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METHODOLOGY FOR ORGANIZING PROJECT-BASED PHYSICS LABORATORY CLASSES: A FIVE-STAGE SYSTEM AND THE INTEGRATION OF VIRTUAL AND REAL EXPERIMENTS

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Abstract. The article presents a methodology for transforming general physics laboratory classes from the traditional receptive “cookbook” format into a problem- and project-based format. Seven methodological requirements for developing students’ design competence are substantiated, together with a methodological system comprising motivational-problem, theoretical-analytical, design-planning, experimental-practical, and analytical-reflective stages. The didactic potential of the “Problem – Project – Experiment – Analysis”, “Predict – Experiment – Explain”, “Small-Group Experiment Design”, and “Integration of Virtual and Real Laboratories” methods is revealed. A system of project-based tasks and an assessment rubric comprising six criteria and four performance levels are also proposed.

Keywords: laboratory class, project-based learning, design competence, ISLE, virtual laboratory, PhET, assessment rubric, general physics.

Annotatsiya. Maqolada umumiy fizika kursi laboratoriya mashg‘ulotlarini an’anaviy retseptiv shakldan muammoli-loyihaviy shaklga o‘tkazish metodikasi bayon etilgan. Talabalarning loyihalash kompetentligini rivojlantirishga qo‘yiladigan yetti metodik talab hamda motivatsion-muammoli, nazariy-tahliliy, loyihaviy-rejalashtiruvchi, eksperimental-amaliy va tahliliy-refleksiv bosqichlardan iborat metodik tizim asoslangan. “Muammo – loyiha – tajriba – tahlil”, “Taxmin – tajriba – izoh”, “Kichik guruhda tajribani loyihalash” hamda “Virtual va real laboratoriyalarni integratsiyalash” metodlarining didaktik imkoniyatlari ochib berilgan. Shuningdek, loyihaviy topshiriqlar tizimi hamda olti mezon va to‘rt darajadan iborat baholash rubrikasi taklif etilgan.

Kalit so‘zlar: laboratoriya mashg‘uloti, loyihaviy ta’lim, loyihalash kompetentligi, ISLE, virtual laboratoriya, PhET, baholash rubrikasi, umumiy fizika.

Аннотация. В статье изложена методика перевода лабораторных занятий по курсу общей физики из традиционной рецептивной формы в проблемно-проектную. Обоснованы семь методических требований к развитию проектировочной компетентности студентов, а также методическая система, включающая мотивационно-проблемный, теоретико-аналитический, проектировочно-планировочный, экспериментально-практический и аналитико-рефлексивный этапы. Раскрыты дидактические возможности методов «Проблема – проект – эксперимент – анализ», «Предсказание – эксперимент – объяснение», «Проектирование эксперимента в малой группе» и «Интеграция виртуальной и реальной лабораторий». Также предложены система проектных заданий и рубрика оценивания, включающая шесть критериев и четыре уровня.

Ключевые слова: лабораторное занятие, проектное обучение, проектировочная компетентность, ISLE, виртуальная лаборатория, PhET, рубрика оценивания, общая физика.

INTRODUCTION

Developing students’ practical, experimental, and research skills is an important priority in modern physics education. Resolution No. PP-5032 of the President of the Republic of Uzbekistan, dated 19 March 2021, *“On Measures to Improve the Quality of Education and Develop Scientific Research in the Field of Physics,”* emphasizes improving the quality of physics education, introducing modern teaching methods, developing independent and creative thinking, and strengthening the practical orientation of learning.

In this context, general physics laboratory classes provide significant opportunities for organizing students’ learning activities on the basis of independent inquiry, experimental design, measurement, analysis, and interpretation. The traditional instructional format can be further enriched through problem- and project-based

approaches that encourage students not only to perform experiments according to established procedures, but also to participate in defining experimental objectives, selecting appropriate equipment, choosing measurement methods, predicting outcomes, and interpreting the obtained results. Such an approach enhances the cognitive and methodological potential of the physics experiment as a means of investigating physical phenomena and modelling the laws of nature.

For future physics teachers, the ability to design experiments, adapt them to different educational conditions, select appropriate methods and equipment, and critically evaluate experimental results constitutes an important component of professional competence. Therefore, the development of a clear, step-by-step, and practically applicable methodology for organizing project-based laboratory classes is of particular scientific and pedagogical importance. The aim of this article is to substantiate the structure, methods, and assessment tools of a methodology designed to develop students' design competence in general physics laboratory classes.

LITERATURE REVIEW

The role of laboratory work in science education was comprehensively analysed by A. Hofstein and V. N. Lunetta, who emphasised that laboratory activities should serve not only to reinforce theoretical knowledge but also to develop students' ability to formulate and test hypotheses, interpret data, and engage in scientific reasoning (Hofstein & Lunetta, 2004). In a large-scale study involving more than six thousand students, R. Hake demonstrated that interactive-engagement methods can significantly improve students' conceptual understanding of mechanics compared with predominantly lecture-based instruction (Hake, 1998).

Within the ISLE (Investigative Science Learning Environment) approach developed by E. Etkina and colleagues, students construct explanatory models based on observations, derive predictions from these models, and test them through experimental investigation. Rubrics based on a 0–3 scale have also been proposed for assessing students' scientific abilities (Etkina et al., 2006). L. C. McDermott developed a systematic inquiry-based approach to physics learning through the *Physics by Inquiry* programme (McDermott, 1996). E. Mazur, through the Peer Instruction method, demonstrated the pedagogical value of peer explanation and discussion in supporting deeper understanding of challenging physical concepts (Mazur, 1997).

In the field of digital learning resources, the PhET interactive simulations developed by K. Perkins, C. Wieman, and colleagues have become widely used tools in physics education (Perkins et al., 2006). The theoretical foundations of the project method can be traced to the works of W. H. Kilpatrick (1918) and J. Dewey (1916), while S. Bell considers project-based learning an effective means of developing 21st-century skills (Bell, 2010). D. Kolb proposed a four-stage experiential learning cycle that highlights the importance of reflection as an integral component of the learning process (Kolb, 1984).

In Uzbekistan, problem-based teaching technologies in physics have been studied by Sh. T. Boymirov (2021), the development of students' practical competence in technical higher education institutions by E. B. Maxmanov (2023), and the formation of research competence within a laboratory-cluster environment by U. Sh. Turdiyev (2025). Building on these studies, the present research focuses on integrating the organization of laboratory classes as a complete project cycle, combining traditional and virtual experiments within a unified analysis framework, and applying multi-criteria assessment to students' design competence.

RESEARCH METHODOLOGY

The study employed comparative analysis of international and national scientific and methodological literature, generalization of advanced pedagogical practices, pedagogical modelling and instructional design, observation of laboratory classes, student interviews, and expert evaluation. The methodological framework was based on the ISLE approach, project-based learning, experiential learning theory, and E. Etkina's scientific ability assessment rubrics, which were adapted to the requirements of national educational standards.

In preparing and editing the article, artificial intelligence tools were used as an auxiliary resource to a limited extent, accounting for no more than 10% of the overall text preparation process. The core scientific analysis, methodological design, conclusions, and recommendations were developed by the author.

ANALYSIS AND RESULTS

Methodological requirements. The development of design competence is a systematic process guided by clearly defined didactic principles. Based on the study, seven key requirements for organizing laboratory classes were identified: (1) the task should originate from a problem situation; (2) students should understand the purpose of the experiment and independently plan its implementation; (3) theoretical knowledge, experimentation, and analysis should form an integrated whole; (4) students should be provided with opportunities to make independent decisions under changing conditions; (5) each laboratory activity should

include a design component, such as modifying the experimental setup, identifying an alternative measurement method, or proposing a practical application of the obtained result in a technical device; (6) the results should be presented in the form of graphs, tables, diagrams, or computer models; and (7) each activity should conclude with reflective analysis and self-assessment.

The five-stage methodological system. The development of design competence is most effective when organized as a gradual and continuous process based on a clear didactic and psychological sequence. Accordingly, a five-stage methodological system was developed to support the student's progressive cognitive and practical development throughout the learning process (Table 1).

Table 1

Stages of Organizing a Project-Based Laboratory Class

Stage	Student activity	**Teacher's role**
1. Motivational-problem	Accepts the problem question, understands the role of the phenomenon in technology and everyday life	Creates a situation that stimulates cognitive engagement
2. Theoretical-analytical	Identifies physical laws and formulas, analyzes relationships between quantities, puts forward a hypothesis	Directs to sources, discusses the hypothesis
3. Design-planning	Formulates the aim, selects equipment, draws up the setup diagram and measurement sequence, prepares a data table	Reviews the design documents, checks safety
4. Experimental-practical	Assembles the setup, takes measurements, plots graphs, calculates absolute and relative errors	Observes and provides guidance when additional support is needed
5. Analytical-reflective	Justifies whether the hypothesis is confirmed, analyzes sources of error, proposes improvements to the setup	Asks reflective questions, organizes the defence

Source: developed by the author.

For example, in the "Electric Current" section, the class may begin not with the conventional task "Verify Ohm's law," but with a problem-based question: "Why does the current in a circuit decrease when microchips overheat, and how can this relationship be tested experimentally using different materials?" Such a context enables students to investigate the physical basis of a real technical problem and strengthens the practical relevance of the experiment.

The third, design-planning stage constitutes a central component of the methodology. At this stage, the student independently completes a laboratory design map consisting of the following elements: "problem – aim – hypothesis – equipment – diagram – measurement – calculation – analysis – conclusion." The map makes the student's reasoning process explicit and enables the teacher to evaluate the proposed experimental design before the experiment is conducted.

A set of methods. To ensure methodological diversity across different topics, a set of complementary methods was developed for implementing the five-stage system.

The "Problem – Project – Experiment – Analysis" method represents the complete form of the five-stage system and serves as a general model for the main laboratory activities. For example, in the topic "Determining the Density of a Body," the student is provided with an irregularly shaped unknown object. Using the relationship (\rho = m/V), the student designs a procedure for measuring mass with an electronic balance and determining volume using the hydrostatic method, carries out the measurements, and compares the obtained density value with reference data in order to draw a justified conclusion about the type of material.

The "Predict – Experiment – Explain" method is intended for classes with limited instructional time and corresponds to the testing-experiment format of the ISLE approach. Students first make a written prediction about the expected outcome of a phenomenon and then conduct a short experiment. If the experimental result differs from the prediction, the discrepancy is analysed and explained on the basis of physical principles. The method promotes evidence-based reasoning and encourages students to justify conclusions through experimental data.

In the "Laboratory Project" method, a major laboratory activity is organized as a small research project, while the report is structured in a format close to that of a scientific article: topic and problem, aim and theoretical basis, equipment and setup diagram, measurement table and graph, error analysis, conclusion, and suggestions for improvement. This approach helps prepare students for future graduation projects and research activities.

In the "Small-Group Experiment Design" method, students are divided into groups of 3–4 and assigned roles such as project leader, theoretical analyst, experimenter, data processor, and presenter. The roles rotate from one class to another, giving each student the opportunity to master different aspects of design activity while simultaneously developing communication, collaboration, and teamwork competences.

The “Integration of Virtual and Real Laboratories” method is based on two parallel experimental streams that converge within a unified analysis stage. In the first stream, the student investigates the process using an interactive simulation such as PhET, varies the parameters freely, and formulates a theoretical prediction. In the second stream, the same experiment is conducted in a real laboratory, where factors such as air resistance, instrument limitations, and measurement uncertainty are naturally present. In the third stage, the virtual and real results are compared and the reasons for possible differences are analysed.

The combined use of virtual and real experiments allows the strengths of both environments to complement one another. Virtual simulations make it possible to visualize processes that may be difficult to observe directly and to vary parameters efficiently, whereas real experiments provide experience with actual equipment, measurement uncertainty, and physical conditions. Their integration is particularly effective in the sections on electricity, molecular physics, and geometrical optics.

System of project tasks. Open-ended project tasks were developed within the methodology to provide students with greater independence in experimental planning. In these tasks, only the final objective is specified, while the choice of method, equipment, and sequence of actions is determined by the student (Table 2).

Table 2

Examples of Project Tasks for Laboratory Classes

Section	Project task	Competence developed
Mechanics	Design a method to determine the free-fall acceleration in the classroom with minimum error using threads of different lengths and different masses	Experiment planning, statistical analysis, reducing uncertainty
Molecular physics	Choose the most suitable methods for determining the density of unknown liquids and compare their uncertainties	Decision-making on instrument selection
Electricity and magnetism	Assemble a measurement system to study the current-voltage characteristics of conductors and semiconductors	Drawing a circuit diagram and assembling it safely
Geometrical optics	Design an optical system of lenses that produces a sharp image of a given size on a screen	Modelling, visualizing ray paths
Oscillations and waves	Design an experiment that establishes how the period of a spring pendulum depends on the load mass and spring stiffness	Empirical justification of a functional dependence

Source: developed by the author.

Assessment system. The project-based methodology applies a comprehensive assessment approach that extends beyond recording procedural completion and focuses on the development of students’ design competence. Design competence is assessed according to six criteria: motivational, cognitive, design, practical-technological, analytical, and reflective. The results are diagnosed across four levels that conceptually correspond to the 0–3 scale used in E. Etkina’s assessment rubrics (Table 3).

Table 3

Levels of Development of Design Competence

Level	Description
Low (reproductive)	Works mainly with ready-made instructions, partially understands the purpose of the experiment, and records readings according to the given procedure
Medium (exploratory)	Performs standard steps with assistance and is developing the ability to formulate a hypothesis and draw up an alternative plan in an unexpected situation
Good (constructive)	Independently draws up an experimental plan, selects instruments reasonably, analyzes data statistically and defends conclusions using physical laws
High (creative)	Develops a project from scratch, identifies opportunities for improving the experiment, proposes non-standard solutions, and reflects deeply

Source: developed by the author.

Multi-criteria assessment enables the teacher to identify the component in which a student requires additional support and to select subsequent tasks accordingly. For example, a student demonstrating a lower result on the analytical criterion may be assigned tasks focused on error analysis, while a student requiring further development in the design criterion may be provided with guiding questions for completing the design map step by step.

CONCLUSION AND SUGGESTIONS

Based on the results of the study, the following conclusions were drawn:

Developing design competence in laboratory classes is most effective when learning is organized through problem situations, active inquiry, and project-based activity in accordance with the seven identified methodological requirements.

The methodological system comprising motivational-problem, theoretical-analytical, design-planning, experimental-practical, and analytical-reflective stages supports students' cognitive and practical development as a continuous process, with the design map serving as one of its central tools.

Integrating virtual and real experiments within a unified analysis framework makes it possible to visualize aspects of physical phenomena that are difficult to observe directly, to model experimental conditions in advance, and to compare theoretical predictions with real measurement results.

The system of open-ended project tasks and the assessment rubric comprising six criteria and four levels provide a methodological basis for the comprehensive development and objective assessment of the main components of design competence.

Based on these conclusions, it is recommended to enrich general physics laboratory manuals used in pedagogical higher education institutions with open-ended project tasks, to integrate appropriate virtual simulations into laboratory activities where pedagogically relevant, and to apply multi-criteria rubrics for assessing students' learning and design activities. Further research may focus on evaluating the effectiveness of the proposed methodology through pedagogical experiments and mathematical-statistical analysis.

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