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ORIGINAL RESEARCH PAPER

The Effect of Education based on Modeling with COMSOL Simulation Software on Correcting Misunderstandings and Misconceptions of Electricity Physics Concepts

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ABSTRACT

Background and Objectives: The topic of electricity is often considered a challenging and abstract concept in physics. Learning non-intuitive scientific concepts can be challenging for students because they often hold incorrect conceptions about natural phenomena that lead them toward errors. Many students struggle to understand the underlying principles and behaviors of electrical systems. Identifying and correcting misconceptions about electricity physics is essential for promoting meaningful learning and conceptual understanding. Nowadays, using technology in educational settings is considered an essential aspect of teaching and learning. Utilizing technology, such as simulation software like COMSOL, can help to visualize and better understand these concepts. This research has been done with the aim of identifying and correcting the misunderstandings of 11th-grade high school students in learning the concepts of electricity by simulating COMSOL software.

Materials and Methods: The present research is an applied study in terms of its objective and a mixed-methods research in terms of its methodology. The qualitative section utilized content analysis to extract misconceptions about the concepts of electricity in physics. Semi-structured interviews were conducted with SIX teachers using purposive sampling. Three types of coding, namely open, axial, and selective, were employed to extract the main misconceptions. The main misconceptions identified were Coulomb's law, the shape of field lines between two point charges, the electric field between capacitor plates, the motion of electric charges in an external electric field, charge distribution on surfaces, and the effect of an external electric field on conductive and non-conductive shells. Based on this pattern, a 6-item questionnaire was designed to validate the pattern of misconceptions about electricity concepts among students. The validation of the extracted pattern and the content validity of the questionnaire were assessed by experts in the field of physics education. The quantitative section of the research was a quasi-experimental study with a pretest-posttest design and a control group. The target population consisted of all male eleventh-grade students in high schools in Bojnurd city during the academic year 2022-2023. Using random sampling, 30 students were selected for each group. In the first stage, both groups took a pretest. Then, the experimental group received the independent variable (simulation-based learning using the COMSOL software) in six sessions of 90 minutes each. Meanwhile, the control group received traditional lecture-based instruction. After the intervention, both groups (experimental and control) took the dependent variable (the misconceptions test on electricity concepts). The data were analyzed using ANCOVA (Analysis of Covariance) with the help of SPSS software.

Findings: The post-test results showed that in addition to correcting students' misconceptions and increasing their learning level, the use of computer and COMSOL simulation software helped them better understand the concepts and increased their concentration. The results of this analysis showed a significant difference ($p<0.05$) between the learning and progress of the experimental group and the control group. The errors of the experimental group changed significantly compared to the control group. In the topics under investigation, the minimum percentage of misconception correction in the experimental group was 46.66%. Meanwhile, the minimum percentage of misconception correction in the control group was observed to be 36.66%.

Conclusions: The research results have demonstrated that Simulation software enables students to visualize and interact with abstract concepts, making them more tangible and easier to comprehend. By using COMSOL, students can manipulate different variables in electrical systems, observe the effects, and gain insights into the underlying principles. This hands-on approach can correct misconceptions and improve students' understanding of electricity in physics. By providing interactive and visual representations of electrical phenomena, simulation software can make the subject more accessible and engaging, leading to improved learning outcomes. According to the obtained results, it is suggested that educational technology and modeling using COMSOL software be promoted in teachers' professional development programs. This action can lead to the development of knowledge of educational content and the correction of misunderstandings of concepts.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
35	8	5

مقاله پژوهشی

تاثیر آموزش مبتنی بر مدل‌سازی با نرم‌افزار شبیه‌ساز کامسول بر اصلاح سوء تفاهم‌ها و کج فهمی‌های مفاهیم فیزیک الکتریسیته

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چکیده

پیشینه و اهداف: موضوع الکتریسیته اغلب یک مفهوم چالش برانگیز و انتزاعی در فیزیک در نظر گرفته می‌شود. یادگیری مفاهیم علمی غیر شهودی می‌تواند برای دانش آموزان چالش برانگیز باشد، زیرا آنها اغلب تصورات نادرستی در مورد پدیده‌های طبیعی دارند که آنها را به سمت خطا سوق می‌دهد. شناسایی و اصلاح باورهای غلط فیزیک الکتریسیته برای ارتقای یادگیری معنادار و درک مفهومی ضروری است. امروزه استفاده از فناوری در محیط‌های آموزشی یکی از جنبه‌های ضروری آموزش و یادگیری محسوب می‌شود. استفاده از فناوری مانند نرم‌افزار شبیه‌سازی کامسول می‌تواند به تجسم و درک بهتر این مفاهیم کمک کند. این تحقیق با هدف شناسایی و اصلاح سوء تفاهمات دانش‌آموزان پایه یازدهم در یادگیری مفاهیم الکتریسیته با شبیه‌سازی نرم‌افزار کامسول انجام شده است.

روش‌ها: روش پژوهش حاضر از نظر هدف یک پژوهش کاربردی و از نظر نوع روش، یک تحقیق ترکیبی است. بخش کیفی با روش تحلیل محتوا با هدف استخراج مقوله‌های کج فهمی‌های فیزیک الکتریسیته انجام گرفته است. در این راستا، از پروتکل مصاحبه‌های نیمه ساختار یافته از ۶ معلم با روش نمونه‌گیری هدفمند استفاده گردید. در این بخش از پژوهش، از سه نوع کدگذاری باز، محوری و انتخابی استفاده گردید. مقوله‌های اصلی کج فهمی‌ها از این نوع کدگذاری استخراج گردید. مقوله‌های اصلی الگوی سوء تفاهم‌های مفاهیم فیزیک الکتریسیته عبارت شدند از: قانون کولن، شکل خطوط میدان بین دو بار نقطه‌ای، میدان الکتریکی بین صفحات خازن، حرکت بار الکتریکی در میدان الکتریکی خارجی، توزیع بار روی سطوح و اثر میدان الکتریکی خارجی بر روی پوسته‌های رسانا و نارسانا. براساس این الگو، پرسشنامه ۶ سوالی برای اعتباریابی الگوی سوء تفاهم‌های مفاهیم فیزیک الکتریسیته دانش‌آموزان طراحی گردید. برای اعتباریابی الگوی استخراجی و روایی محتوایی پرسشنامه از نظر متخصصان حوزه اموزش فیزیک استفاده شد. بخش کمّی پژوهش حاضر یک تحقیق شبه آزمایشی با طرح پیش آزمون- پس آزمون با گروه کنترل بود. جامعه آماری کلیه دانش‌آموزان پسر پایه یازدهم دبیرستان شهر بجنورد در سال تحصیلی ۱۴۰۱-۱۴۰۲ بود. با بهره‌گیری از روش نمونه‌گیری تصادفی، ۳۰ دانش‌آموزان برای هر گروه انتخاب شدند. در مرحله اول از هر دو گروه پیش آزمون به عمل آمد. سپس بر روی گروه آزمایش، متغیر مستقل (آموزش مبتنی بر مدل‌سازی با نرم‌افزار شبیه‌ساز کامسول) طی ۶ جلسه، ۹۰ دقیقه‌ای انجام شد. همزمان، در گروه گواه از آموزش سنتی (سخنرانی) استفاده گردید. پس از مداخله، بر روی هر دو گروه (آزمایش و کنترل) متغیر وابسته (آزمون سوء تفاهم‌های مفاهیم فیزیک الکتریسته) اجرا شد. داده‌ها با استفاده از روش آماری تحلیل کوواریانس با کمک نرم‌افزار SPSS مورد تجزیه و تحلیل قرار گرفت.

یافته‌ها: نتایج پس از آزمون نشان داده‌اند که استفاده از کامپیوتر و نرم‌افزار شبیه‌سازی کامسول، بهبود قابل توجهی در تمرکز دانش‌آموزان، اصلاح کج‌فهمی و افزایش سطح یادگیری آن‌ها داشته است. همچنین، این روش به دانش‌آموزان در درک بهتر مفاهیم کمک کرده است. نتیجه حاصل از این تجزیه تحلیل نشان داد که میزان یادگیری و پیشرفت دانش آموزان گروه آزمایش نسبت به گروه گواه تفاوت معناداری دارد ($p<0/05$). اشتباهات گروه آزمایش نسبت به گروه کنترل به‌طور قابل توجهی تغییر کرده است. در مباحث مورد بررسی کمترین درصد اصلاح کج فهمی

در گروه آزمایش ۴۶/۶۶٪ می‌باشد. در حالی که کمترین درصد اصلاح کج فهمی در گروه گواه ۳۶/۶۶ ٪ مشاهده شده است.

نتیجه‌گیری: نتایج پژوهش نشان داده‌اند که با استفاده از نرم‌افزار شبیه‌سازی کامسول، دانش‌آموزان قادر به تصویرسازی و تعامل با مفاهیم انتزاعی می‌شوند که آنها را قابل درک‌تر و قابل فهم‌تر می‌کند. با استفاده از کامسول، دانش‌آموزان می‌توانند متغیرهای مختلف در سیستم‌های الکتریکی را تغییر داده، تأثیرات آن را مشاهده کرده و به اصول پایه آن بیشتر آگاه شوند. این رویکرد عملی به دانش‌آموزان در اصلاح کج‌فهمی‌ها و بهبود درک آنان از الکتریسیته در فیزیک کمک می‌کند. با ارائه نمایش تعاملی و تصویری از پدیده‌های الکتریکی، نرم‌افزار شبیه‌سازی موضوع را قابل دسترس و جذاب می‌سازد و در نتیجه، بهبود عملکرد و یادگیری دانش‌آموزان را به همراه دارد. بر اساس نتایج بدست آمده، پیشنهاد می‌شود که فناوری آموزشی و مدل‌سازی با استفاده از نرم‌افزار کامسول در برنامه‌های توسعه حرفه‌ای معلمان ترویج یابد. این اقدام می‌تواند به توسعه دانش محتوای آموزشی و اصلاح کج‌فهمی مفاهیم کمک کند.

Introduction

According to the theory of constructivism, students, upon entering each new stage or educational situation, bring with them a set of conceptions based on their prior experiences and knowledge. Prior to entering the classroom, students have ample opportunities to form various and sometimes incorrect mental models and conceptions about the surrounding world and scientific phenomena [1]. Many of these mental conceptions held by students are the result of their daily experiences, observations of scientific phenomena, and the application of science and technology in human life. These misconceptions are referred to as 'misconceptions' or 'misunderstandings'.

Misconception is defined as any type of unfounded belief that does not include fear, luck, faith, or metaphysical interference. Misunderstanding is caused by people's incomplete and faulty reasoning. Some of the attitudes that students use to make sense of the world are partial and incomplete truths and are called misunderstandings. Misunderstanding is a knowledge structure that is activated in various contexts is resistant to change and is not compatible with accepted scientific knowledge [2].

When these misconceptions are addressed in the classroom, they appear as preconceived notions or prior learning, influencing the learning process [3]. Some of these conceptions may be completely different from or in contradiction with accepted scientific principles, and students may struggle to provide accurate explanations of scientific phenomena due to these misconceptions. Many researchers around the world focused on identifying and correcting students' misconceptions in various subjects. Researchers describe these misconceptions using different terms such as misconceptions, misunderstandings, naive conceptions, alternative conceptions, or preconceptions. It is crucial for educators to be aware of the common misconceptions that students may hold and actively work on to help students overcome these misconceptions [4]. By identifying misconceptions educators can guide students toward a more accurate understanding of scientific principles and promote deeper learning. To address misconceptions, educators can implement various strategies such as formative assessments, concept mapping, hands-on activities, and targeted questioning. These approaches encourage students to actively engage with the subject matter, identify their misconceptions, and reconstruct their understanding based on evidence and scientific principles [5-6]. Misconceptions in understanding the concepts of the subjects can arise from incorrect teaching by instructors. Some instructors may face difficulties in conveying the material to learners due to preconceived notions (which may be personal interpretations or what they learned from their own teachers). These difficulties lead to learners' aimless and unfocused mental engagement. Therefore, researchers recommend that educational authorities provide the necessary training for instructors and mentors to ensure proper teaching practices [7]. This issue becomes particularly important when dealing with abstract concepts [8].

Physics is one of the subjects that can create misconceptions for students due to its difficulty and the use of specialized and conceptually rich vocabulary. The topic of electricity is also considered a challenging and abstract concept in physics [9-11]. By identifying and correcting misconceptions of electricity concepts, educators can create a more effective learning environment that supports students in developing a solid foundation of knowledge and promoting conceptual understanding. By Identification and correcting students' misconceptions, educators can help students develop a more accurate understanding of scientific principles and foster their scientific literacy [12-17]. As a result, teaching electricity in physics poses numerous challenges, and many studies have been conducted to explore suitable instructional strategies for this topic. The past studies done in this field mostly focused on changing teaching methods and inventing new methods to solve the problem of misunderstandings [18-20]. Correcting misunderstandings of physics concepts using simulation software adds to the novelty of the subject. Today, computers help to teach and facilitate education, as well as create opportunities for students in the field of using technology, and are considered useful tools for implementing and improving educational methods. Technology and computers have revolutionized the field of education by providing various tools and resources that enhance the teaching and learning experience. Technology and computers have transformed education by expanding access to information, enhancing learning experiences, promoting collaboration, and providing personalized learning opportunities [21]. They continue to shape the education landscape, make it more accessible, engaging, and effective. Educational technology and computers have become invaluable tools in modern education. They offer numerous benefits and opportunities for both students and educators [22].

The topic of electricity is one of the very important concepts that are discussed in science books in the pre-university and university levels. By providing students with a visual representation of scientific principles, they can better understand and correct their misconceptions. Considering the importance of physics concepts and misunderstandings related to this field, using COSMOL software [23] to model and correct misconceptions related to electricity in physics could be an effective approach. The purpose of this research is to correct the misunderstandings of the concepts of electricity physics by using modeling with the help of COSMOL software.

Review of the Related Literature

Due to the mental nature of human beings, every person has various misunderstandings. Distortion of a concept in itself is not considered a misunderstanding, but it may cause misunderstanding. In conveying a concept to others, each person may choose only one set of information to present, but the receiver can imagine other concepts about the presented concept that may be incorrect. There are different types of misunderstanding, the most common of which are briefly defined here [9]

- Preconceived concepts: general concepts that are rooted in everyday experiences.
- Non-scientific beliefs: includes concepts learned by students from sources other than scientific education such as stories or legends.
- Perceptual misunderstandings: when students have learned scientific information in such a way that even if this information is in conflict with their previous ideas and non-scientific opinions, they do not pay attention to the interpretation and find the cause of the conflict and to get rid of the generated mental confusion provides weak models. These models are so weak that the students themselves are not sure enough about their concepts.
- Verbal misunderstandings: This category of misunderstandings is caused by the use of words that have one meaning in everyday life and another meaning in the scientific field.
- Practical (real) misunderstandings: This category of misunderstandings are mistakes that are made at a young age and are completely preserved in adulthood.

What leads to misunderstanding in the minds of students is simplistic in the learning process. The misunderstanding is a concept that is not in agreement with our current understanding of nature and is a private version of students' understanding [10]. In other words, misunderstanding is used for a situation in which the idea that people make of a concept in their mind is in conflict with the ideas of the experts of that science. This situation is different from the situation where an inadvertent error occurs due to ignorance. Misunderstanding causes systematic conceptual errors; that is, mistakes that happen in similar situations [12]. Identifying and correcting misunderstandings about different scientific concepts is one of the common research in the field of education. Researchers in the field of physics education have investigated common misunderstandings related to the electricity concept, which are mentioned below.

In a 2023 study, Siong et al. investigated the use of conceptual cartoons in overcoming misconceptions about electrical concepts to improve students' understanding of direct current circuits. The results of this research showed an increase in students' conceptual understanding after using conceptual cartoons [5].

In a 2022 study, Mason et al. examined how critical thinking skills affect misconceptions in the electrical field. The study was conducted with the aim of determining the effect of critical thinking skills on false beliefs using a five-layer tool in mixed research. The descriptive results of critical thinking skills data show that the average of critical thinking skills is 68.50, which means that students' critical thinking skills are in a good status [24].

In a 2019 study, Moodley et al. investigated teachers' perceptions and learners' misconceptions about electrical circuits education. In this research, an exploratory case study involving six 9th-grade science teachers was conducted to examine how teachers' understanding of learners' misconceptions is related to their understanding of teaching simple circuits. The results were analyzed using content analysis and interpreted using educational content knowledge. The results showed that the understanding of learners' misconceptions is not always related to the conceptual understanding of electrical circuits education. While a fair understanding of misconceptions was shown by teachers who had studied physics at the undergraduate level, only those who also had a degree showed a conceptual understanding of electrical education. Teachers who had not studied science education revealed technical perceptions, focusing on facts, demonstrations, and calculations [25].

In a 2018 study, Nancevici et al. investigated neural correlations related to the correction of errors by novices in the fields of electricity and mechanics. According to their report, recent studies have shown that students with advanced scientific training use brain areas related to inhibitory control and memory retrieval to avoid making mistakes for questions related to non-intuitive scientific concepts. The results of this research show that the frontal and parietal regions of the brain are more active after correcting errors than before. These findings show that novice error correction mechanisms, which are established by providing correct answers to learners at the very beginning of the learning process, are related to memory retrieval, but not to inhibitory control [26].

In a 2018 study, Asghari et al. investigated the use of the conceptual change model in teaching basic physics concepts and correcting misconceptions. This study was conducted with the aim of investigating the effectiveness of the Conceptual Change Model (CCM) in learning the basic concepts of electrostatics. CCM is an active learning method that emphasizes children's anticipation. The underlying principles of CCM are derived from constructivist theory. The findings of the research showed that the CCM teaching methods are superior to the traditional teaching and learning methods of physics concepts in detecting and correcting misconceptions [27].

In a research in 2017, Hermita et al. developed and implemented a four-tier test on static electricity to detect the misconceptions of pre-service elementary school teachers. They already developed and implemented a diagnostic test composed of four levels to detect elementary school teachers' false beliefs about static electricity. The method used in this research was three-dimensional (definition, design, development, and implementation) done for pre-service elementary teachers. The results of this research show several misconceptions regarding the concept of static electricity. In addition, the results of the research show that the diagnostic test is able to analyze the number of false beliefs and classify the level of understanding of elementary school teachers, which is scientific knowledge, misconception, lack of knowledge, and error [28].

In a 2014 study, Guyer investigated teachers' awareness and planned correction of learners' misconceptions about electrical circuits. This paper reports an exploratory multi-case study of how science teachers understand and intend to address learners' misconceptions about electrical circuits. The results indicate that teachers' understanding of students' misconceptions is related to their own subject knowledge. Furthermore, this study showed that the technique of asking teachers about learners' anticipated responses is a promising way to examine teachers' understanding of learners' misconceptions and the strategies they use to address these misconceptions [29].

In a research in 2017, Sert Jibik determined the scientific knowledge and misconceptions of science teacher candidates about electric currents. This research had two goals. The first objective is to determine the knowledge (academic success) and misconceptions of science teacher candidates about electric current and the second objective is to compare these results in the academic year and gender of the participants. The results of the study showed that while there is no significant difference between the academic successes of students in terms of electric current based on their academic year, there is a significant difference based on the gender of the participants and men get a better score. The findings also showed that the teacher candidates have many misconceptions, especially related to the concepts of current, electric field, generators, supply EMF, and potential difference. In addition, it was observed that the teacher candidates had wrong ideas about the operation of magnetic fields and energy conversion in power plants, a topic that is discussed in the field of alternating current [30].

In a research in 2013, Shokarbaghani compared the understandings of third-year high school students about the concepts of electricity with undergraduate and graduate students. With the aim of evaluating the understanding of third-grade high school students and undergraduate and graduate students about the concepts of static electricity, he conducted descriptive survey research. The findings of this research show new ideas and misunderstandings about static electricity concepts. Based on these findings, they stated that it is necessary to pay more attention to the revision of physics curricula and teaching materials that are currently being done [31]. In a 2017 study, Ramnaraina et al. investigated the effectiveness of using interactive computer simulations to address misconceptions of South African grade 10 students in electrical circuits. The results of this research showed that simulations may be a suitable cognitive learning tool to enable learners to check their presuppositions and as a result conceptual change [32].

So far, there has been no research on the use of modeling with COSMOL simulation software to correct misunderstandings of electricity physics concepts. COSMOL simulation software allows students to visualize and interact with abstract concepts, making them more concrete and easier to understand. This approach can help correct misconceptions and increase students' understanding of electricity in physics. Considering the importance of electricity in life and the importance of correcting misunderstandings, the purpose of this research is to correct misunderstandings of the concepts of electricity physics by using modeling with COSMOL simulation software.

Method

The current research method is applied in terms of its purpose and mixed research (Mixed methods) in terms of the type of method. It involves administering pre-tests and post-tests in both experimental and control groups.

Participants

The participants of this study were male students at the 10th grade of high schools in the city of Bojnourd during the academic year 2022-2023. The age range of the participants was between 15 and 16 years old. The target population was randomly sampled, and a total of 60 students were selected, with 30 assigned to the experimental group and 30 to the control group.

Instruments

The research study employed a mixed-methods approach, utilizing both qualitative and quantitative instruments to gather the required data. The instruments are divided into two sections: the qualitative section and the quantitative section.

For the qualitative section, the instrument used was semi-structured interviews with six purposively selected teachers. The interviews aimed to extract misconceptions in the physics of electricity. The following details the process: Selection of Participants: Six teachers were purposively selected based on their expertise in physics education.

Semi-Structured Interviews: The interviews were conducted in six 90-minute sessions. The interviewer prepared general and targeted questions in advance, which were provided to the interviewees during the interviews. These questions focused on extracting misconceptions in the physics of electricity.

Content Analysis: Content analysis was employed as the method for analyzing the data obtained from the interviews. Open, axial, and selective coding techniques were used to identify and categorize the main categories of misconceptions in the physics of electricity. The identified categories included:

a) Coulomb's law (interaction between like and unlike charges)

b) Shape of electric field lines for point charges

c) Electric field between capacitor plates

d) Torque on electric dipoles in the presence of an external electric field

e) Charge distribution on surfaces

f) Effect of an external electric field on conductive and non-conductive shells

Expert Validation: To validate the extracted pattern of misconceptions, experts in the field of physics education were consulted.

The quantitative section of the research employed a quasi-experimental design with a pretest-posttest and a control group. The instrument used was a researcher-made questionnaire designed based on the identified main categories of misconceptions in the physics of electricity. Here are the details of the quantitative section:

Questionnaire Design: A 6-item questionnaire was developed, with each question addressing one misconception from the identified pattern. The questionnaire consisted of three main options and one justification option for each question. Each question was scored as either one (no misconception) or zero (misconception).

Content Validity: The content validity of the questionnaire was ensured by subjecting it to evaluation by experts in the field.

Pretest and posttest: In the first stage, both the experimental group and the control group completed a pretest to assess their initial level of misconceptions in the physics of electricity. Following this, the experimental group received the independent variable, which was simulation-based modeling instruction using the COMSOL software, in six 90-minute sessions. The control group received traditional instruction through lectures. After the intervention, both groups took a posttest to assess their level of misconceptions.

Data Analysis: The data collected from the pretest and posttest was analyzed using the statistical method of ANCOVA (Analysis of Covariance) with the assistance of SPSS software.

By employing both qualitative and quantitative instruments, the study aimed to comprehensively explore and measure misconceptions in the physics of electricity and evaluate the effectiveness of the simulation-based modeling instruction in reducing these misconceptions.

Design

To identify misunderstandings, various diagnostic tools are used, the most important of which are interviews, multiple-choice tests, and multiple tests, as conceptual tests. Interviews are considered the most accurate method as they provide in-depth information about students' cognitive patterns and arguments. However, interviews have limitations, such as the need for significant precision, time, and resources, difficulty in organizing and analyzing data, and limited applicability to a large number of students. To overcome the disadvantages of interviews, diagnostic multiple-choice questions have been widely used. These questions are easily scored and applicable to a larger number of students. However, they cannot examine students' arguments in depth and may not capture the full range of students' understanding. The design aimed to evaluate the effectiveness of an instructional program in correcting misconceptions about electricity concepts. It incorporated both qualitative content analysis and quantitative quasi-experimental design techniques.

In the qualitative section, a content analysis is conducted using semi-structured interviews. The purpose of this qualitative component is to identify misconceptions about electricity concepts among the participants. The researchers will conduct interviews with participants to gather qualitative data on their understanding and misconceptions related to electricity.

The quantitative section of the study employs a quasi-experimental pretest-posttest design with a control group. The pretest will establish a baseline measure of the participants' initial understanding of electricity concepts, with participants individually completing a pretest questionnaire before the instructional program. The instructional program will be a six-session program that addresses different aspects of electricity concepts, utilizing simulation modeling activities with COMSOL software. The control group will not receive the instructional program but will undergo the pretest and posttest assessments, providing a basis for comparison to evaluate the effectiveness of the instructional program. The posttest will be administered after the completion of the instructional program to assess the participants' improved understanding.

The rationale for the pretest-posttest design with a control group is to enable a comparison of pretest and posttest scores to evaluate the impact of the intervention on learning outcomes, account for external factors by assessing participants' understanding before the instructional program and using a control group for comparison, and allow for causal inferences by attributing improvements in posttest scores to the instructional program itself. Additionally, this design is relatively straightforward to implement and can be conducted within a reasonable timeframe, providing a robust framework for assessing the effectiveness of the instructional program in correcting misconceptions and improving the understanding of electricity concepts.

By employing this mixed-methods approach, combining qualitative insights through content analysis and quantitative data through the pretest-posttest design, the researchers aim to gain a comprehensive understanding of the impact of the instructional program on participants' knowledge and understanding of electricity concepts.

Procedure

This research provides two separate sections of information for the procedure. The first part describes the procedure for identifying topics with the highest level of misunderstanding among students in the topic of electricity using a triple test. The second part outlines a protocol for remedying misconceptions in the concept of electricity using simulation modeling with COMSOL software.

Procedure for Identifying Misunderstandings in Electricity

Triple Test: A triple diagnostic test was used to identify topics with the highest level of misunderstanding among students in the topic of electricity. The test consisted of 12 three-part questions related to electricity in the physics course.

Test Administration: The test was administered to students in normal classroom conditions, without prior knowledge, and over a period of 90 minutes. In order to reduce the impact of errors due to stress, the students were assured that the test was for research work the answers were checked confidentially, and would not have any effect on their grades.

Structure of the Triple Test: Each question in the test had two parts. The first part included content questions with multiple options, where only one option was correct, and the others were incorrect. The second part included a set of reasons for each option, consisting of the correct reason and common misconceptions. The reasons were derived from students' answers, interviews, and various articles.

Answer Evaluation: Students' answers to each question were considered correct only if they chose both the correct option and the correct reason. If a student gave an incorrect answer in the first part, selected the reason for the same incorrect answer, and expressed confidence in their answer in the third part, it was assumed that the student had a misconception.

Identification of Misunderstandings: The questions that had the highest level of misunderstanding, based on students' responses, were identified. In the designed triple test, the questions that had the highest level of misunderstanding were included in the appendix of the study.

Procedure for Remedying Misunderstandings in Electricity

Design an Educational Program: Develop an educational program specifically designed for eleventh-grade students to address misconceptions in the concept of electricity.

Utilize COMSOL Software: Incorporate simulation modeling with COMSOL software as a tool to aid in remedying the misconceptions.

Content Validity Ratio (CVR): Determine the content validity ratio (CVR) of the protocol to assess its effectiveness in addressing students' understanding. The CVR for this protocol is 75%.

Reliability Assessment: Evaluate the reliability of the protocol by assessing it with evaluators. The reliability coefficient obtained is 80%.

Implement the Protocol: Follow the protocol in the classroom, ensuring students actively engage with the simulation modeling using COMSOL software.

Effective Remediation: The protocol aims to effectively address students' misconceptions, promoting a deeper understanding of the subject matter.

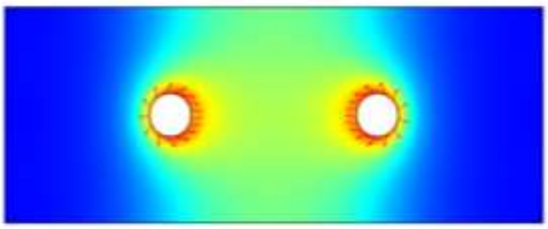
The summary of the instructional program for remedying misconceptions about the concept of electricity using simulation modeling with COMSOL software is depicted in Table 1. Please note that this is a general summary of the instructional program, and detailed descriptions of each session are below.

- Coulomb's law: In this topic, students do not have the ability to analyze the tensile force between two-point loads. According to the answers of the pre-test, it was observed that some students have the wrong idea that identical charges attract each other and dissimilar charges repel each other. The attraction between inhomogeneous charges and repulsion between inhomogeneous charges have created a misunderstanding for students. This idea can be caused by the comparison between different categories of objects or even living things with electric charge, which, just as a dissimilar item has no place in a group, loads also do not tend to have a dissimilar charge next to them.

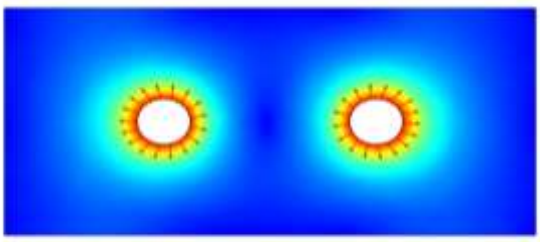
Table 1: Summary of the educational program for correcting misunderstandings of electrical physics concepts by using modeling with COMSOL simulation software.

Session	Session Title	Session Description
1	Coulomb's law	Modeling and simulation of attraction of unlike charges, repulsion between like charges and introduction to the concept of electricity, and initial assessment of student's knowledge. The simulated output is shown in Figure 1.
2	The shape of the field lines between two point charges	The electric field between two electric charges can be modeled and simulated using various concepts. Here are some key concepts: charge polarity, radial symmetry, field line density, superposition, the field lines of the interaction between the charges, and field line Patterns. The simulated output is shown in Figure 2.
3	The electric field between capacitor plates	Teaching students about the electric field inside a capacitor and using modeling and simulation to help illustrate your points. The electric field lines inside a capacitor are generally perpendicular to the plates and uniformly spaced between them, but they can curve outward near the edges of the plates, indicating a non-uniform electric field in that region. The simulated output is shown in Figure 3.
4	Rotation of a charged particle placed in an external electric field	Modeling and simulating electric systems of a position-charged particle inside an external field and charge polarization using three-dimensional models. The simulated output is shown in Figure 4.
5	Electric charge distribution in pointed objects	Teaching students about charge distribution on an object; and the effect of sharp or pointed features of the object using modeling and simulation. The simulated output is shown in Figure 5.
6	Effect of external electric field on conductive and non-conductive shells	Modeling and simulating the behavior of electric field lines when they encounter conductive and non-conductive shells. The simulated output is shown in Figure 6.

The simulated output for designing two point loads and displaying Maxwell's electric stress tensor (tendency to move in each point load) for each pair is shown in Fig. 1.



(a)



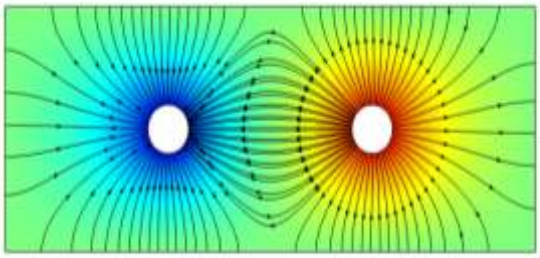
(b)

Fig. 1: shows a) attraction of bases of unlike charges and b) repulsion between like charges

a) Attraction of unlike charges: When two charges of opposite polarity (positive and negative) are brought close to each other, they experience an attractive force. This attraction arises from the interaction of the electric fields generated by the charges. The field lines originating from the positive charge and terminating on the negative charge indicate the direction of the force. The field lines curve towards the opposite charge, illustrating the attractive force between them. This attraction is a fundamental principle in electrostatics and is described by Coulomb's law.

b) Repulsion between like charges: When two charges of the same polarity (both positive or both negative) are brought close to each other, they experience a repulsive force. This repulsion is due to the like charges having the same sign of charge, resulting in the electric fields generated by each charge pushing against each other. The field lines originating from each charge curve away from each other, illustrating the repulsive force between them. The density of the field lines represents the strength of the repulsive force, with denser lines indicating a stronger force. This repulsion between like charges is another fundamental principle in electrostatics and is also described by Coulomb's law.

- The shape of the field lines between two-point charges: In the topic of electric field lines, students often have misconceptions about the direction and placement of the lines between two-point charges. Similarly to the previous topics, it was observed that students mistakenly believe that the direction of the electric field is from a same-sign adjacent charge and that if two opposite charges are placed next to each other, the direction of the field is from the charges towards the surrounding space. By correcting these misconceptions and providing clear explanations and visual aids, students can better understand the behavior of electric field lines and their relationship to point charges. Using simulation output, it has been shown that when two opposite charges are adjacent, the direction of the electric field lines is from the positive charge to the negative charge, and the lines are connected to both electric charges. When two same-sign charges are adjacent, the field lines scatter to the surrounding space. This information can be used to correct students' misconceptions and enhance their understanding of electric field lines (See Fig. 2). For teaching purposes, the movie of charges moving toward each other or away from each other was shown. Showing a movie of charges moving towards each other or moving away from each other twice can be a useful teaching tool. This visual aid can help students better understand the behavior of electric field lines and the direction of the field between point charges. By combining visual aids with clear explanations, educators can create a more effective learning environment and help students develop a solid foundation of knowledge in electricity and physics.



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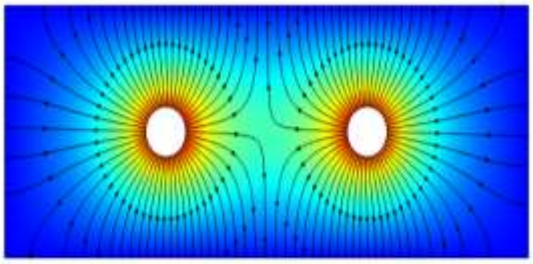


(b)

Fig. 2: Field lines caused by (a) two unlike point charges, (b) two like point charges

Fig. 2 shows the field lines between two-point charges a) unlike b) like. The field lines between two unlike point charges and two identical point charges are different in their patterns.

Non-Identical Point Charges: When two non-identical point charges are present, such as a positive charge and a negative charge, the field lines originate from the positive charge and terminate on the negative charge. The number of field lines originating from the positive charge is greater than the number terminating on the negative charge, reflecting the difference in their magnitudes. The field lines are closer together near the charges with stronger magnitude, indicating a higher field strength, and they spread out as they move away from the charges. The field lines curve towards the negative charge, representing the direction of the force on a positive test charge placed in the field.

Identical Point Charges: When two identical point charges are present, such as two positive charges or two negative charges, the field lines form a symmetrical pattern between the charges. The field lines originate from one charge and terminate on the other charge. The number of field lines originating from each charge is the same, reflecting their equal magnitudes. The field lines are equidistant and spread out uniformly between the charges, forming a pattern that resembles two cones connected at their bases. The field lines curve away from each charge, indicating the repulsive force between them.

In both cases, the field lines provide a visual representation of the electric field and its direction. The density of the field lines represents the strength of the electric field, with denser lines indicating a stronger field. The field lines allow us to understand the interaction between the charges and the forces experienced by other charges placed in the field. Here's how the field lines are formed:

Charge Polarity: The field lines originate from positive charges and terminate on negative charges. If both charges are positive or negative, the field lines will originate from one charge and terminate on the other.

Radial Symmetry: The field lines are radially symmetric around each charge. They spread out uniformly in all directions, perpendicular to the line connecting the charges.

Field Line Density: The density of field lines represents the strength of the electric field. The closer the field lines are to each other, the stronger the electric field in that region.

Superposition: The electric field lines from individual charges superimpose to form the resultant electric field. The direction of the field lines is determined by the vector sum of the electric fields created by each charge.

Interaction: The field lines show the interaction between the charges. If the charges have the same polarity, the field lines will repel each other, while opposite charges attract each other. The field lines curve towards the opposite charge, indicating the direction of the force on a positive test charge placed in the field.

Field Line Patterns: The pattern of field lines depends on the relative magnitudes and distances between the charges. For example, if the charges have equal magnitudes, the field lines will be symmetrically distributed between them. If one charge is much larger than the other, the field lines will be predominantly influenced by the larger charge. It's important to note that the field lines provide a qualitative representation of the electric field. The actual strength and distribution of the electric field require quantitative analysis using mathematical equations, such as Coulomb's law or the principle of superposition, to calculate the electric field at specific points. By visualizing the field lines, we can gain insights into the behavior of electric fields, the interaction between charges, and the forces experienced by other charges placed in the field. This helps in understanding the fundamentals of electrostatics and analyzing the behavior of complex charge distributions.

- Electric field between capacitor plates: Students have misconceptions about the field lines between capacitor plates. The misunderstanding of this topic was corrected with the help of the two-dimensional design of a flat capacitor. By changing the distance of the capacitor plates, the material of the plates, and the charge of the plates, students will see the change in the shape of the field. The output of this simulation was the electric field between the plates of this capacitor is shown in Figure 3. In the case of a parallel plate capacitor, which consists of two flat plates with opposite charges, the electric field lines originate from the positively charged plate and terminate on the negatively charged plate. Between the plates of a parallel plate capacitor, the electric field is uniform and constant in magnitude. This means that the field lines are evenly spaced and parallel to each other. Figure 5 Image of field lines caused by flat capacitor plates in the surrounding space. The field lines are perpendicular to the plates and are uniformly spaced between them. They extend from the positive plate towards the negative plate. Near the edges of the plates, the field lines curve outward from the positive plate and inward towards the negative plate. These curved field lines indicate a non-uniform electric field in this region.

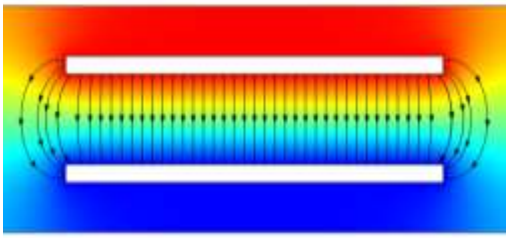


Fig. 3: Showing electric field lines between capacitor plates

Outside the plates, the electric field is negligible or zero. This implies that there are no field lines extending beyond the edges of the plates. The visualization of field lines helps us understand the electric field pattern and strength in the surrounding space of a parallel plate capacitor. It provides a useful representation to analyze and predict the behavior of electric fields in such systems. The shape and dimensions of the capacitor plates can affect the electric field lines. For example, if the plates are not perfectly parallel, the field lines may curve or exhibit uneven spacing. Similarly, if the plates are not large compared to their separation distance, there may be more pronounced edge effects and non-uniform electric field behavior near the edges. The shape and dimensions of the capacitor plates can affect the electric field lines. For example, if the plates are not perfectly parallel, the field lines may curve or exhibit uneven spacing. Similarly, if the plates are not large compared to their separation distance, there may be more pronounced edge effects and non-uniform electric field behavior near the edges. The orientation of the capacitor plates can also influence the electric field lines. In a horizontally oriented capacitor, the field lines are vertical and perpendicular to the plates. In a vertically oriented capacitor, the field lines are horizontal and parallel to the plates. When a dielectric material is inserted between the capacitor plates, it affects the electric field lines. Dielectrics have a relative permittivity (ε_r) greater than 1, which reduces the electric field strength between the plates. The field lines become more closely spaced, indicating a stronger electric field compared to the same capacitor without a dielectric. In real-world capacitors, especially with non-ideal plate shapes or finite dimensions, fringing fields may occur. Fringing fields refer to the electric field that extends beyond the edges of the plates. These fringing fields can cause the field lines to curve and deviate from the ideal straight lines between the plates. Understanding the electric field lines and their characteristics helps in analyzing the behavior of parallel plate capacitors and their interaction with other objects or charges in the surrounding space. It provides insight into the distribution and strength of the electric field, which is essential for various electrical and electronic applications.

It is important to note that the description provided here assumes an idealized scenario of perfect parallel plates and an ideal capacitor. In real-world situations, factors such as edge effects, fringing fields, and the presence of dielectric materials can affect the actual electric field pattern.

- Rotation of a charged particle placed in an external electric field: In this topic, the placement of a charged particle inside an external field applied to the particle was not conceivable for the students and caused misunderstanding. Students have wrong ideas about charge polarization. In order to correct the misunderstanding in this topic, a particle with a positive and negative charge was placed on each side between the plates of the flat capacitor. The output of this simulation is the moving force on the particle, which shows the rotation of the particle according to the figure below.

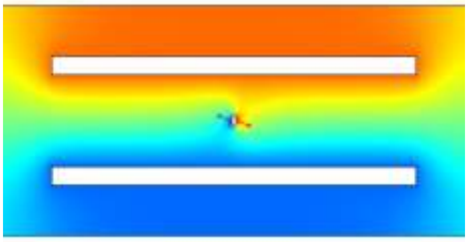


Fig. 4: Torque on an Electric Dipole in a Uniform Electric Field of capacitor

Fig. 4 Image of the tendency to change the location of the particle in the field caused by the capacitor plates. As can be seen in the figure, the part of the object that has a negative electric charge is inclined towards the capacitor plate that has a positive charge and vice versa. When an electric dipole is placed in a uniform electric field, a torque is exerted on the dipole. The magnitude of this torque is given by the formula $\tau = pE\sin\theta$, where τ is the torque, p is the magnitude of the electric dipole moment, E is the magnitude of the electric field, and θ is the angle between the dipole moment vector and the electric field vector. This torque tends to align the dipole moment vector with the electric field vector. In the case of a capacitor, if the electric field is uniform between the plates, then an electric dipole placed in this field will experience a torque that tends to align its dipole moment with the direction of the electric field. It's important to note that the behavior of a charged particle inside a capacitor can be complex and dependent on various factors, including the strength and uniformity of the electric field, the charge and mass of the particle, and any external forces or influences present. Detailed analysis and simulations may be required to accurately predict the particle's trajectory and behavior inside the capacitor.

- Load distribution in pointed objects: In this topic, the idea of accumulation of loads in sharp points and corners of shapes has created misunderstanding for students. The results of the pre-test showed that some students mistakenly think that the load distribution depends only on the transfer agent or that the loads are uniformly distributed on the surface of the object.

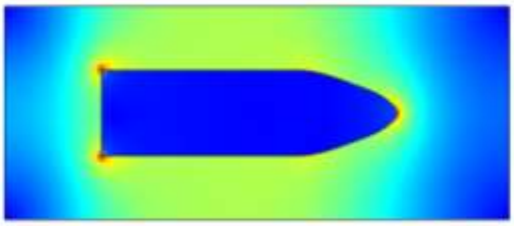


Fig. 5: Electric charge distribution in pointed objects

Fig. 5 shows how the electric charge is distributed in objects. The charge distribution on an object is influenced by several factors. The charge distribution in pointed objects is influenced by their shape and the electric field in their vicinity. When a pointed object, such as a sharp conductor, is exposed to an electric field, several phenomena come into play. Here are some key factors that determine the charge distribution and can be shown in the simulation, as follows:

Electric Field Concentration: The sharp or pointed feature of the object leads to a higher concentration of electric field lines in that region. According to Gauss's law, the electric field is stronger in areas with high curvature. This concentration of electric field lines can result in a higher charge density in the pointed portion of the object.

Charge Accumulation: Due to the concentration of the electric field, charged particles tend to accumulate on the pointed surface. If the object is made of a conductive material, such as a metal, the excess charges can freely move within the object and redistribute themselves. This redistribution leads to a higher charge density on the pointed region.

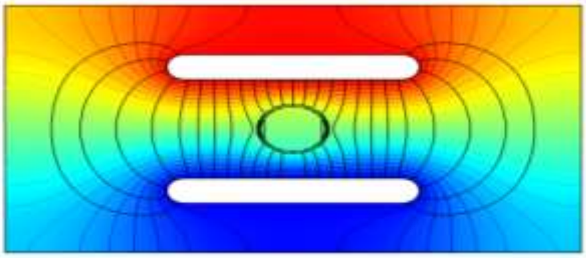
Ionization and Discharge: In certain conditions, the electric field at the pointed surface can become strong enough to ionize surrounding air molecules. This ionization can create a conductive path between the object and the surrounding air, allowing charges to flow in the form of a corona discharge. The corona discharge can further enhance the charge accumulation on the pointed surface.

The purpose of these phenomena is to reduce the electric field strength at the pointed region. By accumulating charges on the pointed surface, the object can effectively disperse the electric field, reducing the likelihood of electrical breakdown or sparking. This is why pointed objects are often used in applications such as lightning rods or sharp conductors on high-voltage equipment.

It is important to note that the charge distribution on pointed objects can vary depending on factors such as the material properties, the sharpness of the point, and the strength of the electric field applied. Additionally, the presence of nearby objects or conductors can also influence the charge distribution on the pointed object through induction or electrostatic interactions.

- Effect of external electric field on conductive and non-conductive shells: In this topic, the concept of changes in the direction of electric field lines when encountering conductive and non-conductive shells has been difficult for students to understand, leading to confusion. Analysis of the results showed that some students did not understand the changes in the electric field when it passes through conductive and non-conductive objects. They mistakenly believed that the magnitude of the electric field determines its ability to pass through objects. To address this issue, a parallel plate capacitor was simulated to create an external electric field, and then in two stages, a spherical shell made of gold (conductive) and a spherical shell made of glass (non-conductive) were placed between the capacitor plates. The output of this simulation demonstrated the changes in the electric field lines when passing through conductive and non-conductive shells. This can help students better understand how the external electric field affects the behavior of conductive and non-conductive shells. Fig. 6 shows the field lines resulting from the flat capacitor plates passing through the spherical shell a) conductive b) non-conductive. As can be seen, the electric field passes through the non-conductive shell, but does not pass through the conductive spherical shell, without changing the original algorithm with a slight deviation in the location of the shell.

When an external electric field is applied to a conductive spherical shell, such as one made of gold, the electric field lines pass through the shell and distribute the charge uniformly on its outer surface. This is known as the Faraday cage effect. Due to the high conductivity of the metal, the charges redistribute themselves to neutralize the electric field inside the shell. Consequently, the electric field inside a conductive spherical shell is zero, and the charges reside solely on the outer surface.



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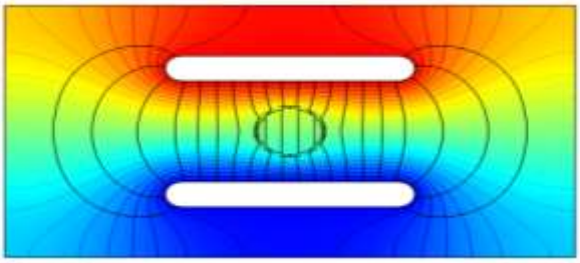

(b)

Fig. 6: Passage of the field through spherical shells of, (a) gold (conductive) and (b) glass (non-conductive)

In the case of a non-conductive (insulating) spherical shell, such as one made of glass, the behavior is different. Since insulators do not allow the free movement of charges, the electric field lines cannot pass through the shell. Instead, they terminate on the surface of the shell. This causes a non-uniform charge distribution on the outer surface of the shell, with a higher charge density at regions of higher curvature. The reason for the non-uniform charge distribution on the outer surface of an insulating spherical shell is due to the polarization of the material. Within the insulator, the electric field induces a separation of charges, with positive charges attracted towards the side facing the external field and negative charges repelled towards the opposite side. This polarization effect creates an internal electric field that counteracts the external electric field, resulting in a lower net electric field inside the insulating shell compared to the external field. In summary, for a conductive spherical shell, the charge distributes uniformly on the outer surface, with no electric field inside the shell. For a non-conductive spherical shell, the charges accumulate on the outer surface, and the electric field inside the shell is not completely canceled by the charges, resulting in a non-zero internal electric field. It's important to note that the behavior described here assumes idealized spherical shells and simplified conditions. In real-world scenarios, factors such as imperfections in the shells, surface roughness, and the presence of other objects can affect the charge distribution and electric field behavior.

Results and Findings

In this study, there were 60 male students from the eleventh grade, with 30 students assigned to the control group and 30 students assigned to the experimental group. The findings of the present research are presented in two sections: qualitative and quantitative. By incorporating both qualitative and quantitative findings, the research provides a comprehensive understanding of the research topic, allowing for a more robust and nuanced interpretation of the results.

Qualitative findings

The pattern extracted from interviews for misunderstanding categories is shown in Fig. 7. The results of the interviews indicated that the components of misunderstanding were as follows:

Coulomb's Law: Participants had difficulty understanding and applying the principles of Coulomb's Law, which describes the interaction between charged particles.

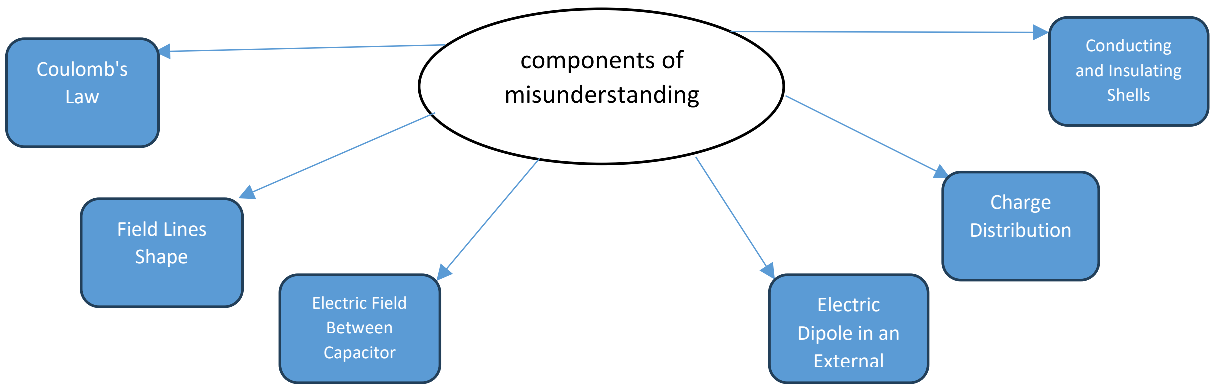

Fig. 7: The pattern extracted from interviews for misunderstanding categories.

Field Lines Shape: Some participants struggled to comprehend the concept of field lines and the shape they take around charged objects, leading to misunderstandings.

Electric Field Between Capacitor Plates: Participants faced challenges in understanding the electric field between the plates of a capacitor, including its direction and magnitude.

Rotation of an Electric Dipole in an External Electric Field: Some participants had difficulties grasping the concept of a charged particle's rotation when placed within an external electric field.

Charge Distribution on Pointed Objects: Participants had trouble understanding the distribution of charges on pointed objects, particularly how the charges accumulate or redistribute.

Effect of External Electric Field on Conducting and Insulating Shells: Understanding the impact of an external electric field on conducting and insulating shells posed difficulties for some participants.

Quantitative findings

The quantitative findings are presented in two sections: descriptive and inferential findings.

Descriptive findings

After collecting the pre-test papers in two classes and correcting them, the results were observed in Fig. 8.

After the end of the training sessions, two groups of 30 students from the 11th grade participated in the test again. The post-test results of both groups were observed in Fig. 9. According to in Fig. 10, the minimum percentage of correction of misunderstandings in the experimental group was 46.66%, while in the control group, it was 36.66%.

Using simulation-based modeling with software like COMSOL can have a positive impact on correcting misconceptions about concepts in electrical physics. Fig. 8 is shown the effects of this instructional approach on rectifying misconceptions. Utilizing simulation software like COMSOL helps students gain a better understanding of electrical physics concepts by visualizing them. After examining the correct answers of the experimental group in two tests and comparing them with the results of the control group, it can be seen that the effect of teaching with the help of simulation software in increasing the correct answers of students is far more than teaching with the traditional method. As can be seen in Fig. 10, the number of correct answers has increased significantly in the post-test phase. Descriptive findings are shown in Table 2. According to Table 2.

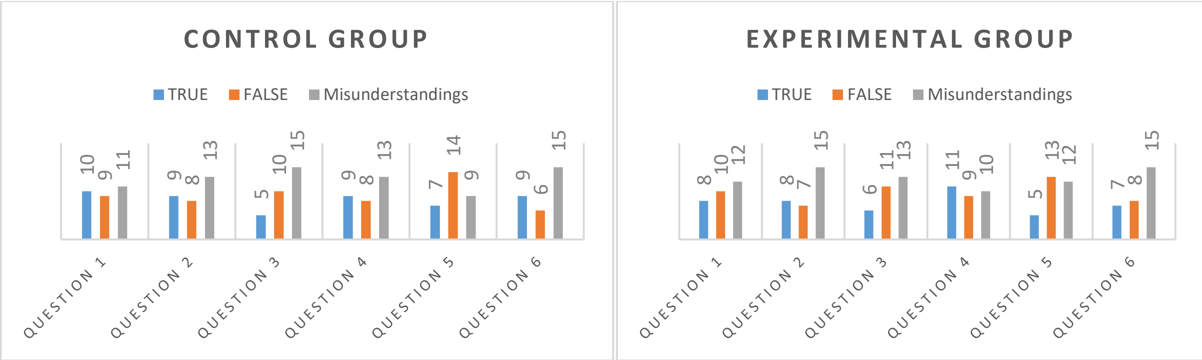

Fig. 8: The pre-test results of the experimental and control groups

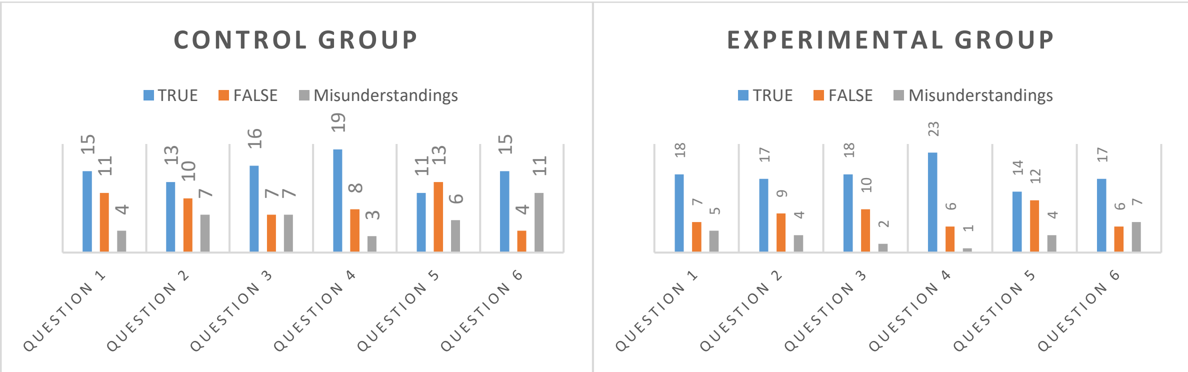

Fig. 9: The post-test results of the experimental and control groups

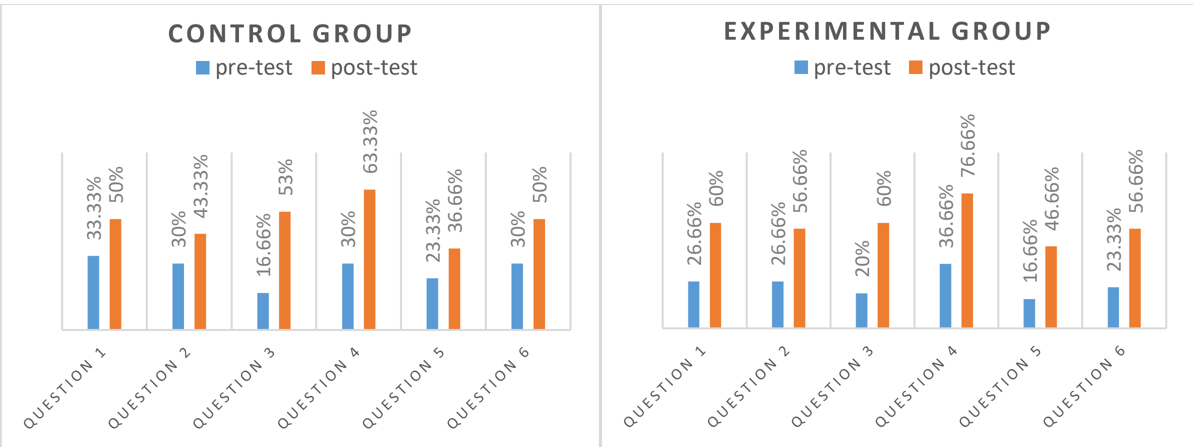

Fig. 10: Comparison of the correct answers of a sample of 30 people in two tests post-test and pre-test

Table 2: Descriptive statistics of research variables

Categories of misunderstandings of electrical physics concepts	Group	Pre-test	post-test
Coulomb's Law	control group	11	4
	experimental group	12	5
Field Lines shape	control group	13	7
	experimental group	15	4
Electric Field Between Capacitor Plates	control group	15	7
	experimental group	13	2
	control group	13	3

Categories of misunderstandings of electrical physics concepts	Group	Pre-test	post-test
Electric Dipole in an External	experimental group	10	1
Charge Distribution	control group	14	6
	experimental group	12	4
Conducting and Insulating Shells	control group	15	11
	experimental group	15	7

In the category of Coulomb's Law, initially, 11 students from the control group and 12 students from the experimental group had a conceptual misunderstanding. After the training sessions, the number of students with misunderstandings decreased to 4 in the control group and 5 in the experimental group.

In the category of Field Line Shape, initially, 13 students from the control group and 15 students from the experimental group had a conceptual misunderstanding. After the training sessions, the number of students with misunderstandings decreased to 7 in the control group and 4 in the experimental group.

In the category of Electric Field Between Capacitor Plates, initially, 15 students from the control group and 13 students from the experimental group had a conceptual misunderstanding. After the training sessions, the number of students with misunderstandings decreased to 7 in the control group and 2 in the experimental group. In the category of Electric Dipole in an External, initially, 13 students from the control group and 10 students from the experimental group had a conceptual misunderstanding. After the training sessions, the number of students with misunderstandings decreased to 3 in the control group and 1 in the experimental group.

In the category of Charge Distribution, initially, 14 students from the control group and 12 students from the experimental group had a conceptual misunderstanding. After the training sessions, the number of students with misunderstandings decreased to 6 in the control group and 4 in the experimental group. These findings indicate that the training sessions were effective in reducing conceptual misunderstandings in various categories for both the control and experimental groups.

Inferential findings

Based on the information provided in Table 3, the mean and standard deviation of post-test misconception scores for the experimental and control groups are as follows:

Experimental Group:

- Mean of post-test misconception scores: 0.1278
- The standard deviation of post-test misconception scores: 0.0712

Control Group:

- Mean of post-test misconception scores: 0.211
- The standard deviation of post-test misconception scores: 0.0935

Table 3. Mean and Standard Deviation of Post-Test Scores for Control and Experimental Groups

	Misconception pre-test		Misconception post-test	
Group	Control group	Experimental group	Control group	Experimental group
Mean	0.3	0.3056	0.211	0.1278
SD	0.0935	0.0712	0.1428	0.1369

These statistics provide insights into the average level of misconceptions and the variability of scores within each group. The experimental group, which received the simulation-based teaching method, had a higher mean score in the pre-test (0.3056) compared to the control group (0.3). However, in the post-test, the experimental group demonstrated a lower mean score (0.1278) compared to the control group (0.211), indicating a greater reduction in misconceptions among the experimental group. Moreover, the standard deviation of post-test misconception scores in the experimental group (0.0712) is smaller than that of the control group (0.0935), suggesting less variability in scores among the experimental group. These findings suggest that the simulation-based teaching method may have superiority over the traditional method in terms of reducing misconceptions and improving understanding of electrical physics concepts. The results of this variance analysis are summarized in Table 4.

Table 4: **Summary of variance analysis to investigate the effect of teaching methods (traditional and teaching using COMSOL simulation software) to correct misunderstandings of electrical physics**.

Sources Change	SS	df	MS	F	sig
Teaching methods	3.66	1	3.76	4.95	0.030
error	42.18	57	0.74		

The results of the analysis of variance (ANOVA) indicate that there is a significant difference in the effectiveness of different teaching methods (traditional and simulation-based using CAMSOL software) in correcting misunderstandings in electrical physics concepts ($F=4.95$, $P<0.05$). Furthermore, the mean score of the experimental group (0.76) is significantly lower than the mean score of the control group (1.26). Additionally, the mean score of the experimental group in the post-test (0.76) is significantly lower than the mean score of the experimental group in the pre-test (3.66).

These findings suggest that the simulation-based teaching method using CAMSOL software is more effective in correcting misunderstandings in electrical physics concepts compared to the traditional teaching method. The experimental group exhibited a significant improvement in understanding after the intervention, as indicated by the higher post-test mean score compared to the pre-test mean score.

Discussion

This research was conducted with the aim of investigating and correcting the misunderstandings of 11th-grade high school students in learning the concepts of electricity. The study utilized a mixed-methods approach. The qualitative section employed content analysis through semi-structured interviews to identify misconceptions, while the quantitative section employed a quasi-experimental design with a pretest-posttest and a control group.

The findings of this study provide valuable insights into the effectiveness of using COMSOL simulation software in correcting misconceptions and enhancing students' understanding of electricity concepts. The qualitative analysis identified several categories of misconceptions that students commonly held in electrical physics. These included misconceptions related to Coulomb's Law, field line shape, electric field between capacitor plates, rotation of an electric dipole in an external electric field, charge distribution on pointed objects, and the effect of external electric fields on conducting and insulating shells.

The quantitative analysis revealed positive outcomes in both the control and experimental groups. Descriptive findings indicated a decrease in the number of students with misconceptions in all categories after the training sessions. However, the experimental group, which received instruction using COMSOL simulation software, showed a greater reduction in misconceptions compared to the control group. The descriptive indices indicated improvements in understanding for both groups, but the experimental group showed more significant improvements. This suggests that the interactive and visual nature of the simulation software aided in correcting students' misunderstandings.

Inferential findings, including mean scores and standard deviations, further supported the effectiveness of the simulation-based teaching method. The experimental group had a lower mean score in the post-test compared to the control group, indicating a greater reduction in misconceptions. The standard deviation of post-test scores in the experimental group was smaller, suggesting less variability in understanding among students. The analysis of variance revealed a significant difference in the effectiveness of teaching methods in correcting misconceptions in electrical physics. The results of the analysis of variance indicate that there is a significant difference between the teaching methods (traditional and simulation-based instruction using COMSOL software) in correcting misconceptions about electricity concepts in physics ($F=4.95$, $P<0.05$).

Overall, the combination of qualitative and quantitative findings provided a comprehensive understanding of the topic and supported the efficacy of the simulation-based teaching approach. The findings of the study also demonstrated the simulation-based teaching method using COMSOL software was found to be more effective than the traditional teaching method. The experimental group demonstrated a significant improvement in understanding. These software tools present concepts in a visual and interactive manner, demonstrating how physics concepts work in practical applications. This aids students in establishing a stronger connection between theoretical concepts and real-world experiences. Simulation software enables students to conduct experiments and explore different settings and circuit configurations. This allows them to identify their own errors and gain a better understanding of the relationship between physics concepts and experimental results.

Similar studies in physics education have demonstrated the benefits of simulation-based instruction in enhancing students' conceptual understanding and promoting engagement in the learning process. The results align with the findings of studies conducted by Cunningham-Nelson et al. [22], Ramnarain et al. [32], and Jaakkola et al. [33], which highlight the positive impact of simulation-based instruction on learning outcomes in various subject areas. Comparing these findings with past literature, the use of simulation software in education has shown promise in improving learning outcomes and correcting misconceptions across various subject areas. The current study adds to this body of literature by specifically focusing on electricity concepts and highlighting the effectiveness of COMSOL simulation software in addressing misconceptions.

Conclusions

The use of COMSOL simulation software in this study effectively corrected misconceptions related to electricity concepts, resulting in a significant improvement in understanding among students. The simulation-based teaching method using COMSOL software was found to be more effective than traditional teaching methods in correcting misconceptions about electricity concepts.

The use of COMSOL simulation software in teaching electricity concepts can effectively correct misconceptions and enhance students' understanding. The interactive and visual nature of the software allows students to explore and experiment with different scenarios, facilitating a deeper understanding of the underlying concepts.

The use of simulation software, such as COMSOL, has significant implications for physics education, curriculum development, and instructional practices. Integrating simulation-based activities and experiments into teaching can provide students with interactive and engaging learning experiences, promoting deeper understanding and correcting misconceptions.

Moreover, simulation software can extend beyond the classroom and be utilized for self-directed learning and personalized instruction. Students can explore concepts at their own pace, allowing for individualized learning experiences and a better grasp of the subject matter.

The findings of this study contribute to the existing literature on simulation-based instruction, further highlighting the potential of COMSOL simulation software in addressing misconceptions and enhancing students' understanding of electricity concepts. This research provides valuable insights for educators, curriculum developers, and instructional designers, encouraging them to consider the integration of simulation software into physics education to improve learning outcomes and promote conceptual understanding.

Despite its implications and applications, the study had some limitations. The small sample size and the restriction to one high school grade limit the generalizability of the findings to a larger population. Additionally, the short duration of the instructional program is a limitation as it does not allow for an assessment of the long-term retention of knowledge and the persistence of the correction of misconceptions. The effectiveness of the simulation-based teaching method was evaluated immediately after the program, but the long-term retention of knowledge and the persistence of correction of misconceptions were not assessed.

While acknowledging the study's limitations, the results emphasize the potential of simulation-based teaching approaches in improving learning outcomes in physics education. The findings of this study can inform curriculum development and instructional practices in physics education. According to the findings of the current study, Educators and curriculum designers are recommended to incorporate simulation-based learning experiences into their curricula to address misconceptions and promote a deeper understanding of electricity concepts.

To effectively implement simulation-based teaching approaches, providing professional development programs for teachers is crucial. These programs can train teachers in utilizing simulation software, such as COMSOL, and integrating it into their instructional strategies. Equipping teachers with the necessary skills and knowledge will enable them to effectively leverage simulation software to enhance student learning outcomes.

Furthermore, the findings of this study lay the groundwork for future research. Similar studies can explore the effectiveness of simulation-based teaching approaches for other physics concepts and subjects outside of physics. Additionally, expanding the research to different grade levels and diverse student populations would provide a more comprehensive understanding of the potential benefits of simulation-based instruction.

Authors' Contribution

Guidance in the implementation of the research plan, data analysis and manuscript writing has been provided by Dr. Fatemeh Khodadadi Azadbani. Data collection was done by Mr. Javad Kamali.

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Conflicts of Interest

The authors have no conflicts of interest.

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Appendix

Diagnostic test for misconceptions about electricity physics concepts.

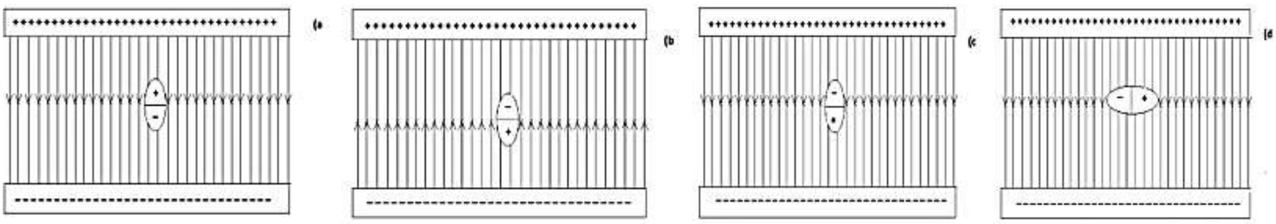
1. We place a positively charged sphere near a negatively charged sphere, what happens?
a) They approach each other.
b) move away from each other.
c) They remain fixed in place.
What is the reason for this?
a) Charges of the same name attract each other.
b) unlike charges attract each other.
c) Charges of the same name can be placed next to each other.
d) Non-identical charges do not react with each other.
Are you sure of your answer?
a) Yes
b) No

2. What is the electric field between two charged spheres?
a) From negative charge to positive charge
b) From positive charge to negative charge
c) from negative charge to negative charge
d) from adjacent positive and negative charges to the surroundings
What is the reason for this?
a) Field lines do not have a specific direction.
b) The field lines disperse with increasing distance from the charge.
c) The direction of the field lines is from the positive charge to the negative charge.
d) The direction of the field lines is from the negative charge to the positive charge.
Are you sure of your answer?
a) Yes
b) No

3. Consider a particle whose charges are polarized. An external field is applied to it by a flat capacitor, the particle is able to rotate in place, which form is true for this problem?
What is the reason for this?
a) The charged part of the particle rotates towards its homonymous charge and the direction of the field is always from positive to negative.
b) The charged part of the particle rotates towards its opposite charge and the direction of the field is always from negative to positive.
c) The particle remains motionless and the direction of the field is from positive to negative.
d) The charged part of the particle rotates towards the inhomogeneous charge and the direction of the field is always from positive to negative.
Are you sure of your answer?
a) Yes
b) No

5. Does the charge distribution in an object depend on the geometric shape of the object?
a) Yes
b) No
What is the reason for this?
a) The charge distribution depends only on the charge transfer agent.
b) The load distribution is more on the smooth sides of the object.
c) The load distribution is uniform.
d) The load distribution is more in the sharp corners of the object.
Are you sure of your answer?
c) Yes
d) No

6. How does the external electric field pass through an object, depends on the material of the object (conductor or insulation of the object)?
a) Yes
b) No
What is the reason for this?
a) Electric field passes through conducting bodies.
b) Electric field does not pass through conducting bodies.
c) Electric field passes through non-conducting objects.
d) The effect of the electric field and its penetration depends only on the intensity of the field.
Are you sure of your answer?
a) Yes
b) No



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