Investigating students' understanding of electric fields at boundaries

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Students often find it difficult to connect abstract ideas to complex problem solving. While much of the research on student difficulties in problem-solving focuses on mechanics, comparatively fewer studies have addressed challenges in electricity and magnetism, where boundary conditions near conductors are a topic that has received very little attention. This study explores student misconceptions related to electric fields in the context of conductive surfaces through a qualitative analysis of interview data. Six open ended interview questions were designed, focusing on key concepts such as electric field orientation on the surface of a conductor, surface charge distribution and importance of these kind of questions. Student responses were analyzed using NVivo, enabling the identification and categorization of common themes and misconceptions. Based on these findings, ten multiple choice questions were developed to serve as the basis for a future quantitative study.

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I. INTRODUCTION

Physics aims to uncover the fundamental principles that govern the universe. A key skill in mastering physics is problem solving, which connects abstract theory to real-world applications. Yet many students struggle to apply conceptual knowledge effectively, especially in areas like electricity and magnetism that intertwine mathematics and physical reasoning. These challenges have been widely documented in Physics Education Research [1–5].

This study focuses on students' conceptual understanding of electric fields near conductors. Such understanding is essential for solving advanced problems and bridging formalism with intuition. Boundary conditions in electrostatics, which describe how electric fields behave at material interfaces, are especially prone to misconceptions. Foundational texts such as Griffiths' *Introduction to Electrodynamics* highlight their importance [6], yet students often misinterpret the orientation and magnitude of electric fields at boundaries.

Prior research shows that students frequently confuse electric fields with forces or misunderstand their origin. Adrian and Fuller (1997) found that many introductory students described electric fields as areas, forces, or even charges, and struggled with superposition and vector representation [7]. At the upper-division level, Ryan, Pollock, and Wilcox (2015) found that many students had difficulty activating and applying boundary conditions, particularly in unfamiliar or mathematically complex contexts [8].

To address this gap, we investigate how students reason about electric fields in the context of boundary conditions. Rather than focusing on problem solving performance, we examine conceptual understanding as a foundation for transferable reasoning. This work also contributes to the development of diagnostic multiple choice questions (MCQ's) grounded in authentic student thinking, with potential applications in both instruction and research.

A. Present goals

The primary objective of this study is to investigate students' conceptual understanding of electric fields near conductors. The study aims to analyze how students reason about electric fields at the boundaries of conductors and how well they understand the boundary conditions described in standard physics instruction. The study aims to:

- Analyze how students conceptualize the direction and behavior of electric field lines at conductor interfaces.
- Evaluate their reasoning processes when interpreting changes in the magnitude and direction of electric field.
- Identify common misconceptions students hold regarding boundary conditions in electrostatics.

The study investigates whether students understand fundamental ideas about electric fields near conductors in electrostatics such as the perpendicular nature of the field at the surface in equilibrium, the contrast between fields just inside and outside the conductor, and the vanishing of the parallel component. It also explores their understanding of how surface charge relates to field discontinuity, and their ability to reflect on the role of boundary conditions in problem solving and reasoning.

B. Institutional context

The work was conducted at a large, urban R1 university with a total enrollment of over 25,000 students. This university offers nearly 400 degree and certificate programs on a centrally located campus. The Physics Department currently has 15 full-time faculty members and offers B.S., M.S., and Ph.D. degrees. Nearly 30 % of undergraduate students are first-generation college students.

II. METHODOLOGY AND DATA ANALYSIS

This study employed a qualitative research approach using semi-structured interviews to investigate students' understanding of electric fields at boundaries. We acknowledge that there are different methods but we decided to use interview method. The flexible format allowed students to elaborate on their reasoning, while follow-up questions helped explore their thought processes [5, 9, 10]. This approach was effective in revealing misconceptions and pinpointing areas where students struggled. While we use the term "misconception," we acknowledge that many of these ideas stem from students' intuitive reasoning and can serve as meaningful starting points on the path toward more scientifically accurate understanding. The interview questions focused on the orientation and components of electric fields near conductors, the influence of surface charges, discontinuities in the field, and the importance of these considerations in analyzing electric fields around conductors. Institutional Review Board (IRB) approval was obtained before recruiting the students for interview.

The questions designed for the study are as follows:

Q1. How does the orientation of the electric field behave at the surface of a conductor?

Q2. Does a conducting surface affect the component of the electric field perpendicular to the surface? If yes, explain how.

Q3. What about the component of the electric field parallel to the surface? Again, explain what you are thinking.

Q4. How is the magnitude of the electric field related to any charges that might be on the surface?

Q5. Consider a case where an electric field suddenly changes from one value to another at a specific position. Does that tell you anything about nearby charged particles?

Q6. Why is it important to consider these kinds of questions when analyzing the electric field near conductors?

Follow-up questions were used to clarify or probe reasoning, such as asking students to elaborate on ambiguous terms or consider alternative scenarios. For example, if a student conflated electric field and electric force, they were asked *"Can you explain how these two are different?"* Eight students participated in the study: three undergraduates who completed a calculus based E & M course and five graduate students who had taken at least one advanced E & M course. Participants were recruited via email and received a $20 gift card. Selection was based on willingness and availability. We acknowledge that "the self-selection" process could introduce bias, as those who volunteered may have had greater confidence or interest in the subject matter than the broader population. Additionally, the small number of participants limits the generalizability of the findings. Interviews followed a structured protocol that included an introduction, interview questions, follow-ups, and closing prompts. Written consent was obtained before video and audio recording. Students received a study information sheet and consent form outlining the purpose of study, potential risks, confidentiality, compensation, and their right to voluntary participation. They were encouraged to think aloud and use a whiteboard, prompts were provided if they struggled. Transcriptions were done using Microsoft Copilot, and all data were anonymized and stored securely. A grounded theory approach was used for analysis, allowing themes to emerge from the data [11]. The codes and categories were not imposed beforehand but they were developed inductively from student responses. As patterns emerged, initial codes were refined, grouped into themes, and compared across interviews to develop a more comprehensive understanding of students' thinking. Transcripts were obtained using Microsoft Copilot and were coded in NVivo. To ensure reliability, a second graduate student independently coded the same data. Inter-rater agreement was assessed, and discrepancies in coding were discussed and resolved through consensus.

III. FINDINGS OF THE STUDY

1. Quantitative Summary of Responses and categorization of misconceptions

Table I contains the number and percentages of correct, partially correct and incorrect answers from students' responses. In the following, we will abbreviate "Electric Field" using EF. In the table, first column contains interview questions which are stated in Section II A. For all the questions, number of participants is 8. Table II includes the common misconceptions made by the students. In first column, we have the interview questions and in second column, we have different misconceptions. This table helps us to get an idea regarding common misconception for each interview question.

2. Frequency of misconceptions across students

Table III presents the frequency of misconceptions identified among students, offering valuable insight into the conceptual areas where misunderstandings are most prevalent. By organizing the data according to misconception themes, the number of students who exhibited each type of misunderstanding, and the specific interview questions related to those themes, the table helps highlight patterns of conceptual difficulty.

IV. DISCUSSION

Section A to F will provide details of student responses to each of the six questions.

A. How does the orientation of electric field behave at the surface of a conductor?

Among eight students, two correctly stated that electric fields are perpendicular to the surface in electrostatic equilibrium, such as "*Electric fields are always perpendicular to the surface of a conductor.*" Five responses were partially correct, including "*So it might be outward or inward depending on the test charge. So for if it will, if it is negative, meaning it is going inside and positive, it is outward. It will be perpendicular.*" There was one incorrect response. Misconceptions included confusing electric field with electric force, as seen in the misuse of Coulomb's law.

Others confused electric and magnetic fields, referencing the right-hand rule "*So I know if you have any wire using right hand rule, if you have a wire, you'd use a right hand rule* "or linking field direction to current "*It goes in the direction of the current along the conductor.* " These findings suggest the need for more explicit instruction that distinguishes electric and magnetic field concepts, especially in contexts involving conductors.

TABLE I. Categorization of student responses to each interview question on electric fields.

Interview Question	Correct	Partially Correct	Incorrect
Q1	2 (25%)	5 (62.5%)	1 (12.5%)
Q2	0 (0%)	4 (50.0%)	4 (50.0%)
Q3	2 (25%)	1 (12.5%)	5 (62.5%)
Q4	2 (25%)	2 (25.0%)	4 (50.0%)
Q5	0 (0%)	5 (62.5%)	3 (37.5%)

B. Does a conducting surface affect the component of electric field perpendicular to the surface? If yes, explain how?

Among the eight students, four responses were partially correct, for example, "*I would think so, yes. I would think just place them next to each other because they have a charge; it's going to affect a different charged field just by being around it.*" and four were incorrect. Surprisingly, there were no fully correct responses, indicating a significant conceptual gap, especially since the second question was related to the first. Even students who answered the first question correctly struggled to provide a complete answer to the second. Among the partially correct responses, a few students recognized that the perpendicular component of the electric field is affected by the presence of a conducting surface and referred to boundary conditions or field continuity. However, many responses lacked clarity and precision. Some students incorrectly stated that the perpendicular component of the electric field is zero while the parallel component is non-zero. From the video recording, it was clear that they were not considering the electric field in terms of its components relative to the unit normal vector. One student, for instance, remarked, "*I would say that the perpendicular component would be 0 and the parallel component is going to be some number.*" Others denied that the conductor would affect the field orientation at all.

Additionally, some students continued to confuse electric and magnetic phenomena, describing behaviors more applicable to magnetic fields. These misunderstandings highlight the challenges students face in visualizing and reasoning about field vectors at material interfaces. Emphasizing component wise analysis of field behavior, and encouraging students to draw and label field vectors explicitly, may help address these conceptual gaps.

TABLE II. Identified misconceptions categorized by interview question.

Interview Question	Identified Misconceptions
Q1	(a) Confusion between electric field and electric force (b) Confusion with magnetic field concepts (c) Mixing electrostatics with current related reasoning
Q2	(a) Mixing up perpendicular and parallel components (b) Confusion with magnetic fields
Q3	(a) Incorrect statements about the magnitude of the parallel component
Q4	(a) Confusion with magnetic field (b) Mixing electric and magnetic field equations
Q5	(a) Misinterpretation of how EF changes with charge motion or rearrangement (b) Confusion between charge and distance

C. What about the component of the electric field parallel to the surface? Again, explain what are you thinking?

Only two students correctly answered that the parallel component of the electric field must be zero at the surface of a conductor in electrostatic equilibrium. One said "*Electric field in conductor on the surface when it is parallel, I think it's 0.*" One response was partially correct, and five were incorrect. One student remarked "*I can't really explain that.*" Misconceptions included statements like "*Parallel to the surface, it would have it would fully affect it because thinking back to the formula, can I bring up the formulas or if you know, you can just write it's a cosine theta, so if it's completely parallel with it, it will affect it entirely.*" These responses suggest difficulty connecting mathematical and physical reasoning, especially regarding vector components and boundary conditions.

These findings reinforce the importance of teaching field behavior in the context of equipotential surfaces and encouraging students to connect mathematical expressions with physical meaning. Providing problem-solving tasks that explicitly require comparison of field components, alongside conceptual explanations, may help clarify the conditions under which certain field components vanish.

TABLE III. Frequency of identified misconceptions across students.

Misconception Theme	Number of Students	Relevant Questions
(a) Confusion with magnetic field concepts	4	Q1, Q2, Q4
(b) Misunderstanding of charge distance relationship	3	Q5
(c) Mixing electrostatics with current related ideas	3	Q1
(d) Substitution of mathematical formulas (e.g., $E = \frac{kQ}{R^2}$)	2	Q4
(e) Confusion between parallel and perpendicular components of EF	2	Q2, Q3
(f) Incorrect reasoning about EF direction on conductors	2	Q1

D. How is the magnitude of the electric field related to any charges that might be on the surface?

Two students correctly stated that the electric field magnitude is proportional to surface charge density "*It depends on the magnitude of the charges like the bigger the charge, the stronger the field.*" Two responses were partially correct, and four were incorrect. Misconceptions included confusion between electric and magnetic fields, e.g., "*A larger surface charge would result in a stronger magnetic field.*" and denying surface charge on conductors "*Conductors cannot have surface charges.* " These results suggest the need for instruction that emphasizes the physical origin of the electric field, particularly the role of surface charges on conductors. Teaching strategies should include visual models of field lines emerging from charged surfaces and exercises that apply Gauss's law in symmetric and asymmetric contexts. Further, clarification of the distinction between electric field sources and test charges may help reduce confusion in interpreting and applying field equations.

E. Consider a case when an electric field suddenly changes from one value to another at a specific position. Does that tell you anything about nearby charged particles?

This question brought out a wide range of student ideas: some were on the right track, while others showed confusion. We acknowledge that this question could have been more clear in distinguishing a sudden change in space from a sudden change in time. A few students correctly recognized that a change in the electric field signals a change in the charge distribution, often mentioning moving charges or the superposition of fields. This shows some emerging understanding of how electric fields behave. However, many students struggled to clearly explain the cause of these changes. Some thought the field changes just because something moves, without connecting it to changes in the source charges. Others focused only on distance as the factor that affects the field, missing the importance of how charges are arranged or how their strength might change. A few even thought the field could change without anything physical happening at all. These mixed responses suggest that students need more support in learning to reason causally about electric fields. Teaching with dynamic visual tools can help make these invisible processes more concrete and intuitive.

F. Why is it important to consider these kinds of questions when analyzing the electric field near conductors?

This was an open ended question and was therefore not categorized as having correct, partially correct, or incorrect answers. Instead, the goal was to explore the areas in which students believed these questions were beneficial to their understanding. Student responses to this question included themes such as finding the topic interesting to learn stating, for example, "*it was very interesting to learn*"and recognizing its relevance for practical applications. They also mentioned using it for Maxwell's equation calculations, improving problem-solving skills, understanding the mechanics of conductors "*Well, I think these are sort of the fundamental mechanics of conductor*"and deepening their understanding of the underlying physics.

G. Development of Multiple Choice Questions (MCQ's)

Based on the misconceptions identified through student interviews, the study developed ten MCQ's that reflect real student thinking, with answer choices designed to uncover and challenge these common misunderstandings. Two among them are as follows:

1. What is the orientation of the electric field near a conductor?
    - It is always perpendicular to the surface of a conductor. (Correct)
    - It runs parallel to the surface.
    - It wraps around the conductor.
    - It follows the right-hand rule.
2. How does a test charge behave in an electric field compared to a conductor?
    - A test charge and a conductor behave the same way in an electric field.
    - A test charge does not alter the field, while a conductor redistributes charge. (Correct)
    - A test charge creates its own electric field strong enough to influence conductors.
    - Conductors do not respond to external electric fields.

V. CONCLUSIONS

In response to our research questions, we found that students often exhibit mixed or inconsistent reasoning when interpreting electric field direction and magnitude near conductors. The confusion between electric field and magnetic field is common among students which is surprising to us. Some students confused electrostatic behavior with DC currents. To address these difficulties, the study developed ten MCQ's (Section G) to assess specific misconceptions, supporting the development of more effective instructional strategies. We intend to convert our 10 MCQ's to a survey and investigate its validity and reliability for broader instructional use. This will help us better understand how students' ideas about electrostatic boundaries shape their problem solving approaches and allow us to design more meaningful support to help them connect and apply what they've learned.

[1] A. B. Arons, *Teaching Introductory Physics* (Wiley, 1997).
[2] M. T. H. Chi, M. Bassok, M. W. Lewis, P. Reimann, and R. Glaser, Self-explanations: How students study and use examples in learning to solve problems, Cognitive Science , 145 (1989).
[3] P. Heller, R. Keith, and S. Anderson, Teaching problem solving through cooperative grouping. part 1: Group versus individual problem solving, American Journal of Physics **60**, 627 (1992).
[4] L. C. McDermott, *Physics by Inquiry (Second Edition)* (Wiley, 1996).
[5] E. F. Redish, Implications of cognitive studies for teaching physics, American Journal of Physics **62**, 796 (1998).
[6] D. J. Griffiths, *Introduction to Electrodynamics* (Cambridge University Press, 2017).
[7] B. W. Adrian and R. G. Fuller, A qualitative investigation of college students' conceptions of electric fields, in *Joint Meeting of the Arkansas-Oklahoma-Kansas and Nebraska AAPT Sections* (Manhattan, KS, 1997) retrieved from PER-Central.
[8] Q. X. Ryan, B. R. Wilcox, and S. J. Pollock, Student difficulties with boundary conditions in electrodynamics, in *2015 Physics Education Research Conference Proceedings*, edited by A. D. Churukian, D. L. Jones, and L. Ding (American Association of Physics Teachers, 2015) pp. 283–286.
[9] D. Hammer, Two approaches to learning physics, The Physics Teacher **27**, 664 (1989).
[10] D. Hammer, Epistemological beliefs in introductory physics, Cognition and Instruction **12**, 151 (1994).
[11] H. Chun Tie, M. Birks, and K. Francis, Grounded theory research: A design framework for novice researchers, SAGE Open Medicine **7**, 1 (2019).