HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

PEDAGOGICAL POTENTIAL OF VIRTUAL LABORATORIES AND DIGITAL SIMULATIONS IN PHYSICS TEACHING

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Doi: https://doi.org/10.5281/zenodo.23656002

Abstract. This article discusses the opportunities offered by virtual laboratories and digital simulations in physics teaching, drawing on scientific literature. Virtual experiments can model processes that are complex, expensive, or difficult to observe directly; allow learners to change physical variables and compare outcomes; and support independent inquiry. The article also considers limitations of digital tools, including technical conditions, digital literacy, and the need to connect virtual work with real experiments.

Keywords: physics education, virtual laboratory, digital simulation, PhET, experiment, digital pedagogy, practical skills, scientific inquiry.

Introduction. In physics, experimentation is an important means of testing theoretical knowledge, observing phenomena, and identifying regularities. When students observe mechanical motion, an electric circuit, or the propagation of light through experiments, they can connect the topic with everyday life. However, not all educational institutions have sufficient laboratory equipment. Some experiments require considerable time to organise, while certain physical processes are difficult to observe directly under ordinary conditions.

As digital technologies have developed, virtual laboratories and simulations have become more widely used in physics education. In such environments, students can change physical quantities, observe how a model behaves, and explain the resulting outcomes. For example, a simulation can be used to investigate how acceleration changes when the mass of an object or the applied force is varied. In an electric-circuit model, students can explore how current relates to changes in resistance or voltage.

Research on virtual experiments indicates that their usefulness depends not only on the availability of technology but also on how the lesson is designed. Wang, Zhang, and Pang reviewed 45 articles published between 2001 and 2023 and analysed how virtual experiments can help address certain equipment-related and experimental constraints in physics education [1]. A meta-analysis by Wang and colleagues, based on studies published between 2001 and 2021, reports that combining real and virtual experiments may have a positive effect on learning outcomes [2].

Methods. This article was prepared as a descriptive literature review. Scientific articles on virtual laboratories, PhET simulations, digital experiments, and the integration of real and virtual laboratories in physics education were examined. Publications relevant to search terms such as "virtual experiments in physics education," "PhET simulation conceptual understanding," "virtual laboratory physics learning," and "real and virtual experiments" were selected.

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The sources were compared in relation to the following themes: alignment of virtual experiments with learning objectives; support for visualising physics concepts; opportunities to repeat experiments and vary parameters; teacher guidance and student activity; integration with real experiments; and technical and pedagogical limitations. Common trends and practical recommendations were identified during the analysis.

A methodological limitation of this work is that it is neither a full systematic review nor a meta-analysis. It was not intended to cover every article in every database, follow a protocol such as PRISMA, or recalculate effect sizes. The findings should therefore be understood as an accessible synthesis of important sources on the topic. No claim is made that a separate experiment was conducted in a local school or higher education institution.

Results. A virtual laboratory is a learning environment that allows a physical process to be observed and manipulated through a model on a computer, tablet, or another digital device. Unlike an ordinary video, an interactive simulation allows the user to change parameters and observe how the outcome changes. For example, students can investigate physical relationships by increasing the mass attached to a spring, changing the resistance in an electric circuit, or altering the direction of light.

A virtual laboratory does not fully reproduce every feature of a real laboratory. In a real experiment, students learn to handle equipment, take measurements, account for measurement error, and follow safety rules. A simulation is useful for changing parameters quickly, repeating the same situation, and visualising processes that cannot be seen directly. A virtual laboratory should therefore be regarded not as a simple replacement for real experimentation, but as an additional learning environment selected to suit the teaching objective.

Some concepts in physics cannot be observed directly. Diagrams and formulas may not always provide a sufficient mental picture of electric fields, interactions between charges, processes at the atomic scale, or the propagation of waves. A simulation can represent changes in a model through animations, vectors, graphs, or colour-coded indicators. These representations can help students observe relationships between physical quantities.

A literature review on PhET interactive simulations examined 31 experimental or quasi-experimental studies, and the authors reported that such simulations may improve students' understanding of physics concepts [3]. However, a simulation should not become a source of ready-made answers. If students only watch movements on the screen, opportunities for active learning may be limited. Asking a question before the activity, recording observations in a table, and explaining the cause of the outcome afterwards make the learning process more meaningful.

The literature gives particular attention to the combined use of virtual and real experiments. A meta-analysis by Wang and colleagues reported a moderate positive effect on learning achievement when real and virtual experiments were combined [2]. This does not mean that both types of experiment must be used for every topic. Instead, the teaching tool should be selected according to the learning objective.

This sequence helps students understand both the possibilities and limitations of models. A virtual model is usually based on assumptions and may omit some complex factors. Real experimental results, in contrast, depend on measurement methods and environmental conditions. Comparing the two can develop scientific reasoning and the ability to evaluate evidence.

A digital tool does not automatically ensure an effective lesson. Teachers should first define the learning objective, check whether the simulation is appropriate, and prepare the tasks students will

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complete. If the objective is graph analysis, the task should require students to read values from the graph, compare rates of change, and explain their conclusions. If the objective is to understand a physical model, students can change parameters and explain the resulting changes.

A lesson can be organised in the following sequence: first, a problem question and prediction; second, a guided investigation using the simulation; third, recording observations in a table; fourth, a graphical or verbal explanation; fifth, connecting the findings with the relevant physical law; and sixth, a short final question. This structure turns digital activity from mere entertainment into work directed towards learning objectives.

Discussion. The sources reviewed indicate that the main pedagogical value of virtual laboratories lies in visualising physical processes, manipulating parameters, repeating experiments, and engaging students in making testable predictions. These opportunities support learning only when combined with carefully designed tasks. If students are not clearly told what to observe, which quantity to change, and how to explain the result, a simulation can become a passive viewing activity.

The review by Wang, Zhang, and Pang describes applications of virtual experiments in physics teaching and identifies research directions [1]. The meta-analysis on combining real and virtual experiments indicates that the two environments can complement one another [2]. The review of PhET simulations also highlights the importance of integrating simulations into active-learning approaches [3]. Although these studies do not make identical claims, they share a central point: technology itself is not enough; it must be connected to a pedagogical purpose.

A practical recommendation for teachers is to identify the concepts for which virtual laboratories are particularly useful rather than using them obligatorily in every topic. Simulations can be valuable for processes involving multiple parameters, phenomena that are not directly visible, experiments that need to be repeated quickly, or processes that are better modelled in a safe environment. Practical laboratory work should be retained for topics in which handling equipment and making real measurements are essential.

Conclusion. The review of scientific literature suggests that virtual laboratories and digital simulations can be useful tools in physics lessons for visualising physical processes, observing relationships between quantities, repeating experiments, and supporting independent inquiry. They offer particular opportunities for explaining abstract concepts and engaging students in prediction, observation, and drawing conclusions.

At the same time, virtual experiments cannot replace every aspect of real laboratory work. Practical experiments remain important for learning measurement techniques, handling equipment, evaluating experimental error, and understanding factors present in real conditions. Teachers are therefore advised to combine virtual and real experiments according to lesson objectives, ask focused questions before using a simulation, and connect the results with theoretical knowledge.

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