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From curricular prescription to digital practice: an analysis of the didactic transposition of the Bohr Atomic model

Summary

The teaching of modern physics at the secondary level faces the challenge of the didactic transposition of abstract concepts. This article investigates this process through an in-depth case study, analyzing the interactive simulation "Models of the Hydrogen PhET's Atom" curriculum, which utilizes the curriculum design framework of the Province of Buenos Aires, Argentina, as a framework. The study employs Didactic Transposition Theory to analyze the coherence between the "knowledge to be taught" of the curriculum and the "knowledge taught" in the simulation. It utilizes the concept of Semantic Gravity from Legitimation Codes Theory (LCT) to examine the specific didactic mechanisms. The results reveal a remarkable alignment, demonstrating that the simulation materializes the curricular narrative of "problem → solution" through a deliberate management of Semantic Gravity. It is concluded that the interactive design of the simulation effectively executes a "semantic swell" that guides students from concrete experiences towards an understanding of abstract principles, such as quantization. This work provides a theoretical explanation, based on LCT, for the recognized pedagogical effectiveness of PhET simulations, and offers a detailed analysis of how transposition strategies are designed in digital educational resources.

Keywords: T Didactic Transposition; Legitimation Code Theory (LCT); Semantic Gravity; Quantum Physics Education; Interactive Simulations; Scientific Literacy

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Guillermo Cutrera
Science Education Department, Facultad Ciencias Exactas y Naturales, Universidad Nacional de Mar del Plata, Argentina

Correspondence: Guillermo Cutrera, Science Education Department, Facultad Ciencias Exactas y Naturales, Universidad Nacional de Mar del Plata, Buenos Aires, Argentina, Funes 3350, CP: 7600

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Introduction

Teaching modern physics at the secondary level presents a considerable pedagogical challenge, given that concepts such as energy quantization are fundamentally abstract and counterintuitive.[1] Within an educational paradigm oriented toward scientific literacy, the goal is no longer merely the transmission of a body of knowledge to future specialists, but rather to foster in all students an understanding of science as a human, dynamic, and model-based activity.[2] This end necessitates a careful transformation of scientific knowledge for use in the classroom, a process referred to in science education as didactic transposition.[3]

While this process has been extensively analyzed in traditional resources such as textbooks, the growing prominence of interactive digital educational tools opens a new field of research. These tools, such as PhET simulations, not only present information but also design learning experiences whose pedagogical mechanisms are not always explicit.[4] The question then arises: how do these digital artefacts transpose complex concepts, and to what extent do their strategies align with the objectives of a formal curriculum? This article addresses this issue through an in-depth case study. It analyses the interactive simulation "Models of the Hydrogen Atom" by PhET, using as a reference framework the Curriculum Design for the subject "Classical and Modern Physics" of the 6th Year of secondary school in the Province of Buenos Aires, Argentina. The central argument is that there is a remarkable coherence between the pedagogical intention of the curriculum —which frames modern physics in a problem → solution narrative— and the didactic strategies materialized in the simulation. It is argued that the effectiveness of the simulation in facilitating understanding lies in its deliberate management of Semantic Gravity, a concept from Legitimation Codes Theory (LCT), which guides the student from concrete experiences toward the inference of abstract theoretical principles.[5]

To develop this argument, the article is structured as follows: first, the theoretical framework that combines Didactic Transposition and LCT is presented. Next, the study's methodology is detailed, including the translation tool used for the analysis. The results of the analysis are then presented, followed by a discussion that connects these findings with the relevant literature. Finally, the study's conclusions are presented, and future research directions are suggested.

Theoretical framework

This study is based on a two-level theoretical framework. At the macro level, the Theory of Didactic Transposition is used to understand the general process of transforming scientific knowledge into academic content. At the micro level, the Semantics dimension of the Theory of Legitimation Codes is used as an analytical tool to examine specific pedagogical strategies within educational resources.

Didactic transposition: A framework for analysing school knowledge

The Theory of Didactic Transposition, originating from the work of Yves Chevallard, has established itself as a fundamental framework for analyzing the inevitable transformations that knowledge undergoes when it is taught.[3] Its importance lies in the fact that it reveals the complex process by which scientific knowledge is adapted for teaching purposes, allowing for a critical analysis of curricula and classroom practices.[6] The theory conceptually distinguishes between different states of knowledge. The starting point is "scholarly knowledge" (savoir savant), which is knowledge as it is produced, debated, and validated by scientific communities. This knowledge, in its original state, is dense, depersonalized, and interconnected in a complex theoretical network that makes it inappropriate for direct introduction in the school environment. This complexity is not trivial; In the case of quantum physics, for example, Bohr's atomic model cannot be fully understood without prior knowledge of classical

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electromagnetism, spectroscopy, and the blackbody radiation crisis. It is precisely this dense interconnectedness that makes didactic transposition indispensable. Teaching cannot replicate the entire theoretical network, so it must select and reorder concepts in a pedagogically functional sequence, like the "problem → solution" narrative discussed later.

Therefore, it must undergo an initial transformation to become "knowledge how to teach" (savoir à ensigned). This is the knowledge as it is presented in curricular designs and school texts, the product of a selection, decontextualization, and reorganization of scholarly knowledge.[7] Finally, "taught knowledge" (savoir ensign) is the version of knowledge that teachers, mediated by resources and their own interpretations, effectively present to students in the classroom.[8]

The relevance of this framework is enhanced when considered in the context of scientific literacy, a primary goal proposed for contemporary secondary education. Scientific literacy is understood as a strategy aimed at ensuring that citizens acquire scientific knowledge and understanding that enables them to participate and inform their decisions in society.[2] This objective contrasts with the traditional purpose of science teaching, which has focused almost exclusively on preparing a minority for higher education. In this new paradigm, the process of didactic transposition takes on a new complexity: it is not just a matter of simplifying the content, but of transforming it in a way that fosters an understanding of science as a human, cultural, and historical activity, avoiding the "deformed and impoverished view of scientific activity" that a purely conceptual transposition can generate.[2]

The impact of this approach in the classroom is direct. In traditional teaching, for example, the postulate of energy quantisation might be presented as an isolated fact to be memorised. However, from the perspective of scientific literacy, its didactic transposition requires contextualizing it. Thus, the concept is introduced as the necessary solution to a previously posed problem—the unexplained stability of the atom and discrete emission spectra—transforming an abstract rule into a tool with clear explanatory power. This shift in approach not only organizes the content but also models scientific work for students.

The relevance of this framework for the present work is twofold. First, it methodologically justifies the analysis of the double instance of transposition: first, that carried out by Curriculum Design when transforming "scholarly knowledge" into "knowledge to teach," and second, that executed by the PhET simulation when transforming "knowledge to teach" into interactive "taught knowledge." Second, and more importantly, the theory of transposition frames the central problem of this study. In an era with an abundance of digital educational resources, whose didactic design processes are not always explicit, it becomes imperative to analyze how these artefacts carry out transposition.[9] This article, therefore, uses the concept of transposition not only as a theoretical background, but as the very object of the research: to make visible and analyzable the process of knowledge transformation within an interactive digital tool.

Since its formulation, the theory has evolved and been enriched with perspectives that call for "epistemological vigilance" to prevent the simplification of content from distorting scientific knowledge.[10] This concept is particularly pertinent to our analysis, as this study can be understood as an act of epistemological vigilance. By examining whether the PhET simulation, in its effort to make quantization accessible, preserves the integrity of the "problem → solution" narrative and the logic of scientific modelling prescribed in the curriculum, we are assessing the fidelity of the transposition. The central question is whether the "knowledge taught" by the simulation, although simplified, remains coherent with the epistemic core of "knowing how to teach," a challenge often undermined by teachers' difficulties in mediating this transformation.[11]

The Legitimation Code Theory (LCT) and semantic gravity

To conduct a detailed analysis of transposition strategies, this study employs tools from Legitimation Codes Theory (LCT). LCT is a sociological framework that offers a precise language for analyzing knowledge practices, thereby overcoming the "knowledge - blindness" often found in educational research.[12] Its importance for science education is substantial, as it allows us to "make the invisible visible," that is, to reveal the underlying principles that structure knowledge and that students must master to succeed. Unlike other theories that focus on the social characteristics of students, LCT offers a conceptual framework for analyzing the nature of knowledge itself and how its structure influences teaching and learning.

This paper focuses on one of the dimensions of LCT: Semantics, which addresses the complexity and context of meaning. A central concept in this dimension is Semantic Gravity (SG), which refers to the degree to which meaning depends on its context. SG operates on a continuum:

a) A Strong Semantic Gravity (GS+) indicates that the meaning is highly dependent on its particular context and is anchored in the concrete.

b) A Weak Semantic Gravity (GS-) indicates that the meaning is more abstract, generalizable, and less dependent on its original context.[5]

The pedagogically productive movement between these two poles is called "semantic wave." Effective teaching practice, the theory goes, often involves "unpacking" an abstract concept (GS-) by presenting it in a concrete context (GS+) and then, once understood, "repacking" it back into its abstract form. This process of "unpacking and repackaging" knowledge is crucial for deep, cumulative learning.[13] The application of this concept is especially pertinent in physics, where teaching seeks to connect abstract principles with observable phenomena—a challenge that teaching research has extensively addressed.[14]

The application of Semantic Gravity in educational research is a rapidly expanding field. A significant number of works have utilized GS to analyze classroom discourse[15,16] and curricular materials, including textbooks.[17] More recently, a growing body of research has begun to explore multimodal and digital resources.[18,19] These studies demonstrate that the deliberate management of GS is a central feature of effective pedagogies across diverse disciplines.

It is in this latter context that the present work positions itself as an original contribution. While previous research has analyzed the discourse surrounding digital resources or their overall effect, this study offers a granular analysis of how a simulation's interactive functionalities are explicitly designed to execute semantic variations. Research on simulations, such as PhET, has confirmed their effectiveness in improving conceptual understanding,[20] but often without a theoretical framework to explain the underlying mechanisms. This work, therefore, seeks to close that gap. By examining the pedagogical architecture of the tool itself through the lens of LCT, this study presents a detailed case study of the materialization of the principles of didactic transposition in the design of a digital educational artefact, highlighting how design decisions can actively scaffold students' transition from the concrete to the abstract.

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Methodology

This study analyses the didactic transposition of a modern physics concept using a qualitative approach. A widely used international digital educational resource is examined through the lens of the pedagogical objectives outlined in the Curriculum Design for the subject "Classical and Modern Physics" for sixth-grade secondary school students in the Province of Buenos Aires, Argentina.

The resource selected for this analysis is the interactive simulation "Models of the Hydrogen Atom," developed by the PhET project at the University of Colorado. The choice of this object of study is based on three key criteria:

a) PhET simulations are a benchmark resource for science education globally, making this case a representative example of contemporary digital teaching practices.

b) Stability: Unlike transient audiovisual resources, the simulation constitutes a stable and citable digital artefact, guaranteeing the replicability of the analysis.

c) Interactivity: Its interactive nature makes it a vibrant object of study for teaching, as learning occurs through user action and experimentation, rather than passive reception.

The "knowing how to teach" that serves as a frame of reference for this study is defined in the Curriculum Design for Secondary Education: Classical and Modern Physics, 6th Year, of the General Directorate of Culture and Education of the Province of Buenos Aires, Argentina.

a) This document establishes a break with traditional science teaching, which had as its almost exclusive purpose the preparation for higher education.

b) Instead, the curriculum is based on the principle of scientific literacy, conceived as a strategy for citizens to acquire the knowledge of and about science necessary to participate and inform their decisions in society. This approach seeks to overcome a "deformed and impoverished vision of scientific activity," promoting an understanding of science as a human endeavour, contextualized within its historical and cultural context.

For the present analysis, the focus is on the "Thematic Axis: Modern Physics." The structure of this axis is particularly relevant, as the first instance of didactic transposition is evident in its very organization. The content is articulated around a conceptual narrative that begins with "The Failure of Classical Physics," identifying "the speed of light and atomic spectra" as key problems. It then presents new theories, such as "The First Proposed Solutions: Albert Einstein and Niels Bohr: Relativity and Quantization." It is this curricular guideline, which frames learning as a journey from problem to solution, that will be used as a criterion to evaluate the transposition executed by the digital resource.

To examine simulation transposition strategies, the concept of Semantic Gravity (SG) from Legitimation Code Theory (LCT) is used as an analytical tool. Semantic Gravity refers to the degree to which the meaning of knowledge depends on its context. To systematically apply this concept, the following translation framework has been developed:

Table 1 Translation device. Source: Own elaboration

Semantic Gravity (GS)	Definition in the Context of Analysis	Specific Indicators in the PhET Simulation
Strong (GS+)	Knowledge whose meaning is abstract and depends on its relationship to a complex network of theoretical concepts.	The theoretical concept of "energy quantization" The theoretical concept of "energy quantization". The mathematical equations that describe energy levels.
Intermediate (GS+/-)	Symbolic representations that act as a bridge, linking abstract theory with concrete experience.	The energy level diagram with its textual labels ("n=1", "n=2", etc.). The spectrometer that displays spectral lines at specific numerical wavelengths.
Weak (GS-)	Knowledge whose meaning is concrete and is derived directly from the observable and interactive experience of the simulation.	The visual image of the atom The user's action of "shooting" photons. The observable animation of the electron "jumping" or collapsing.

The analysis is carried out through a detailed examination of the simulation's functionalities. The procedure consists of:

a) Identify the key interactions that the simulation offers to the user.

b) Classify the visual, textual, and interactive elements of each interaction using the translation device categories (GS+, GS+/-, GS-).

c) Describe the "pedagogical journey" that the simulation designs, mapping how it manages the movement between different levels of semantic gravity—particularly the weakening of GS—to facilitate the transposition of the abstract concept of quantization and fulfil the curricular objective of showing the "failure" of the classical model.

To ensure the rigour of this qualitative analysis, Guba and Lincoln's trustworthiness framework is adopted. The credibility of the findings is established through prolonged engagement with the PhET simulation, which ensures a deep understanding of its functionalities, and through the systematic use of the translation device as an internal consistency tool. In turn, the transferability of the study is enhanced through a detailed description of both the analyzed digital resource and the reference curricular context, enabling other researchers to assess the applicability of the results to other settings. Finally, the explicit methodology and the translation device form a clear audit trail (audit trail) that guarantees the dependency and confirmability of the analysis, making the process traceable and ensuring that the conclusions are derived directly from the observable characteristics of the simulation and not from the researcher's biases.

Results

This section analyses the didactic transposition process in two successive stages. First, it examines the didactic decisions present in the Curriculum Design of the Province of Buenos Aires. Second, it

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analyses how the PhET simulation implements and materializes these curricular guidelines.

The transposition of the "Failure of classical physics"

In the curriculum design

The first instance of didactic transposition is identified in the conceptual architecture of the curriculum. The document does not introduce modern physics as a mere collection of theories, but instead frames it within a precise narrative. Under the heading "The Failure of Classical Physics," the text establishes the pedagogical starting point as "The Problems of Classical Physics at the Beginning of the 20th Century". It positions the theories of Bohr and Einstein as "The First Proposed Solutions."

This decision to structure the content as a problem-solution narrative is a fundamental transposition. This structure articulates directly with the philosophy of "scientific literacy" that the document itself promotes. 4 In contrast to traditional teaching, described as a "ritual of initiation" into a world of decontextualized formulas, this narrative presents science as a rational and dynamic enterprise that advances by resolving the inadequacies of previous theories. In this way, the narrative structure not only organizes the content but also modifies the logic of knowledge legitimation in the classroom. Bohr's model is not presented as a fact to be accepted by the authority of the teacher or the text; instead, its validity is legitimized for the student by its superior explanatory power in the face of a problem that has been previously established and understood.

In the PhET simulation

The second instance of transposition is observed in the way the PhET simulation materializes the narrative direction of the curriculum. The digital resource does not limit itself to presenting Bohr's model, but first invites the user to interactively experience the "failure" of Rutherford's classical model. By selecting this model, the user is positioned as an active agent who "tests" the theory and observes an unequivocal animation of the atom's collapse, with the electron describing a spiral trajectory toward the nucleus. By applying the translation device, this functionality constitutes a deliberate and effective weakening of Semantic Gravity (SG). The simulation condenses the complex history of experimental anomalies and theoretical contradictions into a single, powerful and concrete visual metaphor. This act of transposition contrasts sharply with a purely textual approach, providing an experiential anchor that justifies the need for a new paradigm. Furthermore, the active role of the student, who must select the model to observe its inadequacy, aligns with the curriculum's "Didactic Guidelines," which advocate overcoming conceptual reductionism through proposals that engage students in "scientific practices that integrate conceptual, procedural, and axiological aspects." The simulation, therefore, not only teaches content but also models a practice of scholarly research where theories are tested to assess their validity.

The transposition of the concept of "Quantification"

In curriculum design: from scholarly theory to pedagogical prescription

The first instance of transposition is observed in the curriculum's selection and treatment of the concept of "quantification." The document performs a fundamental didactic operation by isolating and explicitly naming Niels Bohr's contribution to this term. In doing so, it elevates a highly complex physical-mathematical principle (Strong GS) to the status of a central teaching object.

An analysis of Semantic Gravity in the curriculum text itself reveals a deliberate tension. On the one hand, the document maintains a Strong Semantic Gravity (GS+) when describing the theoretical context, indicating that the discontinuities in the spectra "were not explainable in terms of the theory of electromagnetic wave emission." This language is abstract and presupposes prior theoretical knowledge. However, the curriculum immediately modulates the GS by providing didactic guidelines. It suggests that the treatment should not be "extensive" and proposes addressing it through "research or seminars that address issues such as: experiences that preceded the new theories [...] validity scales of the new theories [...]."

This orientation is an explicit instruction to weaken Semantic Gravity (GS-). The curriculum is telling teachers not to teach "quantification" from pure theory (GS+), but rather to anchor it in more concrete contexts: the history of "experiences" and the "scales" where phenomena are manifest. Therefore, the curriculum itself prescribes a "semantic surge": it recognizes the abstract nature of the concept (GS+), but instructs teachers to ground it in the classroom through contextual anchoring (GS-).

PhET simulation: from prescription to interactive experience

The second instance of transposition is manifested in how the PhET simulation executes the curriculum directive, translating the abstract concept of "quantification" into an interactive procedure. The simulation operates as a Semantic Gravity weakening engine, guiding the student through a cycle of experimentation and discovery. This process can be broken down into more detailed phases:

a) Familiarisation and Free Action (Weak GS): The initial interface presents a simplified visual representation of the atom. The user is invited to a purely contextual and physical action: using the "light gun" to "shoot" photons. At this stage, there is no theory, only concrete interaction within the rules of the virtual environment.

b) Pattern Identification (Transition from GS- to GS+/-): Through experimentation, the student discovers a pattern: most photons have no effect, but specific photons (identified by their colour and position in the spectrum) cause an observable reaction. The concrete experience (seeing a photon pass through or be absorbed) begins to take on a more general meaning: there is a selective "rule" in the system.

c) Symbolic Linking (Intermediate GS): At the instant a photon is absorbed and the electron "jumps," the simulation simultaneously activates the symbolic indicators: an arrow appears in the energy level diagram (labelled "n=1," "n=2," etc.) and a bright line is recorded in the spectrometer. This is the crucial moment of the transposition. The simulation explicitly connects the concrete action (GS-) with an abstract symbolic representation (GS+/-) that encodes the theoretical rule of discrete energy levels.

d) Inference of the Abstract Principle (GS+ Construction): After repeating this cycle, the student can infer the general theoretical principle: the energy of the atom is "quantized." They have not been told the definition; they have constructed it from the evidence generated by their own interaction. The simulation, therefore, does not simply "show" the concept; it creates an environment where understanding the abstract principle (GS+) becomes the logical conclusion of a concrete experience (GS-).

Contrast between models as a teaching strategy

In curriculum design: the prescription of a semantic wave

The first instance of transposition is articulated in the curriculum's "Didactic Guidelines," which establishes a highly complex

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pedagogical guideline. The document explicitly instructs that the teaching of models as "static schemas" and devoid of content must be overcome. The goal is for students to analyze "what the purpose of their construction is, what question or problem the model addresses [...] what aspects it takes into account and which it omits."

From the perspective of Semantic Gravity, this guideline is a prescription for the teacher to generate a semantic wave in the classroom. It is not enough for the student to learn the concrete and contextualized characteristics of a particular model (knowledge with Weak Semantic Gravity, GS-). The curriculum demands that this concrete knowledge be used as a springboard to reach an abstract and decontextualized understanding of the nature of scientific modelling itself (knowledge with Strong Semantic Gravity, GS+). In essence, the teacher is instructed to guide the student on a journey from the object (the Bohr model) to the epistemological logic of the discipline (what a model is and what it is used for in Physics).

PhET simulation: executing semantic swell through interactivity

PhET simulation materializes this complex curriculum guideline through its model selector functionality. This interactive tool acts as a powerful engine to execute the semantic wave prescribed by the curriculum, guiding students on a specific cognitive journey.

The process can be analyzed as follows:

a) Immersion in the Concrete (GS-): The student interacts with visual and concrete representations of each model. They observe a collapse in Rutherford's model (a GS- event) and stability in Bohr's (another GS- event). These experiences are grounded in the immediate context of the simulation.

b) Juxtaposition as a Catalyst: The key action that simulation promotes is the direct and interactive juxtaposition of these different models. Unlike a text that describes the models sequentially, the simulation enables the user to switch instantly between them. This active comparison forces the student to transcend simply observing each model and to ask higher-order questions: Why did the model change? What problem did the new model solve that the old one could not?

c) Ascent to the Abstract (GS+): To answer these questions, the student must necessarily move to a more abstract plane. They must infer the principles and limitations of each model and, ultimately, arrive at a more general and decontextualized understanding of the nature of science: that scientific knowledge is provisional and evolving, and that models are tools with specific ranges of validity.

In this way, the simulation not only presents the models; its interactive design scaffolds and facilitates semantic ascent. It transforms the problematic task of reflecting on the epistemology of science into a natural consequence of interacting with the resource, thus developing the student's ability to navigate between the concrete and the abstract.

Discussion

The central finding of this study is the remarkable alignment between the pedagogical intention of the Buenos Aires Province Curriculum Design and the teaching strategies embodied in the PhET simulation. As demonstrated in the analysis, the curricular decision to frame modern physics within a problem-solution narrative is a key instance of transposition. The power of this choice merits further exploration, as it is not a simple organizational decision but a central act of didactic transposition that transforms the complex history of science.

In historical reality ("scholarly knowledge"), the transition from classical to quantum physics was not a single, orderly event, but a decades-long process with anomalous experiments and multiple theoretical proposals. The first instance of transposition is "translating" that complex reality into a logical sequence. Research in science education has shown that incorporating historical and philosophical context helps students understand paradigm shifts and break away from their classical preconceptions.[21] The curriculum implements this strategy by isolating a "problem" (atomic spectra) and presenting the Bohr model as the direct "solution."

This narrative structure is robust because it fulfils fundamental pedagogical and cognitive functions. First, it creates an intellectual need. By exposing the inadequacy of the classical model, a cognitive tension is generated that motivates the student to seek a solution. This strategy aligns with pedagogical models that aim for a "radical conceptual shift" to overcome students' traditional intuitions.[22] Second, it gives purpose to abstraction. The incredibly abstract idea of "quantization" becomes the functional "key" that solves the mystery. As Legitimation Codes Theory describes, this structure creates a "semantic wave" that deliberately connects concrete examples with abstract theory, which is crucial for building deep, cumulative knowledge.[5] Finally, this narrative reflects the logic of scientific inquiry. Although simplified, it teaches that science advances by confronting anomalies and proposing new models to explain them.[23] This aligns with the Curriculum Design goal of overcoming the "deformed and impoverished vision of scientific activity".[24] The decision to transpose history into this narrative is, therefore, the didactic mechanism that prepares the student's mind, justifies the need for abstract theory, and models a powerful version of scientific endeavour.

The results of this analysis are not only consistent with the empirical literature but also offer a theoretical framework to explain its findings. Research has consistently shown that interactive simulations significantly improve conceptual understanding of quantum mechanics.[25] Our analysis provides a theoretical explanation for this phenomenon: the simulation's weakening of Semantic Gravity is a highly effective guided inquiry mechanism. By transforming an abstract theoretical failure into a visually observable (GS-) collapse and the quantization principle into an interactive "rule of the game," the simulation scaffolds knowledge construction. This strategy aligns with findings that underscore the importance of linking simulations with structured worksheets and activities,[26] demonstrating that the simulation's intrinsic design already serves as a pedagogical guide.

Likewise, our study is part of the debate on the use of the Bohr model in secondary school. The literature identifies a controversy in which some researchers warn about the misconceptions that this model can generate, even proposing its exclusion in favour of more modern models. Others, on the other hand, defend its value as a conceptual "springboard" if it is appropriately contextualized within a historical and philosophical framework or integrated with interactive tools.[27] The analysis of the PhET simulation presents a practical case of how to resolve this tension. As demonstrated, the simulation does not teach the Bohr model in isolation. However, it integrates it into a model-testing tool —a strategy that has been identified as crucial in helping students develop a more sophisticated understanding and overcome simplistic atomic views.

However, it is important to recognize that the transposition achieved by simulation, like any didactic simplification, is not

without weaknesses. Research has indicated that while interactive visualizations are powerful, they can lead to oversimplification if not accompanied by appropriate pedagogical guidance that connects experience with theoretical formalism.[28] Furthermore, the very nature of Bohr's visual model, although useful as a "springboard," runs the risk of solidifying in students a conceptually incorrect planetary image of the atom that must later be unlearned. Therefore, the effectiveness of simulation lies not only in its design, but in how the teacher integrates it into a broader teaching sequence that explicitly addresses these limitations.

Ultimately, this work presents itself as a contribution to the growing body of research that applies LCT to analyze educational practices. A review of the literature on the topic confirms that semantic waves—the movement between meanings of high and low semantic gravity—are a central pedagogical mechanism for building cumulative knowledge across diverse resources, including digital tools and multimodal texts.

While much of the research in LCT has focused on analyzing texts or classroom discourse,[16] this study provides a granular analysis of how LCT principles are realized in the interactive functionalities of a digital resource. It has been shown how specific design features—a model chooser, an interactive photon "gun," and the synchronous linking of an animation (GS-) with a symbolic diagram (GS+/-)—operate as Semantic Gravity management engines. Therefore, this work functions as an in-depth case study that not only uses LCT as an analytical framework but also contributes a detailed empirical example of how its theoretical principles can be "designed" into the architecture of an interactive learning tool—an area that, although emerging, is fundamental to understanding pedagogy in the digital age.[29,30]

Conclusion

This work analyses the didactic transposition of the concept of energy quantization, examining the articulation between the guidelines of a secondary-level curriculum and the pedagogical strategies of an international digital resource. The analysis demonstrated a notable coherence between the intention of the Curriculum Design of the Province of Buenos Aires—which frames modern physics in a problem → solution narrative—and the materialization of said narrative in the interactive simulation PhET "Models of the Hydrogen Atom". It has been argued that the simulation's effectiveness in facilitating the understanding of abstract concepts lies in its deliberate management of Semantic Gravity, guiding the student from concrete, interactive experiences to the inference of theoretical principles. This study makes a twofold contribution to the field of science education. First, it provides a theoretical framework, based on Legitimation Code Theory (LCT), to explain the pedagogical effectiveness of PhET simulations —a phenomenon widely reported in the empirical literature. Second, it presents an in-depth analysis of how research-based didactic strategies—such as creating an intellectual need, justifying abstraction, and teaching about the nature of scientific models—can be designed and integrated into the functionalities of a digital tool.

Like any case study, this research has limitations. The analysis has focused on the design of the resource and the curriculum, rather than on its actual implementation in the classroom or on the learning measured among students. These limitations are precisely the basis for future research. It would be valuable to conduct empirical studies that observe students' interactions with the simulation to validate whether the "semantic surge" described here corresponds to their cognitive processes. Likewise, this analytical framework could be applied to other digital resources to compare their transposition strategies or extended to investigate how teachers use, adapt, or even subvert the pedagogical intentions of these tools in their daily teaching practices.

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