Addressing Conceptual Difficulties in Electrical Circuits: What is V? What is I? What is R?

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Outline

Survey of the literature:
• A typical response and an interpretation
• A catalog of common misconceptions

Working hypothesis:
• Conceptual difficulties are linked to inadequate or missing *qualitative* models connecting macroscopic observations with microscopic interactions.

Elements of a *qualitative, concept-oriented* approach
• Proper use of words and symbols
• Macro/Micro viewpoints
• Magnifying and exploiting transients
• A modified hydraulic analogy
• Resistance versus conductance
• Connecting wires as electrical points
• 3-D circuit diagrams
• Explicit comparison of current vs. emf sources
• Kirchhoff’s rules and self-consistency

Summary
A Typical Response and an Interpretation

Q: What happens to the brightness of bulbs A and B when bulb C is removed from this circuit

A: The current that used to flow through C must now pass through B. Therefore, B gets brighter. No change in A.

Interpretation: “Battery is constant current source” (??)
A Catalog of Common (Apparent) Misconceptions

- Batteries produce constant current.
- Charge/current originates in the battery.
- Charge/current is “used up” by circuit elements.
- Alterations in circuits have only “downstream” effects.
- Resistors (or light bulbs, etc.) are barriers to current flow; the more resistors the more resistance.
- Larger resistors use greater amounts of energy.
- Elements connected closer to the positive terminal (and thus “at higher voltage”) use larger amounts of energy.

Working Hypothesis

Conceptual difficulties are linked to inadequate or missing qualitative models connecting macroscopic observations with microscopic interactions. This results in

- undifferentiated views of charge, current, potential, potential difference, energy, and power.
- lack of appreciation for the ways in which equilibrium is dictated by self-consistency.
- failure to recognize global effects of local changes.
- careless (or uncritically applied) language that reinforces (but also reveals) faulty concepts.
Words and Symbols

• Prepositions (e.g., “across,” “through,” “in,” “of,”...)

• V (“potential,” not “voltage”) versus ΔV (“potential difference” or “p.d.,” not “voltage”)  
  \[ \Delta V = IR \]  
  \[ V_B = V_A + \Delta V \]

• Implications of the word “resistance.” How about “conductance”?

• Capacitance versus capacity
Macro-Micro Viewpoints

- Batteries maintain a potential difference by separating charge.
- Potentials and electric fields in circuits are the same kinds of things and exist for the same reasons as in electrostatics.
Macro-Micro Viewpoint: Charge Arrangement

The “desired” steady state
- Excess charge on surface produces $E$.
- $E$ drives steady (divergenceless) current.

Arriving at the steady state
- The arrangement takes time to establish.
- During the transient phase, current is not steady.
- Its divergence produces the excess charge.
- The excess charge appears just where it is needed.

This process produces and maintains a self-consistent solution.
Magnifying and Exploiting Transient Phenomena

\[ \Delta V_1 = \frac{\varepsilon}{2} \]
\[ \Delta V_2 = \frac{\varepsilon}{2} \]

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Modified Hydraulic Analogy
Is Resistance or Conductance the Relevant Concept?

• For elements in series, each element represents an additional impediment through which the current must flow.

⇒ “Resistance” is the appropriate concept.

\[ R_{\text{tot}} = R_1 + R_2 + R_3 + \ldots \]

• For elements in parallel, each element represents an additional path through which current may choose to flow.

⇒ “Conductance” (\( S = 1/R \)) is the appropriate concept.

\[ S_{\text{tot}} = S_1 + S_2 + S_3 + \ldots \]
Point A: “Positive battery terminal is connected to three resistors.”
Point B: “One of these resistors is connected to a capacitor.”
Point C: “The capacitor and the other two resistors are connected to a fourth resistor.”
Point D: “The fourth resistor is connected to the negative battery terminal.”
3-D Diagrams for Visualizing Relative Potentials

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What happens after the switch is closed?

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These curves reflect the choices $R_1 : R_2 : R_3 = 2 : 6 : 3$. 

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Removing a bulb: Constant current source

Before: \( i_1 = I, \ i_2 = i_3 = I/2 \)

After: \( i_1 = i_2 = I \)  \( \Rightarrow \)  (\#1 stays the same, \#2 gets brighter)
Removing a bulb: Constant emf source

Before: \[ i_2 = i_3 = \frac{i_1}{2} \implies V_1 > \frac{\mathcal{E}}{2} > V_2 = V_3 \]

After: \[ i_1 = i_2 \implies V_1 = V_2 = \frac{\mathcal{E}}{2} \]  (#1 gets dimmer, #2 gets brighter)
Self-Consistency and Kirchhoff's Laws

- Six currents and four potentials to be determined.
- Five loops and five junctions yield ten Kirchhoff equations.
- Problem is designed so that a step-by-step method will work.
Summary

An old refrain:

An ability to solve traditional quantitative problems does not imply “understanding.”

Instructional approaches to electric circuits should include qualitative, concept-oriented material designed to enhance students’ ability to

- differentiate between charge, current, potential, potential difference, energy, and power.
- appreciate the ways in which equilibrium is dictated by self-consistency.
- recognize global effects of local changes.

Elements of such an approach

- Proper use of words and symbols
- Macro/Micro viewpoints
- Magnifying and exploiting transients
- A modified hydraulic analogy
- Resistance versus conductance
- Connecting wires as electrical points
- 3-D circuit diagrams
- Explicit comparison of current vs. emf sources
- Kirchhoff’s rules and self-consistency
References

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