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A METHODOLOGY FOR DEVELOPING STUDENTS' PROFESSIONAL COMPETENCE THROUGH THE ASSESSMENT OF EXPERIMENTAL DATA RELIABILITY AND MEASUREMENT UNCERTAINTY IN PHYSICS PRACTICUM

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Laboratory activities in physics education are one of the important didactic means of connecting students' theoretical knowledge with real experimental practice, developing their ability to observe and measure physical phenomena, process experimental data, and formulate scientifically grounded conclusions. In particular, Physics Practicum classes in higher education provide an environment in which students move from the acquisition of ready-made theoretical knowledge toward independent reasoning based on experimental evidence. In this context, the outcome of laboratory work is determined not only by obtaining a numerical value of a physical quantity but also by the ability to justify the reliability of the obtained result.

In experimental physics, every measurement result is characterized by a certain degree of uncertainty. Therefore, measurement uncertainty is not merely a mathematical parameter describing the technical aspects of a physical experiment; it is also an important tool for interpreting experimental data, comparing different measurement results, and drawing scientifically grounded conclusions from experimental evidence. Contemporary research in physics education increasingly considers measurement uncertainty as an important learning outcome of laboratory instruction. In particular, studies focusing on measurement uncertainty emphasize its fundamental importance in evaluating and comparing experimental results.

However, teaching students how to calculate measurement uncertainty in laboratory classes does not, by itself, indicate that their experimental competence has been adequately developed. A study published in Physical Review Physics Education Research in 2024, involving more than 1,500 students from 20 higher education institutions, showed that students performed relatively well on certain practical tasks, including calculating the mean of measurements. However, they experienced considerable difficulties when comparing measurements while taking uncertainty into account and when correctly propagating uncertainties using mathematical relationships.

This situation presents an important methodological problem for the organization of Physics Practicum: a student may be able to answer the question “How should measurement uncertainty be calculated?”, while experiencing difficulties in answering research-oriented questions such as “How reliable is the obtained result?”, “Are two experimental results consistent with each other?”, and “Is the observed difference attributable to a physical phenomenon or can it be explained by measurement uncertainty?”. Research also indicates that there is a distinction between possessing conceptual knowledge about measurement uncertainty and being able to apply that knowledge to decision-making based on real experimental data.

From this perspective, expanding the methodological potential of Physics Practicum by treating measurement uncertainty not as an isolated calculation procedure but as an integral component of the process of assessing the reliability of experimental data, comparing data, interpreting their physical meaning, and drawing evidence-based conclusions represents an important scientific and methodological task. Researchers have also increasingly focused on the potential of using standardized approaches in teaching measurement uncertainty.

At the same time, an analysis of existing studies indicates that the problem of measurement uncertainty has primarily been investigated from the perspectives of identifying students’ conceptual understanding, calculating uncertainty, comparing experimental data, and developing specialized assessment instruments. However, the integration of measurement uncertainty into the holistic methodological system of Physics Practicum, its connection with the assessment of experimental data reliability,

and the systematic development of students' professional competence through this process require further investigation as a distinct methodological model. In particular, it is important to develop didactic mechanisms that facilitate students' transition from the stage of "calculation" to the stages of "evaluation and decision-making."

This approach makes it possible to transform Physics Practicum from a learning environment focused primarily on performing laboratory procedures and obtaining results using predetermined formulas into a competency-oriented learning environment focused on evaluating experimental evidence, taking measurement uncertainty into account, and making scientifically informed decisions.

In physics laboratory education, issues related to measurement uncertainty and the interpretation of experimental data have become an important area of research in physics education methodology in recent years. An analysis of existing studies allows research in this field to be provisionally classified into four main groups: first, the content of measurement uncertainty and the challenges associated with teaching it; second, students' conceptual and procedural understanding of uncertainty; third, the transformation of laboratory courses toward learning about measurement and uncertainty; and fourth, the development of assessment instruments for evaluating students' competencies in these areas.

Measurement uncertainty is one of the fundamental concepts in experimental physics because it makes it possible to determine the limits of an obtained result and assess its consistency with other results. Therefore, in higher education physics laboratory classes, it is important to teach students not only to determine numerical values of physical quantities but also to express and interpret the uncertainty associated with those values.

This finding indicates the need to conceptualize measurement uncertainty in Physics Practicum not as an isolated mathematical operation but as a competence integrated into all stages of experimental activity. Although this body of research provides an important methodological foundation for our study, its primary focus has been on the development of students' understanding of measurement and uncertainty. In the approach proposed in the present study, however, the calculation of uncertainty is explicitly connected to the

subsequent stage—assessing the reliability of experimental data and making professionally grounded decisions.

This finding is of particular significance for our study because it demonstrates that calculation competence and competence in making experimental decisions are distinct constructs. A student may be able to calculate measurement uncertainty; however, this does not automatically mean that the student is able to assess the reliability of the obtained result or justify the consistency of two experimental results. This conclusion indicates that competence in working with measurement uncertainty does not develop automatically and therefore requires purposeful methodological support.

Furthermore, studies on measurement uncertainty have shown that students do not interpret sources of uncertainty in the same way across different experimental contexts. For example, in classical mechanics experiments, students tend to focus more on the experimental apparatus and its limitations, whereas in other contexts they may identify theoretical physical principles as potential sources of uncertainty.

This finding suggests that, in the methodology of Physics Practicum, rather than providing students with a predetermined list of uncertainty sources, it is necessary to encourage them to independently address the question: “Which specific factors in this experiment affect the reliability of the result?”

The reviewed studies demonstrate that measurement uncertainty is an important component of physics laboratory education, that students experience certain difficulties in developing an adequate understanding of this concept, and that purposeful pedagogical transformation can contribute to the development of their reasoning. At the same time, the major directions of existing research have primarily focused on the following issues:

- identifying students’ understanding of measurement uncertainty concepts;
- identifying typical difficulties in students’ reasoning;
- developing assessment instruments for measurement uncertainty;
- transforming laboratory courses toward learning about measurement uncertainty.

Although these research directions provide an important scientific foundation, the direct integration of measurement uncertainty with the assessment of experimental data reliability and the transformation of this process into a holistic methodological

mechanism for developing students' professional competence have not yet been sufficiently systematized.

Therefore, in the present study, measurement uncertainty is considered not as an independent instructional element, but as an integral component of the following coherent methodological system:

Measurement → Identification of Uncertainty → Calculation of Uncertainty → Assessment of Data Reliability → Comparison of Results → Physical Interpretation → Evidence-Based Conclusion.

The student does not treat the result merely as a "number." Instead, the student analyzes the limits of the result, the sources of uncertainty, and the conclusions that can be drawn from the available evidence. As a result, measurement and calculation skills become integrated with analytical, research, and professional competencies. Thus, the main scientific gap addressed by this study can be formulated as follows: although a substantial scientific foundation exists for teaching and assessing measurement uncertainty in physics laboratory education, the organization of the assessment of experimental data reliability based on measurement uncertainty as a holistic methodological system aimed at developing students' professional competencies has not yet been sufficiently developed at the level of a distinct pedagogical model. This scientific gap determines the methodological direction of the present study.

International research has also increasingly recognized measurement uncertainty as an important component of physics laboratory education. In particular, a study involving more than 1,500 students from 20 higher education institutions found that students performed relatively well on tasks such as calculating mean values, but experienced difficulties when comparing measurements while taking uncertainty into account and when correctly propagating uncertainties using mathematical relationships.

Furthermore, research has demonstrated that reorganizing laboratory courses around the explicit development of students' understanding of measurement uncertainty can lead to positive changes in their experimental reasoning. In such courses, greater emphasis is placed on experiments whose outcomes are not known in advance and on the analysis of

uncertainty, rather than on laboratory activities designed primarily to verify predetermined theoretical results.

Based on these considerations, the following author-developed methodological model is proposed in this study:

Measurement → Uncertainty → Reliability → Interpretation → Conclusion

The methodological essence of this sequence is that, at each stage of experimental activity, students seek answers not only to the question "What result did I obtain?", but also to the following questions:

- Under what conditions did I obtain the result?
- What factors affected the measurement?
- How large is the uncertainty of the result?
- How reliable is the obtained data?
- Is the difference between two results a genuine physical difference, or can it be explained by measurement uncertainty?
- What scientific conclusion can be drawn from these data?

The proposed methodology consists of six interconnected stages.

Stage	Main Objective	Student Activity	Expected Output	Competency Developed
1. Measurement planning	Determining the experimental conditions	Selects the instrument, physical quantity, measurement method, and number of repeated measurements	Measurement plan	Measurement competence
2. Experimental data collection	Obtaining primary data	Performs measurements and records the data	Primary data table	Practical-experimental competence
3. Identification of uncertainty sources	Identifying factors affecting the result	Analyzes uncertainty associated with the instrument, method, environment, and repeated measurements	Map of uncertainty sources	Analytical competence
4. Uncertainty estimation	Determining the uncertainty interval of the result	Calculates uncertainty and expresses the result in an appropriate form	Result expressed as $x = \bar{x} \pm u(x)$	Calculation competence

Stage	Main Objective	Student Activity	Expected Output	Competency Developed
5. Reliability assessment	Determining the scientific value of experimental data	Compares results while taking measurement uncertainties into account	Evidence-based reliability judgment	Research competence
6. Interpretation and conclusion	Revealing the physical meaning of the result	Interprets the result in terms of physical relationships and formulates an evidence-based conclusion	Scientific conclusion	Professional and communication competence

Stage 1 — Measurement Planning

In conventional laboratory classes, students often perform measurements by following predetermined methodological instructions. In such situations, the question “Why am I measuring this quantity using this particular method?” may become secondary to the execution of the prescribed procedure.

The proposed methodology, in contrast, begins with a measurement-planning stage, in which students are encouraged to justify the experimental design before performing the measurements.

In the proposed methodology, the experiment begins with a planning stage prior to measurement.

The student is required to answer the following questions:

- Which physical quantity is to be determined?
- Which measurement method should be selected to determine this quantity?
- Which measuring instruments should be used?
- How might the accuracy of the instruments affect the result?
- How many repeated measurements would be appropriate?
- Which factors may affect the experimental result?

As a result, the student begins to act not merely as a performer of an experiment but as a researcher who plans the experiment.

Stage 2 — Experimental Data Collection

At this stage, students collect primary experimental data. Each measurement result is recorded separately. Rather than reporting the measurement results only as a final mean value, the original dataset is retained.

The key methodological change is that the mean value is not regarded as the final answer of the experiment, but rather as the initial dataset for subsequent uncertainty and reliability analysis.

This approach moves students away from the simplified assumption that "more data automatically means a better result." Contemporary research also indicates that students do not always interpret the relationship between the number of measurements and data quality in the same way.

Stage 3 — Identification of Sources of Uncertainty

This stage constitutes an important component of the proposed methodology. Students should not simply interpret uncertainty in a measurement result as "instrument error."

Sources of uncertainty are analyzed according to the specific conditions of the experiment. These may include:

- metrological characteristics of the measuring instrument;
- measurement method;
- variation among repeated measurements;
- changes in experimental conditions;
- limitations of the experimental apparatus;
- uncertainty associated with quantities included in the measurement model.

Therefore, instead of assigning students a task such as "Identify the error," they are given tasks formulated as follows: "Identify the sources of uncertainty that may affect the result and explain their influence on the experimental outcome."

This methodological change has important pedagogical implications because research indicates that students do not identify sources of uncertainty in the same way across different experimental contexts.

Therefore, students should be required to answer the following three questions:

1. What caused the uncertainty?
2. How did it affect the final result?

3. How could the experiment be improved to reduce it?

Competency-Based Assessment Criteria of the Methodology

In the proposed methodology, student performance is not assessed solely on the basis of the final result of the laboratory work. The assessment process covers all stages of the experimental activity.

Criterion	Main Indicator	High-Level Performance
Measurement competence	Selection of the measurement method and instrument	Provides a physical justification for the selection
Analytical competence	Identification of sources of uncertainty	Distinguishes between major and secondary sources of uncertainty
Calculation competence	Estimation of uncertainty	Justifies the selected calculation method
Data analysis competence	Comparison of results	Makes decisions while taking measurement uncertainty into account
Research competence	Interpretation of experimental evidence	Identifies the problem and proposes an alternative experimental design
Communication competence	Presentation of results	Provides an evidence-based conclusion using tables, graphs, formulas, and explanatory text

Based on these criteria, the proposed assessment rubric may evaluate each competency using, for example, a 0–3 point scale:

0 points — unable to complete the task, or the response lacks a scientific basis;

1 point — partially completes the task, but the justification contains significant deficiencies;

2 points — completes the task correctly and provides an adequate justification;

3 points — independently and comprehensively completes the task based on scientific evidence and proposes a way to improve the result or experimental procedure.

At this stage, this scale is proposed in the article as an author-developed assessment instrument. Its validity and reliability should be examined separately using the results of the experimental study. Existing research on the assessment of measurement uncertainty likewise emphasizes the importance of statistically examining the validity and reliability of specialized assessment instruments.

The proposed methodology introduces a new type of methodological task in Physics Practicum. Unlike traditional laboratory tasks that primarily require students to obtain a numerical result, the new tasks require students to evaluate the reliability of the obtained result, interpret experimental evidence, and justify their conclusions.

Traditional task: “Determine the physical quantity.”

Proposed task: “Determine the physical quantity, estimate its measurement uncertainty, and justify the reliability of the obtained result.”

Traditional task: “Compare the experimental value with the theoretical value.”

Proposed task: “Interpret the difference between the experimental and theoretical values while taking measurement uncertainty into account.”

Traditional task: “Which result is correct?”

Proposed task: “Justify which result is supported by stronger experimental evidence based on measurement uncertainty, repeatability, and experimental conditions.”

Thus, the proposed methodology transforms laboratory work from a conventional “measurement–calculation–conclusion” sequence into an integrated system of “planning–measurement–identification of uncertainty–reliability assessment–comparison–interpretation–conclusion.”

This transformation enables students to move from simply obtaining experimental results toward evaluating the quality of evidence and making scientifically justified decisions. Consequently, measurement and calculation skills are integrated with analytical, research, professional, and communication competencies.

The practical difference of the proposed methodology is manifested in the transformation of the content of laboratory tasks.

Traditional task: “Determine the physical quantity.”

Proposed task: “Determine the physical quantity, assess the measurement uncertainty, and justify the reliability of the obtained result.”

Traditional task: “Compare the experimental value with the theoretical value.”

Proposed task: “Interpret the difference between the experimental and theoretical values while taking measurement uncertainty into account.”

Traditional task: “Which result is correct?”

Proposed task: “Justify which result is supported by stronger experimental evidence based on uncertainty, repeatability, and measurement conditions.”

As a result, the laboratory activity is no longer limited to the triad of “measurement–calculation–conclusion”; instead, it is transformed into a systematic process of

“planning–measurement–identification of uncertainty–reliability assessment–comparison–interpretation–conclusion.”

Thus, the developed methodology contributes to the development of students’ professional competence not as a mere accumulation of separate theoretical knowledge, but as an integrated outcome of knowledge, practical skills, analytical thinking, evidence-based reasoning, and scientifically grounded decision-making in real experimental situations.

The results of the theoretical and methodological analysis demonstrated that integrating the assessment of experimental data reliability with measurement uncertainty in Physics Practicum provides an important methodological opportunity for developing students’ professional competencies. The analysis substantiated the need to use measurement uncertainty not merely as a mathematical calculation component, but as a tool for analyzing, comparing, interpreting experimental results, and formulating scientifically justified conclusions.

Therefore, integrating the assessment of measurement uncertainty with the determination of experimental data reliability in Physics Practicum establishes a holistic methodological mechanism for developing students’ professional competencies. The pedagogical effectiveness of the proposed methodology should be examined at the subsequent stage through experimental testing. This stage should include the assessment of the validity and reliability of the developed competency-based criteria and assessment rubrics, as well as the identification of statistically significant changes in students’ competency development.

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