

Teaching learning sequence for introductory instruction in the physics laboratory in upper secondary school

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Citation: Lazos, P., Kateris, A., Tsoukos, S., Tzamalīs, P. G., & Velentzas, A. (2025). Teaching learning sequence for introductory instruction in the physics laboratory in upper secondary school. *Contemporary Mathematics and Science Education*, 6(2), ep25016. <https://doi.org/10.30935/conmaths/17308>

ABSTRACT

The present work introduces a teaching learning sequence (TLS) aimed at familiarizing upper secondary school students with basic concepts related to physics laboratory instruction (e.g., measurement–uncertainty–average value), as well as training them to take measurements and process data. Specifically, the rationale behind the TLS, its structure, the findings from its implementation, and areas for improvement based on feedback from its application are presented. The difficulties encountered by students are discussed, and suggestions are made for educators based on these findings.

Keywords: physics laboratory, measurement, teaching physics, teaching learning sequence

Received: 20 Jan. 2025 ♦ Accepted: 02 Sep. 2025

INTRODUCTION

Designing and carrying out experiments is considered to be inextricably linked to the sciences. Distinguished scientists argue that experiments are a basic element of science. For example, Feynman et al. (1963) state that “the test of all knowledge is experiment. Experiment is the sole judge of scientific truth.” There are a number of roles that experiment can serve in science, such as testing the correctness of a theory, demonstrating the need for a new theory, producing evidence for the existence of the entities to which the theories refer, demonstrating the existence of a novel phenomenon, and helping us to choose between competing theories (crucial experiments) (Franklin, 1999).

The usefulness of performing experiments in science courses is widely accepted. The common practice for students is to conduct experiments following specific instructions to arrive at a predetermined result (“cookbook” experiments). The case in which the students choose the scientific question and design the experimental procedure by themselves, without the teacher’s intervention (“self-guided” experiments) is rare (Duit & Tesch, 2010).

The primary goals of laboratory work are to equip students with a solid understanding of experimental concepts, foster their practical

application of scientific methods, and cultivate a positive outlook towards science. By constructing conceptual frameworks, students can actively engage with the subject matter. Additionally, laboratory experiences provide opportunities to develop essential skills and abilities, such as critical thinking, problem-solving, and data analysis, aligning with the pedagogical approach advocated by Hodson (1996).

In particular, taking measurements is a fundamental element of the scientific method and plays a key role in school laboratory activities. Through careful data recording and analysis, students:

- verify or disprove theories (Ma et al., 2023),
- gain direct experience of the scientific process, comparing experimental results with the predictions of natural laws (Andersen & Hepburn, 2015; Wang et al, 2014),
- develop critical thinking skills, as the interpretation of measurements requires critical thinking and the ability to recognize errors or inconsistencies (Jamil et al., 2021),
- improve their accuracy and attention, as meticulous data recording and taking detailed notes cultivates accuracy and attention (Ranggi et al., 2020),
- enhance the understanding of physical phenomena, as the visual representation and analysis of data with graphs and tables

help with visual literacy and a deeper understanding of physical concepts (Susac et al., 2017; Burlinson et al., 2024),

- develop communication skills, as the presentation of experimental results, both in writing and orally, strengthens communication and collaboration skills (Raviv et al., 2019), and
- cultivate a scientific mindset, as taking measurements encourages questioning, curiosity and the search for answers using evidence and data (Hofstein & Lunetta, 2004).

Based on the foregoing, we considered it beneficial to develop and test a teaching learning sequence (TLS) in order to introduce students to basic concepts related to the experimental process (i.e., measurement–uncertainty–mean value) as well as to train them in taking measurements and processing data. In this paper, we present the TLS that we developed and tested on a class of students. More specifically, we present the rationale behind the TLS, its structure, the findings from its implementation, and the points for its improvement, based on the feedback received after its application. Finally, based on the findings, the difficulties encountered by the students are discussed, while suggestions are made to teachers who are considering applying the TLS.

THE STRUCTURE OF THE TEACHING LEARNING SEQUENCE

One of the important fields of research in the teaching of sciences is the design, development, implementation and evaluation of TLS. By TLS we mean a small-scale “curriculum” limited to a unit or a range of units that includes learning and teaching activities which are the result of empirical research and are tailored to students’ reasoning (Méheut & Psillos, 2004). Various theoretical frameworks have been proposed for the design and development of TLSs, such as:

- The “teaching rhombus”, which at its vertices has four factors that are interconnected. These factors are the teacher, the students, the material world and the scientific knowledge to be taught (Méheut, 2005).
- The model of “educational reconstruction”, which proposes the didactic transformation of scientific knowledge from an educational point of view. It includes three components and their interrelationships: The analysis of the scientific content from the educational point of view, the research on learning and teaching, and the design and evaluation of the learning and teaching environment (Duit et al., 2012).
- The model of “design-based research”, which emphasizes the connection between research and practice, the collaboration of teacher and researcher and the management and utilization of the amount of information resulting from the design, implementation and evaluation of the TLS (Tiberghien et al., 2009)
- The approach from the perspective of social constructivism, according to which the design of a TLS should take into account how the scientific knowledge to be taught is perceived in the everyday social language of the students so that the design of instruction takes into account the possible differences (Leach & Scott, 2002).

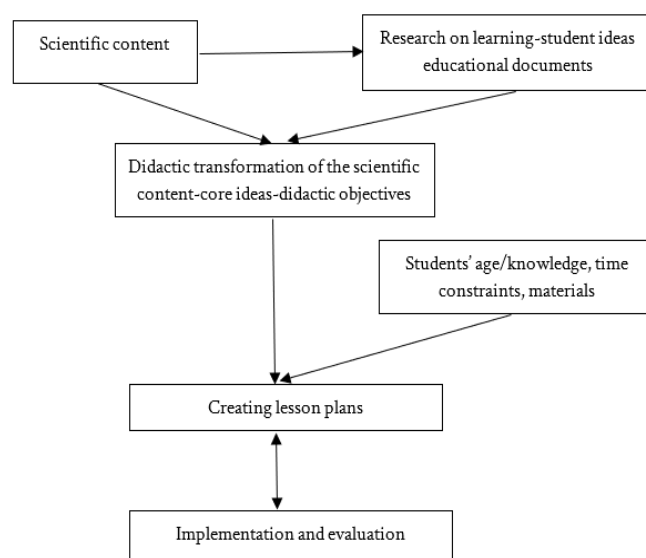


Figure 1. The design structure of the TLS (Original figure prepared by the authors)

However, what seems to be commonplace in the literature is the need for the improvement/revision of the TLS based on the research data resulting from its evaluation during its implementation phase. Méheut and Psillos (2004) take the view that when designing a TLS, teachers do not need to strictly follow a proposed model but should consider both their preferences and the overall context of its implementation. The process we followed for the design and development of the present TLS is schematically described in **Figure 1**.

Specifically, after the study of the scientific content and the literature on learning and teaching in the specific scientific area, we arrived at the content to be taught (i.e., the core ideas and teaching objectives). Then, considering the context (i.e., students’ age and knowledge, time constraints of the school schedule, and use of simple materials), we arrived at the design of the lessons. The lessons were carried out, and their evaluation led to conclusions with the aim of improving the initially designed TLS.

The Scientific Content

For the scientific content, the guide of the Joint Committee for Guides in Metrology (JCGM 100, 2008), reference books (Squires, 1985; Taylor, 1997) and experimental guides for upper secondary school were studied (e.g. International Baccalaureate diploma-program for Science and Greek experimental Guides which support Science curriculum).

The chosen scientific content focused on fundamental measurement concepts. Students delved into the importance of accuracy and precision in measurements, exploring the distinction between random and systematic errors. They also learned about significant digits and their role in representing measurement uncertainty. To quantify uncertainty, students studied methods for calculating uncertainty in both single and repeated measurements. Additionally, they explored the propagation of uncertainty, understanding how uncertainties in individual measurements could affect the overall uncertainty of calculated quantities.

Table 1. The content to be taught per teaching hour and per step

Hour	Step	Content to be taught
1 st	1	The quantitative study of natural phenomena through observations or experimental procedures is based on data obtained from measurements.
	2	The result of a measurement is expressed by a number and the corresponding unit of measurement. The number shows the relationship of the measured quantity to the unit of measurement.
	3	The result of the measurement does not coincide with the “true” value of the unknown quantity. Definition of absolute and relative error.
	4	Classification of errors into random and systematic.
	5	Thinking about various sources of errors can help us to reduce them by appropriate interventions but not totally eliminate.
2 nd	1	Significant digits—rules for determining the significant digits of a number.
	2	Rules for determining the significant digits for the result of different operations.
	3	Rules for writing a number as a power of 10 (Scientific notation).
	4	Rules for rounding to a certain number of significant figures.
3 rd	1	The experimenter must have an estimate of the range of values between which the actual value of the physical quantity being measured lies. He seeks to reduce uncertainty, which however cannot be reduced to zero. The result of a measurement is written in the form $x \pm \delta x$.
	2	The estimation of uncertainty when measuring with an analog instrument.
	3	The estimation of uncertainty in measurement with a digital instrument.
4 th	1	The mean value for a series of repeated measurements.
	2	The mean deviation as a measure of the uncertainty of the mean value. Calculations.
5 th	1	In the case that the quantity f is derived from a sum or a difference, $f = x \pm y$, the rule for calculating uncertainty δf is $\delta f = \delta x + \delta y$.
	2	In case that the quantity f is derived from a product $f = x \cdot y$ or a quotient $f = x/y$ the rule for calculating uncertainty δf is $\delta f = f \left(\frac{\delta x}{ x } + \frac{\delta y}{ y } \right)$.

The Didactic Transformation

Educational research on concepts related to work in the laboratory such as measurement, uncertainty, and mean value, has been mainly conducted at the level of first-year university students as well as middle and high school students.

Students generally take measurements without realizing that their findings are accompanied by uncertainty, or that they need to be supported to be accepted as reliable (Lubben & Millar, 1996). The idea of the true value of a quantity without any uncertainty is particularly strong among students aged 14–17 years. This can be fruitful, as it prompts students to take repeated measurements and develop original procedures to improve the result. However, at the same time, the desire to eliminate all uncertainty can be an obstacle and create a distorted picture of reality, dominated by the possibility of obtaining a “perfect” measurement thanks to “perfect” instruments, methods or scientists. It is possible to have a teaching intervention that will lead to an improvement of the students’ relevant perceptions, but it is time consuming (Coelho & Séré, 1998).

Research has been done, as already mentioned, involving undergraduate students, the academic group which we studied for the present work on the basis that the difficulties encountered by these students will obviously also pose difficulties for younger secondary school students. As has been found (Pollard et al., 2021), many undergraduate students encounter serious difficulties in using significant figures and, even if they have sufficient knowledge about the uncertainty of measurements, they do not use their knowledge appropriately to compare experimental results (Wan, 2023). Moreover, students often think that one measurement is enough, and that taking more measurements is simply to confirm or reject the first measurement. At the same time, they believe that the measuring instruments that exist in the laboratories are of such quality and construction that their measurements are extremely accurate, and thus it is sufficient to take only one measurement. Even after a specially designed course, many students do not recognize the differences between the concepts of “error” and “uncertainty”, nor between systematic and random errors. Apart from that, it is common for

students to consider that the results of measurements processing (e.g., the calculation of the average value) give the true value of the quantities (Evangelinos et al., 2002). Buffler et al. (2001) argue that there is low correlation between students’ ability to process (often mechanistically) data and their understanding of key features of the process. Also, at least at the beginning of their studies, most students perceive measurement as a process involving a single measurement rather than a set of measurements. In order for students to understand that the results of measurements processing are about the measurements themselves and that the concept of uncertainty is inherent in the measurement process, Allie and Buffler (2003) suggested the design of an introductory physics laboratory (for students) according to the guidelines of the International Organization for Standardization.

Our review of the literature identified four central concepts that should underpin the proposed TLS. First, taking measurements is a cornerstone of scientific inquiry. Second, it’s essential to recognize that measurement errors are an inherent and unavoidable aspect of the process, not simply mistakes. Third, while efforts can be made to minimize errors, it’s impossible to eliminate them entirely. Finally, measurements gain significance when accompanied by a clear understanding of their associated uncertainty.

The Content to be Taught

The content to be taught was divided into 5 teaching hours, as shown in **Table 1**.

As already mentioned, the knowledge level of the students was taken into account in determining the scientific content of the lesson. For example, as regards the concept of *mean value uncertainty*, *mean deviation* rather than *standard deviation of mean value* is suggested to be used in order to make sense to secondary school students based on their knowledge.

The Lesson Plans

Based on the content, hourly lessons were planned and five worksheets were structured, one for each lesson, respectively. In order to make it possible to carry out the TLS in all schools, the required materials were kept as simple as possible. The following measuring

Table 2. The proposed procedures per teaching hour and per step

Hour	Step	Procedures
1 st	1	Students express their opinions about why scientists perform measurements in their work. A discussion with the teacher follows.
	2	Students in groups: 1. Measure and record the result of measuring the width of a book and the time between successive sounds with their mobile phones (phyphox app-acoustic stopwatch). 2. Write what, in their opinion, the result of weighing a student 65 kg means. A teacher-mediated discussion follow.
	3	1. Students in groups measure the angle of inclination of an inclined plane with the “phyphox-inclination” app of mobile phones, compare their measurements and speculate on the causes of the deviations. 2. Introduction of the concept of <i>error</i> by the teacher. Then, in groups, students use the phyphox mobile phone app to measure the value of the acceleration of gravity and individually calculate the relative % error, using a reference value from the literature.
	4	Through discussion, the teacher introduces the concepts of systematic and random error. Then, the students have to identify in three different cases whether the errors are random or systematic. Specifically: 1. The index of an analog scale before weighing is not exactly at zero. 2. A tape measure due to some manufacturing problem is shorter in length than the maximum reading. 3. Repeated measurements of the driving time of an electric car between two locations with a hand stopwatch give a different result.
	5	Students propose ways to reduce the errors in the cases of the previous step and predict whether they could be reduced to zero.
2 nd	1	Through discussion, the teacher uses examples to explain the meaning of the significant figures, as well as the rules for determining them. Students then identify in various cases the number of significant figures and match their answer with the rule they used.
	2	Through discussion, the teacher explains the rules for determining the significant digits of the result of operations. Students calculate the result of various operations to the correct number of significant figures and match their answer with the rule they used.
	3	The teacher discusses ways of writing (with the correct significant figures) a number from simple decimal form to expression with scientific notation and vice versa. Students answer corresponding questions.
	4	Through discussion, the teacher explains the rounding rules. Students round numbers to a certain number of significant figures in different examples.
3 rd	1	Introduction of the concepts by the teacher through discussion and examples. The conceptual difference between “error” and “uncertainty” is touched upon. Students discuss the case of two resistors $R_1 = (100 \pm 5)\Omega$ and $R_2 = (100 \pm 1)\Omega$ and choose the appropriate one for use in a circuit that will control a high precision mechanism.
	2	Students observe the scales of two different dynamometers (maximum reading 5 N and 10 N, respectively) and decide on the uncertainty of measurements with each of them. They choose the most suitable for measuring weights of about 4 N and 8 N.
	3	Students measure the angle of inclination of an inclined plane with the mobile phone app “phyphox-inclination” and decide on the uncertainty of the measurement.
4 th	1	Students work in groups with the mobile phones (acoustic stopwatch-phyphox) count 5 times the time a ball falls from a table. Then: 1. Discuss the reasons why the values are not the same. 2. Decide as the best estimate: (a) the mean value of the measurements or (b) the most frequently occurring value, or c) the average of the smallest and largest value. Mediation of the teacher where deemed necessary.
	2	Through discussion, the teacher introduces the concept of mean deviation and explains how to write the final result in the form $x \pm \delta x$. Then the students, individually, calculate the mean value and the mean deviation of the time measurements from step (1) and write the final result.
5 th	1	Students discuss the maximum and minimum possible values for the sum and difference of quantities with a given value and uncertainty, such as two resistors with $R_1 = (100 \pm 5)\Omega$ and $R_2 = (100 \pm 1)\Omega$. The teacher guides the discussion to derive the applicable rule.
	2	1. Students discuss in groups the maximum and minimum possible values for the product (and quotient) of quantities with a known value and uncertainty. For example, they calculate the area of a rectangle with sides of (9.2 ± 0.1) cm and (10.5 ± 0.3) cm. The teacher guides the discussion and introduces the rule. 2. Students then individually apply the rule to calculate the acceleration due to gravity (<i>g</i>) using time and height measurements from a free-fall experiment. It is emphasized that this is the students’ first encounter with this process.

instruments were provided: tape measure, two dynamometers and the mobile smartphones of the students on which, by installing the phyphox application, measurements of various physical quantities can be taken. Thanks to the sensors that modern mobile phones have, their use in taking measurements in school laboratory activities is growing, while it has been suggested that they be used in the context of teaching to introduce the concept of uncertainty in measurement (Listiaji et al., 2021). In summary, the proposed procedures per teaching hour and per step are described in **Table 2**.

THE IMPLEMENTATION OF TLS

The proposed TLS was implemented in two classes of an Athens upper secondary school (grade 10). It was the first time the specific

students came into substantial contact with laboratory activities, as due to the COVID-19 pandemic, they had not participated in such activities since the first year of the middle school (grade 7). A total of thirty-four students participated in the implementation. The students were divided into ten groups of three or four. Each student completed an individual worksheet, as some of the questions had to be answered individually (e.g., the expression of an opinion from previous knowledge). However, other questions required a response from the whole group after discussion.

The five researchers were involved in the implementation of the TLS. Each researcher had the role of teacher for one lesson, while the remaining four researchers as observers recorded their observations at each step of the lesson plan. Specifically, each researcher observed two groups of students, followed the discussions between their members

Table 3. The purpose of performing measurements by scientists

Category	Student opinion	Response frequency
1	To confirm/document/verify opinions/theories	28/61–45.9%
2	Vagueness/ tautology (e.g., physics is an experimental science, for better accuracy, to reduce errors)	23/61–37.8%
3	To draw conclusions	6/61–9.8%
4	To create/introduce theory	3/61–4.9%
5	To disprove a theory	1/61–1.6%

Table 4. Causes of measurement result deviation

Category	Causes of measurement result deviation	Response frequency
1	Vague reference to “experimental errors”	6/14
2	Inclined surface or mobile phone defects (e.g., camera bump)	4/14
3	Different mobile phone device	3/14
4	Human factor	1/14

Table 5. Students’ opinions on error reduction

Case	Students’ opinions on error reduction	Number of students
1	Remove original indicator	25
	Change of instrument or use of another one at the same time	7
	Implies “calibration” (e.g., the experimenter fix the pointer)	2
2	Add 2 mm to the measurement	13
	Subtract 2 mm from measurement	12
	Instrument replacement	9
3	Multiple measurements and finding the mean value	26
	Indefinite answer (e.g., to pay attention/try, to make an algorithm)	5
	I cannot do anything	3

and recorded the points where difficulties appeared, alternative ideas, as well as their interesting comments or opinions. The research utilized both the completed individual worksheets and the researchers’ notes taken during the process as data.

FINDINGS

The presentation of the findings is done per teaching hour and per step.

1st Teaching Hour

Step 1

The 34 students expressed 61 opinions which were categorized as in **Table 3**.

Step 2

1. 9/10 groups gave the result with numerical value and unit of measurement, while one group gave the result with numerical value only.
2. 7/10 groups wrote an answer that could be described as a tautology. For example they wrote “shows mass”, “shows 600 N pull from earth”. 3/10 groups gave an answer that implies a comparison with a unit of measurement, for example “how many times is the mass greater than 1 kg”.

After the class discussion in the following activities all groups wrote the results with numerical value and unit of measurement.

Step 3

1. In the 10 worksheets, the answers mentioned 14 causes and are categorized as in **Table 4**.

2. 30/34 students answered correctly while the remaining 4 students had difficulty with operations and specifically with the decimal point.

Step 4

30/34 correctly classified errors into random and systematic.

Step 5

The responses for error reduction are shown sorted in **Table 5**.

The greatest difficulty was presented in case 2 and specifically most students did not write about proportional addition or subtraction in each measurement but about an absolute measurement with a value of 2 mm.

2nd Teaching Hour

Step 1

The students correctly identified the number of significant figures in 85% of cases, while the choice of rules they used was correct on a case-by-case basis in over 90% of cases. The biggest failure was the question that asked the students to give the significant figures in the length measurement of 2.0×10^2 m where only 55.8% managed to answer correctly. The difficulty may be due to the fact that when the students answered this question the scientific notation had not yet been discussed.

Step 2

Students had particular difficulty expressing the result with the correct number of significant figures with the correct answers to the 7 questions asked ranging from 11.7% to 70.6%. The points that seemed to be particularly difficult for the students and required what seems to be the greatest emphasis during teaching by the teacher, are the cases where they had to express with the correct number of significant figures:

- (a) the sum of decimals with integers and
- (b) the difference when the decimal places are zero (for example 345.009 g – 23.009 g).

Step 3

The students did not seem to have difficulty choosing the correct conversion of a number from scientific notation to simple decimal form, as 94% answered correctly. However, in the question where they had to choose the correct conversion of a number (205,000 km) from decimal form to scientific notation, they had quite a difficult time: 29.4% answered correctly. The difficulty probably lies in the fact that in the teaching, in addition to the rules, not enough examples of recording measurements in scientific notation with a focus on the number of significant figures were mentioned.

Step 4

It appeared that the students did not struggle, as the correct answers to each one of the 4 questions varied from 88.2% to 100%.

3rd Teaching Hour

Step 1

Regarding the difference between the two resistors, 29/34 answers were correct. The remaining 5/34 highlight the notion that the resistor readings are something like a field of definition of a function, but without proceeding to the physical meaning. For example, “R1 can take all of R2’s values while R2 can only take its own.”

Regarding the choice of the appropriate resistor, 31/34 students chose R2. The remaining 3 would not select any resistor due to high accuracy. Of the 31 who had made the choice of R2, 2 did not give a reason, 23 answered clearly that they choose the resistor with the least uncertainty in value, and 6 gave a vague reason, for example “I will prefer R2 because the value I want it is closer to the values of that resistor range”.

Step 2

10/34 students had difficulty in finding the least subdivision of a scale. Then again, 15/34 of the students had difficulty in determining the uncertainty not because of difficulty in applying the rule (one-half least subdivision), but because of difficulty in doing calculations with decimal numbers. The students were then asked which dynamometer they would choose to measure with the smallest uncertainty, and what the potential disadvantage is. All 34 students chose the second, with the smallest minimum subdivision. As a possible disadvantage 30/34 mentioned the smaller value range. The remaining 4 did not complete the question. Finally, regarding the choice of the appropriate dynamometer, all 34 made a correct choice, however 29/34 gave satisfactory reasons and the remaining 5/34 did not give reasons.

Step 3

All students answered correctly based on the previous class discussion; however, only 5/34 also wrote a justification. It is not clear to what extent those who did not answer could justify their answer but did not consider it necessary, or could not and wrote the answer intuitively or uncritically by discussing it with a classmate.

4th Teaching Hour

Step 1

1. 32/34 students reported that the differences were due to random errors and 2/34 to systematic errors. Additionally, only

6 students reported possible causes of random errors. Specifically, the differences are due to

- (a) influencing external sounds (3 students),
- (b) operator errors (1 student), or
- (c) smartphones failures (2 students).

2. All students answered “the mean value”. This is probably due to the fact that from the 1st year of lower secondary school, in all activities in the laboratory, they are always asked for the mean value. Only 12/34 students gave some justification for their opinion. The 7/12 answers that have some form of explanation converge on the fact that by averaging we are considering all values. The remaining 5/12 answers are not justification but tautology.

Step 2

1. Regarding the calculation of the mean value, 29/34 students calculated the mean value to 3 decimal places, the same with the time recorded on the mobile phone screen, while the remaining 5/34 gave an answer with 4 decimal places (as “shown” by the smartphone calculator). Regarding uncertainty, 27/34 students rounded, as discussed in class, to one significant digit, while 7/34 left more digits in the answer.
2. Regarding the final writing of the mean value with uncertainty, 23/34 wrote the result having rounded the mean value with uncertainty to the same number of digits, while the remaining 11/34 wrote an answer that did not match the digits of the mean value with those of uncertainty.

5th Teaching Hour

Step 1

Based on the example, the students correctly identified the maximum and minimum possible values (31/34). However, before the teacher’s intervention, there was difficulty in deriving a rule. Only 12/34 were able to independently formulate a general rule. The rest either did not articulate a rule, formulated one incorrectly (e.g., subtracting the uncertainties in subtraction), or wrote something unrelated to the question.

Step 2

1. For the specific example, all groups found the limits within which the value of the area will lie. However, in the discussion that followed, they could not derive a general rule without the decisive intervention of the teacher.
2. 21/34 answers were correct.

RESULTS

The following results are extracted from the findings, which are presented per concept of the teaching content in the order that they correspond to the five teaching hours.

Measurement–Measurement Error

The students, without having been explicitly taught in previous classes the reasons why scientists perform experiments, mainly expressed the view that scientists experiment in order to confirm/substantiate/verify opinions/theories. They did not seem to have any trouble realizing that “measurement error” is not a “mistake”

but is an “unavoidable” part of a measurement. They understood the difference between random and systematic error but had difficulty “correcting” systematic errors when they required not uniform but “proportional” correction. For example, when measuring lengths with a tape measure that by construction is 2 cm shorter than its maximum reading, they correct by 2 cm all measurements of short or long lengths. At this point, it seems that special attention and persistence are required during the teacher’s intervention.

Significant Figures–Rounding

With the proposed procedure in TLS, it appeared that students realized that the measuring instrument determines the accuracy with which the result of a measurement will be written and in most cases (see findings for the second teaching hour), they appeared to be able to write the result of a measurement with the correct number of significant figures. The cases in which difficulties occurred and special emphasis is required during teaching by the teacher are:

- (a) When the result is given or required to be written in scientific notation.
- (b) Finding and writing the result of adding decimals to integers.
- (c) Finding and reporting the difference result when the decimal places are zero (for example 345.009 g–23.009 g).

Regarding rounding values to a certain number of significant figures, the students did not seem to have difficulty.

Uncertainty of Measurement Result

It seemed to be understood that the estimation and reporting of the uncertainty in the result of a measurement is necessary as scientific knowledge but also as an important element in technological applications. The students had no difficulty in separating the instruments into analog and digital. No difficulty was encountered in estimating uncertainty on digital instruments; however, significant difficulty was encountered in reporting uncertainty when measuring with an analog instrument, which appeared to be based on the difficulty of several students in finding the smallest subdivision of a scale. This is a point that seems to need special persistence and intervention from the teacher as the students, despite being in upper secondary school, still face difficulty with decimal numbers.

Mean Value–Mean Value Uncertainty

The students seemed to know, without justification, from previous classes that in the case of random errors of laboratory measurements, the mean value is the best estimate of the true value. The uncertainty of the mean value (as mean deviation) in the discussion appeared to make sense to the students. They also appeared to be able to perform its calculation process.

The calculation of the mean value and its uncertainty when taking repeated measurements presented some difficulties. These difficulties were not due to the application of the formulas for calculating the mean value and its uncertainty but were related to arithmetic operations, rounding to the correct number of significant figures, and/or the writing of decimal numbers.

Also, a point to which 33% of the students did not answer correctly is that in writing the final result, the answers did not have the correct correspondence between the digits of the mean value and those of the uncertainty. This is a point that apparently needs special effort and persistence from a teacher using the proposed teaching sequence.

Propagation of Uncertainty

It appeared that through appropriate examples, students realized that the uncertainty of a derived quantity is different from the uncertainty of the individual quantities from which the derived quantity is derived. The students, with the help of the teacher, were able to estimate the range of uncertainty in specific cases, such as finding uncertainty in total resistance or in surface area, but they had difficulty formulating a general rule on their own. But it must be emphasized that this was the first time they had come into contact with the concept of error propagation and had never previously applied the rules. Based on the findings, we can say that when specific examples are presented, students understand the uncertainty of the outcome of actions; however, more familiarity and practice is needed by repeating the procedures many times through experiments in order to consolidate the application of the rules.

DISCUSSION AND CONCLUSION

In this work, the building process of a TLS for upper secondary school students, its implementation, and the results of the implementation were presented. The specific TLS is recommended to serve as an introductory physics course to familiarize students with concepts and procedures related to work in the Physics laboratory. As shown by the results of its application, it essentially helped students to approach concepts such as measurement, error, uncertainty of a measurement and of a series of measurements.

In the application described above, most of the barriers arose from the students’ lack of the required mathematical background; in particular, there were obstacles due to scale reading, decimal numbers, and powers of ten. We recommend that a teacher who may subsequently apply this TLS in their class should give more emphasis to those areas, and/or the second teaching hour should be extended to two hours, with more examples presented to students. Also, it would be most beneficial for the application to be carried out at the beginning of upper secondary school, so that students become familiar with the laboratory practices that will follow in the next three years of their schooling.

This work did not extend to the use of diagrams in the educational laboratory, a topic which is suggested as future research to extend the present TLS.

In conclusion, we can say that the implementation of the TLS with the proposed improvements seems to help familiarize the students with the concepts and procedures of the work in the educational science laboratory, especially if it is taken into account that the students were coming into contact with these concepts for the first time. It is our belief that if students in secondary education practice more systematically in the laboratory, they can overcome the obstacles that appeared during the implementation of the proposed TLS.

Author contributions: All authors contributed equally to the following roles: conceptualization, methodology, investigation, data curation, writing – original draft, writing – review & editing. All authors approved the final version of the article.

Funding: The authors received no financial support for the research and/or authorship of this article.

Ethics declaration: All procedures performed in this study involving human participants were in accordance with the ethical standards of the Ministry of Education, Research and Religious Affairs of Greece and with

the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from the school administration and the students' guardians prior to participation. No sensitive or personally identifiable information was collected, and all data were analyzed anonymously.

Declaration of interest: Authors declared no competing interest.

Data availability: Data generated or analyzed during this study are available from the authors on request.

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