

AC 2008-2468: CIRCUIT ELEMENTS ARE PEOPLE TOO—USING PERSONIFICATION IN CIRCUIT ANALYSIS LECTURES TO IMPROVE COMPREHENSION

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Circuit Elements are People Too—Using Personification in Circuit Analysis Lectures to Improve Comprehension

Abstract

An intuitive knowledge of circuit analysis is critical to the success of students in the electrical field. It is regrettable that the typical sophomore becomes so overwhelmed by the abstract aspects of the subject that he/she loses sight of its intuitive nature.

A lecture technique is available that employs the personification of circuit elements to describe their behavior and interaction. Not only does this technique help to retain student interest, it also improves comprehension. A related technique is available to help reduce the occurrence of sign errors when performing mesh analysis. This paper describes the application of these techniques in an introductory circuit analysis course.

Source Behavior

Ideal sources, whether theoretical entities or models for actual components, are selfish devices that leave no provision for compromise. The ideal voltage source in Figure 1a “insists” that the voltage across its terminals is 12 V. More specifically, this source insists that the voltage at its positive terminal is 12 V higher than the voltage at its negative terminal. Likewise, the ideal current source in Figure 1b insists that the current in its branch is 10 mA. Such perspectives provide useful intuition about circuit behavior in general, but they are especially useful when discussing source combination or source neutralization.

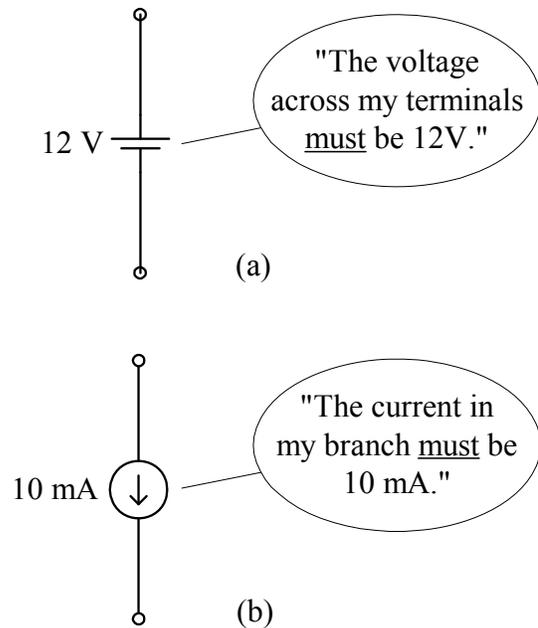


Figure 1: Ideal Source Behavior

Source Combination

The selfish nature of ideal sources provides a memorable explanation about why it is impossible to combine non-identical ideal voltage sources in parallel or non-identical ideal current sources in series. In Figure 2a, the left source insists that the terminal voltage of the circuit is 2V, while the right source insists that the same voltage is 3V. In Figure 2b, the upper source insists that the branch current is 10 mA, while the lower source insists that the same

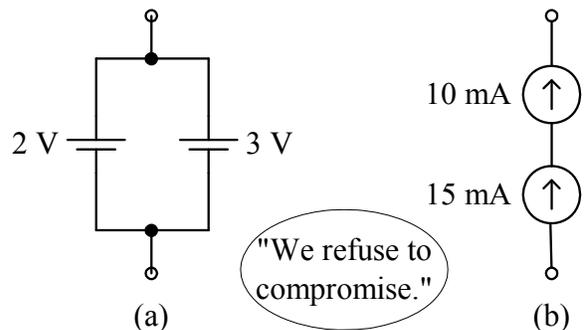


Figure 2: Impossible Source Combinations

current is 15 mA. Since ideal sources lack the ability to compromise, such cases either reflect a theoretical stalemate, or a situation in which at least one of the sources has to either become non-ideal or non-functional.

The selfish source perspective is also useful when combining ideal voltage sources in series or ideal current sources in parallel.

The fact that sources can either “assist” or “oppose” one another is a straightforward concept; the need to add the magnitudes of sources that assist, and subtract the magnitudes of sources that oppose is also apparent. The selfish source perspective provides an intuitive way to determine the voltage polarity (or current direction) of the resultant source in cases where the original sources operate in opposition to one another. The basic principle—“the big one wins”—can be applied to Figure 3a to conclude that the upper terminal of the resultant source is negative, while the same principle can be applied to Figure 3b to conclude that the positive current direction of the resultant source is downward.

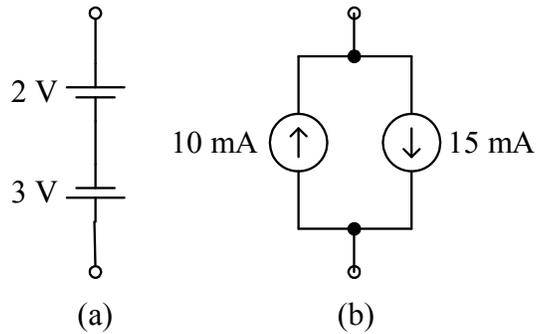


Figure 3: Ideal Sources Operating in Opposition

Source Neutralization

At times, it is necessary to “kill” sources for analysis purposes (e.g., when applying the superposition theorem or when computing the Thevenin resistance). Figure 4a illustrates a “dead” ideal voltage source, which clearly functions as a short circuit since it insists that the voltage across its terminals is 0V. Figure 4b illustrates a “dead” ideal current source, which clearly functions as an open circuit since it insists that no current can flow through its branch.

Resistor Behavior

Parallel resistors can be described as competing for current, while series resistors can be viewed as competing for voltage. Decreasing the value of a parallel resistor enables it to acquire a greater share of the

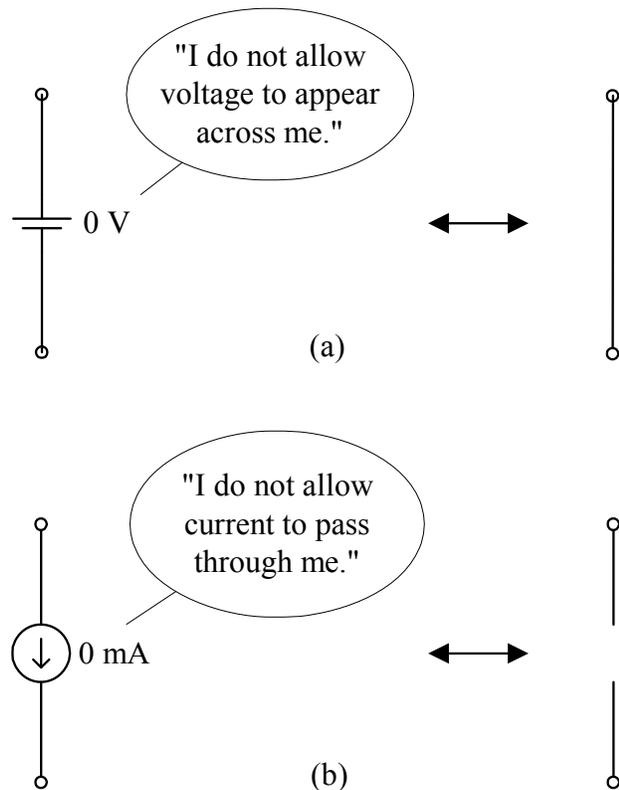


Figure 4: Equivalents of Neutralized Ideal Sources

total current, while increasing the value of a series resistor enables it to capture a greater share of the total voltage. In Figure 5a, R_1 carries the majority of the source current if its value is less than $10\ \Omega$, while in Figure 5b, R_2 drops the majority of the source voltage if its value exceeds $6\ \Omega$.

Short circuits and open circuits present a related special case. When a short circuit appears in parallel with another component, it can be described as a “current hog” since it captures all the available current. When an open circuit appears in series with another component, it can be described as a “voltage hog” since it drops all the available voltage.

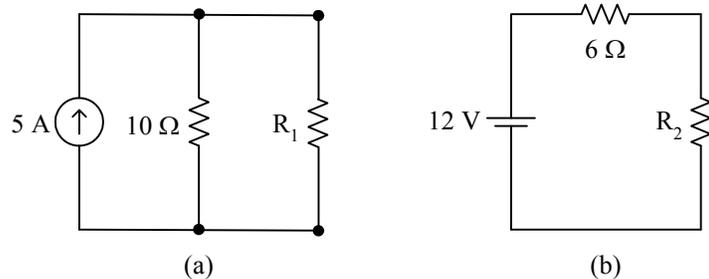


Figure 5: Parallel Resistors and Series Resistors

Capacitor and Inductor Behavior

Reactive elements can be viewed as being either sacrificial or vengeful, depending on the circumstances. Both capacitors and inductors have specific goals they seek to attain, and their quest to achieve these goals usually produces some tangible benefit to the rest of the circuit. Occasionally, however, the behavior of a reactive element toward the rest of the circuit is more akin to that of a “bully.”

The goal of a capacitor is to maintain a constant terminal voltage. Capacitors oppose a sudden increase in voltage by sinking current as quickly as the circuit allows, and they oppose a sudden decrease in voltage by sourcing current as quickly as possible, to the extent that they completely discharge themselves.

The capacitor in Figure 6 exhibits beneficial behavior—its effort to maintain a constant voltage attenuates the ripple voltage (V_r) from the source to provide a nearly constant voltage to the load (R_L). If, however, R_L were to be abruptly replaced by a short circuit, the capacitor would violently thrust its charge into the short in an instinctive effort to oppose the sudden change in voltage. Unless the short is capable of surviving this burst of current, it will “die” as a fuse, and the capacitor will emerge as the victor.

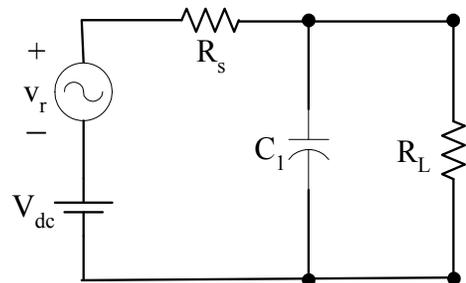


Figure 6: Power Supply Filter

The goal of an inductor is to maintain a constant current in its branch. Inductors oppose an abrupt increase in current by dropping as much voltage as the circuit allows, and they oppose an abrupt decrease in current by sourcing as much voltage as possible, to the extent that they have completely extinguished their internal flux.

The circuit in Figure 7 is a simplified version of a buck converter, which produces an average voltage across the load (R_L) that is proportional to the duty cycle of the perpetually toggling

switch. The inductor exhibits beneficial behavior—it stores energy from the source while the switch is closed and releases energy to the load while the switch is open, thus smoothing the current delivered to the load. In a practical circuit, a “cathode up” diode would take the place of R_1 ; usage of R_1 in its place enables this important inductor application to be discussed long before diodes are introduced. A reference to the inefficiency produced by R_1 provides a natural transition to a statement that “a practical circuit uses a device called a diode, which functions like an electrical check-valve . . .”

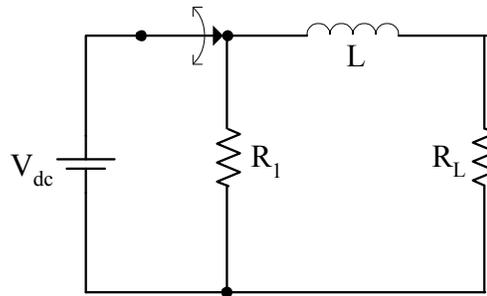


Figure 7: Simplified Buck Converter

The need for R_1 can be demonstrated by temporarily removing it from the circuit. Figure 8 illustrates this case, in which the stage has been set for the inductor to become very angry as the switch starts to open. In its instinctive effort to oppose the tendency of the current to plummet, the inductor will develop a very large voltage, the vast bulk of which will drop across the switch. This result can be demonstrated through a conceptual application of Kirchoff’s Voltage Law—since the source and load voltages in Figure 8 are essentially fixed (the source is “ideal” and the current is virtually constant), the only place the excess voltage can “go” is across the switch. In effect, the inductor throws all its stored energy at the switch in an effort to keep the current from dropping: “Oh no you don’t . . . take that!” Thus, the absence of R_1 has positioned the switch to become the object of the inductor’s wrath.

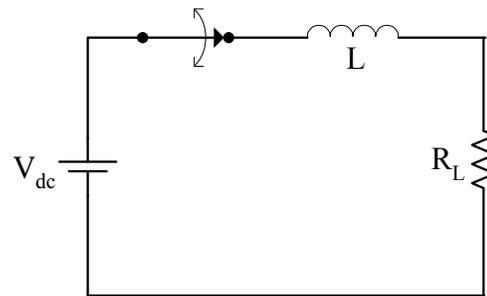


Figure 8: Buck Converter without R_1

Mesh Analysis

Though not, strictly speaking, an application of personification, the task of writing a mesh equation can be simplified by using a related technique: “projecting” yourself into the circuit and pretending to “walk” around the mesh in the direction of its mesh current. Recalling that mesh analysis is merely an application of Kirchoff’s Voltage Law, the task at hand is to add the voltage terms around the mesh and set their sum equal to zero; the sign associated with each term is determined by the first sign you encounter on the corresponding element as you traverse the mesh. Resistor voltages are handled through an embedded application of Ohm’s Law; the sign of each resulting current term is determined through application of the passive sign convention¹, which states that *positive current enters the positive voltage terminal in a passive*

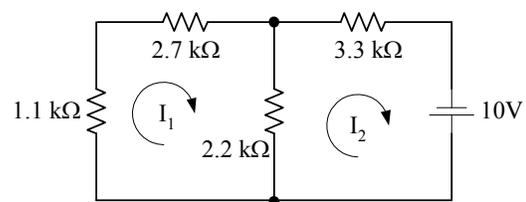


Figure 9: Mesh Analysis by “Walking Around”

component. Thus, the equation for Mesh 2 of the circuit in Figure 9 is obtained by taking a clockwise trip around the mesh:

$$(2.2 \text{ k}\Omega)(I_2 - I_1) + (3.3 \text{ k}\Omega)(I_2) - 10\text{V} = 0$$

I_2 is positive in both cases, because a trip around the mesh in the direction of its mesh current forces the traveler to enter both resistors via the same terminal as the mesh current. I_1 is negative, since it enters the top of the 2.2 k Ω —the lower terminal is the first one encountered during a clockwise traversal of the mesh. The term for the 10V source is negative, because the upper (negative) terminal is the first one you encounter as you walk around the mesh.

Assessment

During the Spring 2008 semester, the students in an introductory circuit analysis course were surveyed to determine whether their comprehension of certain topics had been improved through the use of element personification in lectures. The statements that composed the survey are summarized in Figure 10. A five-point Likert scale was used to construct the possible responses: 1-Strongly disagree, 2-Disagree, 3-Not sure, 4-Agree, and 5-Strongly agree. Participants were asked to select the response “that best describes your level of agreement” with each statement. A summary of the responses is tabulated in Figure 11, while the distribution of responses by statement is illustrated in Figure 12

As shown in Figure 11, the sample means ranged from 3.71 to 4.19, which strongly suggests that the majority of the students benefited from the lecture techniques previously discussed. A brief study of the solid bars in Figure 12 provides additional support for the same conclusion: the combined responses of “Agree” and “Strongly Agree” exceeded 69% for each of the 14 statements. After deciding to interpret a mean response of 3.5 as a “tendency toward agreement,” the t-distribution was used to compute the p-values associated with the hypothesis that *the population mean associated with the responses to a statement exceeds 3.5*. The results for these computations are recorded in the right-most column of Figure 11, enabling the validity of the hypothesis to be evaluated for each of the statements. Considering that the largest p-value is 0.05, the hypothesis appears to present a reasonable conclusion in all cases. Thus, the students “tended to agree” that their ability to learn the material had been positively impacted by the techniques under study.

Application and Reflection

This application of personification to circuit elements is intended to supplement, not replace, the analytical content in a typical circuit analysis lecture. Since the associated narratives are primarily used as interpretive comments about the behavior of circuit elements and their impact on a particular circuit, and since these comments are usually made as a verbal bridge between sketching a circuit and writing the equations to describe its behavior, very little extra time is required to implement this narrative technique.

1. The portrayal of an ideal voltage source in human terms (by stating, for instance, that "a 10V source insists that the voltage at its positive terminal is 10 V higher than the voltage at its negative terminal") improved my understanding of its behavior.
2. The portrayal of an ideal current source in human terms (by stating, for instance, that "a 100 mA source insists that the current in its branch is 100 mA") improved my understanding of its behavior.
3. The statement that "ideal sources refuse to compromise" helped me to understand why ideal voltage sources cannot be combined in parallel and why ideal current sources cannot be combined in series.
4. The statement that "the big one wins" helped me to know how to combine opposing voltage sources in series or to combine opposing current sources in parallel.
5. The statement that "a dead voltage source insists that it has 0V across its terminals" helped me to understand why it can be replaced by a short circuit.
6. The statement that "a dead current source insists that no current will flow through its branch" helped me to understand why it can be replaced by an open circuit.
7. The characterization of parallel resistors as "competing for current" helped to develop my intuition about their behavior.
8. The description of a short circuit as "a 'current hog' when it is paralleled with a resistor" improved my understanding about its behavior.
9. When applying mesh analysis, it is useful to visualize yourself "walking around the mesh" and to "use the first sign you encounter" as an aid for determining the proper signs for terms associated with voltage sources.
10. When applying mesh analysis to a resistor that straddles two meshes, it is useful to view the currents as either being "with you" or "against you" when determining the signs of the mesh currents.
11. The perspective that "a 25 V source insists that the voltage at its positive terminal is 25V higher than the voltage on its negative terminal" helped me to write a supernode supplemental equation such as " $V_2 - V_3 = 25V$ " using the proper signs.
12. Knowledge of the passive sign convention is useful when evaluating whether a source is supplying or dissipating power.
13. When performing a source conversion on a practical voltage source, the passive sign convention is helpful when determining the direction of the resulting current source.
14. When performing a source conversion on a practical current source, the passive sign convention is helpful when determining the polarity of the resulting voltage source.

Figure 10: Statements Used in the Lecture Effectiveness Survey

Statement	Response					Statistics			
	1	2	3	4	5	Total	Mean	Std Dev.	P-value
1	0	2	2	25	8	37	4.05	0.705	0.00001
2	0	1	3	24	9	37	4.11	0.658	0.00000
3	0	3	7	22	3	35	3.71	0.750	0.05013
4	0	2	5	23	7	37	3.95	0.743	0.00041
5	0	1	4	19	13	37	4.19	0.739	0.00000
6	0	2	4	17	14	37	4.16	0.834	0.00001
7	1	0	5	24	7	37	3.97	0.763	0.00029
8	0	1	8	19	9	37	3.97	0.763	0.00029
9	0	2	5	16	14	37	4.14	0.855	0.00003
10	1	2	5	19	10	37	3.95	0.941	0.00331
11	0	2	4	23	8	37	4.00	0.745	0.00012
12	0	3	8	19	6	36	3.78	0.832	0.02646
13	0	0	9	21	6	36	3.92	0.649	0.00024
14	0	0	11	21	4	36	3.81	0.624	0.00291

Figure 11: Survey Responses and Statistics

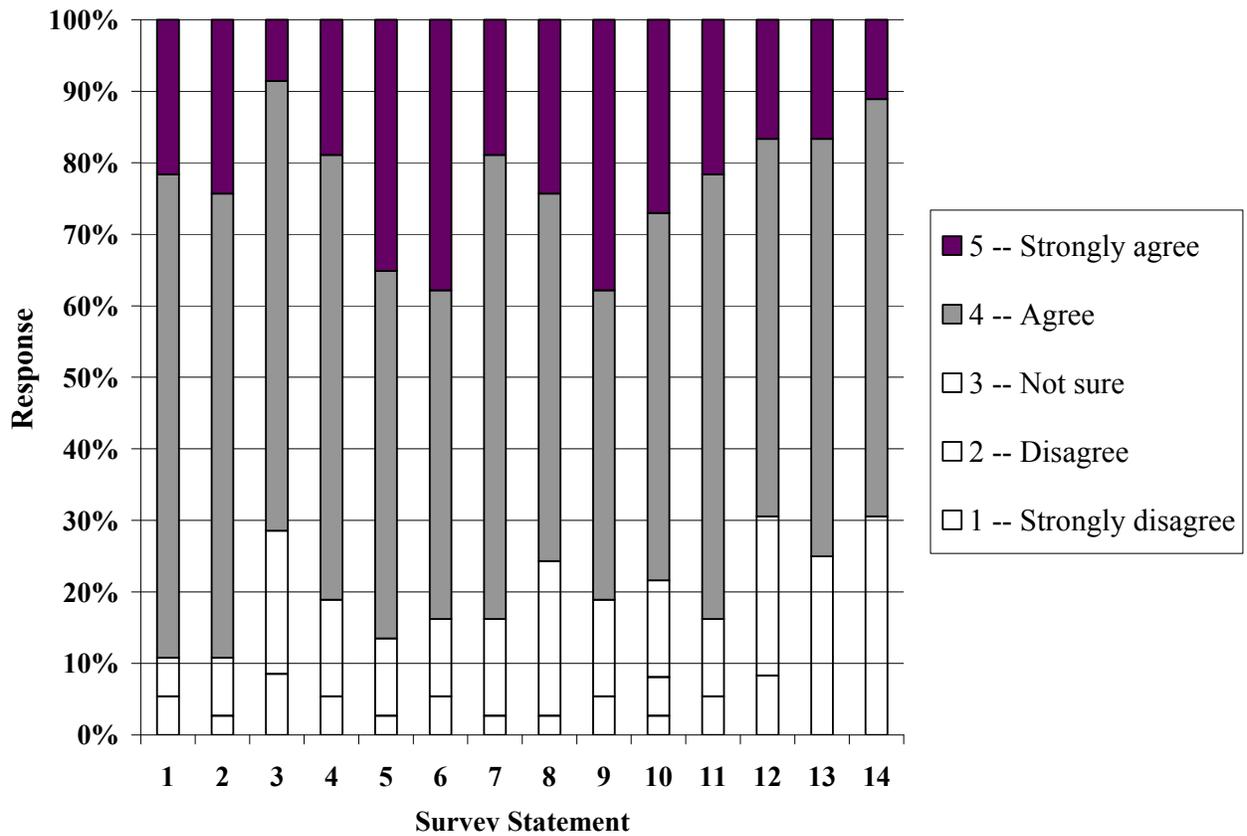


Figure 12: Response Percentages by Survey Statement

Based on classroom observations, the author is convinced that the injection of “element personalities” into circuit analysis lectures helps to retain student interest. The author is also convinced that the intuitive knowledge that the technique conveys helps students to gain a deeper comprehension of the discipline. Students seem to agree—responses to a recent classroom survey appear to support the conclusion that the usage of element personification facilitates learning. The validity of these assertions—that student interest is enhanced and that a deeper comprehension is gained—has not yet been rigorously demonstrated—such a task may present a worthwhile topic for future study.

Bibliography

1. Hayt, William H. et. al., Engineering Circuit Analysis, 7th edition, McGraw-Hill, New York, NY, 2007