

Misconceptions and Difficulties in Undergraduates' Circuit Learning: A Qualitative Research Based on Diagnostic Questionnaires and Interviews

Suyuan Liu

*School of Physics and Astronomy, Beijing Normal University, Beijing, China
202311999043@mail.bnu.edu.cn*

Abstract. Numerous studies have proved that undergraduates commonly hold misconceptions about basic concepts including electric current, voltage and resistance during their learning process. Adopting qualitative research methods and taking diagnostic questionnaires and semi-structured interviews as primary research tools, this paper carries out an empirical investigation on engineering undergraduates from a domestic university. Research findings reveal that conventional teaching has deficiencies in assisting students to build connections between microscopic mechanisms and macroscopic phenomena. This paper provides interview-based qualitative data for the improvement of circuit teaching.

Keywords: Circuits, Misconceptions, Diagnostic Questionnaires, Qualitative Methods, Undergraduates

1. Introduction

1.1. Research background

Circuit theory serves as the core foundational content for majors including physics, electrical engineering, automation and electronic information. Students' accurate comprehension of basic concepts such as electric current, voltage, resistance, power and capacitance directly determines their learning performance in subsequent courses including analog electronics, digital circuits and signal systems. Nevertheless, numerous international studies have verified that students still retain a wide range of systematic misconceptions in circuit comprehension even after receiving formal systematic instruction.

1.2. Domestic and international research status

Internationally, research on misconceptions in circuit learning has been developed for decades. Several studies have found that students tend to reason in a current-centered manner rather than a voltage-centered manner, and confuse cause-and-effect relationships [1]. Other studies have indicated that most students hold the belief that electric current is consumed by electrical loads [2]. Certain researches put forward the sequential reasoning model, which describes the idea held by

students that changes within a circuit can only spread unidirectionally along the direction of electric current [3]. Further studies have pointed out that students struggle to correlate the concepts of electric field and electric potential in electrostatics with current and voltage in circuits, resulting in a divide between macroscopic observations and microscopic principles [4].

Domestically, relevant researches remain relatively insufficient. Several scholars have conducted preliminary discussions on circuit misconceptions in middle school physics teaching, yet systematic researches targeting undergraduate students are scarce. In particular, mixed-method researches combining diagnostic questionnaires and interviews are rarely seen.

1.3. Research purpose and significance

This research intends to systematically identify typical types of misconceptions held by engineering undergraduates in the learning of direct current circuits, uncover the cognitive mechanisms and root causes behind these misconceptions, and provide empirical evidence and diagnostic tools for the optimization of circuit teaching.

In terms of theoretical significance, this study can enrich domestic empirical researches on the understanding of circuit concepts, and verify whether the misconception categories summarized by international scholars are prevalent among Chinese students. In terms of practical significance, this research can provide teaching diagnostic tools for instructors, and help undergraduates clarify their own obstacles in conceptual understanding.

2. Theoretical basis and literature review

2.1. Definition of core concepts

Circuit misconceptions refer to cognitive frameworks constructed by students themselves during the learning of circuit knowledge that contradict scientific consensus, which may manifest as conceptual errors, incomplete models or flawed reasoning patterns.

Electric current is a physical quantity formed by the directional movement of electric charges, with the ampere (A) as its unit. For a node, electric current can be divided into inflow and outflow directions, yet it does not possess spatial directionality like a vector, so electric current is a scalar quantity.

Voltage, also known as potential difference, denotes the work done by an electric field force when moving a unit charge from one point to another within an electric field, and serves as the fundamental cause that drives electric current.

2.2. Framework of learning theories

This study takes the sociocultural constructivist learning theory as its basic framework. The theory holds that learning is a process of internalization shifting from the social plane to the mental plane. Students are exposed to scientific language and thinking modes through interpersonal interactions such as listening to teachers' lectures and discussing problems with peers in class, and gradually convert these elements into personal understanding [5, 6].

Applied to the specific scenario of circuit learning, students face the challenge of converting everyday language into scientific language. Terms such as electric current and energy are usually comprehended intuitively and perceptively in daily life, while scientific language requires reasoning based on an accurate conceptual system including potential difference, electric field and charge

conservation. The difficulties encountered in this conversion process constitute the core of learning demands.

2.3. Literature review: typical types of misconceptions

This study sorts out relevant domestic and international literature systematically and summarizes the following typical types of misconceptions:

The first type is the confusion between electric current and voltage. Most students fail to clarify the respective functions and effects of electric current and voltage. Common misconceptions include the belief that electric current is consumed rather than conserved; regarding a battery as a constant current source instead of a constant voltage source; adopting local reasoning rather than holistic analysis when analyzing voltage division, especially in series circuits; considering electric current a vector with both magnitude and direction; holding the idea that electric current is consumed by electrical appliances or that a battery supplies constant current; even asserting that voltage cannot exist without electric current; failing to distinguish between electric potential and potential difference; making mistakes in applying the formula $V=IR$ and assuming that voltage will inevitably change along with any variation in electric current.

The second type covers misconceptions about electric potential and potential difference. Students often struggle to distinguish and relate the concepts of electric potential and potential difference. They frequently separate voltage readings from microscopic electric field mechanisms and lack a mechanistic understanding that electric fields drive the motion of charges. When confronted with complex circuits composed of multiple batteries, they rely more heavily on electric current and resistance for reasoning and omit the process of voltage analysis.

The third type refers to limitations in causal reasoning. Students mostly adopt simple or linear causal reasoning and lack the capacity for systematic and multi-level reasoning. For instance, they assume voltage must change with altered electric current due to incorrect application of the formula $V=IR$, ignoring that voltage acts as the dominant cause governing circuit behaviors.

The fourth type involves misconceptions related to circuit analysis. Students replace global analysis with sequential reasoning; they judge the direction of electric current merely by the layout of circuit diagrams instead of reasoning based on the principle of charge conservation; they apply total current rather than branch voltage when analyzing parallel branches.

The fifth type consists of misconceptions about capacitors and transient processes. Some students treat capacitors as open circuits and thus believe no electric current can pass through them, further concluding that no voltage exists across capacitors without current. Other students cannot comprehend the correlation between charge accumulation on capacitor plates and the direction of electric current.

3. Definition of learning objectives

Combining the literature review of this study and the requirements of the current teaching syllabus, this research defines the following Learning Objectives (LOs):

LO1: Enable students to understand the function of electromotive force in direct current circuits, and distinguish between the electromotive force of a power supply and terminal voltage.

LO2: Enable students to recognize that electric current originates from potential difference, and correctly apply Ohm's Law $V=IR$ to analyze the relationship between voltage and current across a resistor.

LO3: Enable students to analyze simple direct current resistive circuits including series, parallel and series-parallel combination circuits, and properly apply Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL).

LO4: Enable students to comprehend the physical function of a resistor: a resistor does not consume electric current, and only converts electric energy into internal energy.

LO5: Enable students to master the complete charging and discharging process of capacitors, and analyze the variation of current and voltage in transient circuits.

LO6: Enable students to understand the model of ideal diodes, and analyze simple circuits containing diodes.

These learning objectives will serve as the basis and criteria for the compilation of the diagnostic questionnaire and the evaluation of students' mastery of relevant knowledge in the subsequent research work.

4. Research methodology

4.1. Research design

This study adopts a qualitative research method. Semi-structured interviews are conducted with selected representative students, aiming to deeply explore their reasoning processes and the conceptual frameworks they possess.

4.2. Research participants

The participants of this research are undergraduates from a domestic university who have completed the college physics course. A total of 10 students are recruited for interviews, including eight male students and two female students. All interviewees have taken the basic circuit course previously.

4.3. Research instruments

4.3.1. Diagnostic questionnaire

In the initial phase of the research, a questionnaire consisting of 15 diagnostic questions is developed to assist the formulation of the interview outline. The questionnaire covers the following knowledge points: Kirchhoff's Current Law (Question 4), the scalar or vector property of electric current (Question 4), series and parallel circuit analysis (Question 12), the relationship between current and voltage (Question 9), charge analysis of capacitors (Question 9), the ideal diode model (Question 15), as well as circuit voltage waveform analysis (Question 15).

Several principles are followed during the design of this questionnaire. First, the distractors of each question are set in accordance with typical misconceptions recorded in classic textbooks and relevant literature. Second, all questions are four-option multiple-choice questions. Third, participants are required to elaborate their reasoning for selecting answers in part of the questions.

4.3.2. Semi-structured interview outline

The interview outline is formulated mainly based on questions with high error rates and complex conceptual levels in the questionnaire. Major questions include "Why did you choose this option?", "Could you describe your thinking process?", "How do you think the current or voltage changes in this circuit?" and other related inquiries.

4.4. Research procedures

First, conduct the literature review and define the learning objectives. Second, compile the questionnaire and invite relevant professionals to review it. Third, carry out the formal test, namely conducting semi-structured interviews with the 10 participants respectively, recording the interview content and transcribing the recordings into written texts. The final step is to analyze the collected data and compose the research paper.

4.5. Data analysis method

Thematic analysis is adopted to process the interview data. The specific implementation steps are as follows. Firstly, transcribe all interview recordings verbatim into text files. Secondly, conduct open coding to identify key concepts. Thirdly, establish connections between different concepts through axial coding. Finally, summarize several core themes to describe students' typical misconception types and corresponding cognitive characteristics.

To enhance the reliability of research results, the original interview materials are repeatedly cross-checked throughout data analysis. Typical quotations from student interviews are cited as evidence for analysis, so as to better guarantee the transparency and traceability of the research conclusions.

5. Research results and findings

5.1. Typical types of misconceptions

Through the analysis of questionnaire data and interview records, this study summarizes the following typical types of misconceptions:

The first is the intuitive misconception about Kirchhoff's Current Law. When applying this law, students tend to judge the supposed flow direction of electric current merely by observing the layout of circuit diagrams instead of conducting symbolic analysis based on the principle of charge conservation. For instance, Student 6 stated: "The diagram is drawn this way." This response proves that the student failed to analyze the problem on the basis of charge conservation. Some other students held the view that the current direction at a Y-shaped junction is fixed, claiming that current always flows in through the branch forming an obtuse angle with the other two branches.

The second is the vectorization misconception of electric current. Many interviewees regarded electric current as a physical quantity with both magnitude and direction. For example, Student 3, Student 4 and Student 6 all mentioned statements similar to "It has both magnitude and direction, so it should be a vector". Similar remarks were made by multiple participants, which indicates that students tend to analogize electric current to vector quantities such as force or velocity, thus making mistakes in the classification of physical quantities.

The third is current-centered reasoning in the analysis of parallel branches. Student 3 commented: "After lamp L2 burns out, the total current in the circuit decreases, so the power of lamp L1 drops accordingly." This statement shows that the student adopted total current rather than branch voltage when analyzing the power of lamps in parallel branches. This error reflects the student's current-centered reasoning mode, in which the key property that all branches in a parallel circuit share equal voltage is overlooked.

The fourth is the misconception of *no voltage without current* in the transient analysis of capacitors. Some students cannot understand that voltage can exist across a capacitor at steady state

while the current passing through it equals zero. For example, Student 6 raised such doubt: "How can voltage exist if there is no current at all?" This misconception reveals that the student directly links the existence of voltage to current, lacks understanding of the essence of energy storage of capacitors, and simply regards a capacitor as either a closed circuit or an open circuit.

The fifth is confusion over the charged polarity of capacitor plates. Students cannot establish the correct correspondence between charge accumulation on capacitor plates and the direction of current, which reflects their insufficient comprehension of the physical mechanism of capacitor charging. For example, Student 6 said: "The lower plate carries positive charge, because current flows out from the lower plate."

The sixth is excessive simplification of the ideal diode model. Students only remember the property of unidirectional conduction and ignore the zero resistance characteristic of an ideal diode when it is switched on, which leads to errors in voltage waveform analysis. For instance, Student 1, 3, 4, 5, 6 and 9 all stated: "An ideal diode features unidirectional conduction."

The last one refers to errors in voltage analysis when a diode is cut off. Students mistakenly believe that no voltage exists in the circuit during the period when the diode is non-conducting. They neglect the necessity of analyzing the voltage across resistors and fail to comprehend the waveform variation of the voltage across the diode. Student 1, 3, 4, 5, 6, 8 and 9 expressed similar opinions: "The ideal diode is non-conducting for half of the cycle, so no voltage exists, and the waveform is a half sine wave."

5.2. Analysis of the cognitive mechanisms underlying misconceptions

In-depth analysis of interview materials identifies the following cognitive mechanisms: students tend to make judgments relying on diagrams or superficial features rather than analyzing problems based on physical principles; students incorrectly transfer vector concepts learned in mechanics and causal relation concepts from kinematics to the context of circuit analysis; students struggle to carry out holistic analysis and prefer sequential reasoning or partial judgment only; students fail to connect concepts of electric field and electric potential acquired in electrostatics with current and voltage learned in circuit courses.

6. Discussion

6.1. Comparison with international research

This study observes misconception patterns highly similar to those recorded in international literature among undergraduates at Chinese universities, proving that these cognitive difficulties possess certain universality. For instance, the current-centered reasoning mode [1], the disconnection between macroscopic phenomena and microscopic mechanisms [4], and the sequential reasoning mode [3] summarized in overseas studies are all verified in this research result. It indicates that misconceptions in circuit learning are cross-culturally universal and are likely associated with general inherent features of human cognition.

6.2. Implications for teaching

The causal notion that voltage drives current must be emphasized throughout teaching. Instructors should repeatedly stress that potential difference acts as the fundamental cause of current generation, rather than the reverse case where current produces voltage.

Efforts should be made to help students establish links between macroscopic phenomena and microscopic principles. Teachers may explain circuit behaviors via microscopic models such as electric field line drawing and charge distribution elaboration, so as to foster students' mechanistic understanding.

Targeted diagnostic tools can be developed by educators. Teachers may adopt the questionnaire designed in this research as a pre-class test to identify students' misconceptions and carry out more targeted teaching activities accordingly.

Instructors shall attach importance to cultivating students' capacity for qualitative analysis. Students ought to be prevented from mechanically applying formulas blindly; more training on qualitative reasoning and teaching strategies including concept mapping should be adopted.

6.3. Limitations of the research

All participants are recruited from a single university, which may bring limitations related to regional factors and school types. The questionnaire contains a limited number of items and fails to cover all knowledge points of circuits. The sample size of interviewees is relatively small, and the scale of interviews can be expanded in follow-up studies.

7. Conclusions and recommendations

7.1. Main conclusions

With the application of diagnostic questionnaires and semi-structured interviews, this study systematically identifies typical misconceptions held by engineering undergraduates in the learning of direct current circuits. The primary conclusions are summarized as follows:

First, students hold systematic misconceptions concerning knowledge points including Kirchhoff's Current Law, the scalar property of electric current, parallel circuit analysis, capacitor behaviours and the ideal diode model. Second, the cognitive mechanisms underlying these misconceptions mainly consist of intuitive reasoning, inappropriate analogical transfer, partial reasoning, and the separation between macroscopic phenomena and microscopic mechanisms. Third, conventional teaching methods have evident deficiencies in assisting students to establish connections between microscopic mechanisms and macroscopic phenomena. Fourth, this research verifies that misconceptions recorded in international literature also prevail among learners in the Chinese educational context, which proves the cross-cultural universality of such misconceptions.

7.2. Teaching suggestions

1. The causal relationship that voltage drives current shall be highlighted repeatedly in routine teaching;
2. Microscopic models such as electric fields and charge distribution can be frequently introduced to explain circuit phenomena;
3. Develop teaching intervention tools formulated on the results of misconception diagnosis;
4. Increase the teaching content focusing on qualitative analysis and conceptual reasoning practice.

7.3 Directions for Future Research

1. Expand the sampling scope to conduct comparative research across different universities and regions;

2. Develop a more comprehensive diagnostic tool for circuit concepts;
3. Design teaching intervention experiments based on misconception diagnosis to test the effectiveness of optimized teaching strategies;
4. Explore whether students develop similar patterns of misconceptions in other fields of electromagnetism, such as magnetic fields and electromagnetic induction.

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Appendices

Appendix A: Diagnostic Questionnaire (Sample Questions)

Question 4: As shown in the figure, there are three junctions A, B and C in the circuit. Given $I_1=3A$, $I_2=1A$, $I_3=2A$. Which equation correctly describes the current relationship at junction A?

- A. $I_1+I_2+I_3=0$ B. $I_1=I_2+I_3$ C. $I_1+I_2=I_3$ D. $I_1-I_2+I_3=0$

Question 9: As shown in the figure, a capacitor $C=100\mu F$, $R=1k\Omega$ are connected to a DC power supply of $U=10V$. What is the voltage across the resistor immediately after the switch is closed?

- A. 0 V
B. 5 V
C. 10 V
D. 1 V

Question 15: As shown in the figure, an ideal diode is connected in series with a resistor to an AC power supply with sinusoidal output. What is the waveform of the instantaneous voltage-time $U-t$ curve across the ideal diode and the resistor?

- A. Complete sine wave
B. Half sine wave
C. Triangular wave
D. Square wave

Appendix B: Interview Outline (Excerpt)

1. Please explain why you chose this option.

2. Could you describe your thinking process?
3. How do you think the current or voltage changes in this circuit?
4. What changes do you expect if a certain component in the circuit is replaced?
5. What do you think is the relationship between voltage and current?

Appendix C: Examples of Interview Coding

Table A1. Examples of interview coding

Interviewee ID	Question No.	Concept	Misconception Identified
6	4	Kirchhoff's Current Law (KCL)	Believed that the current directions at a Y-shaped junction are fixed, with current always entering through the branch forming an obtuse angle with the other two branches and leaving through the other two branches. Q: Why do you think $I_1 = I_2 + I_3$? A: Because that's how it is drawn in the figure.
3/4/6	4	Understanding of Electric Current	Believed that electric current is a vector quantity because it has both magnitude and direction. Q: Do you think electric current is a scalar or a vector quantity? A: Since it has both magnitude and direction, I think it is a vector.
3	12	Series-Parallel Circuit Analysis	Used the total circuit current when analyzing the power of a lamp in a parallel branch. Q: Why do you think L_1 becomes dimmer? A: Because when L_2 burns out, the total current in the circuit decreases, so the power of L_1 also decreases.
6	9	Current and Voltage in Electric Circuits	Believed that if there is no current in a circuit, there can be no voltage. Q: Why do you think there is no voltage across the capacitor immediately after the switch is closed, when there is no current in the circuit? A: If there is no current, how could there still be any voltage?
6	9	Analysis of Charged Capacitors	Believed that the capacitor plate from which current flows out is positively charged. Q: Which capacitor plate do you think is positively charged, the upper plate or the lower plate? A: The lower plate is positively charged because current flows out of it.
1/3/4/5/6/9	15	Ideal Diode Model	Focused only on the unidirectional conduction property of an ideal diode and overlooked its zero forward resistance during conduction. Q: Could you explain the physical model of an ideal diode? A: An ideal diode conducts in only one direction. Current can pass through it in only one direction.

Table A1. (cotinued)

1/3/4/5/6/8/9	15	Voltage Analysis in Electric Circuits	Believed that when an ideal diode is non-conducting, there is no voltage across it. Q: What do the instantaneous voltage–time waveforms across the ideal diode and the resistor look like? A: The ideal diode does not conduct for half of the cycle, so there is no voltage during that half. Therefore, the waveform is a half-wave sine wave.
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