*Corresponding Author's Email: m.kuqali@fimif.edu.al
Proceedings of the International Conference on Teaching, Learning and Education
Vol. 2, Issue. 1, 2025, pp. 1-12
DOI: https://doi.org/10.33422/ictle.v2i1.1099

ISSN: 3030-122X online

Integrating Interactive Simulations to Enhance Conceptual Understanding in Introductory Physics Courses – A Case Study

Margarita Kuqali[1*], Megi Plaku[2]

[1*]Department of Physics Engineering, Faculty of Mathematics Engineering and Physics Engineering,
Polytechnic University of Tirana, Albania

[2]Centre of Foreign Languages, Faculty of Mathematics Engineering and Physics Engineering, Polytechnic
University of Tirana, Albania

Abstract

This study investigates the impact of interactive simulations as a pedagogical tool in introductory physics courses for first-year undergraduate engineering students at the Polytechnic University of Tirana. The primary objective of this tool is to enhance conceptual understanding and active student engagement by integrating interactive simulations besides traditional teaching methods. To assess their effectiveness, a study was conducted involving two different groups of students enrolled in the same study program with the same physics subject syllabus: a control group, which followed a traditional lecture-based approach, and an experimental group, where interactive simulations, found online in platforms like "PheT " etc., played a central role in classroom activities. The study focused on electromagnetism, taught in the second semester of the first year of their studies. The data were collected through a beginning of semester (pre-test) and an end-of-semester test (post-test) as well as continuous teacher observations throughout the semester. Findings indicated that the group that was actively engaged with simulations demonstrated stronger conceptual retention and problem-solving abilities compared to the control group which was taught exclusively through traditional methods. Moreover, observations showed that students in the experimental group had greater motivation and a more intuitive grasp of abstract concepts. This approach was successful through the thoughtful design of simulations, the opportunity to work together and exchange ideas, and the guidance provided by instructors to help them navigate complex concepts. These elements worked together to create a supportive learning environment, allowing students to develop a deeper and more intuitive understanding of the material.

Keywords: Physics education, interactive simulations, comprehension

1. Introduction

Physics, due to its abstract nature, is often considered to be very challenging for students. Traditional lectures provide essential theoretical knowledge but may not always be enough to foster deep conceptual understanding. Teachers are always trying to find different approaches to implement in order to facilitate students' comprehension and retention of physics concepts. Interactive simulations offer an alternative approach, allowing students to visualize and manipulate physical phenomena dynamically. This study examines whether these simulations can improve student learning outcomes and engagement. As (Archer, DeWitt & Wong, 2014) state, many formal and informal science initiatives have been based on the belief that if sciences can be made more interesting, then careers in related fields would become more attractive, it is aimed to bring different teaching perspectives into the classroom in order to make the teaching learning process as captivating as possible.

Undoubtedly, the integration of technology into STEM education has significantly transformed the way students engage with and apply their knowledge as well as teaching methodology from teachers' part. (Kelley and Knowles, 2016) emphasize that making crosscutting STEM connections is a complex process, requiring deliberate instructional strategies to help students see how STEM knowledge applies to real-world problems. In the new media's age, where young people spend much of their daily lives in virtual spaces, concerns have arisen about the impact of technology and social media on their social and emotional development (Odgers, Schueller, & Ito, 2020). However, as (Sun, Zhan, Wan, et al., 2023) highlight, rapid technological advancements continue to shape STEM education, offering new ways to integrate learning and innovation.

When it comes to physics, especially as one of the most important subjects for engineering students, attempts should be made in order to increase engagement and comprehension of students. In today's reality of education, students' lack of motivation is a problem. Some of the reasons are related to the abstract nature and the teaching approach and tools or resources teachers use, according to (Hollow & Masperi, 2009) and (Mwale & Bahati, 2021). Even though the study of Hollow & Masperi isn't explicitly for higher education context, its results are strongly supported by today's reality of higher education.

Online interactive simulations have proven to be effective for physics learners. According to (Eckhardt et al., 2013) simulations contribute in teaching by capturing and sustaining students' attention more directly through the visual display of the phenomenon or concept. In a study on interactive simulation-based learning on motivation and academic achievement among Malawian physics students researchers affirm that PhET simulation-based learning can improve students' affective learning domain of motivation by capturing their attention, interest, engagement, interactivity, and desire to be more involved in the oscillation and wave learning process. Moreover, in a study conducted by (Agyei and Agyei, 2021), it is shown that, as they state, "useful instructional ICT tool for enabling content development and conceptual change as well as stimulating students' interest in physics as a science subject". Specifically, (Wienman et al, 2010), consider interactive simulations as "highly effective learning tool".

The impact of interactive simulations is also important and according to (Mirana, 2016) can have a great impact on increasing motivation for students. This statement is also supported by (Prima et al., 2018) who noticed an increase of motivation in a group of students where PhET was implemented.

2. Materials and Methods

2.1 Participants

Fifty first-year students, part of two different groups, enrolled in the Hydrotechnical Engineering study program at the Polytechnic University of Tirana, participated in the study. Using a simple random procedure, one group of 25 students served as the experimental group [EG] and the other with the same number of students as the control group [CG]. Both groups followed the same second-semester introductory physics course, related to electromagnetism, mainly electric and magnetic fields, electromagnetic induction, Faraday's and Lenz's laws and related engineering applications.

2.2 Study Design and Procedure

The CG received instruction through traditional teaching methods: teacher-centered classrooms and activities commonly used in Albanian higher education. These include direct teaching through explanations delivered by making use of PowerPoint slides, whiteboard illustrations, and verbal interaction with students. On the other hand, the EG teaching methodology was combined with online interactive simulations, specifically dynamic visual tools designed to model physical phenomena such as electric and magnetic fields, Faraday's and Lenz's laws, and electromagnetic induction. Moreover, during seminars these simulations gave students the opportunity to manipulate variables in real time and observe immediate feedback, fostering a deeper conceptual understanding. The intervention was present throughout the whole semester.

In order to gather data pertaining to quantitative learning gains and qualitative classroom dynamics, the following instruments were employed:

1. **Diagnostic pre-test (Week 1)**
   A pre-test was administered and handed to the students to evaluate their understanding of electric and magnetic fields, Faraday's and Lenz's laws, and electromagnetic induction. This test in the form of a multiple-choice one also served to verify that the two groups were academically equivalent at the outset.

2. **Summative end-of-semester test, post-test (Week 15)**
   The same test was re-administered in week 15 to assess improvements and gain in conceptual understanding and problem-solving skills after the above didactic intervention.

3. **Classroom observations (Weeks 1-14).**
   Teachers' observations consisted of weekly notes on student engagement (frequency of questions, on-task behavior), peer interaction, and motivation elements such as autonomous use of simulations outside the classroom.

Together, these data sources provided a balanced, holistic picture of students' conceptual growth and the day-to-day learning behaviors that accompanied it. The test aimed to evaluate students' critical thinking skills rather than just their memorization or recall of certain concepts.

Specifically, questions aimed to reveal students' conceptual understanding of key phenomena like magnetic flux, induced currents, and the operation of devices such as transformers and generators— which are all considered essential concepts for real-world engineering applications.

The test consisted of 15 questions, each scored equally. By comparing results from the pre- and post-tests, we gained valuable understanding into the effectiveness of different teaching strategies in encouraging conceptual mastery in electromagnetism.

PRE and POST-TEST QUESTIONS

1. What is electromagnetic induction?
A) Production of magnetic field from a battery
B) Generation of electric current by changing magnetic flux
C) Movement of electrons in a conductor
D) Acceleration of a charged particle by a magnetic field

2. When a bar magnet is pushed into a coil connected to a galvanometer, the needle deflects. This is because:
A) The magnet generates electricity inside the coil
B) Magnetic field heats the coil
C) The changing magnetic flux induces a current
D) The galvanometer is malfunctioning

3. A magnetic field lines around a straight current-carrying conductor are:
A) Radially outward
B) Parallel to the wire
C) Concentric circles around the wire
D) Absent if wire is horizontal

4. A charged particle moving perpendicular to a magnetic field will:
A) Move in a straight line
B) Be unaffected
C) Spiral along the field
D) Move in a circular path

5. What does Lenz's Law explain?
A) The energy of magnetic fields
B) The polarity of batteries
C) The direction of induced currents
D) The magnitude of current in a resistor

6. If the magnetic flux through a loop decreases, the induced current will:
A) Reinforce the decrease
B) Oppose the change
C) Be zero
D) Flow in random directions

7. Why does the current stop when the magnet stops moving into the coil?
A) Because magnetic fields only act briefly
B) Because the galvanometer resets
C) Because magnetic flux is constant
D) Because there's no magnetism left

8. Faraday's Law tells us that:
A) A voltage is only induced when current is flowing
B) The induced EMF is proportional to the rate of change of magnetic flux
C) Magnetic fields produce heat in conductors
D) A magnetic field causes current to stop

9. Which of the following will *not* increase the induced EMF in a coil?
A) Increasing the number of turns
B) Using a stronger magnet
C) Moving the magnet more slowly
D) Moving the magnet faster

10. Magnetic fields do not do mechanical work because:
A) They do not exert forces
B) Magnetic forces are always perpendicular to velocity
C) Charges are not affected by magnetism
D) Work is done only by electric fields

11. In a solenoid, the magnetic field strength is greatest:
A) Outside the coil
B) At the ends
C) In the center
D) It's uniform everywhere

12. A transformer works only with:
A) Direct current
B) Alternating current
C) Static electricity
D) Magnetic monopoles

13. If a wire loop rotates in a magnetic field, what kind of current is generated?
A) Constant DC
B) AC (alternating current)
C) No current
D) High-frequency DC

14. What principle allows electric generators to function?
A) Ohm’s Law
B) Lenz’s Law
C) Faraday’s Law of Induction
D) Coulomb’s Law

15. Why do electromagnetic simulations help in learning?
A) They give answers directly
B) They visualize invisible forces and fields dynamically
C) They reduce the amount of content
D) They replace the teacher entirely

3. Results and Discussion

In this section of the study, we share the key findings of the study and reflect on what they mean in light of the research questions and theoretical background. The discussion connects students’ responses in the pre/post-test and in class observations, in order to provide a clear and meaningful interpretation of the results.

3.1 Overview of the study groups and test scores.

All students completed pre-and post-tests that targeted the main conceptual pillars of electromagnetism: magnetic fields, Faraday’s and Lenz’s laws, electromagnetic induction, and their applications with an undergraduate level of difficulty where conceptual and qualitative reasoning are the key elements. Table 1 presents a summary of average scores (out of 15 points) for both groups.

3.1.1 Quantitative comparison of the two teaching methods.

Table 1 provides the mean pre-test and post-test scores for both the control and experimental groups. Before instruction, the two groups had comparable baseline knowledge of electromagnetism: the control group’s pre-test mean was $\mathrm{M} = 6.2$ ($\mathrm{SD} = 1.12$) and the experimental group’s pre-test mean was $\mathrm{M} = 6.4$ ($\mathrm{SD} = 1.00$) out of 15 points. This small difference (0.2 points) was not statistically significant , $t(48) = 0.66$, $p = 0.51$, 95% confidence interval (CI) $[-0.4, 0.8]$, indicating equivalent starting levels. After the 14 week instructional period, both groups improved on the conceptual test, with the control group’s post-test mean rising to $\mathrm{M} = 10.8$ ($\mathrm{SD} = 1.53$) and the experimental group’s post-test mean reaching $\mathrm{M} = 13.2$ (SD = 1.19).

Table 1. Mean pre-test and post-test scores on the electromagnetism conceptual test.

Group (n = 25 student)	Pre‑test Mean ± SD	Post‑test Mean ± SD	Mean Gain ± SD
Control	6.2 ± 1.12	10.8 ± 1.53	+4.6 ± 1.12
Experimental	6.4 ± 1.00	13.2 ± 1.19	+6.8 ± 0.82

Paired-samples t-tests (which compare two related measurements for the same participants) confirmed that both groups achieved significant learning gains from pre to post-test. The control group's mean score increased from 6.2 to 10.8, an average gain of 4.60 points (SD of gain = 1.12). This improvement was statistically significant, $t(24) = 20.54$, $p < 0.001$, 95% CI $[4.14, 5.06]$, with a very large effect size (Cohen's d = 4.11). Likewise, the experimental group's mean rose from 6.4 to 13.2, a gain of 6.80 points ($SD = 0.82$), and this increase was also significant, $t(24) = 41.46, p < .001$, 95% CI $[6.46, 7.14]$, Cohen's $d = 8.29$. We verified the normality of the gain scores with Shapiro–Wilk tests ($p > 0.05$ in each group), confirming that the parametric assumptions for the paired t-tests were met. The extremely large effect sizes for these pre–post gains indicate that both teaching methods by themselves led to substantial conceptual improvements within each group, with the simulation-based approach yielding especially pronounced gains.

Finally, an independent-sample t-test (which compares the means of two separate groups) was conducted to determine whether the experimental teaching method led to greater improvement than the traditional method. Levene's test confirmed that the assumption of equal variances was satisfied ($p > 0.05$). The independent t-test showed that the experimental group's average gain ($M = 6.80, SD = 0.82$) was significantly higher than the control group's gain ($M = 4.60$, $SD = 1.12$), $t(48) = 7.92, p < 0.001$. This difference of 2.20 points on the 15-point test (95% CI $[1.64, 2.76]$) corresponds to a very large effect (Cohen's $d = 2.24$) in favor of the simulation-based approach. In practical terms, students taught with interactive simulations achieved roughly 15% higher gains (relative to the test's total score) than those taught through lectures alone, underscoring the educational significance of integrating interactive simulations into the curriculum.

3.1.2 Qualitative Observations and Learning Behaviors

In addition to quantitative test scores, continuous observations and student feedback provided valuable insights into how these interactive simulations influenced learning behaviors. The following key aspects emphasize the benefits of simulation-based teaching:

1. **Deeper Engagement**

During in-class activities, students in the EG were seen manipulating virtual controls (e.g., magnet speed, coil turns), eagerly testing multiple scenarios to see how these changes affected induced current and voltage, rather than just watching passively. For example, they see that a faster-moving magnet entering a coil causes the galvanometer's needle to move more, etc.. On the other hand, CG students tended to rely on the teacher's examples and lecture notes without exploring "what-if" scenarios.

2. Immediate Feedback and Conceptual Reinforcement

In the simulations, real-time visualizations of field lines and induced currents helped students fully grasp cause-and-effect relationships. They quickly connected the speed of movement or changes in magnetic field strength to the intensity of the induced current. In contrast, many CG students found it challenging to visualize invisible phenomena, such as changes in magnetic flux or the direction of induced currents, which often remained abstract concepts until they were encountered in problem solving exercises. Simulations enabled students to test their ideas and validate their hypotheses instantly: "What happens if I rotate the loop faster in a magnetic field?" This immediate feedback solidified understanding and boosted confidence.

3. Addressing Common Misconceptions

Observations suggested that using simulations directly corrected misconceptions, particularly regarding the direction of magnetic forces (the right-hand rule) and the role of flux change in inducing current. For instance, students experimenting with magnets in a simulated coil observed that once the magnet's motion stopped, the induced current dropped to zero, reinforcing the principle that "no flux change" equals "no induced current". In the CG, some students persistently misunderstood Lenz's Law, believing induced currents "reinforce" the flux change rather than oppose it. These misunderstandings often showed up in questions about the direction of the induced current.

4. Dynamic, Exploratory Learning Style

Students demonstrated active inquiry through the use of simulations: This was noticed while they formed hypotheses such as (e.g., "If I reverse the magnet's polarity, what happens to the current direction?), tested them in real time, and observed immediate outcomes. Stronger conceptual recall and transfer to new challenges were made possible by this method. The CG's learning approach was more memorization-oriented, frequently depending on formulas without completely internalizing the physical meaning, even though they were still improving. Persistent errors in post-test responses regarding force directions and field interactions indicated that their conceptual knowledge was occasionally still not complete.

5. Learning Vectors and Spatial Thinking

Encompassing visual aids in the form of interactive simulations, rather than only simple images, played a significant role in enhancing students' understanding of the most important vector-based concepts in electromagnetism. Simulations allowed students to see and manipulate vector directions dynamically, which greatly contributed to their comprehension of how magnetic fields and forces operate in space. These tools helped clarify why the magnetic force on a charged particle is always perpendicular to both the magnetic field and the particle's velocity, a concept that is often challenging to grasp through traditional teaching. As a result, students understood better why charged particles follow circular or spiral trajectories when moving through magnetic fields. By making these invisible interactions visible and intuitive, the simulations effectively supported the development of spatial reasoning, a critical skill for mastering vector physics.

6. Curiosity and Motivation Encouragement

The interactive environment fosters curiosity. This was found in situations where students asked, “Is moving the coil toward the magnet equivalent to moving the magnet toward the coil for inducing current?”, or “What changes if I use a bigger coil?” These kinds of questions stimulate further research and persistent learning, which subsequently fosters autonomous learning and enhances motivation as well, because, as (Slavin, 2018) and (Wentzel & Brophy, 2014) state, motivation is influenced by factors, internal or external ones, one of which is precisely the learning environment.

7. Connection of concepts to the real world

Simulations link classroom concepts to real-world technology: e.g. electric generators, like those in bicycles, transformers in power systems and innovations like wireless charging and magnetic brakes. These connections make physics relevant and engaging.

3. 2 Post-Test Item Analysis

Table 2. Percentage of correct answers for five representative conceptual electromagnetism questions.

Question	**Concept Probed**	**CG (%)**	**EG (%)**
Q3	Direction of B-field around a straight conductor	85	95
Q4	Trajectory of a charged particle moving perpendicular to a B-field	72	91
Q6	Lenz’s Law (induced current opposes $\Delta\Phi$)	68	93
Q8	Faraday’s Law ($\epsilon = -\frac{\Delta\Phi}{\Delta t}$)	90	98
Q10	Magnetic fields do no mechanical work	59	87

Table 2 presents the percentage of students who answered five representative conceptual electromagnetism items correctly. These items assessed understanding of key principles including magnetic field, force direction reasoning, magnetic flux variation, and Lenz’s and Faraday’s Laws. The EG students outperformed the CG on every question, with the largest gains on questions requiring vector or dynamic-flux reasoning (Q4, Q6, and Q10). Regarding Q4 (motion of charged particle in a field): 91% of students in the EG answered correctly, compared to 72% in the CG. This gap suggested that visualizing force vectors in a simulation effectively clarified why particles move in circular paths when velocity is perpendicular to the magnetic field. Real-time exploration of changing flux in the simulation reinforced Lenz’s Law and helped EG perform better in Q6, with 93% correctness, compared to CG with only 68%. The answers to Q10 with an accuracy of 87% versus 59% reflected a better understanding of the concept. Overall, these results demonstrate the pedagogical effectiveness of interactive visual aids in physics education by showing that the most noticeable learning gains happened in topics demanding deep conceptual reasoning as opposed to rote memorization.

4. Conclusion

This study, conducted with two groups of undergraduate students, highlights the propitious role of interactive simulations in enhancing the teaching and learning of basic physics in higher education. The findings suggest that integrating interactive tools into traditional instruction increases the active engagement of students and creates a student-centered learning environment. Students exposed to simulations not only performed better on conceptual assessments but also demonstrated higher levels of motivation, curiosity, and confidence in tackling physics problems. So, there is an academic growth and a significant improvement concerning socio-cognitive aspects of students.

Compared to the CG, students of which were introduced to traditional teaching, the EG exhibited deeper conceptual understanding, greater participation during class activities, and stronger problem-solving abilities. These outcomes align closely with previous research, including the work of (Fan et al., 2018) and the study by (Ganasen and Shamuganatha, 2017), both of which support the idea that visual and interactive learning can bridge the gap between abstract theory and real-world understanding in science education.

Most importantly, the simulations enabled students to visualize abstract phenomena, such as electromagnetic induction or magnetic field interactions, in ways that traditional teaching methods often struggle to convey. This visual reinforcement, combined with real-time experimentation, appears to help students build stronger mental models and long-lasting conceptual knowledge.

While the results are encouraging, they also open the door to further exploration. Future studies could investigate the long-term effects of using interactive simulations on student retention and performance over multiple semesters. Moreover, their potential application across other engineering disciplines, such as mechanical, civil, or electrical engineering, could provide valuable insights into how technology-enhanced learning strategies impact different fields.

In conclusion, this study reinforces the value and the effectiveness of interactive simulations as not only a supplementary tool but also as a reframing component in modern physics education. If they are integrated carefully, such tools can make abstract concepts more accessible for students and, on the other hand, foster a deeper, more organic understanding of scientific principles.

Acknowledgments

The authors gratefully acknowledge the financial support provided by the Polytechnic University of Tirana (PUT) for participation in this conference. All relevant approvals from the responsible authorities have been obtained.

References

Agyei, Elizabeth & Agyei, Douglas. (2021). Enhancing Students' Learning of Physics Concepts with Simulation as an Instructional ICT Tool. European Journal of Interactive Multimedia and Education. 2. e02111. 10.30935/ejimed/11259.

Archer, L., DeWitt, J., & Wong, B. (2014). Spheres of influence: What shapes young people's aspirations at age 12/13 and what are the implications for education policy? *Journal of Education Policy, 29*(1), 58–85.

Banda, H. J., & Nzabahimana, J. (2023). The impact of Physics Education Technology (PhET) interactive simulation-based learning on motivation and academic achievement among Malawian physics students. *Journal of Science Education and Technology, 32*, 127–141. https://doi.org/10.1007/s10956-022-10010-3

Eckhardt, M., Urhahne, D., Conrad, O., & Harms, U. (2013). How effective is instructional support for learning with computer simulations? *Instructional Science, 41*, 105–124. https://doi.org/10.1007/s11251-012-9220-y

Fan, X., Geelan, D., & Gillies, R. (2018). Evaluating a novel instructional sequence for conceptual change in physics using interactive simulations. *Education Sciences, 8*(1), 1–19. https://doi.org/10.3390/educsci8010029

Ganasen, S., & Shamuganathan, S. (2017). The effectiveness of physics education technology (PhET) interactive simulations in enhancing matriculation students' understanding of chemical equilibrium and remediating their misconceptions. In Karpudewan, M., Md Zain, A., & Chandrasegaran, A. (Eds.), *Overcoming students' misconceptions in science* (pp. 145–162). Springer. https://doi.org/10.1007/978-981-10-3437-4_9

Hollow, D., & Masperi, P. (2009). An evaluation of the use of ICT within primary education in Malawi. *International Conference on Information and Communication Technologies and Development (ICTD)*, 27–34.

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education*, *3*(1), 11. https://doi.org/10.1186/s40594-016-0046-z

Mirana, V. P. (2016). Effects of computer simulations and constructivist approach on students' epistemological beliefs, motivation, and conceptual understanding in physics. *International Conference on Research in Social Sciences, Humanities and Education*, 89–93. https://doi.org/10.17758/URUAE.UH0516087

Mwale, C. C. K., & Bahati, B. (2021). Examining the effect of Solve Elec simulation on students' understanding of electric current in high school physics in Lilongwe, Malawi. *Journal of Research Innovation and Implications in Education*, *5*(3), 136–152.

Odgers, C. L., Schueller, S. M., & Ito, M. (2020). Screen time, social media use, and adolescent development. *Annual Review of Developmental Psychology, 2,* 485–502.

Prima, E. C., Putri, A. R., & Rustaman, N. (2018). Learning solar system using PhET simulation to improve students' understanding and motivation. *Journal of Science Learning, 1*(2), 60–70. https://doi.org/10.17509/jsl.v1i2.10239

Slavin, R. E. (2018). *Educational psychology: Theory and practice* (12th ed.). Pearson Education.

Sun, D., Zhan, Y., Wan, Z. H., Yang, Y., & Looi, C. K. (2023). Identifying the roles of technology: A systematic review of STEM education in primary and secondary schools from 2015 to 2023. *Research in Science & Technological Education,* 1–25. https://doi.org/10.1080/02635143.2023.2179282

Wentzel, K. R., & Brophy, J. (2014). *Motivating students to learn* (4th ed.). Routledge

Wieman, C. E., Adams, W. K., Loeblein, P., & Perkins, K.K. (2010). Teaching physics using PhET simulations. The Physics Teacher, 48(4), 225-227. https://doi.org/10.1119/1.3361987