

# Beyond Fragmented Instruction: A Physico-Mathematical Approach to Teaching Electric Circuit Theory in Higher Education

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<sup>1</sup><https://Orcid.Org/1441-1452-1441-1452>

## HOW TO CITE:

Alex Paredes-Anchatipán  
(2026). Beyond Fragmented  
Instruction: A Physico-  
Mathematical Approach to  
Teaching Electric Circuit Theory in  
Higher Education  
International Journal of Special  
Education, 41(21s), 1441-1452

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## ABSTRACT:

Traditional introductory electric circuit theory courses in university engineering programs frequently segment direct current (DC) and alternating current (AC) regimes into isolated pedagogical modules. This curricular fragmentation conceals the underlying electromagnetic principles and energy transfer dynamics, encouraging students to rely on fragmented, rule-based algorithm execution rather than developing a unified conceptual framework. This paper proposes an integrated physico-mathematical pedagogical model designed to reconcile DC, transient, and AC steady-state regimes within a continuous analytical framework. By leveraging energy conservation principles, foundational differential and integral constitutive relations, phasor representations, and numerical techniques (e.g., Runge-Kutta), DC is reframed as the zero-frequency limiting case of dynamic AC signals rather than a distinct physical phenomenon. The proposed instructional sequence synergizes predictive conceptual reasoning, active computational simulation, and empirical laboratory verification to address well-documented student learning difficulties—such as local reasoning, sequential current consumption, and misinterpretations of reactive power and phase shifts. This comprehensive approach shifts the educational paradigm from passive algorithmic memorization toward robust scientific modeling, enhancing knowledge transfer across complex electrical configurations and non-sinusoidal excitations.

**Keywords:** Engineering pedagogy, university education, electric circuits, dynamics systems modeling.

## 1. Introduction

Traditionally, the instruction of electric circuits is segmented into isolated direct current (DC) and alternating current (AC) modules, which limits a comprehensive understanding of the underlying electromagnetic phenomena (Fayyaz & Trueman, 2022). This curricular fragmentation—which typically decouples transient regimes from the

fundamental laws of electromagnetism—prevents students from integrating underlying physical principles into a coherent explanatory model. Several textbooks used in this subject divide circuit analysis into unrelated stages as if they were distinct phenomena. Consequently, students may interpret DC and AC as independent phenomena rather than recognizing them as manifestations of a single electrical

behavior dependent on the system's temporal conditions. This difficulty is exacerbated when analysis is reduced to the mechanical application of equations, as students tend to confuse current, voltage, energy, and power, and do not always relate macroscopic observations to the physical processes that generate them (Dori & Belcher, 2005; Engelhardt & Beichner, 2003). Therefore, an integrated framework should originate from common physical quantities, starting from their basic mathematical modeling via differential equations that describe passive element behavior in electrical circuits, to subsequently analyze how sources and circuit components alter their time evolution. In this manner, alternating current can be understood as a dynamic extension of direct current analysis rather than an isolated set of rules. The simultaneous teaching of both regimes constitutes a viable alternative, provided it is accompanied by conceptual activities and a revised instructional sequence that addresses specific student difficulties (Bernhard et al., 2016).

This pedagogical disconnection often hinders the transfer of fundamental physical principles to novel contexts. As a result, students may remain conditioned by a fragmented set of misconceptions that restricts their ability to predict system behavior under parameter variations, particularly in unaddressed scenarios such as random signal analysis, transient regimes, and diverse electronic applications. Specifically, students may analyze only the modified element without considering how the alteration affects the entire circuit's conditions, the relations between voltage, current, and resistance, or the conservation of charge (Başer & Durmuş, 2010; Pitterson & Streveler, 2016). This mode of reasoning makes it difficult to recognize that the same physical relationships describe series, parallel, and combination configurations, even when the circuit geometry and the time dependence of its quantities change (Quezada-Espinoza et al., 2023).

An approach centered on energy conservation and its transfer between the source, electromagnetic fields, and devices replaces the isolated selection of formulas with the

construction of explanatory models applicable across various circuits (Dias, 2013; Fernández et al., 2017). By prioritizing the understanding of fundamental interactions, students transcend superficial circuit features to analyze energy flow holistically (Hernandez et al., 2022). This pedagogical transition is crucial, as it transforms students' intuitive notions—often characterized by local or sequential reasoning—into more robust and generalizable scientific models. To achieve this, it is advantageous to compare the same configuration under constant and time-varying sources, examining the evolution of the electric field, current, potential difference, and transferred energy, rather than presenting each regime as an independent topic (Fernández et al., 2017; Zuza et al., 2020).

Instructional activities should require students to formulate predictions, construct multiple representations, and provide physical justifications prior to introducing algebraic procedures. This sequence allows Kirchhoff's laws and constitutive relations to be understood as expressions of conservation principles and component physical properties, rather than being applied as decontextualized rules. Furthermore, it obliges students to contrast predictions with global circuit behavior and explain how a local modification alters variables throughout the entire system. Thus, the student recognizes that time variation alters the circuit's mathematical description without eliminating the organizing physical principles. This understanding fosters knowledge transfer to new configurations, reduces reliance on memorized algorithms, and provides criteria for revising and reconstructing personal conceptual models (Bernhard et al., 2016).

This unified framework requires analyzing the circuit's energy balance, allowing concepts such as electromotive force and potential difference to be distinguished through the consistent application of energy conservation (Vavasis et al., 2022). By consolidating this physical foundation, students cease to perceive electricity as a collection of isolated diagrams and begin articulating explanatory models wherein operational invariants, such as charge and energy,

act as transversal axes against any external perturbation (Oliveira & Calheiro, 2025). This perspective addresses documented learning difficulties in electromagnetism courses, where the disconnect between circuit theory and fundamental laws—such as the Ampère-Maxwell law—often restricts students' ability to understand dynamic phenomena (Campos et al., 2023; Suárez et al., 2024). By fostering this holistic view, learning shifts from accumulating specific rules to acquiring an analytical tool capable of explaining energy flow behavior in any configuration, regardless of the source's temporal nature (Velasco & Buteler, 2022).

## 2. Methodology

### Common Physical Foundations

To establish this common foundation, it is necessary to relate the electric field to potential difference and transferred energy, recognizing that within a conductor, charge distribution establishes an electric field whose line integral determines the potential difference and directs charge movement (Zuza et al., 2020). Electrical conductivity ( $\sigma$ ) and resistivity ( $\rho = 1/\sigma$ ) characterize the material response such that, in the ohmic regime, current density satisfies  $\mathbf{J} = \sigma \mathbf{E}$ , whereas an ideal resistor relates voltage and current through ( $V = RI$ ). This relationship must be complemented by the time-dependent behavior of energy-storage elements: in a capacitor, ( $q = CV$ ) and ( $i = C \cdot dV/dt$ ), meaning current appears during charging and discharging, and under a steady-state DC source, a potential difference can be maintained even when current drops to zero; in an inductor, ( $V = L \cdot dI/dt$ ), such that its opposition depends on the rate of change of current (Erol & Önder, 2021).

For a sinusoidal source, these responses can be expressed via impedances ( $Z_R = R$ ), ( $Z_C = 1/(j\omega C)$ ), and ( $Z_L = j\omega L$ ), allowing frequency to be interpreted not as an isolated property of the source, but as the parameter determining the phase relationship between voltage and current, as well as the energy distribution among the capacitor's electric field, the inductor's magnetic

field, and resistive dissipation through the solution of differential equations with sinusoidal forcing functions. Presenting these cases jointly fosters a unified understanding in which direct current constitutes the zero-frequency limit of the alternating current description, without losing sight of the fact that transient and steady-state processes require analyzing how energy is accumulated, returned, or dissipated in each component (Bernhard et al., 2016; Erol & Önder, 2021).

This integration enables students to view inductors and capacitors as dynamic elements for energy storage and transfer, facilitating an understanding of their role in the temporal evolution of electrical quantities (Erol & Önder, 2021). Thus, they can interpret that the capacitor stores energy associated with the electric field and the inductor stores energy in the magnetic field, while the resistor transforms part of the energy into heat; this distinction explains, without resorting to isolated rules, why transients depend on the time constant and why, in the sinusoidal regime, frequency modifies effective impedance and the phase shift between voltage and current (Erol & Önder, 2021). Comparing these behaviors at zero- and high-frequency limits further provides a pedagogical resource to bridge DC and AC responses, making the conceptual continuity between both regimes explicit.

### Direct current circuits.

In this state, since the signal frequency is zero, the dynamics of passive elements are simplified remarkably: capacitors satisfy

$$(i_C = C \cdot dv_C/dt = 0)$$

when they reach a constant voltage and are thus modeled as open circuits in the steady state, whereas inductors satisfy

$$(v_L = L \cdot di_L/dt = 0)$$

when the current ceases to vary and behave as ideal short circuits (Erol & Önder, 2021). This conclusion does not imply that these elements lack energy, but rather that their energy remains stored without instantaneous exchange: ( $U_C = \frac{1}{2} C v_C^2$ ) in the capacitor and ( $U_L = \frac{1}{2} L i_L^2$ ) in the

inductor, while the resistor dissipates power according to  $(P = vi = Ri^2 = v^2/R)$ . Consequently, Ohm's law,  $(v_R = Ri)$ , directly describes the resistive steady state and can be interpreted as the limiting case where the relation between voltage and current contains no time derivatives; in contrast, the equations for capacitors and inductors show that their dynamic effects disappear only after variations in voltage or current have ceased (Ballato & Ballato, 2024). DC circuit analysis must thus distinguish between the transient interval—during which capacitors charge or discharge and current is established in inductors—and the steady state, in which physical quantities reach constant values and Kirchhoff's laws enable their distribution across the circuit to be determined. This distinction provides a conceptual basis for understanding direct current as the zero-frequency limit of general circuit analysis, without confusing the absence of temporal variation with an absence of stored energy (Bernhard et al., 2016; Erol & Önder, 2021).

In this manner, reactive components operate as energy storage units: the inductor retains energy in its magnetic field, whereas the capacitor does so in its electric field, according to  $(U_L = \frac{1}{2}LI^2)$  and  $(U_C = \frac{1}{2}CV^2)$  (Erol & Önder, 2021). As time derivatives vanish in the steady state, their constitutive equations  $(i = C \cdot dV/dt)$  and  $(V = L \cdot di/dt)$  demonstrate, respectively, that the capacitor stops conducting current and the inductor stops opposing a constant current, even though both maintain their previously accumulated energy. This confirms that the resistive behavior described by Ohm's law constitutes the algebraic response of a circuit whose source does not alter its magnitudes over time, whereas reactive effects reemerge whenever voltage or current changes. In the transient regime, derivatives describe how changes in voltage and current govern energy exchange: for a capacitor,  $(i_C = C \cdot \frac{dv_C}{dt})$ , such that a rapid voltage variation produces a larger current, whereas for an inductor,  $(v_L = L \cdot \frac{di_L}{dt})$ , a rapid current variation generates a voltage opposing

that change. Applying Kirchhoff's laws yields  $(RC \cdot \frac{dv_C}{dt} + v_C = V_s)$  for a series RC circuit, and  $(L \cdot \frac{di}{dt} + Ri = V_s)$  for an RL circuit; hence, both constitute first-order circuits whose response depends on initial conditions and evolves exponentially toward the steady state (Wang, 2010). During capacitor charging, the voltage derivative progressively decreases to zero, whereas in the inductor, the current derivative decays until the current reaches a constant value; the time constants  $(\tau = RC)$  and  $(\tau = L/R)$  quantify the rate at which the transient response decays. Thus, the derivative should not be interpreted merely as a mathematical operation, but as the instantaneous measure of the rate of change of an electrical quantity and, consequently, as the link between circuit dynamics and energy transfer. Replaces of time-varying signals in the derivative with continuous DC voltages yields the conventional Ohm's law representation taught in continuous control circuits.

### Alternate current circuits

In this regime, consider a sinusoidal voltage source  $(v(t) = V_m \cos(\omega t))$ , where  $(V_m)$  is the amplitude and  $(\omega)$  is the angular frequency. For a capacitor, the constitutive relation  $(i_C(t) = C \cdot dv_C(t)/dt)$  indicates that the current is obtained by differentiating the voltage; thus, if  $(v_C(t) = V_m \cos(\omega t))$ , then

$$(i_C(t) = C[-\omega V_m \sin(\omega t)] \\ = \omega C V_m \cos(\omega t + \pi/2))$$

such that its amplitude is  $(I_m = \omega C V_m)$  and the current leads the voltage by  $(90^\circ)$ . Equivalently, starting from a sinusoidal current  $(i_C(t) = I_m \cos(\omega t))$ , the voltage is obtained via integration:

$$(v_C(t) = \frac{1}{C} \int i_C(t) dt = \frac{I_m}{\omega C} \sin(\omega t) + K \\ = \frac{I_m}{\omega C} \cos(\omega t - \pi/2) + K)$$

where K represents the initial voltage or the constant component associated with previously stored charge; in sinusoidal steady-state, this

constant is analyzed separately from the alternating response.

For an inductor, the relation ( $v_L(t) = L \cdot di_L(t)/dt$ ) indicates that voltage is obtained by differentiating current, whereas current is determined by integrating voltage: if ( $v_L(t) = V_m \cos(\omega t)$ ), then

$$\begin{aligned} i_L(t) &= \frac{1}{L} = V_m \cos \int (\omega t) \cdot dt \\ &= \frac{V_m}{\omega L} \sin(\omega t) + K \\ &= \frac{V_m}{\omega L} \cos(\omega t - \pi/2) + K \end{aligned}$$

such that the current lags the voltage by ( $90^\circ$ ) and its amplitude is ( $I_m = V_m/(\omega L)$ ) (Erol & Önder, 2021). The integration constant  $K$  expresses the initial current of the inductor, as the coil conserves stored magnetic energy and cannot instantaneously modify its current; analogously, the constant term for the capacitor represents its initial voltage condition.

When representing these operations using phasors, time differentiation corresponds to multiplication by ( $j\omega$ ) and integration to division by ( $j\omega$ ), yielding ( $\tilde{I}_C = j\omega C \tilde{V}_C$ ), ( $\tilde{V}_C = \tilde{I}_C / (j\omega C)$ ), ( $\tilde{V}_L = j\omega L \tilde{I}_L$ ) ( $\tilde{I}_L = \tilde{V}_L / (j\omega L)$ ).

Consequently, the impedances are ( $Z_C = 1/(j\omega C) = -j/(\omega C)$ ) and ( $Z_L = j\omega L$ ), with magnitudes ( $1/(\omega C)$ ) and ( $\omega L$ ), respectively, while the factor  $j$  encapsulates the quarter-cycle phase displacement (Gerardo & Orlando, 2016).

A resistor, by contrast, satisfies ( $\tilde{V}_R = R \tilde{I}_R$ ) and introduces no phase shift. Therefore, in a series RLC circuit, the total impedance is expressed as ( $Z = R + j(\omega L - \frac{1}{\omega C})$ ), and the phase angle ( $\varphi = \tan^{-1}[(\omega L - \frac{1}{\omega C})/R]$ ) allows for the joint interpretation of resistive opposition, energy storage, and the temporal phase relationship between voltage and current. Thus, phasors do not replace the physical explanation of derivatives and integrals, but rather condense their sinusoidal solutions into an algebraic representation suitable for the steady state, wherein frequency preserves

waveform shape and determines response magnitude (Gerardo & Orlando, 2016).

This conceptual unification enables students to view reactive elements not as isolated components, but as devices that modulate signal amplitude and phase shift as a function of frequency. From this perspective, direct current can be presented as the limiting case of alternating current as frequency approaches zero, while sinusoidal analysis allows both transient and steady-state responses to be interpreted within a single physico-mathematical framework. This continuity is pedagogically relevant, as the simultaneous introduction of both regimes fosters an understanding of their relationships, provided it is supported by scaffolded activities that explicitly link time-domain, phasor, and experimental representations (Bernhard et al., 2016). In this way, students recognize that differences between the two analytical approaches stem not from distinct physical laws, but from excitation temporal conditions and the manner in which elements store, transfer, or dissipate energy (Erol & Önder, 2021).

Consequently, the pedagogical transition from time-domain response to phasor representation integrates energy storage phenomena with signal processing, overcoming conventional fragmentation that often hinders a deep understanding of the steady state. A coherent instructional sequence can begin with a single circuit configuration and contrast its response under constant sources, sinusoidal excitation, and varying frequencies, requiring students to correlate voltage and current plots with differential expressions, impedances, and experimental measurements. This design prevents phase shift from appearing as an isolated formal procedure, framing it instead as an observable consequence of energy exchange between the source and reactive elements; furthermore, systematically articulating models, simulations, and experiments helps establish connections between theoretical representations and real circuit phenomena (Carstensen & Bernhard, 2009; Kautz, 2011). Experience with introducing DC and AC concurrently also demonstrates that this integration requires

progressively adjusting activities to focus on conceptually decisive tasks that consolidate learning (Bernhard et al., 2016).

### Learning Difficulties

Traditional instruction frequently fragments the study of these regimes, inducing persistent conceptual misconceptions, such as the belief that electric current is consumed as it flows through components, that a battery supplies a constant current regardless of the load, or that current intensity decreases with distance from the source (Cohen et al., 1983; Lee & Law, 2001). These interpretations reveal a local and sequential understanding of the circuit, wherein current is mischaracterized as a consumable substance and charge conservation, potential difference, and energy transfer dynamics are neglected.

When direct current and alternating current are presented as independent domains, students may acquire isolated procedural skills without recognizing that the relationships among voltage, current, frequency, and phase describe distinct behaviors of a single underlying physical system; thus, while extending the mathematical formalism from one regime to another is relatively straightforward, achieving conceptual understanding remains difficult (Bernhard et al., 2016; Kautz, 2011). This disconnection becomes particularly evident in the study of RC filters, where, even after theoretical instruction and laboratory experimentation, some students fail to identify the circuit as a filter or to apply Kirchhoff's and Ohm's laws correctly to predict its response (Coppens et al., 2017). Consequently, these foundational difficulties propagate to advanced applications, such as filter design, power electronics, and converters, where integrating temporal, phasor, and energy models while linking component behavior to operating conditions and system control is required (Almeida, 2023; Coppens et al., 2012).

For example, confusion surrounding reactive power and power factor typically stems from an inability to visualize how the cyclic storage and release of energy by inductors and capacitors modify phase relationships. In this context, students frequently misinterpret reactive power

as energy permanently consumed by the load or assume that any power exchange implies net energy transfer, rather than distinguishing reactive power from active and apparent power (Hai-biao, 2008). This difficulty is exacerbated when the power factor is introduced strictly as an abstract mathematical expression without being tied to line current, measured phase shift, or capacitive power factor correction. Therefore, an instructional task combining an RL circuit, oscilloscope phase observation, power calculations, and the progressive addition of a capacitor can clarify the correspondence between the phasor model, dynamic energy exchange, and physical operating conditions (Millard et al., 2020).

### Integrated Didactic Proposal

The proposed pedagogical sequence articulates circuit analysis through a grounded mathematical and physical progression, beginning with direct current circuits wherein students correlate constant quantities, derivatives, and integrals with the processes of charge and energy accumulation and transfer, culminating in the formalization of Ohm's Law as an expression of steady-state conditions. Building upon this same framework, sinusoidal signals are introduced to demonstrate how differentiation and integration operations modify amplitude and phase, gradually leading to the concept of impedance and phasor representation without decoupling them from laboratory voltage and current measurements. Subsequently, step, random, and Dirac delta signals enable variations in excitation conditions to distinguish transient from steady-state responses, while the numerical resolution of differential equations provides an alternative for analyzing circuits whose symbolic solution is complex (Jenko, 2015; Thomas & Rosa, 2020). At each stage, mathematical expressions are contrasted with simulations, graphs, schematic diagrams, and experiments so that students interpret differences between phenomena without assuming fragmented physical principles; thus, impedance, time response, and energy transfer are understood as complementary manifestations of a single circuit subjected to

distinct excitation signals (Bernhard & Carstensen, 2017; Carstensen & Bernhard, 2009).

This methodological transition—supported by numerical methods such as Runge-Kutta algorithms to solve differential equations—overcomes the rigidity of traditional analytical calculus and fosters an intuitive understanding of the dynamic behavior of electrical systems. By programming the governing circuit equations step by step, students observe how initial conditions, component parameters, and input signals dictate the temporal evolution of voltage and current without delegating physical interpretation to an opaque, 'black-box' simulation tool (Jenko, 2015). Comparing numerical solutions, analytical predictions, and experimental data further allows for discussions on approximation error, algorithmic stability, and model validity boundaries, thereby reinforcing the connection between mathematical formalism and real circuit behavior (Farias et al., 2022). In this way, excitation signals cease to be reduced to mere calculation exercises and instead serve as operational conditions for exploring transients, steady states, and energy transformations within a unified conceptual framework.

Furthermore, treating time-domain discontinuity functions—such as step and impulse functions—provides a unified framework to analyze how an abrupt change in excitation dictates initial conditions and transient circuit evolution without treating each signal as an independent physical principle. By comparing predictions derived from these representations with simulations and experimental measurements, students recognize that impulsive, step, and sinusoidal responses correspond to different ways of exciting the same physical system, whose dynamics depend inherently on its energy-storage elements and physical parameters. Consequently, computational rules are directly tied to the continuity or instantaneous variation of circuit variables, while numerical resolution offers an accessible methodology for studying configurations in which analytical formulations are less direct (Jenko, 2015).

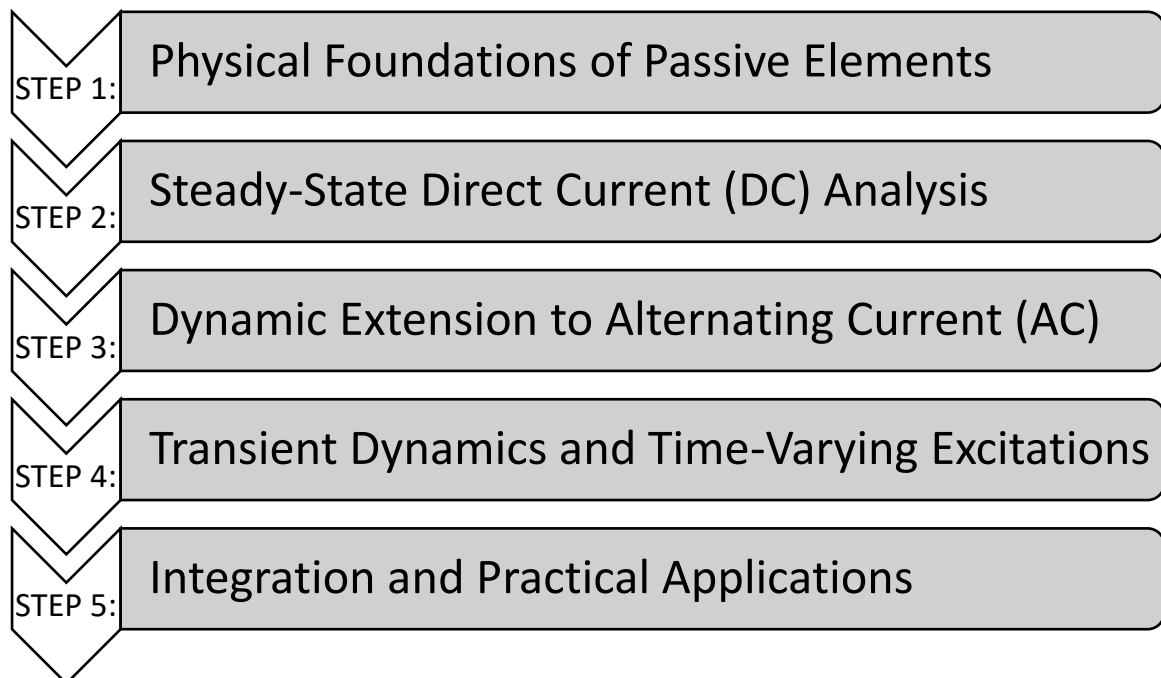
### Learning Strategies

The implementation of strategies is grounded in active learning and digital environments, where simulation and physical experimentation act as cognitive bridges for technical reasoning. Rather than following prescribed procedures, students formulate predictions, construct mathematical circuit models, modify parameters, and contrast analytical and numerical solutions against simulated graphs and laboratory measurements. This question-guided comparison—for example, evaluating the effects of altering resistance, frequency, or initial conditions—fosters the identification of causal relationships among electrical variables and prevents software outputs from being interpreted as automated answers. The carefully designed integration of hands-on experimentation and simulations bridges theoretical models and observable phenomena, strengthening conceptual understanding beyond the exclusive use of either modality (Bernhard & Carstensen, 2017; Zacharia, 2007). Likewise, collaborative work and the discussion of discrepancies between predictions and results enable students to justify model approximations, recognize the limitations of each representation, and transfer principles learned in direct current circuits to sinusoidal and transient configurations (Carstensen & Bernhard, 2009; Ronen & Eliahu, 2000).

Supported by empirical evidence, this methodological integration demonstrates that interactive platforms enhance conceptual understanding by making relationships among variables, models, and phenomena visible that are not always directly observable; however, their efficacy depends on articulation with guiding questions, predictions, and experimental verifications, as isolated simulation can reinforce procedural routines without guaranteeing model transfer to real circuits. Consequently, digital resources must serve as mediators for physical reasoning rather than replacements for explanation, analytical derivation, or physical experimentation, ensuring that students justify their results and recognize the continuity of physical principles across distinct operating regimes (Bernhard & Carstensen, 2017; Ronen & Eliahu, 2000).

In this regard, the instructional sequence can be organized around the mathematical and physical analysis of passive element behavior, linking resistance, capacitance, and inductance to the energy dissipation and storage processes that govern their constitutive equations. Subsequently, circuits powered by constant voltages are analyzed, solving derivatives and integrals to describe relationships among charge, current, and potential difference, culminating in the formalization of Ohm's law as a representation of steady-state resistive behavior. Sinusoidal signals are then introduced to analyze component responses through differential equations, phasors, and impedances, demonstrating that alternating current constitutes

a dynamic extension of the prior analysis rather than isolated content. In a subsequent phase, random, impulse, step, and other time-varying excitations are employed to study transient dynamics, comparing analytical solutions with numerical approximations obtained through methods such as Euler or Runge-Kutta algorithms, computational simulations, and empirical laboratory measurements. Finally, this knowledge is synthesized in practical applications, such as passive filter design, where students interpret how combinations of resistors, capacitors, and inductors modify signal amplitude and phase while evaluating the correspondence among mathematical models, simulated responses, and real circuit behavior.



### 3. Results

Adopting this integrated approach requires the teacher to serve as a facilitator of critical thinking, designing learning situations that demand the articulation of concepts through active experimentation and reflection on model validity. To this end, instructors must organize learning sequences in which students formulate predictions, confront their initial preconceptions with graphical representations, simulations, and real circuits, and explain discrepancies using physical arguments rather than relying solely on procedural algorithms. This mediation is

especially critical when utilizing simulators; purely procedural guidance often fails to promote deep conceptual understanding, whereas combining simulation with physical experimentation yields greater learning gains than using either resource in isolation (Jaakkola et al., 2010; Jaakkola & Nurmi, 2007). Furthermore, teacher training must include criteria for selecting problems, scaffolding mathematical rigor, connecting direct and alternating current through shared variables, and assessing both the numeric solution and the physical interpretation of the phenomenon. Conceptual change activities

supported by simulations have demonstrated favorable effects on comprehension and the reduction of alternative conceptions in DC circuits (Taşlıdere, 2013); however, transferring these gains to other contexts requires follow-up questioning, peer discussion, and experimental verification. Successful implementation also demands planning time, equitable access to physical instruments and digital platforms, and assessment strategies that evaluate students' abilities to model, justify, and transfer core principles beyond mere numerical accuracy.

In an interactive classroom comparison, students who used the Circuit Construction Kit simulator achieved a relative gain 47% higher—equivalent to an 11 percentage point gain in absolute score—than those who observed traditional demonstrations, underscoring the value of dynamic representations when paired with conceptual questioning and active engagement (Keller et al., 2007). This finding does not imply that digital tools automatically produce learning improvements; rather, efficacy depends on integrating the tool into a structured sequence of prediction, exploration, explanation, and verification aimed at linking current, potential difference, and resistance to observable circuit behavior. Thus, empirical evidence calls for a nuanced interpretation of normalized gains: while they serve as an indicator of conceptual progress within a specific intervention, they must be supplemented by transfer tasks to verify whether students can apply these same principles when transitioning from direct current to alternating current and to novel experimental setups.

Ultimately, the success of this proposal hinges on consolidating a pedagogical structure that prioritizes scientific modeling competencies over the rote memorization of isolated laws, utilizing tasks that require linking electrical quantities, representations, and operating conditions across both current regimes. This framework fosters a more stable and transferable understanding, as interventions grounded in integrated conceptual models demonstrate superior knowledge integration and retention compared to conventional instruction (Liu et al., 2024). To evaluate this transformation, assessment

strategies must incorporate qualitative explanations, predictive tasks, graphical interpretation, and novel problem-solving, distinguishing mechanical formula application from a true grasp of the physical principles unifying direct and alternating current.

#### 4. Conclusion

The integrated teaching of electric circuits requires a pedagogical transition that combines the rigor of mathematical analysis with simulation tools to visualize the physical continuity among direct current responses, transient phenomena, and frequency-domain behavior, rather than presenting alternating current as isolated content. Consequently, the instructional sequence can introduce direct current as the zero-frequency limiting case, employing time-domain functions, phasors, and frequency response diagrams to demonstrate how a single physical model describes distinct operating conditions. This framework begins with mathematical formulations and numerical analysis of basic circuits, progresses to parameter exploration through interactive simulations, and culminates in physical laboratory verification, enabling students to correlate governing differential equations, graphical outputs, physical measurements, and real component behavior. Within this approach, transient dynamics and noise-like perturbations are framed as natural variations in system excitation or operating conditions rather than as anomalous exceptions disconnected from direct current laws.

Looking ahead, future empirical research must determine which instructional sequences, visual representations, and pedagogical scaffolding strategies best facilitate conceptual transfer across domains. Comparative studies should evaluate these effects in cohorts with varying levels of mathematical preparation using conceptual diagnostics, scientific modeling tasks, and novel experimental problem-solving scenarios.

Furthermore, it is imperative to investigate how integrating advanced analytical tools—such as the Laplace transform—can foster a deeper, unified understanding of RLC systems across diverse student profiles. To avoid becoming an isolated

algebraic routine, the Laplace domain must be introduced as an explicit bridge linking differential equations, temporal step responses, and steady-state frequency domain characteristics. Empirical investigations should compare instructional sequences that initiate with transient observations and simulations before introducing s-domain representations against traditional top-down mathematical formalisms, assessing their relative impacts on conceptual

understanding, cognitive load, and model transferability. Ultimately, future research must identify how instructional scaffolds—such as representation mapping, scaffolded problem sets, dynamic visualizations, and predict-observe-explain tasks—enable students to interpret RLC parameters, justify waveform shapes, and recognize direct current as a fundamental boundary case within a unified physico-mathematical framework

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