Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-8, Issue-6, June 2026
DOI: 10.66069/ojspub.16560606

Reframing the Sliding Conductor Problem: Integrating Physical Principles and Pedagogical Scaffolding for Enhanced Conceptual Understanding

Yubin Zheng

Jiangsu Normal University, Xuzhou 221116, Jiangsu, China

Abstract: ***Conceptual understanding of physics is a core objective in science education. This study presents a systematic pedagogical analysis of a canonical electromagnetic system—a conducting bar sliding on rails in a uniform magnetic field—by examining both its intrinsic physical principles (knowledge logic) and the sequential reasoning and instructional scaffolding appropriate for learners (teaching logic). Through rigorous charge-force analysis and coordinate transformation, the paper demonstrates that the Lorentz force performs no net work in this configuration, clarifying a widely misunderstood concept in classical electromagnetism. It further identifies the induced electromotive force expression $\varepsilon = -d\Phi/dt$ as a key conceptual bridge unifying electric and magnetic field representations. By translating these analytical insights into classroom practice, the study proposes a concrete implementation pathway that deepens students' grasp of field-circuit relationships and fosters transferable problem-solving skills, ultimately contributing to the development of robust physical intuition in undergraduate physics education.***

Keywords: Electromagnetic induction, Lorentz force, Conceptual understanding, Physics education, Pedagogical framework, Undergraduate teaching.

1. Introduction

In the current environment of new curriculum reform and the cultivation of core subject competencies, physics teaching is gradually shifting from mere knowledge transmission to concept construction and thinking training. As a key component of physics, electromagnetism is highly abstract and comprehensive. The relationships among the Lorentz force, electromotive force (EMF), current, and magnetic fields involved in the electromagnetic induction unit often become difficult points for students to understand and challenging aspects for teachers during instruction. In traditional classrooms, students mostly rely on memorizing formulas and applying models to solve typical problems, but they struggle to truly grasp the underlying physical principles. For instance, the proposition "the Lorentz force does no work," though frequently mentioned, appears contradictory when dealing with phenomena such as EMF and induced current generated by a conductor rod cutting through a magnetic field, easily causing cognitive conflict among students. During exchanges on teaching practices with frontline teachers, the author found that students lack a unified understanding of phenomena like "magnetic fields cannot do work on charges" and "internal charges in a moving conductor rod being driven." The root of this issue lies in neglecting to explain the essential connection between electric and magnetic field concepts in teaching, and the lack of guidance for students to integrate their understanding at a higher level. There is an urgent need to reconstruct the knowledge system of electromagnetic induction centered around "big subject concepts," transforming the teaching process from "piecemeal knowledge 串联" to "concept-driven construction," to enhance students' transferability and physics thinking skills. "Electromotive force" is precisely the bridging concept between electric and magnetic fields; it can originate from the vortex electric field caused by a time-varying magnetic field or be generated by a conductor moving within a magnetic field. Regardless of the case, if viewed from the perspective of "static and dynamic reference frame transformations," both ultimately boil down to the understanding of the vortex electric field. Reinterpreting the relationship between the Lorentz force and EMF in a moving reference frame can effectively clarify the seemingly contradictory phenomenon that "magnetic fields do no work but can produce EMF." If teaching strategies such as graphical modeling, charge force analysis, and coordinate system transformations are employed to make the physical picture of such complex problems more concrete, students can not only understand the mechanical principles within the model but also establish the concepts of energy conservation and fields at a higher level. This article uses the typical teaching scenario of "a conductor rod moving in a magnetic field" as an example, exploring the question of "whether the Lorentz force does work" in depth from the two dimensions of knowledge logic and teaching logic, relying on microscopic charge force analysis and reference frame transformation strategies. The study leverages the "big concept" of "electromotive force" as a teaching support point, building a bridge between electric and magnetic fields, and enhancing the integration and transferability of students' physical concepts.

2. Problem Statement

The phenomenon of electromagnetic induction has always been a core component in the teaching and examination of high school electromagnetism [1]. When examining electromagnetic induction, a common problem scenario is "the motion of a metal rod on a track within a magnetic field." Recently, during a discussion with a teacher, the question arose regarding whether the Lorentz force does work in the context of an open-circuit metal rod moving within a magnetic field to generate an induced electromotive force (EMF):

"When charges move within a magnetic field, they experience the Lorentz force, represented as the product of velocity and the magnetic field, so we say that the Lorentz force never does work. However, when a metal rod moves and cuts across a magnetic field, the Lorentz force acts as a non-electrostatic force, causing the generation of motional EMF within the rod. Doesn't this imply that the Lorentz force is doing work?

Of course, if the rod is part of a closed loop, the issue becomes less problematic. In this case, an induced current will be generated within the rod, and the corresponding induced current will experience the Ampere force. The Ampere force, as the macroscopic manifestation of the Lorentz force, performs negative work, which cancels out the positive work done by the Lorentz force acting as a non-electrostatic force. Thus, overall, the Lorentz force still does no work.

However, the problem arises when the metal rod is not part of a closed loop. In this situation, no current will be generated in the rod, meaning there will be no Ampere force and hence no work done. But within the metal rod, a motional EMF will still be produced due to the Lorentz force acting as a non-electrostatic force, and this portion of the Lorentz force does positive work that cannot be canceled out. How do we resolve this apparent contradiction?"

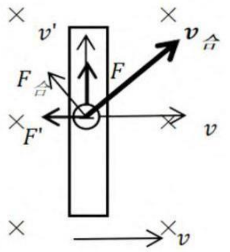

Figure 1: Analysis of electron motion and forces within a metal rod moving through a uniform magnetic field

3. Discussion of the Problem

A review of the literature shows that most research related to electromagnetic induction focuses on its teaching aspects, with fewer studies analyzing the microscopic mechanisms of the Ampere force [2]. There is limited analysis concerning the relationship between the EMF, the Lorentz force, and the Ampere force in the typical scenario of "a metal rod moving along a track within a magnetic field." To address this gap, this paper analyzes the issue from two perspectives: force analysis and coordinate transformation, starting first with the forces acting on charges.

3.1 Force Analysis

The first paragraph mentions that "the Lorentz force is the cross product of velocity and magnetic field," which is the reason why the Lorentz force does no work. As shown in Figure 1, when the metal rod moves in the magnetic field, the electrons within it have the same velocity v as the rod. Under the influence of the Lorentz force F generated by v, the electrons move towards one end of the rod, denoted as v, while simultaneously being acted upon by the corresponding Lorentz force F . Thus, the actual velocity $v_{合}$ of the electron points to the upper right, and the actual Lorentz force $F_{合}$ points to the upper left. The component force F generates motional electromotive force and cannot be regarded as the total Lorentz force $F_{合}$ doing work. Subsequent content repeats the same confusion between resultant force and component forces.

From Figure 1, it can be seen that the motion of electrons in the magnetic field has two components, v and v, which generate Lorentz forces F and F' in two directions. F causes electrons to accumulate at the ends of the conductor, creating a potential difference; F' causes them to accumulate on both sides, forming a Hall field [3], exerting forces on the electrons within, respectively noted as F_E and F_H (as shown in Figure 2).

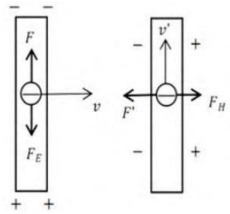

Figure 2: Electrons accumulating at both ends under the action of the Lorentz force

From this, we can observe that when F_E and F reach equilibrium, the electrons become stationary relative to the metal rod, i.e., $v' = 0$, then $F' = -ev' \times B =$ equals 0. Macroscopically, they are no longer subject to the Ampere force, and the charges on both sides will decrease under the effect of F_H, so the Hall effect does not occur. Therefore, when F_E and F are balanced, the Lorentz force does no work.

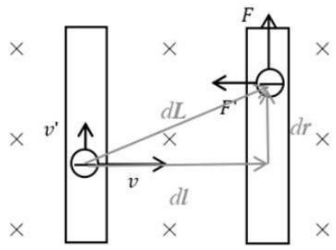

Figure 3: Electron movement under the influence of the Lorentz force

However, before equilibrium, charges will continue to move and accumulate at one end under the influence of F with velocity v (as shown in Figure 3), indicating the presence of an induced current. Then $F' = -ev' \times B \neq 0$, the electrons experience a Lorentz force perpendicular to the direction of the rod. Assuming that within dt time, the metal rod displaces by dl, and the relative displacement between the electrons and the metal rod is dr, then the total displacement of the electrons is $dL = dl + dr$, and the total work done by the Lorentz force on the electrons can be expressed as:

$$dW_{合} = \bar{F} * d\bar{L} = -e(\bar{v}_{合} * \bar{B}) * dL$$

$$= -e(\bar{v} * \bar{B}) * dL - e(\bar{v} * \bar{B}) * d\bar{L}$$

$$\because -e(\bar{v} * \bar{B}) * \bar{L} = -e(\bar{v} * \bar{B}) * \left(d\bar{l} + d\bar{r}\right)$$

$$= -e\left(\frac{d\bar{l}}{dt} * \bar{B}\right) * d\bar{r}$$

$$-e(\bar{v} * \bar{B}) * d\bar{L} = -e\left(\frac{d\bar{l}}{dt} * \bar{B}\right) * d\bar{l} - -e\left(\frac{d\bar{l}}{dt} * \bar{B}\right) * d\bar{r}$$

$$\therefore dW = -\frac{e}{dt}\left(d\bar{l} * \bar{B}\right) * d\bar{r}$$

$$dW' = -\frac{e}{dt}(d\bar{r} * \bar{B}) * d\bar{l} = -\frac{e}{dt}\left(d\bar{l} * \bar{B}\right)d\bar{r}$$

Thus,

$$dW_{合} = dW + dW' = 0$$

It can be seen that before equilibrium, the Lorentz force still does no work.

3.2 Coordinate Transformation

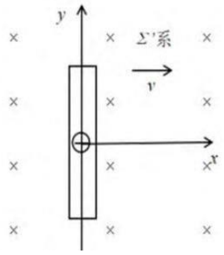

Figure 4: Metal rod moving in the ∑ ' system with velocity v

The above analysis is carried out under the general coordinate system ∑, which already proves that the Lorentz force never does work, and its component acts as a non-conservative force. However, what is the deeper reason for the generation of induced electromotive force? This article attempts to establish a moving coordinate system ∑ traveling at velocity v to analyze it in depth (as shown in Figure 4). In the ∑ system, electrons only have v', and due to $v \ll c$ here, the non-relativistic electromagnetic field transformation can be directly substituted [4], thus yielding

$$\bar{E} = \bar{E}_{库} + \bar{v} * \bar{B} = v * \bar{B} = \bar{E}_{涡}$$

$$\bar{B}' = \bar{B} - \frac{\bar{v}}{c^2} * \bar{E}_{库} = \bar{B}$$

It can be observed that a vortex electric field $E_{j列}$ arises in the ∑ ' frame. Since the electromotive force $\epsilon = -\frac{d\varphi}{dt}$, and the magnetic flux $\varphi = B \cdot S$, we have

$$\epsilon = -\left(\frac{\theta\varphi}{\theta t} * \bar{S} + \bar{B} * \frac{\theta\bar{S}}{\theta t}\right.$$

The first term corresponds to the induced electromotive force, while the latter corresponds to the motional electromotive force. In a closed loop, the electromotive force has

$$\epsilon = \Phi_1 \bar{E} * d\bar{l} = \Phi_1\left(\bar{E}_{库} + \bar{E}_{涡}\right)d\bar{l}$$

Since $E_{库}$ is a conservative field, its loop integral must be 0, hence it can be found that the induced electromotive force is highly likely to involve a vortex electric field. In a non-closed circuit, if the two ends of the metal rod are denoted as a 、 b, then

$$\varepsilon = \int_a^b \left(\bar{E}_{库} + \bar{E}_{涡}\right) \cdot d\bar{l}$$

$$\epsilon = \int_a^b \left(\bar{E}_{库} + \bar{E}_{涡}\right) d\bar{l}$$

As shown in Figure 4, the initial condition involves only the magnetic field B, with no E present, thus $\epsilon = \int_a^b \bar{E}_{涡}\, d\bar{l}$. In summary, the generation of induced electromotive force is fundamentally related to the vortex electric field.

3.3 Answer to the Question

Although the Lorentz force as a whole does no work, the electric field formed by its redistribution of charges can do work on the charges. That is, in the energy conversion path, the Lorentz force facilitates changes in the field structure rather than directly providing energy. When a single metal rod moves at velocity v within a magnetic field, prior to the establishment of a stable motional electromotive force in the metal rod, the internal electrons experience an imbalance of forces, moving toward one end of the rod, resulting in a brief directional movement of electrons, i.e., current. Thus, the Lorentz force still does no work and can be regarded as a mediator converting part of the kinetic energy into electromotive force.

3.4 Teaching Insights from the Problem

From the above analysis, it can be discovered

$$\Phi_1 \bar{E} * dl = \epsilon = -\frac{d\varphi}{dt} = -\left(\frac{\theta\bar{B}}{\theta t} * \bar{S} + \bar{B} * \frac{\theta\bar{S}}{\theta t}\right.$$

$\varepsilon = -\frac{d\varphi}{dt}$ can be associated with the magnetic field when directed rightward and linked to the electric field when directed leftward. Therefore, the electromotive force ε can be placed at the center of teaching about electric and magnetic fields, serving as a unifying concept connecting electric and magnetic fields, thereby enhancing students' physical understanding.

3.5 Re-understanding the Essence of Electromagnetic Induction: From the Perspective of "Motional" and "Induced"

In high school electromagnetics teaching, students often encounter the concepts of "motional electromotive force" and "induced electromotive force", but the essential connection between the two is mostly not clearly explained. This article uses the method of coordinate transformation to point out that both essentially stem from the phenomenon of vortex electric field, which helps students bridge the cognitive gap between electric and magnetic fields. Induced electromotive force is mostly generated by a changing magnetic field, while motional electromotive force is obtained when a conductor cuts magnetic induction lines in a constant magnetic field. If understood from a narrow perspective, only considering the Lorentz force, it's easy to separate the two; however, once reference frame transformation is introduced, it can be found that they are actually two sides of the same coin—motional electromotive force occurs in a stationary frame, while in a moving frame, it manifests as the presence of a vortex electric field. Teaching should guide students to understand electromagnetic induction from a higher unified perspective, breaking the superficial difference between "motion" and "change", and enhancing their physical abstract thinking ability [5].

3.6 Extended Discussion on the Question of Magnetic Field "Doing Work"

Some students may ask: "If the magnetic field itself cannot do work on charges, then what exactly is the source of energy for the charge?" Essentially, this question involves issues of energy conservation and energy flow paths. In the model of "a metal rod moving in a magnetic field", the energy input actually comes from the external force acting on the metal rod, which keeps the rod in uniform motion. During this process, the movement of the metal rod in the magnetic field generates an induced electromotive force, which then drives the current to flow, eventually forming an electric field. The work done by the external force uses the magnetic field as a "transfer channel"—converting into the potential energy of the charge system within the metal rod. Understanding this energy path can help students build a conceptual framework that "a magnetic field cannot do work, but it can change the direction of energy flow" [6].

3.7 Analysis of the Teaching Significance of Diagram Illustrations

In the teaching process at the high school level, visual diagrams are a key tool to help students construct physical models. Images such as Figures 1, 2, and 4 in this article can assist students in understanding complex and abstract phenomena like the motion of charges under force in a magnetic field, the formation process of an electric field, and the electric field structure in a moving frame in a more intuitive way. When conducting lessons, teachers should encourage students to try extracting key variables such as velocity, magnetic field direction, and force direction from the images, and mark them with arrows, gradually building up a trinity cognitive model of "symbols + images + formulas". This model helps improve students' problem-solving abilities and also benefits the training of their logical expression and modeling skills.

4. Question Type Design

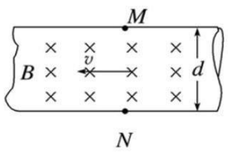

Figure 5: Schematic Diagram of Electromagnetic Flowmeter

Example 1 We know that when a cylindrical magnet falls inside a copper tube, it generates induced eddy currents (electric currents) on the tube walls. These eddy currents then generate a magnetic field opposite to the magnet's field and produce a force opposite to the magnet's motion (as shown in Figure 5), causing the velocity of the falling magnet V_g . If we vertically split the copper tube open along a seam and let the same cylindrical magnet fall through it, its speed v compared to the previous two cases would be ()

(A) $V_g > V > v$. (B) $V_g > V = v$.
(A) $V_g > V > v$. (B) $V_g > V = v$.
(C) $V_g > v > V$. (D) $V_g = v > V$.
(C) $V_g > v > V$. (D) $V_g = v > V$.

5. Discussion

In current physics teaching, instruction regarding electromagnetic induction phenomena often emphasizes conclusions over processes and calculations over understanding. Especially when dealing with the typical model of "a conducting rod moving in a magnetic field," students tend to mechanically memorize the electromotive force formula while neglecting the underlying physical mechanisms. This leads to a lack of transferability and deep comprehension when facing situational variations and comprehensive question types [7]. In textbook organization and classroom teaching, "motion-induced electromotive force" and "induction-induced electromotive force" are often taught separately, failing to establish a unified conceptual framework, resulting in fragmented student understanding of the relationship between electric and magnetic fields. Moreover, although the notion that "Lorentz force never does work" is repeatedly emphasized, specific teaching often lacks reasoning support based on microscopic particle force analysis and coordinate system transformations. As a result, students struggle to form a consistent causal cognitive chain when encountering phenomena such as charge movement in conducting rods, potential difference formation, and energy conversion [8]. Additionally, existing teaching aids and classroom explanations lack systematic guidance on reference frame transformation and electromagnetic field unity. The use of graphical tools and physical modeling in teaching is infrequent, making it difficult for students to construct a complete cognitive model of electromagnetic processes through multimodal representation methods. Furthermore, under the guidance of core competencies, teaching assessments focus more on computation and result accuracy, paying insufficient attention to students' abstract abilities like physical concepts, energy perspectives, and field theory thinking, which restricts the development of higher-order thinking skills.

This paper selects the classic model of "a conducting rod moving in a magnetic field" as the starting point for research, and conducts a comprehensive and systematic analysis of the question of whether the Lorentz force does work. By means of microscopic force analysis on charges and reference frame transformation, it clarifies that the Lorentz force itself never does work, and its seemingly working phenomenon is actually caused by changes in the field structure. After introducing the moving reference frame, the motional electromotive force (EMF) in the conductor can be attributed to the presence of a vortex electric field, thus unifying the physical nature of the two types of EMFs: "motional" and "induced." In the teaching process, students should be guided to understand the concept of energy flow where "the magnetic field does no work but can participate in energy transfer," and use "electromotive force" as the core concept to build a unified knowledge system connecting the electric field, magnetic field, and conservation of energy. Strategies such as image modeling and conceptual linking should be employed to help students construct a "image-symbol-formula" trinity cognitive structure, enhancing their physical modeling and transfer capabilities. This paper advocates that teaching reform should focus on concept-driven approaches to promote students' transition from knowledge acquisition to conceptual construction.

Based on the above theoretical analysis, teachers can use $\varepsilon = -\frac{d\varphi}{dt}$ as the core to establish an initial link between the electric field and the magnetic field in subsequent teaching, helping students construct the connection between the electric field and the magnetic field, thereby better cultivating physical concepts and scientific thinking, and promoting the development of core competencies.

References

[1] Ministry of Education. Physics Curriculum Standards for Ordinary High Schools (2017 Edition) [S]. Beijing: People's Education Press, 2018. 1.
[2] Chen Luchang, Deng Youhong. Intellectual collision on the relationship between Lorentz force and Ampere force [J]. Physics Bulletin, 2017(06): 102-105.
[3] Guo Shuohong. Electrodynamics (3rd Edition) (BZ) [M]. Higher Education Press, 2009.
[4] Li Gang, Lü Lijie. Big Concept Curriculum Design: A Curriculum Framework Aimed at Implementing Core Disciplinary Competencies [J]. Educational Development Research, 2018, 38(Z2): 35-42.
[5] Wu Yangjie. Application of the momentum theorem expression of Lorentz force in a magnetic field [J]. Reference for Middle School Physics Teaching, 2025, 54(03): 74-78.
[6] Zhu Hua. Analysis of the relationship between motional electromotive force and Lorentz force [J]. Physics and Engineering, 2025, 35(02): 22-26+45.
[7] Wu Quanheng, Chen Yunfei. On the correlation between Ampere force and Lorentz force [J]. Technology Wind, 2024, (22): 21-24.
[8] Xu Wenlong. Analysis of deep thinking issues in Lorentz force teaching [J]. Discussion on Physics Teaching, 2024, 42(05): 66-68+72.