal is one of the traditional goals of the physics laboratory course. However, we have abandoned the idea that these skills will be formed spontaneously and have taken the idea of their special purposeful formation. For achieving this goal the whole student activity of carrying out a laboratory work was decomposed into separated elementary skills each of those got its own name. During sessions we described each skill, explained its content, and taught students to fulfil it. Next time we tested their ability to use the skills, and made some final corrections.

We also summarize the information for students on orienting charts (see Figure 1). As it is required by Galperin's theory, a chart presents the sequence of the actions, and serves as the main tool of learner's orientation.

The following principles are offered for achieving this educational goal:

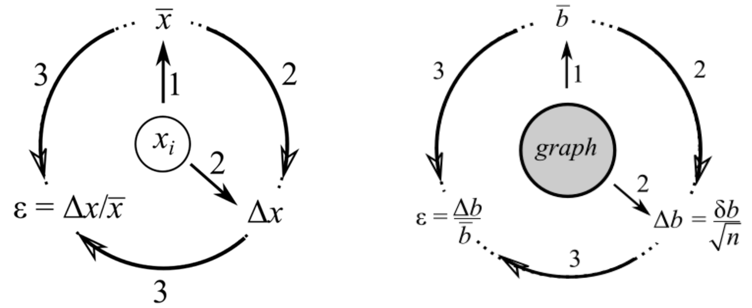
a) The basic principles of the training-interval paradigm should be formulated at the first lesson as deep as possible and vividly interpreted.
b) It is necessary to strictly adhere to this system of views during next sessions.
c) Intuitively understandable interpretation should be given to all abstract mathematical concepts.

The second goal is considered as more important. In our opinion, the fundamental transition from metrology to physics itself has to take place in a laboratory physics course. The basic concept of the course is the concept of 'experimental physics law', and the main tool is a linear function. All processing of experimental data is based on the same scheme as working with parameters of a linear function.

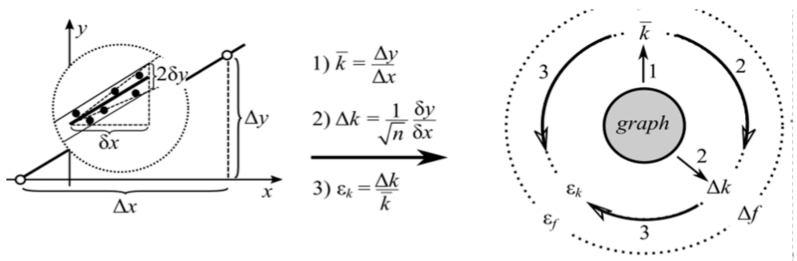
4 Graphical Method as The Thread of The Course

The basic method we teach students is the graphical method of error analysis. It goes through all sessions, starting with the first one (measuring a physics quantity) and ending with the last one (separation of trends and dependencies). This method could give students an intuitive understanding of an experimental situation and the ability to read graphical information.

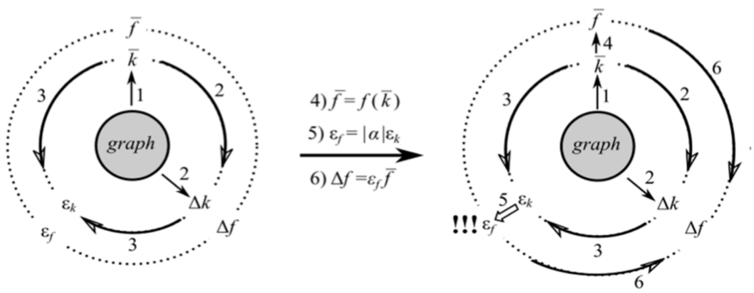
Certainly, the graphical method is just an illustration of the analytical methods of processing experimental data. However, learning the methods of mathematical statistics in depth is premature in the introductory course. We suggest that it could be reasonable to acquaint students with some formulas, and offer them to use these formulas and compare results at the end of each session. But it is important to remember that even the level of such textbooks as [14-15] or special guides as [16] is too high at this stage of studying process.



a) In repeatable measurements b) In y-intercept b



c) In a slope *k*



d) In a power function $f = C \cdot k^{\alpha}$

Fig. 1. Orienting charts for calculating uncertainties

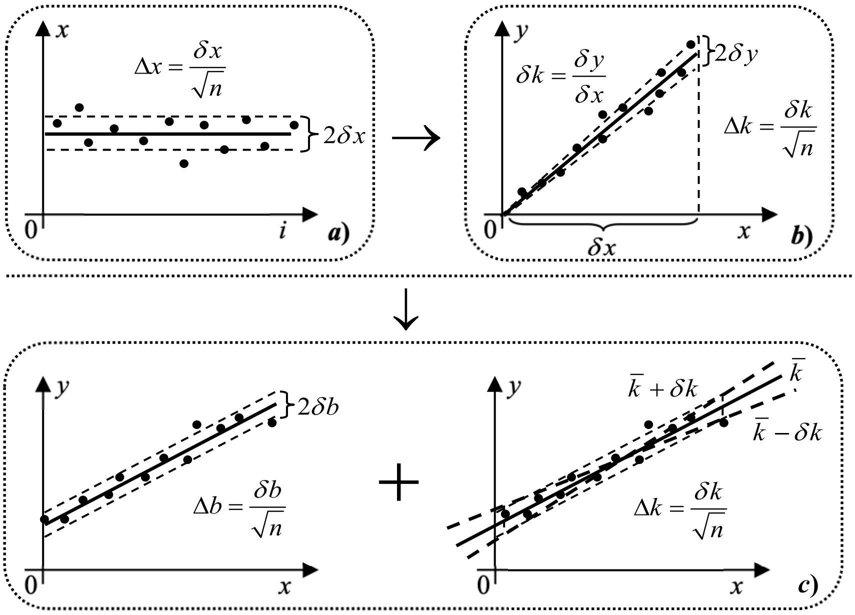


Fig. 2. Scheme of studying the graphical method of error analysis for linear relationships between physics quantities: a) treatment of experimental results after measuring a constant physics quantity; b) analyzing relationships between two physics quantities in a case when the line should go through the origin due to known scientific constraints; c) processing experimental data in a general case of linear relationship

In addition, using the method allows us to link together two procedures of error analysis. Instructions for treatment experimental data after measuring some constant physics quantity are essentially different from instructions for analyzing relationships between physics quantities. The way we teach students to use the graphical method for analyzing different types of linear relationship between variables is shown on Figure 2.

5 Course Description

Our new course "Search for Physics Laws", as well as traditional laboratory physics course, consists of one 2 h session per week and lasts 14 weeks (one semester). It contains six topics with two laboratory works each and two control sessions. A list of the topics and brief descriptions are shown below.

During first two sessions we acquaint students with a concept of a confidence interval. Here we show students orienting charts and start using graphical method. First laboratory work gives students an opportunity to work with random uncertainties, the second one — with instrumental uncertainties (see [17]).

TOPIC 1. Four axioms of physics measurements

Session 1. Concept of a confidence interval. Laboratory work 1 "Buffon – de Morgan experiment".

Session 2. Beginning of graphical method. Laboratory work 2 "Measurement of time".

The main concept for next two topics or four laboratory works is a linear function. We begin with directly proportional cases and teach students how to build a graph, how to find a slope, how to find connection between mathematical and physics symbols. For these two labs we give them the value of a fractional uncertainty. But in the next two laboratory works students have to learn how to build a confidence interval for both *y*-intercept and a slope. Here we use slightly modified well-known laboratory work "Measurement of the Young's modulus".

TOPIC 2. Linear function

Session 3. First acquaintance with a linear relationship. Building a linear function in the laboratory work 3 "Measurement of the age of the Universe".

Session 4. How not to get lost in symbols. Self-dependant building a linear function in the laboratory work 4 "Measurement of the liquid viscosity by Stokes method".

TOPIC 3. Linear function as an objEct of Measurement

Session 5. Building a confidence interval for *y*-intercept of a linear function. Fulfilling this operation in the laboratory work 5 "Hook's law. Measurement of the mass of a 'black' load".

Session 6. Building a confidence interval for a slope of a linear function and for an indirect measured quantity. Laboratory work 6 "Hook's law. Measurement of the Young's modulus".

During the second part of the course students use a linear function as a tool. In the laboratory work "Stefan – Boltzmann law" we demonstrate them an idea of 'straitening' monotonic functions. Further students perform this operation in 3 other cases. In the laboratory work 8 they also use dimensional analysis. In the laboratory work 9 we discuss building a mathematical model of phenomena. And in the laboratory work 10 – a question about experimental proof of a hypothesis.

TOPIC 4. Power function

Session 7. 'Straitening' power functions. Fulfilling this operation in the laboratory work 7 "Stefan – Boltzmann law".

Session 8. Dimensional analysis. Power straitening coordinates. Laboratory work 8 "Simple pendulum".

TOPIC 5. Straitening coordinates

Session 9. Building straitening coordinates in a general case. Laboratory work 9 "Measurement of the lifetime of an incandescent lamp".

Session 10. Experimental proof of hypothesis. Laboratory work 10 "Temperature dependence of semiconductor resistivity".

The aim of two last laboratory works is to acquaint students with basic ideas of data mining. For example, using a given database they have to discover Dulong–Petit law. And in the last laboratory work students should find a hidden parameter — a sheet of conductive paper and electrodes are turned by some angle. Note, that the results of the study [18] indicate that the presenting anomalous data has an effect and contributes on improving student's critical thinking ability.

TOPIC 6. The Basis of Data Mining

Session 11. The basic concepts of intelligent search in databases: trends and physical laws. Laboratory work 11 "Dulong–Petit law".

Session 12. Interpretation of experimental patterns. Laboratory work 12 "Electrostatic field simulation by using a conductive paper".

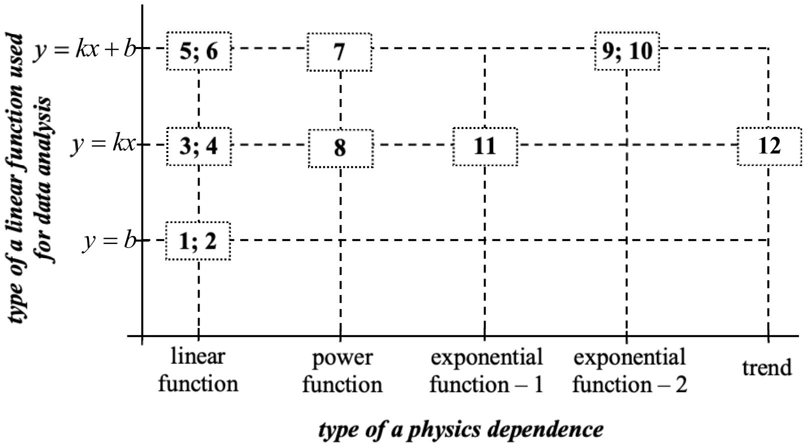


Fig. 3. Structure of the course (1, …, 12 are numbers of laboratory works, 'exponential function – 1' is $y(t) = y_0 \exp(-\alpha t)$, 'exponential function – 2' is $y(T) = A \exp(\beta/T)$

As can be seen from the list, the presentation of the material is unhurried, with a gradual complication (see Figure 3). At the beginning of the course, we consider the simplest data sets (a degenerate case, a directly proportional function, a general case of a linear function). In the second part of the course, a linear function applies to the processing of more complex sets of experimental data (power functions, functions in a general form).

We would like to emphasize that after minor alteration this course can be put into practice by using different laboratory equipment. The main difference between the new course and the traditional laboratory physics course (in Zaporizhzhia Polytechnic National University) is using different teaching ideas and methods.

6 Evaluation of The First Part of The New Course

6.1 Methodology

The evaluative data was obtained from responses of 85 students to a questionnaire after a first part of our new physics laboratory course over 2017. These students were present at first six laboratory sessions and had an opportunity to learn the first three topics.

There were two control groups: a cohort of 61 students after a first semester of a traditional laboratory course was used as a first control group, 23 students which had not yet studied any university physics course formed a second control group. All these students were first-year undergraduate students followed 4-year BSc programmes in Engineering at Zaporizhzhia Polytechnic National University but could have a different background: some of them were graduated from a high-school; the other entered the university after some technical college. Table 1 represents the number of such students in the experimental and control groups.

Table 1. Student background of the experimental and control groups

Groups of students	Graduated from a high-school (%)	Graduated from a college (%)
Experimental Group (after the new course, $n = 85$)	55 (65)	30 (35)
Control Group 1(after a traditional course, $n = 61$)	20 (33)	41 (67)
Control Group 2(no university physics course, $n = 23$)	13 (57)	10 (43)

Calculation a chi-square statistic by using information about students' External Independent Evaluation scores and college final scores showed that the experimental and both control groups had similar admissions standards.

Students from the Control Group 1 were present at six traditional laboratory sessions. According to the laboratory work instructions students should calculate uncertainties in each work.

Note also, that students from our experimental group used the same devices and instruments as students from the first control group. And students from both groups conducted experiments in small teams (3-4 students) over a course of the entire semester.

The questionnaire was composed of six tasks five of which are related to the first part of the new course and will be reported in this study. Each task targets a particular elementary skill. The student was required to fill in omitted numerical answers, and had 15 min to complete all tasks. The questionnaire was answered individually and under examination conditions, it had originally been given in Ukrainian but the questions had been translated here.

Results in details

Now consider results of students' answers for each question.

The first task of the questionnaire asks students to rewrite an interval of some experimental data.

Question 1. A student obtained an interval for coordinates of an object at the same instant: from 24.3 cm to 24.9 cm. Rewrite this result in the form $\bar{x} \pm \Delta x$.

Answer: $x =$ _____ ± ______ (cm)

For this question, the majority of students from the experimental group gave the right answer (see Table 2). Approximately half of students after a traditional course (Control Group 1) and one third of students from the Control Group 2 answered correctly.

Table 2. Students' results of Question 1

	Correct value of the mean (%)	**Correct value of the uncertainty (%)**
Experimental Group (after the new course, $n = 85$)	71(84)	61(72)
Control Group 1 (after a traditional course, $n = 61$)	40 (66)	27 (44)
Control Group 2(no university physics course, $n = 23$)	9 (39)	6 (26)

The second and third questions refer to the connection between the mean, the absolute and the fractional uncertainties.

Question 2. Find the fractional uncertainty in the following experimental result: 64±16 (µC).

Answer: _____%

Question 3. Find the absolute uncertainty in the following experimental result: 15 cm ± 20%.

Answer: 15 ± ____ (cm)

These questions had the greatest number of correct responses among the students from the first control group (see Table 3). The experimental group had slightly lower results, and, as expected, the second control group obtained marked lower number of right answers.

Table 3. Students' results of Questions 2 and 3

	Correct value of the fractional uncertainty (%)	**Correct value of the absolute uncertainty (%)**
Experimental Group (after the new course, $n = 85$)	65 (76)	64 (75)
Control Group 1 (after a traditional course, $n = 61$)	47 (77)	50 (82)
Control Group 2 (no university physics course, $n = 23$)	12 (52)	15 (65)

The fourth task asks students to rewrite a result in the appropriate form:

Question 4. Round the following experimental result: height = 1.6432±0.237 (m).

Answer: _______ ± ______ (m)

For this question, the difference between the experimental group and the control groups was appreciable (see Table 4).

Table 4. Students' results of Question 4

	Correct value of the mean (%)	Correct value of the uncertainty (%)
Experimental Group (after the new course, $n = 85$)	49 (58)	64 (75)
Control Group 1 (after a traditional course, $n = 61$)	21 (34)	27 (44)
Control Group 2(no university physics course, $n = 23$)	7 (30)	9 (39)

The last question required to estimate uncertainties in repeatable measurements.

Question 5. A student measured some quantity three times, and obtained the following values: $x_1 = 24, \quad x_2 = 24, \quad x_3 = 21$. Write down the experimental result in the form $\bar{x} \pm \Delta x$.

You can use a hint: $\Delta x = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2}$.

Answer: $x =$ _____ ± ______

Despite the hint (the formula for Δx) this question turned out the most difficult for all students (see Table 5).

Table 5. Students' results of Question 5

	Correct value of the mean (%)	Correct value of the uncertainty (%)
Experimental Group (after the new course, $n = 85$)	53 (62)	35 (41)
Control Group 1 (after a traditional course, $n = 61$)	32 (52)	15 (25)
Control Group 2(no university physics course, $n = 23$)	7 (30)	3 (13)

The results of students' answers are summarized on Figure 4.

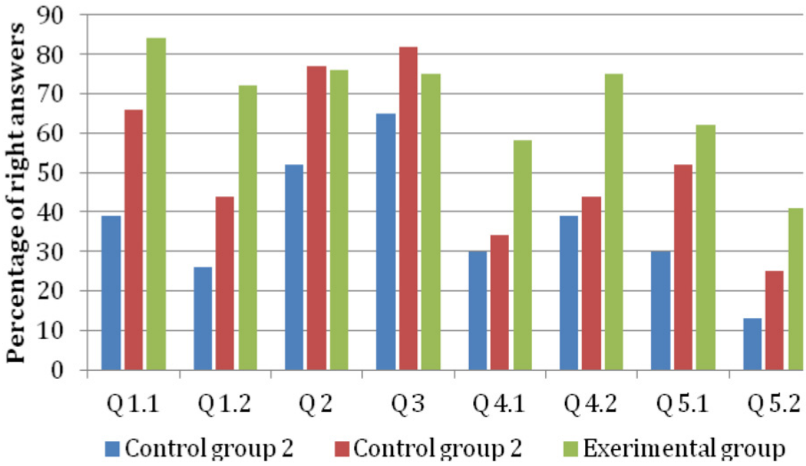


Fig. 4. Histograms of students' results for each question

6.2 General results of the course evaluation

For comparison the experimental and control groups students' answers to all questions were combined by assigning 1 point for a right answer, and 0 points for a wrong answer (see Figure 4). In that way, students who answered all questions correctly would receive a score of 8 points.

The highest number of students (18 or 21%) given all right answers was in the experimental group, only a few (2 or 3%) was in the first control group, and there were no such students in the second control group.

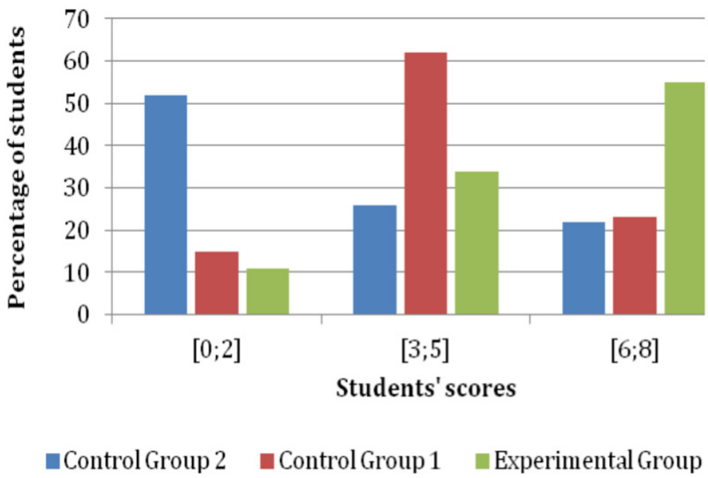


Fig. 5. Students' results in general

The effectiveness of the first part of the new course was evaluated by comparison students' scores (see Table 6).

Table 6. Students' results of Questionnaire

	Number of students (%)		
	scores are from 0 to 2	*scores are from 3 to 5*	*scores are from 6 to 8*
Experimental Group (after the new course, $n = 85$)	9 (11)	29 (34)	47 (55)
Control Group 1 (after a traditional course, $n = 61$)	9 (15)	38 (62)	14 (23)
Control Group 2(no university physics course, $n = 23$)	12 (52)	6 (26)	5 (22)

For the first and the second control groups, a chi-squared calculation results in a value 35.182 (df 2, p value of <0.00001), which confirms that the difference is statistically significant. For the experimental and the first control group, a chi-squared calculation results in a value 21.903 (df 2, p value of <0.0001), which confirms that the difference is also statistically significant.

It can be seen that after a traditional physics laboratory course (Control Group 1), about one in four of the students (23%) had the basic skills of error analysis, whereas more than half of the students (55%) reached this result after the new course. It is also noticeable that there were only a few students with these skills among those who had not studied any university physics course yet.

7 Discussion

The new physics laboratory course "Search for Physics Laws" based on the idea about systematic formation of mental actions has been described in this paper, and students' understanding of the basic concepts of experimental uncertainties after the first part of the course has been evaluated. We explored students' responses to the five questions that required using connection between the mean, the absolute and the fractional uncertainties, estimating uncertainties in repeatable measurements, and rewriting an experimental result in the appropriate form.

The obtained results show that before studying university physics course students have some fragmentary knowledge about uncertainties in physics experiments. The traditional laboratory course improves students understanding in this area noticeably. In general, our findings about the students' understanding the uncertainties after a traditional physics laboratory course (Control Group 1) are consistent with the research [9] which shows that students have a lot of difficulties carrying out error analysis.

The evidence strongly suggests that the organized in the new way laboratory sessions have improved students' basic knowledge and skills of error analysis more substantially than a traditional laboratory course.

It should be noted that this study has some limitations. The main of them is the fact that the majority of students in the experimental group was graduated from a high-school but the majority of students in the Control Group 1 — from a college.

8 Conclusion

In this study, we presented a new introductory laboratory course "Search for Physics Laws" and examined the effectiveness of this course in improving students' understanding of the uncertainties. We compared the responses of students after the new course, after a traditional course, and before any university physics laboratory course to the written questionnaire. After examining outcomes of 169 first-year undergraduate students followed 4-year BSc programmes in Engineering at Zaporizhzhia Polytechnic National University, our statistical analysis concluded that the organized in the new way laboratory sessions have been more effective than a traditional laboratory sessions.

Our research indicates that using Galperin's stepwise procedure for teaching first-year engineering students the basis of error analysis improve students' understanding in this area. This provides a good starting point for further researches. It will be important and interesting to investigate in details the process of students' understanding of uncertainties over the whole course. The quality of students' understanding of more complex concepts of error analysis may also constitute the object of future studies.

Since the ideas used in our course "Search for Physics Laws", such as Galperin's approach, orienting charts, unhurried presentation of the material about error analysis, can be put into educational practice by using different laboratory equipment, we welcome colleagues to engage with the course and try it in their teaching practice.

9 Acknowledgement

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