Students' understanding in DC analysis of bipolar junction transistor circuits

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Abstract
This research investigates the depth of students' understanding of fundamental circuit concepts, the characteristics of bipolar junction transistor (BJT), and their integration in solving DC transistor circuit analysis problems. Adopting a qualitative research design, the study involved undergraduate students enrolled in an introductory electronics course. The validity of the data was ensured through methodological triangulation employing comparative testing and Socratic dialogue. The comparative test consisted of two models: one focusing on current-strength comparisons and the other on voltage-level comparisons. The findings were verified and elaborated through Socratic dialogue using critical and exploratory questions to probe and test students' ideas, assumptions, and beliefs. Data analysis and interpretation were facilitated through an integration matrix that aligned students' comparative-test responses with their corresponding Socratic dialogues. Findings on the understanding in DC analysis of BJT circuits revealed three distinct categories of understanding: (1) Students who merely guessed answers without grasping either fundamental circuit principles or transistor behavior; (2) Students capable of performing mathematical analysis but lacking a sound conceptual understanding of transistor behavior; and (3) Students who could perform mathematical analysis and demonstrated a reasonable understanding of transistor behavior, yet still exhibited certain misconceptions. The findings imply the importance of fostering conceptual synthesis in BJT circuit analysis to enhance transferable problem-solving skills for analyzing more complex electronic systems and to support deeper analytical reasoning in electronics learning.

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1. Introduction

A bipolar junction transistor (BJT), often referred to simply as a bipolar transistor, is widely used in basic amplifier circuits. In general, bipolar transistors are employed to amplify AC signals while utilizing a DC power supply (Boylestad & Louis, 2013). Considering that the power supply of a transistor amplifier circuit is DC, whereas the input to be amplified is an AC signal, circuit analysis is therefore performed using two approaches: DC analysis and AC analysis. The key to successfully solving DC transistor analysis problems lies in: (1) the skill to apply basic circuit concepts, (2) the skill to apply transistor concepts, and (3) the ability to integrate basic circuit concepts with transistor concepts (Boylestad & Louis, 2013; Docktor et al., 2016; McDermott & Shaffer, 2002; Van De Bogart & Stetzer, 2018).

Being able to apply concepts to solve novel or modified problems is one of the hallmarks of conceptual understanding (McDermott & Shaffer, 2002; Van De Bogart & Stetzer, 2018). Success in addressing new problem forms indicates that a learner is not merely memorizing but truly mastering the meaning and application of the concepts (Docktor et al., 2016). Research on students' mastery of basic circuit concepts has shown that: (1) students fail to apply Ohm's law and Kirchhoff's laws, (2) students do not apply basic circuit concepts consistently and systematically (Coppens et al., 2017; Ercan, 2016; Liu et al., 2022; Ünal, 2022). With respect to mastery of transistor concepts, research has revealed that novice students tend to search for superficial matches to solutions when solving analysis problems (Narayanan et al., 2023). Although students studying transistor circuits have previously taken basic circuit courses (e.g., Fundamental Physics II), in reality, many lack understanding and skill due to retention issues, while others never grasped the concepts from the outset (Docktor et al., 2016).

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Skills in integrating the interrelationships among concepts are essential for solving electrical circuit problems. In reality, students tend to rely on a single concept when solving problems and have yet to utilize the connections among multiple concepts, even though solving electrical circuit problems often requires the ability to synthesize (Ibrahim & Ding, 2021) by integrating various concepts. The analysis of transistor circuits likewise demands a synthesis of concepts, including basic circuit concepts. Unfortunately, students frequently fail to grasp the circuit as a whole (McPadden et al., 2018).

Van De Bogart & Stetzer (2018) conducted a research entitled "Investigating Student Understanding of Bipolar Junction Transistor Circuits." In their research, Van De Bogart used a comparative test (McDermott & Shaffer, 2002). The DC transistor circuit analysis in Van De Bogart's research tended to focus on students' understanding of transistor characteristics. The questions in Van De Bogart's research predominantly required solutions based on the application of transistor characteristic concepts. In contrast, the questions in our research require solutions that utilize both basic circuit concepts and transistor characteristics in an integrated manner. Accordingly, our research focuses on exploring the extent of students' understanding of basic circuit concepts, the characteristics of bipolar transistors, and their integration in solving DC transistor circuit analysis problems.

The study by (Handhika et al., 2025) revealed that students tend to rely on trial-and-error strategies when solving circuit problems and potentially increasing the likelihood of incorrect answers. The interviews in that study focused on students' responses and explored the potential use of trial-and-error reasoning based on the answers provided. In the present study, the interviews were conducted in a more random manner, yet they still focused on responses related to fundamental concepts. When students' responses were inconsistent with these fundamental concepts, the likelihood of incorrect answers became substantially higher. This approach, implemented through Socratic dialogue, distinguishes the present study from previous research.

To sharpen the investigation, this research did not rely solely on data collected through the comparative test but also incorporated Socratic dialogue (Balbay, 2019; Skrefsrud, 2024). The comparative test (McDermott & Shaffer, 2002) was designed to encourage students to engage in analytical thinking by integrating multiple concepts when solving problems, rather than relying on rote memorization. This approach makes the differences between answers derived from concept integration and those based on memorization clearly observable. The Socratic dialogue was conducted to obtain more comprehensive information and to more accurately determine the extent to which students understood basic circuit concepts, grasped transistor characteristics, and demonstrated the ability to integrate multiple concepts when solving problems. Socratic dialogue is regarded as highly effective in qualitative research because the method does not merely seek 'correct answers'; rather, it facilitates the disclosure of the deeper meanings underlying human experience. In the article Socratic Dialogue as a Way Toward Wonder and Aletheia in Qualitative Research and Action Research (Dinkins & Cangelosi, 2019), the authors emphasize that Socratic dialogue operates through a process of shared reflection that creates space for 'wonder' (philosophical astonishment) and 'aletheia' (unconcealed truth or truth as disclosure).

2. Method

This research involved ten respondents enrolled in an introductory electronics course and adopted a qualitative approach. The validity of the data was ensured through methodological triangulation using a comparative test and Socratic dialogue. This article presents two essential comparative-test questions in two models: one comparing current magnitude and the other comparing voltage levels. The questions for the comparative test were developed through discussions among the researchers and were content-validated before administration. We used content validation (involving experts) in both the development of the test items and the assessment process. In conducting the assessment, both experts agreed and shared the same understanding in evaluating the responses.

The test was administered after the respondents had studied bipolar transistors, including biasing and their characteristics. Before the test, it was assumed that students had already learned basic circuit concepts in the Fundamental Physics II course and had revisited them sporadically during the introductory electronics course. After the test, the students' answers were reviewed to examine and identify their reasoning patterns. These patterns served as the basis for initiating the Socratic dialogue, which was conducted in a separate session. To further substantiate the findings, the Socratic dialogue involved posing critical questions designed to explore and test students' ideas, assumptions, and beliefs. These questions were progressively deepened and directed to explore and confirm the extent of students' understanding of basic circuit concepts, the characteristics of bipolar transistors, and their integration in solving DC transistor circuit analysis problems. Figure 1 shown a research flow.

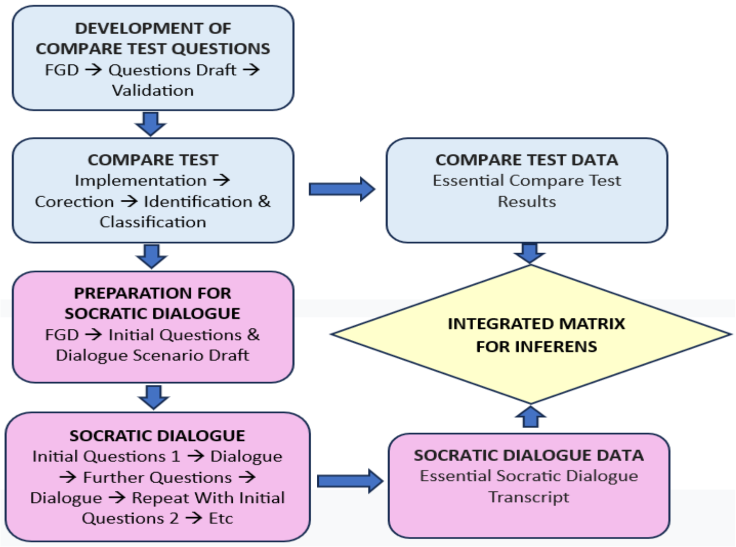

Figure 1. The Research Flow

Data analysis was carried out by reducing the data, sorting and classifying essential data, and determining the correspondence between the results of the comparative test and the Socratic dialogue. The corrected answers from the comparative test were sorted and classified. To facilitate the identification of essential data from the comparative test and the transcripts of the Socratic dialogue, coding and thematic analysis of the dialogue transcripts were performed with reference to the test classifications. Conclusions were drawn with the aid of a matrix that integrated key data from both the comparative test and the Socratic dialogue.

2.1. Comparative test Questions

The transistors in all three of the following circuits have βdc = 100. **Figure** 2 shown a BJT transistor circuit configurations for comparative analysis, including the original circuit, Modification A, and Modification B.

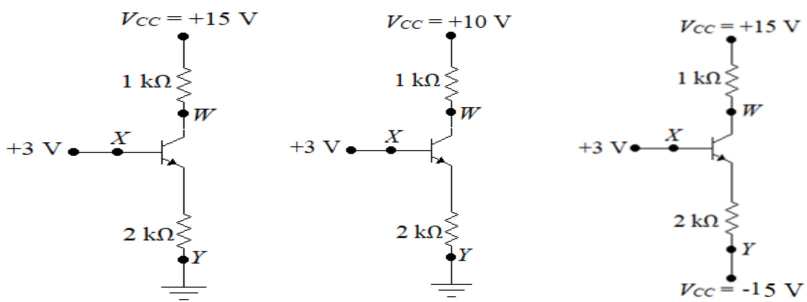

Figure 2. BJT transistor circuit configurations for comparative analysis, including the original circuit, Modification A, and Modification B

a. If the original circuit is changed to Modification A, will the current at point W (expressed as IW) increase, decrease, or remain the same? Explain your answer.

b. If the original circuit is changed to Modification B, will the current at point W (expressed as I_W) increase, decrease, or remain the same? Explain your answer.

A transistor (βdc = 200) is connected in a circuit as shown in the accompanying figure. Arrange the values of VE, VB, and VC with respect to ground from the largest to the smallest. Explain your answer. Figure 3 shown a BJT transistor circuit for analyzing the collector, base, and emitter voltages relative to ground.

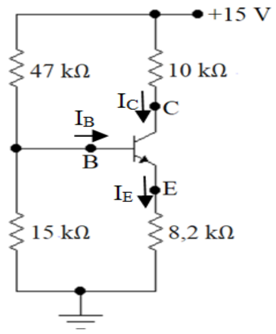

Figure 3. BJT transistor circuit for analyzing the collector, base, and emitter voltages relative to ground

3. Results and Discussion

The results and discussion in this article are presented in an integrated manner to enhance the efficiency of data interpretation and facilitate readers' understanding. They are organized into two sections: (1) the Current Comparison Model and (2) the Voltage Comparison Model.

3.1. Current-Comparison Model

The respondents' answers to question 1.a and the Socratic dialogue are grouped into three answer variants. To facilitate interpretation and produce high-quality conclusions, the discussion refers to the integration matrix in Table 1, Table 2, and Table 3.

Table 1. Integration matrix of the "Current Comparison Model" for answer variant 1.a.1
(Respondents no. 2, 4, 6, 7, 8, 10)

Test Answer Excerpt	Excerpt from Essential Socratic Dialogue (related to Q1.a)	Inference
Since the collector supply voltage (VCC) decreases, the collector current (IW = IC) also decreases.	Lecturer: Can you calculate the base current I_X using Ohm's Law? M2: Yes. Lecturer: What's the mathematical expression? M2: $I_X = \frac{V}{R}$ Lecturer: Which voltage (V) do you mean? M2: Vin = 3 Volt, Sir. Lecturer: Which resistance (R)? M2: 2 kΩ Lecturer: Please calculate it. M2: $I_x = \frac{3\,Volt}{2\,k\Omega} = 1.5\,mA$ = 1.5 mA	The respondent merely guessed the answer based on the difference between modified circuit A and the original circuit.

Respondents in answer variant 1.a.1 did not understand that the collector current is determined by the base emitter configuration rather than by the collector voltage, provided that the collector voltage remains sufficiently high. When randomly questioned through Socratic dialogue regarding basic circuit concepts (Ohm's law), the respondents merely engaged in a plug-and-chug approach when calculating the base current by substituting the 2 kΩ resistor into Ohm's law, even though the resistor was located in the emitter path rather than in the base path. Consistent with the findings of Helping First-Year University Students to Overcome the Threshold Concept of Ohm's Law, this plug-and-chug behavior appears to stem from respondents' reliance on memorizing the mathematical expression of Ohm's law without being able to apply it appropriately (Jose Canet et al., 2025). In the study Investigating Student Understanding of Bipolar Junction Transistor Circuits (Van De Bogart & Stetzer, 2018), such plug-and-chug behavior was not observed. Instead, Van De Bogart's study primarily highlighted responses grounded in students' understanding of transistor characteristics.

Although the random questioning of respondents was not yet well-directed and was less relevant to the test answers, it is already very clear that the respondents did not understand basic circuits. Therefore, it can be concluded that respondents in answer variant 1.a.1 were merely guessing the transistor circuit question based on the differences between modified circuit A and the original circuit.

Table 2. Integration matrix of the current-comparison model, answer variant 1.a.2
(Respondents No. 3, 9)

Test Answer Excerpt	Excerpt from Essential Socratic Dialogue (related to Q1.a)	Inference
$V_E = V_B - V_{BE}$ $= 3 - 0.7 = 2.3\ Volt$ $I_E = \frac{V_E}{R_E} = \frac{2.3\ Volt}{2\ k\Omega}$ $= 1.15\ mA$ $I_C = \frac{\beta_{dc}}{\beta_{dc}+1} I_E$ $= \frac{100}{100+1} x1.15\ mA$ $= 1.139\ mA$ There is no calculation explanation for either the original circuit or modification A. The collector current (IC) decreases because VCC drops from 15 Volt to 10 Volt.	lecturer: Is your calculation of IC = 1.139 mA for the original circuit or for modification A? M9: The original circuit. Lecturer: Can you calculate the base current IX using Ohm's law? M9: I can't, because VB is not yet known. Instructor: Isn't Vin the same as VB ? M9: Yes, it's the same, so I could but since there is no base resistor, I can't. Instructor: Can the emitter current be calculated directly? M9: Yes. Instructor: Using Ohm's law, KCL, or KVL? M9: Ohm's law. Instructor: Could you use KCL? M9: No, because the base current and collector current is not yet known. Instructor: Using KVL? M9: No, because KVL is for calculating voltages. Instructor: Are there any other factors affecting the collector current besides VCC ? M9: None.	The respondent demonstrated the ability to calculate currents in the transistor circuit procedurally but has not yet understood the conceptual relationship between the circuit parameters and the transistor's behavior. The respondents assumed that Kirchhoff's Voltage Law (KVL) is used solely for calculating voltage.

Respondents with answer variant 1.a.2 had already adopted an appropriate initial approach to calculate the emitter and collector currents, indicating a sufficient level of procedural understanding of basic circuit concepts. This understanding was further tested when they were asked to use Ohm's Law to calculate the base current. Although initially hesitant, they quickly understood after receiving follow-up questions. Nevertheless, the respondents had not yet fully mastered the application of fundamental laws. When calculating the emitter current using the base–emitter loop, they chose to apply Ohm's Law and declined to use KVL, reasoning that KVL is only for calculating voltages. In the study Towards a Research Program in Designing and Evaluating Teaching Materials: An Example from DC Resistive Circuits in Introductory Physics (Zuza, Cock, et al., 2020; Zuza, Sarriugarte, et al., 2020), many students were found to be unable to correctly apply Kirchhoff's laws at the conceptual level. Overall, it can be concluded that the respondents understood how to compute transistor currents procedurally (Van De Bogart & Stetzer, 2018) but lacked a complete conceptual understanding and coherent logical reasoning about how changes in parameters (IE, IB, dan Vcc) affect the transistor's operating condition (IC). In drawing their conclusions, the respondents overlooked the characteristics/behavior of the bipolar transistor. They did not recognize that, in the active region (with the collector saturated and VCC still providing sufficient reverse voltage), the collector current depends solely on the base current through the relationship IC = βdcIB (Boylestad & Louis, 2013; Staffas, 2017; Van De Bogart & Stetzer, 2018). A synthesis of the test answers and excerpts from the Socratic dialogue transcripts revealed that the respondents did not understand that the collector current is determined by the base–emitter configuration rather than by the collector voltage (as long as the collector reverse voltage remains sufficiently high).

Table 3. Integration matrix of the current-comparison model, answer variant 1.a.3
(Respondents No. 1, 5)

Test Answer Excerpt	Excerpt from Essential Socratic Dialogue (related to Q1.a)	Inference
$V_E = V_B - V_{BE} = 3 - 0.7$ $= 2.3\ Volt$ $I_E = \frac{V_E}{R_E} = \frac{2.3\ Volt}{2\ k\Omega} = 1.15\ mA$ $I_C = \frac{\beta_{dc}}{\beta_{dc}+1} I_E$ $= \frac{100}{100+1} x1.15\ mA$ $= 1.139\ mA$	Lecturer: Is your calculation of IC = 1.139 mA for the original circuit or for modification A? M5: For both the original circuit and modification A. Lecturer: Can you calculate the base current IX using Ohm's Law? M5: No, because there is no base resistor. Lecturer: Can the emitter current be calculated directly? M5: Yes.	The respondent demonstrated the ability to calculate currents in a transistor circuit procedurally and showed a limited understanding of the conceptual relationships between

Test Answer Excerpt	Excerpt from Essential Socratic Dialogue (related to Q1.a)	Inference
There is no calculation explanation for either the original circuit or modification A. The collector current (IC) remains the same because the collector voltage does not affect the current magnitude	Lecturer: Using Ohm's Law, KCL, or KVL? M5: Ohm's Law. Lecturer: Can you use KCL? M5: No, because the base current and the collector current are not yet known. Lecturer: Can you use KVL? M5: No, because KVL is for calculating voltages. Lecturer: Does VCC affect IC? M5: No. Lecturer: Why? M5: Because the magnitude of IC is determined by the emitter current IE . The value of IE in modification A is the same as in the original circuit, so IC in both circuits remains the same.	circuit parameters and transistor behavior. However, the respondent did not understand that their answer applies only when the collector is in saturation.

Respondents with answer variant 1.a.3 had already adopted an appropriate initial approach to calculate the emitter and collector currents. This indicates that they demonstrated an adequate procedural understanding of basic circuit concepts. However, they did not fully demonstrate a comprehensive understanding of the application of fundamental laws. When calculating the emitter current using the base–emitter loop, the respondents chose to apply Ohm's Law and refused to use KVL, reasoning that KVL is only for calculating voltages. In the study Investigating Student Understanding of Bipolar Junction Transistor Circuits (Van De Bogart & Stetzer, 2018), the use of Kirchhoff's Voltage Law (KVL) did not appear to underlie the analysis, as the study placed greater emphasis on transistor concepts, particularly the parameters αdc and βdc. Overall, the respondents could be said to understand how to calculate transistor currents procedurally, but they still lacked full conceptual understanding and logical reasoning about how changes in parameters (IE, IB, dan Vcc) affect the transistor's operating condition (IC). When drawing conclusions, the respondents did consider the characteristics and behavior of the bipolar transistor, and their reasoning was already based on correct calculations. However, their statement that "the collector voltage (Vcc) does not affect the collector current" shows that they did not fully understand that in extreme cases (for example, when VCC is too small or does not provide sufficient reverse voltage), the collector current is no longer controlled by the base current through the relationship IC = βdcIB (A. Malvino & Bates, 2016) or by the base–emitter configuration (Boylestad & Louis, 2013; A. Malvino & Bates, 2016). The most plausible explanation is that students never critically questioned or verified what occurs when extreme values are applied in a circuit.

Referring to the discussion of the research findings presented in Tables 1 through 6, it was found that all respondents tended to use Ohm's Law to calculate current even though KVL is actually more practical and carries a lower risk of error. The respondents did not understand that Ohm's Law is only appropriate for special cases, whereas KVL is more suitable for general cases. More critically, they believed that KVL is only applicable for calculating voltages.

The respondents' answers to question 1.b and the relevant Socratic dialogues are categorized into three groups of answer variants. To facilitate interpretation and produce high-quality conclusions, the discussion refers to the integration matrices presented in Table 4, Table 5, and Table 6.

Table 4. Model Integration Matrix Comparing the Current Strength of Answer Variant 1.b.1
(Respondents No. 2, 4, 5, 7, 8, 10)

Test Answer Excerpt	Excerpt from Essential Socratic Dialogue (related to Q1.b)	Inference
The collector current (IW) decreases to zero because the emitter is connected to -15 Volt, causing the transistor to become inactive.	Lecturer: What is the supply voltage of the base–emitter loop? M7: VB = 3 Volt, while VE = -15 Volt. Lecturer: Is the transistor in modification B in the active region? M7: No. Lecturer: Is the emitter forward-biased or reverse-biased? M7: Reverse-biased. Lecturer: What is the reason? M7: Because the emitter is connected to -15 Volt.	The respondents did not understand the basic circuit concepts (particularly the potential difference), nor did they understand the concept of biasing or the behavior of the transistor.

Respondents with answer variant 1.b.1 were completely incorrect because whether a transistor is active or not is determined by the supply voltage of the base–emitter loop (the difference between VBB and VEE). In modification B, the base–emitter loop supply voltage is 3 Volt – (-15 Volt) = 18 Volt, which is far above 0.7 V (the standard VBE for silicon-based transistors). This means the transistor is strongly active (and could even approach extreme saturation if not limited), so the collector current is guaranteed to be sufficiently large, as correctly calculated in the answer for question 1.b (approximately 8.564 mA).

In the dialogue, "What is the supply voltage of the base–emitter loop?", the respondents' numerical answer, VB = 3 Volt and VE = -15 Volt, indicates a lack of understanding that voltage is a potential difference. The study Teaching Electric Circuits with a Focus on Potential Differences (Burde & Wilhelm, 2020) suggests that instruction on electric circuits should not begin with a primary focus on electric current, but rather on potential difference (voltage) as the central concept for understanding electric circuits. The study Coupling of External Electric Circuits with Computational Domains (Burde & Wilhelm, 2020; Scorretti, 2021) emphasizes that voltage is not merely a simple 'potential difference' that can be easily understood. From the dialogues "Is the transistor in modification B active?" and "Is the emitter forward- or reverse-biased?", the answers show that the respondents did not understand transistor behavior or the concept of transistor biasing (Boylestad & Louis, 2013; A. Malvino & Bates, 2016; Staffas, 2017). Their reasoning that the emitter is reverse-biased because it is connected to -15 V indicates a failure to understand the concepts of forward and reverse transistor biasing. The respondents also failed to distinguish between absolute voltage relative to ground and the relative voltage between the base and emitter potentials. Overall, both in written answers and dialogue responses, the respondents exhibited misunderstandings regarding voltage as a potential difference, determining the direction of base–emitter bias, and evaluating the transistor's active condition.

Table 5. Integration matrix of the current-comparison model, answer variant 1.b.2
(Respondents No. 1, 6)

Test Answer Excerpt	Excerpt from Essential Socratic Dialogue (related to Q1.b)	Inference
The collector current (IW) increases because the emitter is connected to -15 Volts, causing the voltage between the collector and emitter to increase.	Lecturer: What is VC in modification B? M1: VCE = 15 Volt – (-15) Volt = 30 Volt. Lecturer: What is the supply voltage of the base–emitter loop? M1: VBB = 3 Volt and VEE = -15 Volt, so the base–emitter loop supply voltage is 3 Volt – (-15 Volt) = 18 Volt. Lecturer: What is the emitter current? M1: $I_E = \frac{18\,Volt - 0.7\,Volt}{2\,k\Omega} = 8.65\,mA$. Lecturer: Is the emitter forward- or reverse-biased? M1: Forward-biased. Lecturer: What is the reason? M1: Because the N-type emitter is connected to -15 V.	The respondents demonstrated the ability to calculate currents in transistor circuits procedurally and understood the concept of transistor biasing, but they could not provide an accurate explanation for the cause of the increase in collector current.

Respondents with answer variant 1.b.2 stated that "the collector current (IW = IC) increases because the emitter is connected to -15 Volts, causing the voltage between the collector and emitter to increase," which is technically incorrect (Boylestad & Louis, 2013; A. Malvino & Bates, 2016; Schroter & Pawlak, 2018). The study Heuristic for Learning Common Emitter Amplification with Bipolar Transistors (Staffas, 2017) explains that students' main difficulties typically arise in understanding the relationship among base, collector, and emitter currents, changes in collector voltage, and the concept that a transistor controls a large current by means of a small current. The dialogue shows that the respondents believed the collector–emitter voltage is VCE = 15 volt – (-15) Volt = 30 Volt. This opinion is mistaken. The correct VCE in modification B should be calculated using KVL through the equation VCC – VEE – IC RC – VCE – VE = 0. Through the Socratic dialogue, the respondents indicated that they thought the increase in collector current was due to the potential difference between VCC and VEE . This reasoning is also incorrect because, in the active region, the increase in collector current is actually caused by VBB – VEE = 3 Volt – (-15) Volt = 18 Volt, which increases the emitter and base currents in modification B compared to the original circuit.

Based on an integrated analysis of the test answers and Socratic dialogues, it can be concluded that respondents with answer variant 1.b.2 are able to calculate currents in transistor circuits procedurally and understand the concept of transistor biasing, but they cannot provide an accurate explanation for the cause of the increase in collector current.

Table 6. Integration matrix of the current-comparison model, answer variant 1.b.3
(Respondents No. 3, 9)

Test Answer Excerpt	Excerpt from Essential Socratic Dialogue (related to Q1.b)	Inference
The collector current (IW) increases because $VV_B - V_E = 3 - (-15) = 18\ Volt$. VB−VE=3−(−15) =18Volts	Lecturer: What is the supply voltage of the base–emitter loop? M9: The supply voltage of the base–emitter loop is 3 Volt – (-15 Volt) = 18 Volt. Lecturer: What is the emitter current? M9: $I_E = \frac{18\ Volt - 0{,}7\ Volt}{2\ k\Omega} = 8.65\ mA$. Lecturer: Is the emitter forward- or reverse-biased? M9: Forward-biased. Lecturer: What is the reason? M9: Because the N-type emitter is connected to -15 V. Lecturer: If -15 V is replaced with +1 V, is the emitter forward- or reverse-biased? M9: Reverse-biased, because the N-type emitter is connected to +1 V.	The respondents demonstrated a fairly good and consistent understanding of potential difference, but their technical reasoning regarding transistor biasing was still expressed intuitively

The test answer of respondents with answer variant 1.b.3, "The collector current (IW) increases because $V_B - V_E$ = 3 – (-15) = 18 Volt" demonstrates a fairly good understanding, although the notation is somewhat inaccurate (it should be $VV_{BB} - V_{EE}$). The respondents were not misled by the increase in potential difference between VCC and VEE. This indicates a good understanding that the collector current is controlled by the base–emitter voltage (Boylestad & Louis, 2013; A. Malvino & Bates, 2016; Schroter & Pawlak, 2018; Staffas, 2017), rather than solely by the collector–emitter voltage.

The respondents also answered the dialogue question regarding the emitter current correctly, showing that they could apply basic circuit concepts. In the dialogue, the respondents consistently calculated voltages and currents correctly and concluded that the emitter was forward-biased; however, their explanation for the cause of the forward bias still requires further elaboration. Regarding transistor bias, the respondents still provided answers and reasoning intuitively. The dialogue transcript, "reverse-biased because the N-type emitter is connected to +1 V," indicates that the respondents did not fully understand the concept of forward and reverse biasing in a transistor (Boylestad & Louis, 2013; A. Malvino & Bates, 2016; Schroter & Pawlak, 2018; Staffas, 2017).

In the current-comparison model, the comparison between the present study and the research conducted by Van De Bogart & Stetzer (2018) is presented in Table 7.

Table 7. Current research vs. Van De Bogart & Stetzer (2018) in the current-comparison model

Aspect	Current Research	(Van De Bogart & Stetzer, 2018)
Procedural understanding at a good level	Students calculate IE and IC using basic circuit concepts as well as transistor concepts through the relationships of parameters βdc and αdc.	Students calculate basic parameters, but tend to use transistor concepts mainly through the relationships of parameters βdc and αdc.
Conceptual understanding at a good level	Students understand that IC is determined by the base–emitter configuration and Vcc, but neglect the active and saturation conditions.	Students think that VCE or VCC directly determines IC , and that IC depends on IB, but they neglect the active and saturation conditions.

3.2. Voltage Comparison Model

Identification of respondents' answers to question number 2 and the relevant Socratic dialogue is divided into three groups of answer variants. To facilitate interpretation and produce high-quality conclusions, the discussion is conducted with reference to the integration matrices in Table 8, Table 9, and Table 10.

Table 8. Integration Matrix of the Voltage-Comparison Model for Answer Variant 2.1
(Respondent No. 1)

Test Answer Excerpt	Excerpt from Essential Socratic Dialogue (related to Q1.b)	Inference
The order of voltages from the largest to the smallest is VE > VC > VB	Lecturer: In an electrical circuit, is the electric current determined by the magnitude of the voltage? M1: Yes. Lecturer: In a transistor circuit, is the order of currents from largest to smallest IE > IC > IB? M1: Yes. Lecturer: Because the order of currents is IE > IC > IB, does that mean the order of voltages is VE > VC > VB? M1: Yes.	The respondent uses faulty logic, directly linking the order of current strength with the order of voltage

The respondent's answer of "yes" to the dialogue question "In an electrical circuit, is the electric current determined by the magnitude of the voltage?" is not wrong but not entirely correct. In general circuits, voltage indeed enables current flow, but more precisely, current is determined by both voltage and resistance. In a transistor circuit, the behavior of the transistor (whether it is saturated or unsaturated, active or inactive) also plays a major role in determining the electric current in the transistor (Boylestad & Louis, 2013; A. Malvino & Bates, 2016; Schroter & Pawlak, 2018; Staffas, 2017). The respondent's test answer was VE > VC > VB. After verification through the Socratic dialogue, the result showed that the respondent reasoned: because IE > IC > IB, then the voltages also follow the same order, namely VE > VC > VB. The respondent used faulty logic, directly linking the order of current magnitudes to the order of voltages.

Table 9. Integration Matrix Model Comparing Voltage for Answer Variant 2.2
(Respondents No. 5, 7)

Test Answer Excerpt	Excerpt from Essential Socratic Dialogue (related to Q1.b)	Inference
The order of voltages from the largest to the smallest is VB > VC > VE	Lecturer: What is VB? M7: (Silent / confused). Lecturer: What is VE? M7: (Silent / confused). Lecturer: What is VC? M7: (Silent / confused). Lecturer: When measuring VB, to which points are the voltmeter connectors attached? M7: To the base and emitter leads. Lecturer: When measuring VC, to which points are the voltmeter connectors attached? M7: To the collector and emitter leads.	The respondent answered the test without applying concepts because they did not understand the concept of voltage.

Respondents in answer variant 2.2 made a fundamental error in distinguishing between voltages across transistor nodes/pins and voltages with respect to ground (Boylestad & Louis, 2013; Burde & Wilhelm, 2020; A. Malvino & Bates, 2016; Schroter & Pawlak, 2018; Staffas, 2017). The Socratic dialogue revealed that the respondents measured voltages between transistor terminals rather than with respect to ground (Felgueiras et al., 2018; Van De Bogart & Stetzer, 2018). This understanding needs to be corrected so that students do not develop misconceptions when reading and analyzing electronic circuits. The study teaching electric circuits with a focus on potential differences (Burde & Wilhelm, 2020), positions voltage as the central concept.

The answers and Socratic dialogue between the lecturer and M7 illustrate a typical situation in electronics learning: confusion between measuring voltage with respect to ground and the potential difference between two points (Felgueiras et al., 2018; Nethra Devi & Raghuram, 2021). The respondents answered the test without applying the basic circuit concept because they did not understand the concept of voltage.

Table 10. Integration Matrix Model Comparing Voltage-Answer Variant 2.3
(Respondents No. 2, 3, 4, 6, 8, 9, 10)

Test Answer Excerpt	Excerpt from Essential Socratic Dialogue (related to Q1.b)	Inference
The order of voltages from the largest to the smallest is VC > VB > VE	Lecturer: What is VB? M9: $V_B = \frac{R_2}{R_1} V_{CC} = \frac{15}{15+47} x15\ Volt = 3.63\ Volt$ Lecturer: What is VC? M9: $V_E = V_B - V_{BE} = 3.63 - 0.7 = 2.93\ Volt$ Lecturer: What is VC? M9: (Silent / confused) Lecturer: When measuring VC, between which points are the voltmeter connectors attached? M9: At the collector pin and ground. Lecturer: Why do you conclude that VC is the largest? M9: Because the collector is directly connected to VCC.	The respondent demonstrated a fairly good understanding, although guidance through dialog questions was needed. However, the respondent still had difficulty calculating VC because they had not yet fully understood the basic circuit.

Seven respondents belonged to answer variant 2.3; however, in this section, the Socratic dialogue transcript of one respondent (M9) is presented for discussion. The respondents' test answer, "the voltage order from highest to lowest is VC > VB > VE," was correct, but there was no explanation of how the respondent arrived at this conclusion. Exploration through the Socratic dialogue revealed that the respondent already possessed a relatively good basic understanding of DC biasing in transistors, particularly in calculating the base (VB) and emitter (VE) voltages. However, the dialogue also indicated a gap in understanding regarding the determination of the collector voltage (VC). M9 demonstrated an understanding of the voltage divider concept (Fauzi et al., 2021) used to provide bias to the transistor base. This concept is an important foundation for DC transistor analysis with voltage-divider biasing (Fauzi et al., 2021). The respondent also understood how to calculate the emitter voltage (VE) using both basic concepts and transistor characteristics (Felgueiras et al., 2018; Nethra Devi & Raghuram, 2021; Van De Bogart & Stetzer, 2018).

The dialogue response, "VC is the largest because the collector is directly connected to VCC," indicated that the respondent did not yet fully understand basic circuit concepts (Docktor et al., 2016; Fauzi et al., 2021). Based on the test answers and the integrated Socratic dialogue, the respondent demonstrated a fairly good understanding, although guidance through questioning was still necessary. However, the respondent continued to struggle with calculating VC because they did not yet fully understand the basic circuit.

In the voltage-comparison model, the comparison between the current research and Van De Bogart & Stetzer (2018) is presented in Table 11 below.

Table 11. Current Research vs. Van De Bogart & Stetzer (2018) in the Voltage-Comparison Model

Aspect	Current Research	Van De Bogart & Stetzer (2018)
Procedural Understanding at a Good Level	Procedures are carried out quite well but often without understanding the concepts behind them.	Procedures are carried out quite well but often without understanding the concepts behind them.
Conceptual Understanding at a Good Level	Menganggap VC paling besar hanya karena dihubungkan ke VCC. Assumes VC is the largest simply because it is connected to VCC.	Assumes the transistor is a switch without considering specific bias conditions.

The research findings regarding the respondents' conceptual framework are shown in Figure 4 and Figure 5.

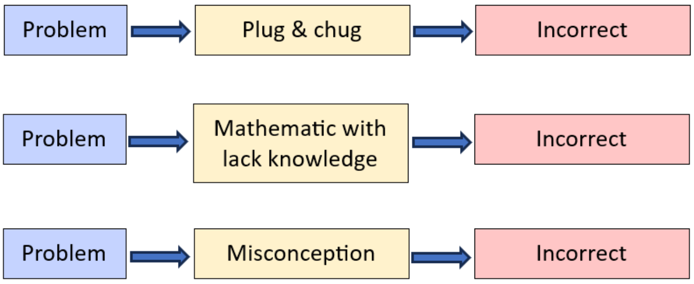

Figure 4. Respondents' conceptual framework

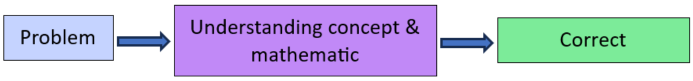

Figure 5. Ideal conceptual framework

4. Conclusion

In the current-comparison model, three levels of understanding were identified: (Group 1) Students guessed the answers solely based on differences in circuit variable values. In-depth verification revealed that they lacked understanding of basic circuit concepts, biasing, and transistor behavior. (Group 2) Students demonstrated the ability to calculate current in transistor circuits procedurally using basic circuit concepts. However, in-depth verification showed that they still did not understand the conceptual relationships between circuit parameters and transistor behavior. (Group 3) Students demonstrated the ability to calculate current in transistor circuits procedurally using basic circuit concepts and also understood the conceptual relationships between circuit parameters and transistor behavior. Nevertheless, deeper verification indicated that they still tended to rely on intuition and overlooked the saturation and active regions of the transistor. In the voltage-comparison model, three levels of understanding were also identified: (Group 1) Students answered the questions without applying any concepts. In-depth verification revealed that they did not understand the concept of voltage. (Group 2) Students applied faulty logic. In-depth verification showed that they directly linked the order of current magnitudes to the order of voltages. (Group 3) Students showed a fairly good understanding. However, in-depth verification indicated that they still did not fully understand basic circuit principles. Overall, students tended to use Ohm's Law to calculate current, even though Kirchhoff's Voltage Law (KVL) is actually more practical and carries a lower risk of error. They did not realize that Ohm's Law is strictly applicable only to special cases, whereas for more general cases, KVL is more appropriate. More critically, students assumed that KVL is only suitable for calculating voltage. These finding sugest that diagnostic assessment should be conducted prior to instruction in order to determine the extent to which students have mastered the prerequisite fundamental concepts. Without being informed by the results of such diagnostic assessment, the instructional process is unlikely to be effective. Instructors must ensure that students possess a strong understanding of fundamental circuit concepts as a foundation for learning transistor circuits.

These findings also suggest that fostering conceptual synthesis in BJT circuit analysis has implications beyond improving students' performance on basic transistor problems. Students who are able to integrate mathematical analysis with conceptual understanding of biasing, transistor operating regions, and circuit laws are more likely to develop transferable problem-solving skills applicable to more complex electronic systems, such as multistage amplifiers, switching circuits, and analog-digital interfaces. In particular, understanding the relationship between circuit parameters and transistor behavior may help students construct more coherent mental models when analyzing nonlinear electronic systems, where reliance on isolated formulas or intuition alone often leads to misconceptions. The results also indicate the importance of instructional approaches that emphasize conceptual integration between Ohm's Law, Kirchhoff's Voltage Law (KVL), and transistor operating principles, rather than treating these concepts as separate procedural tools. Such an approach may support students in developing deeper analytical reasoning, reducing errors in complex circuit analysis, and improving their readiness for advanced studies and professional practice in electronics engineering and physics education.

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