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Detecting Knowledge Construction through Legitimation Code Theory: A Study of Semantic Density in Quantum Mechanics Textbooks[+*]

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Abstract

This study investigates the knowledge presented in Quantum Mechanics textbooks used in higher education, focusing on the definition of the wave function. The theoretical and methodological framework is based on Legitimation Code Theory (LCT), specifically the semantic dimension and the concept of semantic density, which enables the analysis of different levels of complexity and condensation of meanings within texts. The study presents a translation device composed of five levels of semantic density and applies it to the analysis of six sections extracted from three widely used Quantum Mechanics textbooks: The Feynman Lectures on Physics (Feynman, Leighton, & Sands), Quantum Physics (Eisberg & Resnick), and Introduction to Quantum Mechanics (Griffiths). The analysis encompassed both sections dedicated to the conceptual interpretation of the wave function and sections focused on the presentation of the Schrödinger equation. The results also reveal significant differences in the organization of knowledge across the textbooks. Feynman, Leighton, and Sands emphasize quantum concepts and employ narrative and conceptual explanations; Eisberg and Resnick introduce the wave function primarily through references to classical physics; and Griffiths combines conceptual and mathematical

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approaches, placing strong emphasis on mathematical formalism and problem solving. The analysis of semantic profiles showed that texts characterized by semantic waves promote articulation across different levels of semantic density, varying the complexity of meanings and thereby enhancing knowledge building. In contrast, sections characterized by extended passages at high levels of semantic density, particularly at the symbolic level, tend to hinder access to meanings and conceptual understanding. The findings indicate that the semantic organization of textbook discourse directly influences learning opportunities, highlighting the importance of instructional materials that promote movement across different levels of semantic density.

Keywords: *Quantum Mechanics Education; Legitimation Code Theory; Semantic Density; Wave Function.*

I. Introduction

Teaching quantum mechanics represents one of the greatest challenges in the education of physics students, primarily due to the abstract and counterintuitive nature of its fundamental concepts. The conceptual framework of quantum theory breaks with everyday experience and requires students to restructure the conceptions they formed based on classical physics (Greca; Herscovitz, 2011; Pospiech, 2003; Singh; Marshman, 2015). Understanding quantum phenomena requires a paradigm shift away from the deterministic thinking of classical physics, making it essential to adopt an approach to teaching that goes beyond mere mathematical manipulation and prioritize conceptual understanding. However, complex mathematical formalism and probabilistic interpretation pose additional barriers to student learning and understanding (Greca; Freire Júnior, 2003; Lin; Singh, 2010; McKagan *et al.*, 2009). Another factor that hinders the teaching-learning process is the absence of directly observable phenomena, since many concepts in quantum mechanics have no perceptible empirical counterparts, which limits the experimentation and visual support often used in physics teaching. Added to these challenges is insufficient teacher training; many teachers do not have an adequate command of quantum concepts or possess appropriate teaching strategies for addressing them in the classroom (Fanaro; Otero; Moreira, 2009; Lobato; Greca, 2005).

The teaching materials available for higher education generally maintain a strongly formalist approach, centered on problem-solving and the technical mastery of equations, with little emphasis on the conceptual, epistemological, and interpretive dimensions of quantum theory (Greca; Freire Júnior, 2011; Mohan, 2020). Textbooks are instruments through which scientific discourse is presented in a didactic manner, through the various modes that constitute it: writing, images, graphs, tables, and mathematical equations. University courses are structured around the knowledge provided in textbooks, which serve as sources of research for students and reference materials for teachers. The textbooks selected for higher education courses influence both what students learn and what teachers teach. Teachers use textbooks as sources for acquiring and expanding their knowledge and for structuring their classes, as well as materials for reviewing topics that will be addressed in the classroom. The way content is presented in quantum mechanics textbooks plays a central role, as these materials guide both pedagogical practice and conceptual learning, becoming, in practice, one of the main sources of scientific knowledge in the initial and continuing education of teachers (Ogan-Bekiroglu, 2007; Greca, Moreira; Herscovitz, 2001).

The main objective of this study is to investigate the knowledge made available in sections of quantum mechanics textbooks used in higher education, drawing on a sociological framework derived from social realism. This framework emphasizes the epistemic dimension of knowledge and provides an analytical tool, the Legitimation Code Theory (LCT) (Maton; Hood; Shay, 2016). The epistemic analytical framework comprises three dimensions that have been explored: Specialization, Semantics, and Autonomy (Maton; Hood; Shay, 2016). Each of these dimensions has its own codes and concepts, which are used to analyze knowledge. These dimensions can be used separately or in conjunction with one another, depending on the purpose of the study. In this research, we will use the semantic dimension as an analytical tool, focusing on one of its codes: semantic density (SD).

All the sections analyzed define the wave function and were taken from quantum mechanics textbooks for higher education that are widely used by some of the leading universities in Brazil: *Introduction to Quantum Mechanics* (Griffiths, 2011); *Quantum Physics* (Eisberg; Resnick, 1979); and *The Feynman Lectures on Physics* (Feynman, Leighton & Sands, 2008). The choice of the sections that define the wave function is justified by the fact that the wave function is a fundamental concept in quantum mechanics, supporting the understanding of the quantum behavior of physical systems. The wave function is an element that synthesizes the theoretical structure of quantum mechanics and enables the transition between mathematical formalism and the physical interpretation of phenomena. It provides the basis for calculating observable quantities and for understanding the probabilistic behavior of particles.

> *The concept of the wave function lies at the heart of the formulation of quantum mechanics. The 'wave function' is the quintessence for obtaining physically measurable quantities, such as probability, expectation value, uncertainty, etc. In other words, it is an extremely important formulation in quantum mechanics and a crucial ingredient in establishing a correspondence between theoretical results and experiments* (Chhabra; Das, 2017, p. 3, our translation).

II. Theoretical Framework

The theoretical framework adopted in this study is the Legitimation Code Theory (LCT), which provides sociological tools for the study of practice and considers knowledge as socially produced. The scientific language presented in textbooks to define the wave function will be characterized in terms of Semantic Density (SD), one of the variables of the semantic dimension.

Semantic Density refers to the level of complexity of the meanings conveyed by a text, whether oral or written, or, more broadly, to the complexity of practices (Martin; Maton; Doran, 2020). The more condensed the meanings, the stronger the SD; the less condensed they are, the weaker the SD. This condensation may occur through symbols, theories, or concepts, such that the strength of SD increases as a greater number of meanings is brought together within these forms of representation. Another way of understanding SD is through the notion of **relationality**, understood as the number of relationships established between one meaning and other meanings. The greater the number of relationships mobilized, the stronger the semantic density (Martin; Maton; Doran, 2020). From this perspective, SD constitutes a continuum of strengths that can be dynamically shifted either toward strengthening, for example, by moving from a simple symbol to a more complex concept, or toward weakening, when complex concepts are broken down into simpler terms (Martin; Maton; Doran, 2020).

There is already a diverse body of research in Brazil using LCT to analyze different aspects of Physics and Chemistry education, with several studies focusing on the semantic dimension. Among these studies, we highlight the article by Bocheco *et al.* (2022), which examines physicomathematical structures and the use of mathematics in physics education through the SD.

Legitimation Code Theory makes use of translation devices that allow, for example, considerations regarding the complexity of meanings to be translated into observables, which can then be used to identify variations in SD in a lesson or written text. Translation devices thus make it possible to translate the theoretical constructs of LCT into observable variables.

III. The Translation Device

For this study, a translation device applied to physics was developed, as described below (Table 1), based on the work of Dos Santos and Mortimer (2019), who developed a similar device applied to chemical knowledge. The translation device was developed using five levels of SD, ranging from the strongest (5) to the weakest (1), to analyze the sections of the textbooks. The units of analysis were the text segments, consisting of one or more clauses. In defining a text segment, the portion from one full stop to the next is considered.

For the construction of the translation device, we used a distinction between theory and concept. A theory consists of a set of falsifiable hypotheses that are confronted with one another and with facts that constitute scientific evidence; a concept can be defined as a notion or idea, a general and abstract representation of reality. From this perspective, a theory may encompass several concepts and, in this sense, is broader and more complex than a single concept.

According to Bruner (1990), there are two modes of cognitive functioning, and these modes construct realities by organizing experience in their own ways: the paradigmatic mode, which expresses logical-scientific thinking, and the narrative mode, which addresses how human intentions operate in a variety of situations. Although, in this study, the language predominantly follows the paradigmatic mode, this is not a general rule. Narrative is used primarily in *The Feynman Lectures on Physics*, by Feynman, Leighton, and Sands (1964), to highlight observations concerning the history of quantum mechanics and particular aspects that the authors wish to emphasize.

In this study, we will use the meaning attributed to narratives by Bruner (1990). According to the author, a narrative requires four crucial grammatical features: human action or agency, understood as goal-directed action controlled by agents; the establishment and maintenance of a sequential order; sensitivity to what is canonical and what violates canonicity; and the narrator's perspective, whose voice is always present.

Table 1 presents the translation device for the analysis of SD, which was used by considering each text segment, to which one of the SD levels was assigned, with values ranging from 1 to 5. The highest level of SD, level 5, corresponds to the symbolic form, referred to as **Symbolic**, which includes mathematical expressions, equations, and graphs. Level 4, referred to as **Theoretical**, corresponds to explanations of physical content using physical theories, such as, for example, associating the wave function with the de Broglie principle. Level 3, entitled **Conceptual**, requires an understanding of physical concepts that are simpler than the theories at level 4 in order to understand the content, such as the concept of probability for understanding the definition of the wave function. Level 2, called **Narrative**, relates historical or non-historical facts presented in ordinary language. The weakest level of SD, level 1, termed **Metacommentary**, is related to portions of the text in which the author comments on the textual structure and aims to guide the reader in understanding the structure and the main concepts that will be developed throughout the text. In order to characterize the strengthening and weakening movements of SD, semantic profiles were plotted, which can be visualized through semantic waves (presented in the following section).

It should be noted that levels 1 and 2 do not refer to physical knowledge, but rather to the way in which this knowledge is articulated with other narrated facts (in the narrative form, level 2) or with textual construction strategies (in the form of metacommentary). This does not invalidate their consideration, since these narrative and textual elements provide coherence to the text being constructed, and this text, in turn, conveys knowledge of quantum mechanics.

Table 1: Levels of Semantic Density (SD) for Physical Knowledge.

Semantic Density	**Level**	**Form**	**Description**	**Examples**
Strong	5	Symbolic	Equations, diagrams, graphs	Mathematical equation of the wave function
	4	Theoretical	Requires an understanding of physical theories to explain the content	Association of the wave function with the principle of conservation of energy
	3	Conceptual	Requires an understanding of physical concepts to explain the content	Association of isolated quantum concepts (probability, state vector, amplitude) with the content presented. Understanding of simplified physical concepts and their relationship to the content
	2	Narrative	Relates facts and ideas narrated in ordinary language	Association between the wave function and everyday examples
Weak	1	Metacommentary	Parts of the text in which the author comments on the textual structure	Comments on the organization of the text and the sequence of ideas

Source: Authors' elaboration, based on Dos Santos and Mortimer (2019).

IV. Methodology

The sections to be analyzed define the wave function in the three works and were divided into two parts for the analysis. The first part contains the more conceptual sections, in which the authors conceptually define the wave function, while the second part comprises the more "mathematized" sections, in which the authors present the Schrödinger equation. In the first part, we present three sections entitled: The Meaning of the Wave Function, from *The Feynman Lectures on Physics*, by Richard Feynman, Robert Leighton, and Matthew Sands (1964); Introduction, from *Quantum Physics*, by Eisberg and Resnick (1974); and The Statistical Interpretation, from *Introduction to Quantum Mechanics*, by David Griffiths (1994). In the second part, we present three additional sections: The Schrödinger Equation, from *The*

Feynman Lectures on Physics, by Richard Feynman, Robert Leighton, and Matthew Sands (1964); Plausible Arguments Leading to the Schrödinger Equation, from *Quantum Physics*, by Eisberg and Resnick (1974); and The Schrödinger Equation, from *Introduction to Quantum Mechanics*, by David Griffiths (1994).

To define the textbooks used in this study, a survey of the basic and supplementary bibliographies listed in course syllabi available online on the websites of six Brazilian universities was conducted. The survey included the syllabi of nineteen courses offered in six undergraduate Physics programs in Brazil (encompassing both teacher education and bachelor's degree programs). The universities were: UFG, UFMG, UnB, UFRGS, USP, and UNICAMP. The textbooks analyzed are translated editions of works originally published in English in earlier years, as shown in Table 2 below. Throughout this article, we chose to cite the authors using the date of the first edition, to maintain the historical chronology.

Table 2: Publication dates of the analyzed textbooks and the editions consulted.

Book	**Year of first edition**	**Year of edition consulted**
The Feynman Lectures on Physics (Lições de Física, in Portuguese*)* ***by Richard Feynmann, Robert Leighton & Matthew Sands***	1964	2008
Quantum Physics (Física Quântica, in Portuguese*)* ***by Eisberg & Resnick***	1974	1979
Introduction to Quantum Mechanics (Mecânica Quântica, in Portuguese*)* ***by David Griffiths***	1994	2011

To construct the graphs, we used the SD levels derived from the translation device developed for physical knowledge. We analyzed each text segment, from one full stop to the next, assigning a semantic level to each segment. This allowed us to plot semantic profiles of the sections analyzed, using the semantic levels on the y-axis and the text segments on the x-axis. In determining the semantic profiles, both semantic waves, in which the levels of semantic density vary, and flat lines, in which no such variation occurs, may be obtained. The importance of the occurrence of semantic waves lies in the body of evidence indicating that their production has a positive impact on student learning (Macnaught *et al.*, 2013; Maton, 2013, 2014). Alongside these graphs, tables (Tables 3 to 9) are presented showing the percentage of each density level, together with the percentage of quantum or classical concepts used in the text.

V. Quantum Mechanics Textbooks

The sections analyzed in this study were taken from three quantum mechanics textbooks for higher education that are among the most widely used by some of the leading universities in the country, according to the survey of Physics course syllabi described above.

These works also emerged within a specific historical context: the Cold War, which followed World War II. At that time, American physics departments experienced a dramatic increase in the number of students. The primary objective of physics education during this period was to train quantum physicists as quickly and efficiently as possible, setting aside the conceptual and interpretive reflections that had previously occupied valuable class time; students were expected to become more like engineers or quantum mechanics, with a strong command of the mathematical calculations of quantum physics (Greca; Freire Júnior, 2011). Thus, the philosophical aspects of quantum mechanics were largely set aside. Following this period of intensive training for quantum physicists, and with the decline in the number of physics students at American universities, there was an attempt to modify textbooks by incorporating conceptual aspects of quantum mechanics. This is the case, for example, with the textbook by Eisberg and Resnick (1974), which includes a list of questions for conceptual discussion in addition to the extensive list of traditional Quantum Mechanics exercises, characterized by a strong emphasis on mathematical problem-solving and little or no exploration of the physical concepts involved. It should be noted that, although this represented an attempt at change, this approach still did not lead the authors to formulate conceptual and philosophical questions concerning the interpretations and foundations of quantum mechanics.

The book by Richard Feynman, Robert Leighton, and Matthew Sands (1964) is the result of part of a two-year period of lectures delivered at the California Institute of Technology (Caltech). Richard Feynman wrote a preface to the collection, introducing the work and explaining that the main objective of the Caltech lectures was to maintain the enthusiasm of outstanding students by presenting new and modern ideas. Feynman points out that he "saw no reason to organize the lectures in any definite order, in the sense that a particular topic could not be mentioned until they were ready to discuss it in detail" (Feynman, Leighton & Sands, 2008). In other words, the work follows an organizational structure that differs from that of traditional textbooks. Volume III of the collection, which is devoted to quantum mechanics, includes an introduction written by Matthew Sands, with comments on how quantum mechanics will be addressed in the book and on the authors' approach to the wave function.

> *These lectures are an attempt to present the basic and essential ideas of quantum mechanics in a way that we hope will be understandable. The approach you will find here is new, particularly at the level of a course for students at an intermediate stage, and was regarded as a teaching experiment. After observing how readily some students embraced it, I believe that the experiment was a success (*Feynman; Leighton; Sands, 2008, p. 7, our translation*).*

> *Quantum physics concepts were introduced whenever they were necessary for understanding the phenomena being described. Moreover, the final twelve lectures provided a more coherent introduction to the concepts of quantum mechanics. However, as the lectures progressed toward their conclusion, it became clear that the time devoted to quantum mechanics had not been sufficient. As the material was being prepared, it was continually discovered that other interesting and important topics could be addressed using the tools that had been developed. There was also concern that the overly brief treatment of Schrödinger's wave function included in the twelfth lecture would not be sufficient to provide a bridge to the more conventional treatments found in many of the books that students would read* (Feynman; Leighton; Sands, 2008, p. 7, our translation).

David Griffiths's book (1994) is the most recent of the three works. It presents equations and predominantly mathematical descriptions and advocates problem-solving as a means of understanding quantum mechanics. In this text, students are expected to develop expertise in solving quantum mechanics problems (Mohan, 2020). In the preface, the author states that the main objective of the book is to teach students how to do quantum mechanics through a mathematical approach, while philosophical questions are reserved for the end of the book.

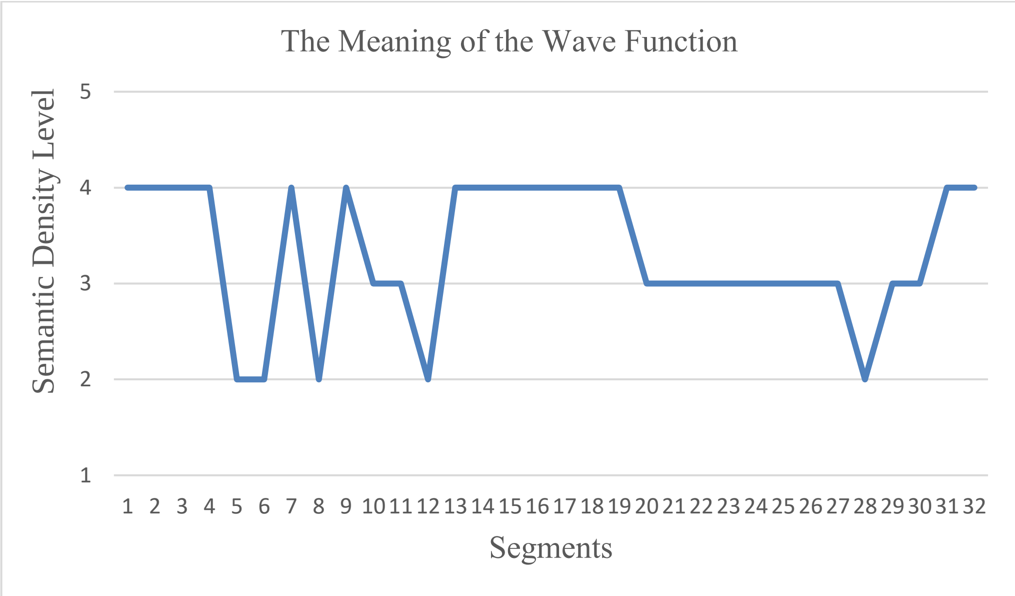
> *I do not believe it is possible to intelligently discuss what quantum mechanics means until one has a firm grasp of what quantum mechanics does. It is therefore essential to develop special techniques for tackling more realistic problems. Perhaps not, but physics is like carpentry: using the right tool makes the job easier, not harder, and teaching quantum mechanics without the appropriate mathematical equipment is like asking a student to dig a foundation with a screwdriver (*Griffiths*, 2011, p. 8, our translation).*

VI. Analysis and Results

The first three sections correspond to the presentation of the wave function in a more conceptual form, without the use of mathematics, in the three works. Richard Feynman, Robert Leighton, and Matthew Sands (1964) present the wave function in a section entitled "The Meaning of the Wave Function", only in the final chapter of the third volume of their collection, which is entirely devoted to quantum mechanics. Presenting the wave function in the final chapter of the volume on quantum mechanics indicates that Feynman, Leighton, and Sands (1964) adopt a distinctive approach in their work, one that is not historical and follows an order in which concepts are presented differently from traditional approaches (Hoernig; Massoni; Lima, 2020; Karam, 2018). Eisberg and Resnick (1974) present the wave function in a section entitled "Introduction", which introduces the fifth chapter of their book. The preceding four chapters address what is known as "old quantum mechanics", covering topics such as: thermal radiation and Planck's postulate, photons, the de Broglie postulate, and the Bohr model. David

Griffiths (1994) presents the wave function in a section entitled "The Statistical Interpretation", which is the second section of the first chapter of his book. The author chooses to introduce the wave function first in its mathematical form and only later presents it in its conceptual form.

Section of *The Feynman Lectures on Physics* by Richard Feynman, Robert Leighton, and Matthew Sands (1964): "The Meaning of the Wave Function"



Graph 1: Analysis of Semantic Density (SD): "The Meaning of the Wave Function".

Table 3: Distribution of Forms in the section "*The Meaning of the Wave Function*".

Level	**Form**	**Percentage**	**Classical/ Quantum**	
5	Symbolic	0%		
4	Theoretical	47%	C 0%	Q 100%
3	Conceptual	37%	C 0%	Q 100%
2	Narrative	16%		
1	Metacommentary	0%		

The discourse analysis in relation to the semantic profile, based on variations in SD and the identification of semantic waves throughout Graph 1, shows that, in the initial portion, semantic waves are present, with alternating density between the Theoretical (4) and Narrative (2) levels, suggesting movements of unpacking and repacking of meaning. According to Macnaught *et al.* (2013), these movements refer to variations in SD throughout discourse: *unpacking* corresponds to the process of decondensing meaning, in which abstract and highly complex concepts are translated into simpler forms, whereas *repacking* refers to the opposite movement, that is, the recondensation of meaning, in which these explanations are once again articulated in more abstract and conceptually dense terms. The construction of semantic waves depends precisely on the articulation between these two movements, enabling transitions between different levels of density and complexity, which favors knowledge building. In the subsequent portion of the graph, two plateaus of SD can be observed (segments 12–19 and 20–27), with a flat line established at level 4 (Theoretical) and another at level 3 (Conceptual), indicating periods of less variation and, therefore, stabilization of the discourse at particular semantic levels.

In the section analyzed, Feynman, Leighton, and Sands (1964) use three levels of SD: 4, 3, and 2, with a predominance of levels 4 (Theoretical) and 3 (Conceptual). The authors do not use level 5, Symbolic, to present the meaning of the wave function. They choose to discuss the meaning of the wave function without using any mathematical equations, relying predominantly on the Theoretical and Conceptual levels. At level 4 (Theoretical), the authors draw on physical theories, such as Born's interpretation of the Schrödinger equation, which introduced the issue of probabilities and uncertainties regarding the location of particles into quantum mechanics, as illustrated in the following excerpt:

> *It was Born who correctly interpreted (as far as we know) the ψ in Schrödinger's equation in terms of the probability amplitude – the difficult idea that the square of the amplitude is not the charge density but simply the probability per unit volume of finding an electron there, and that when you find the electron somewhere, all the charge is there* (Feynman; Leighton; Sands, 2008, p. 21-6, our translation).

Level 3, Conceptual, requires an understanding of physical concepts that are simpler than the theories presented at level 4. In this section, they appear in passages in which the authors address concepts such as charge density, electric current, and state in order to give meaning to the wave function.

> *On the other hand, think of a situation in which there is an enormous number of particles in exactly the same state, a very large number of them with the same wave function* (Feynman; Leighton; Sands, 2008, p. 21-6, our translation).

> *Then, in a situation in which we can have many particles in exactly the same state, a new physical interpretation of the wave function becomes possible. The charge density and the electric current can be calculated directly from the wave functions, and the wave functions acquire a physical meaning that extends to classical, macroscopic situations* (Feynman; Leighton; Sands, 2008, p. 21-6, our translation).

Level 2, Narrative, appears in this section when the authors describe the challenges encountered in the discovery of the wave function.

> *He soon discovered, by solving a series of problems, that this was not working properly. It was at this point that Born made an essential contribution to our ideas*

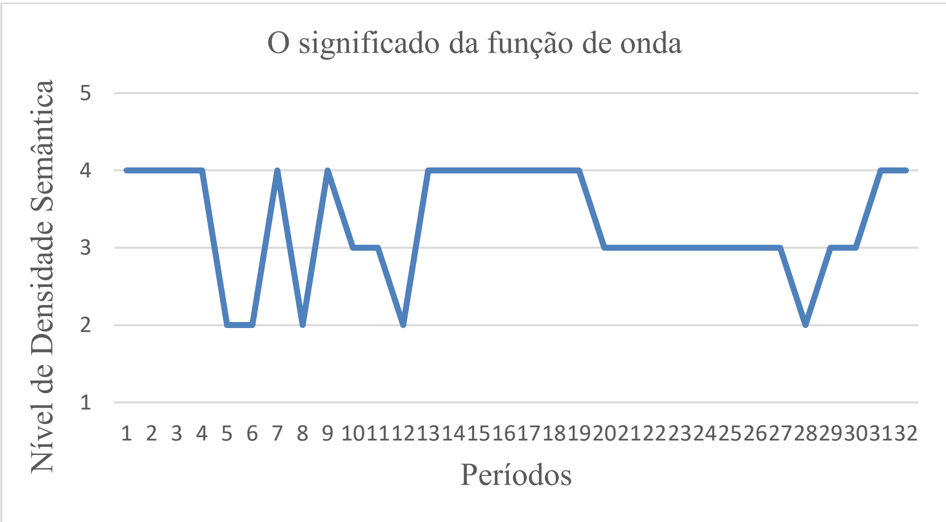
concerning quantum mechanics (Feynman; Leighton; Sands, 2008, p. 21-6, our translation).

Karam (2018), in a study entitled *O que diferencia as Feynman Lectures de livros tradicionais?*, points out that the extensive amount of text in this collection is justified by the fact that the books are direct transcriptions of the lectures and prioritize a conceptual approach. Another characteristic identified in this study (Karam, 2018) is that the books in the *Feynman Lectures on Physics* collection discuss epistemological aspects of physics throughout their text.

The authors use only quantum concepts in the section in which they give meaning to the wave function. The exclusive use of quantum physics is a deliberate choice by the authors, who state that they will describe quantum mechanics in a quantum-mechanical way rather than attempting to establish connections with classical mechanics and, therefore, will discuss something new in a new "language" (Feynman; Leighton; Sands, 2008). According to Karam (2018), Feynman's didactic discourse is highly metacognitive and philosophical, differing considerably from traditional textbooks, as epistemological discussions are present in virtually every chapter and are closely connected to the specific knowledge being addressed, making the discussion much richer.

It is important to note that, at levels 2 (Narrative) and 1 (Metacommentary), no distinction was made between quantum and classical physics, since physics is not being used at these levels to define the wave function. It would not be meaningful to indicate percentages of classical and quantum physics at these levels, as the Narrative level relates facts presented in ordinary language, while the Metacommentary level concerns the authors' considerations regarding textual structure, regardless of the associated physical content.

Section of *Quantum Physics* by Eisberg and Resnick (1974): "Introduction"



Graph 2: Analysis of Semantic Density (SD) of the section "Introduction".

Table 4: Distribution of Forms in the section "*Introduction*".

Level	Form	Percentage	Classical/Quantum	
5	Symbolic	21%	C 84%	Q 16%
4	Theoretical	27%	C 88%	Q 12%
3	Conceptual	17%	C 20%	Q 80%
2	Narrative	3%		
1	Metacommentary	31%		

In the semantic profile presented in Graph 2, there are numerous semantic waves, evidenced by oscillations between level 1 (Metacommentary) and the higher levels, 4 (Theoretical) and 5 (Symbolic). These movements express the alternation between processes of *unpacking*, in which meanings are decondensed and made more accessible, and *repacking*, in which knowledge is recondensed into more abstract and conceptually dense forms. In this graph, a high semantic amplitude can be observed, with variations extending from level 1 to level 5. The graph also contains short flat lines distributed across the different levels of SD. These segments indicate moments in which the discourse remains stabilized at the same level of meaning, without shifts along the semantic scale. The flat lines observed are short in duration and, although they occur at all levels of SD, they do not persist long enough to disrupt the dynamics of the profile's oscillations.

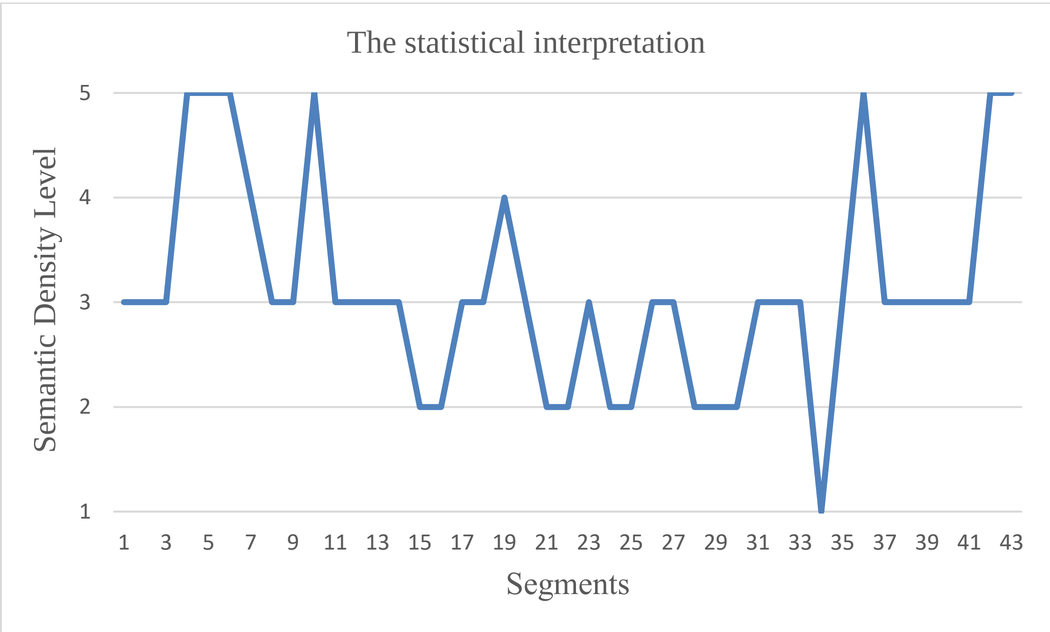
Eisberg and Resnick (1974) use all five levels of SD, with a predominance of levels 1 (Metacommentary), 4 (Theoretical), and 5 (Symbolic). As this section serves as an introduction to the chapter entitled *Schrödinger's Theory of Quantum Mechanics*, it contains a predominance of metacommentary, which characterizes level 1. The authors make several metacommentary statements when discussing their intentions for the book and how their ideas will be presented throughout the work, indicating what will be presented to students in the following sections and what they need to know in order to continue reading.

> *Obviously, the student most likely already has some experience with ordinary differential equations from their study of classical mechanics. We will develop the essential points of Schrödinger's theory and use them to address a series of important microscopic systems* (Eisberg; Resnick, 1979, p. 172, our translation).

Eisberg and Resnick's 1974 book was an attempt to incorporate some conceptual discussion into the teaching of quantum mechanics and it was published at the editor's suggestion, drawing on the authors' successful experiences with other physics publications. Eisberg and Resnick (1974) prepared a draft of the book and tested it in the classroom and with departmental colleagues, which is reflected in the book's structure (Fantin, 2024). The book contains various qualitative problems (without mathematical components), similar to physics textbooks covering other topics, including discussion questions such as: "*Consider a water wave propagating across the surface of the ocean. If no one were observing the wave, or even* *thinking about it, would you say that this wave exists? Would you give the same answer for a wave in quantum mechanics? If not, why?*"

At the Symbolic level, the authors use the classical wave equation to introduce the quantum mechanical wave function and draw on classical wave mechanics to introduce the Schrödinger equation. This accounts for the predominance of classical physics at SD levels 5 and 4. At level 3, the Conceptual level, there is an inversion in the use of classical and quantum physics, with quantum concepts predominating in the text. Although this level 3 is less prevalent throughout the text, the authors refer to the de Broglie postulate as a fundamental step in the development of Schrödinger's theory.

Section of *Introduction to Quantum Mechanics* by David Griffiths (1994): "The Statistical Interpretation"



Graph 3: Analysis of Semantic Density (SD) in the Section "The Statistical Interpretation".

Table 5: Distribution of Forms in the section *"The Statistical Interpretation"*.

Level	**Form**	**Percentage**	**Classical/Quantum**	
5	Symbolic	16%	C 0%	Q100%
4	Theoretical	7%	C 0%	Q100%
3	Conceptual	55%	C 0%	Q100%
2	Narrative	20%		
1	Metacommentary	2%		

The semantic profile presented in Graph 3 is characterized by the presence of semantic waves throughout the sequence, with variations in the amplitude of these waves. Initially, oscillations can be observed between the Conceptual (3) and Symbolic (5) levels. In the middle portion of the graph, waves of smaller amplitude emerge, with variations between the Conceptual (3) and Narrative (2) levels, which suggests more limited movements of unpacking and repacking, since these levels are relatively close to one another. This semantic wave, characterized by movement between the Narrative (2) and Conceptual (3) levels, reflects the author's use of conceptual explanations of quantum concepts, followed by recourse to narrative resources, such as interpretations of the theory, thereby making the knowledge less complex for the reader. In the final portion of the graph, there is a wave of greater amplitude, varying between levels 1 (Metacommentary) and 5 (Symbolic), as well as another wave varying between level 3 (Conceptual) and level 5 (Symbolic). Variation in wave amplitude is an important aspect: smaller-amplitude waves tend to mobilize knowledge to a lesser extent by remaining within levels of similar complexity and abstraction, whereas larger-amplitude waves expand this potential by connecting more distant levels and articulating simpler and more complex forms of knowledge. The graph also presents short flat lines at the Narrative (2) and Conceptual (3) levels, which are the predominant levels in the section.

In the section entitled *The Statistical Interpretation*, level 3 of SD, Conceptual, predominates. David Griffiths (1994) chooses to use quantum concepts such as measurement, statistical interpretation, probability, state, and the realist, orthodox, and agnostic positions to address the section's opening question: *what exactly is this 'wave function', and what does it do for you when obtained?* The section also includes level 5 (Symbolic), as it presents two graphs: one illustrating the probability of finding the particle between two points, represented by the area under a typical wave function graph, and another illustrating the collapse of the wave function. Level 2, Narrative, includes passages that help the reader distinguish the main schools of thought concerning quantum indeterminacy in relation to the measurement of the particle's position (wave function), as illustrated below.

> *Eisberg and Resnick's 1974 book was an attempt to incorporate some conceptual discussion into the teaching of quantum mechanics and it was published at the editor's suggestion, drawing on the authors' successful experiences with other physics publications. Eisberg and Resnick (1974) prepared a draft of the book and tested it in the classroom and with departmental colleagues, which is reflected in the book's structure* (Griffiths, 1994, p. 3, our translation).

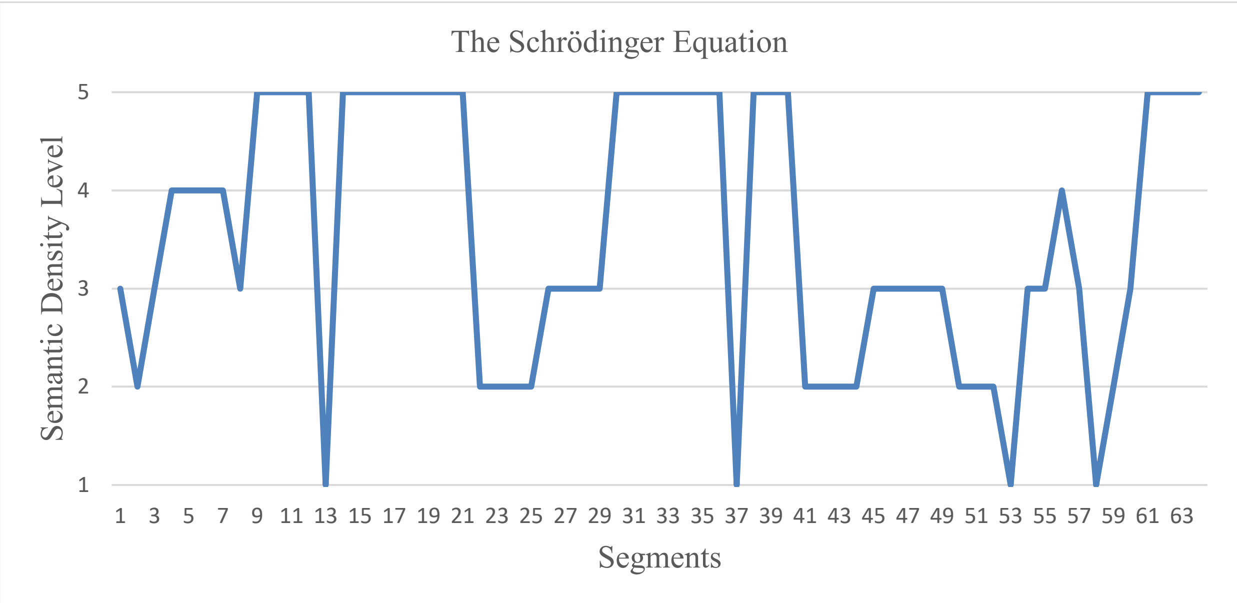
> *Among physicists, this has always been the most widely accepted position. Note, however, that if it is correct, there is something very peculiar about the act of measuring something that more than half a century of discussion has done little to clarify* (Griffiths, 1994, p. 3, our translation).

The section does not use classical concepts to statistically interpret the wave function at any of the SD levels employed. According to the study by Dubson *et al.* (2009), Griffiths's

(1994) textbook is the most widely used among American universities: 65% of the institutions surveyed use Griffiths (1994), and 63% of the professors interviewed use or plan to use Griffiths's (1994) book. Despite the popularity of this textbook, the study reports that professors who use it rarely follow it closely and rely heavily on their own lecture notes.

The second part of the analysis corresponds to the three sections that present the wave function in its mathematical form, in which the authors introduce the wave function through the Schrödinger equation. Richard Feynman, Robert Leighton, and Matthew Sands (1964) present the mathematical treatment of the Schrödinger equation in a section entitled *The Schrödinger Equation*. In the book, this section appears in a chapter that precedes, by five chapters, the previously analyzed section entitled *The Meaning of the Wave Function*. Eisberg and Resnick (1974) present the section *Plausible Arguments Leading to the Schrödinger Equation* in the fifth chapter of their book (the first chapter on the new quantum mechanics), immediately after presenting the theoretical section on the wave function previously analyzed. David Griffiths (1994) begins his book with a section entitled *The Schrödinger Equation*, which provides the mathematical presentation of the wave function.

Section of *The Feynman Lectures on Physics* by Richard Feynman, Robert Leighton, and Matthew Sands (1964): "The Schrödinger Equation"



Graph 4: Analysis of Semantic Density (SD) in "The Schrödinger Equation".

Table 6: Distribution of Forms in the section "The Schrödinger Equation".

Level	**Form**	**Percentage**	**Classical/Quantum**	
5	Symbolic	41%	C 12%	Q 88%
4	Theoretical	8%	C 0%	Q 100%

3	Conceptual	25%	C 44%	Q 66%
2	Narrative	20%		
1	Metacommentary	6%		

Graph 4 presents a semantic profile characterized by the presence of semantic waves throughout the entire sequence. Particularly noteworthy are the higher-amplitude transitions, which occur most frequently between levels 1 (Metacommentary) and 5 (Symbolic), revealing substantial variation in the complexity and abstraction of knowledge and forming high-amplitude waves. Lower-amplitude transitions can also be observed, such as those between levels 3 (Conceptual) and 2 (Narrative), corresponding to more localized oscillations between adjacent levels. These variations in SD are fundamental to the construction of semantic profiles that enable articulation between different semantic levels, thereby supporting the cumulative construction of knowledge (Maton, 2013). Short flat lines are also observed, predominantly at the highest level, Symbolic (5), suggesting moments of discourse stabilization at this SD level, associated with the intensive use of mathematical equations and graphs.

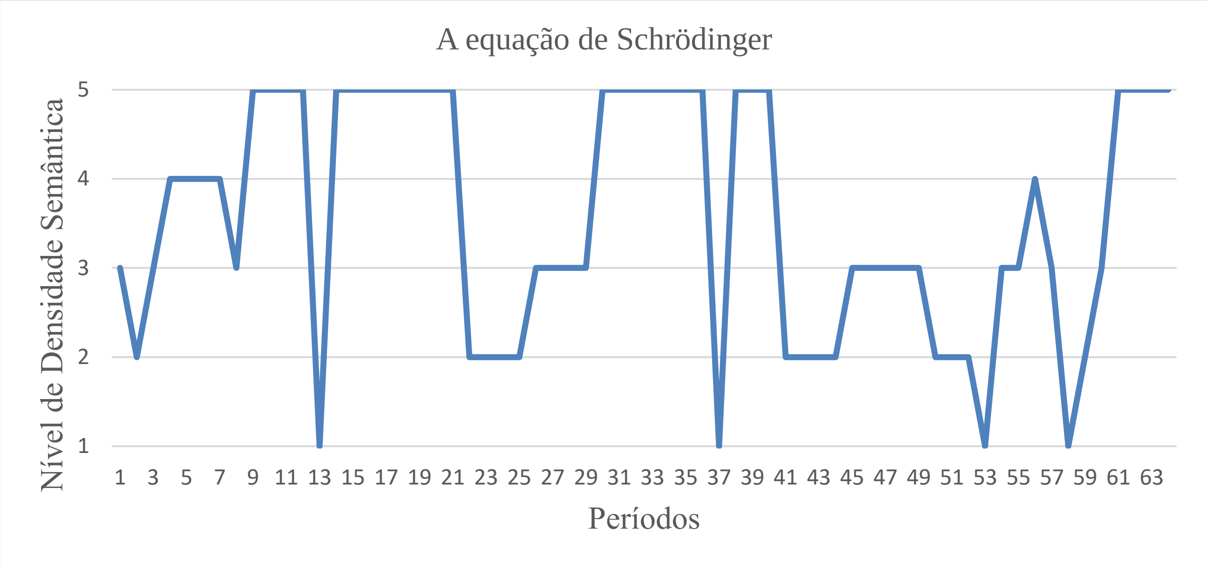
The section *The Schrödinger Equation* appears in Feynman, Leighton, and Sands (1964), in the sixteenth chapter of a total of twenty-one chapters, and precedes the section in which the authors conceptually define the wave function. This section is characterized by a predominance of level 5, Symbolic, with the use of notation specific to quantum mechanics, namely Dirac notation, which is used only in this section among all those analyzed in the study.

For the presentation of the wave function, as proposed in the section, Feynman, Leighton, and Sands (1964) draw on almost the entirety of quantum mechanics. It is important to note that this section differs little from traditional quantum mechanics textbooks, with substantial amounts of mathematical formalism and little conceptual reflection. In this section, there is none of what Karam (2018) identifies in his research as a characteristic feature of *The Feynman Lectures on Physics* (1964): the authors' reflections on the nature of physical knowledge and on the challenges inherent in student/reader learning.

Level 3, Conceptual, is the second most frequently used level in this section to present the wave function. At this level, classical concepts such as energy levels, electronic excitation, potential function, and chemical bonding are employed. Level 2, Narrative, also appears in the text when the authors provide some historical background on Schrödinger's development of the wave function equation.

> *It emerged from Schrödinger's mind, conceived in his struggle to find an understanding of the experimental observations of the real world. It was written by Schrödinger before any of the other quantum equations that we have described in this book had been discovered* (Feynman; Leighton; Sands, 2008, p. 16-13, our translation).

Section of *Quantum Physics* by Eisberg and Resnick (1974): “Plausible Arguments Leading to the Schrödinger Equation”



Graph 5: Analysis of Semantic Density (SD) in the section Plausible Arguments Leading to the Schrödinger Equation.

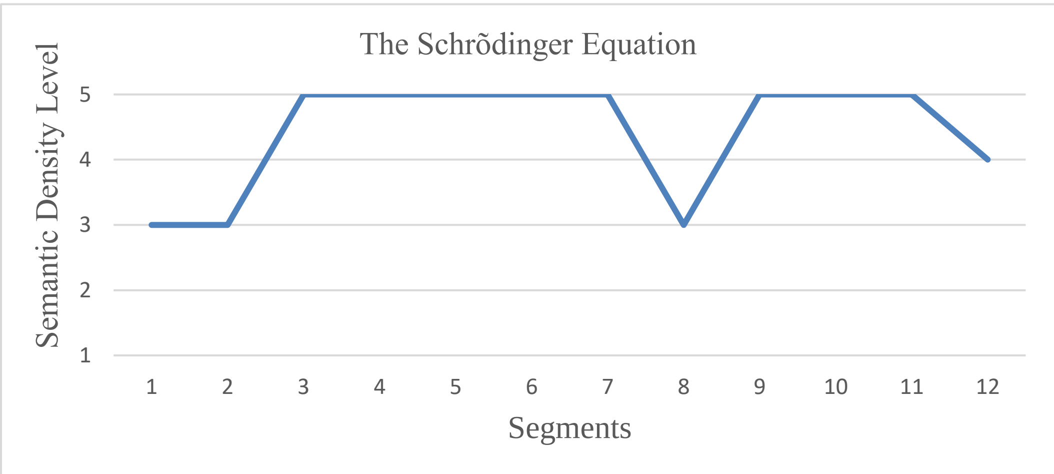
Table 7: Distribution of Forms in the section *Plausible Arguments Leading to the Schrödinger Equation.*

Level	**Form**	**Percentage**	**Classical/Quantum**	
5	Symbolic	65%	C 85%	Q 17%
4	Theoretical	7%	C 33%	Q 66%
3	Conceptual	9%	C 62%	Q 38%
2	Narrative	15%		
1	Metacommentary	4%		

The analysis of the semantic profile corresponding to Graph 5 shows that, both at the beginning and at the end of the sequence, there are variations in the levels of SD, resulting in the discrete formation of semantic waves. In the initial segment, these waves have medium amplitude, with oscillations predominantly between level 3 (Conceptual) and level 5, corresponding to the introduction of the section in which mathematical arguments are developed to explain how the Schrödinger equation was derived. At the end of the graph, there are lower-amplitude waves, concentrated at lower levels of SD, particularly between levels 2 (Narrative) and 3 (Conceptual), and between levels 2 (Narrative) and 1 (Metacommentary). This can be attributed to the narration of a historical event in which the physicist Debye describes the circumstances surrounding the development of the Schrödinger equation. For most of Graph 5, there is a long flat line at the highest level, Symbolic (5), indicating strong condensation of meaning associated with the continuous use of mathematical formalism and symbolic representation, since the authors use mathematical arguments to derive the Schrödinger equation in this section. Profiles characterized by a predominance of high SD, without frequent variations, tend to make access to knowledge more difficult, as they restrict the unpacking movements necessary to make meanings more accessible (Macnaught *et al.*, 2013).

Eisberg and Resnick (1974) present four arguments for arriving at the Schrödinger equation, all of which are mathematical, which accounts for the 65% at SD level 5 (Symbolic) in this section. The authors rely predominantly on classical physics at the Symbolic level to arrive at the Schrödinger equation. In this section, the authors state that Schrödinger arrived at the equation through arguments different from those the authors will use in the text and that these arguments were more esoteric. A quotation is included in which the physicist Debye describes the circumstances surrounding the development of the Schrödinger equation, which accounts for the presence of 15% at SD level 2 (Narrative). Cordeiro e Peduzzi (2013), in a study on decontextualization in the Eisberg and Resnick (1974) textbook, observe that treating the history of science as a means of illustrating scientific knowledge, as is done in this section, does not constitute what is intended by historical contextualization. Attention should be paid to the quality of the history of science presented in textbooks, particularly because these materials are studied by future teachers who will disseminate this content in the classroom. The authors argue that the Eisberg and Resnick (1974) text presents an individualistic image of science, with references to prominent figures such as Schrödinger in this case, thereby contributing to the idea that only privileged minds are capable of doing science and failing to acknowledge the contributors to a scientific theory, who are also essential to the construction of knowledge.

Section of *Introduction to Quantum Mechanics* by David Griffiths (1994): "The Schrödinger Equation"



Graph 6: Analysis of Semantic Density (SD) in the section The Schrödinger Equation.

Table 8: Distribution of Forms in the section *The Schrödinger Equation.*

Level	Form	Percentage	Classical/ Quantum	
5	Symbolic	67%	C 63%	Q 37%
4	Theoretical	8%	C 0%	Q 100%
3	Conceptual	25%	C 100%	Q 0%
2	Narrative	0%		
1	Metacommentary	0%		

Graph 6 presents a semantic profile characterized by low variation in SD, with a predominance of higher levels, particularly level 5 (Symbolic), interspersed with a few transitions to level 3 (Conceptual). The formation of a single semantic wave can be observed. There are two plateaus at the highest level, Symbolic (5)**,** indicating a strong concentration of highly complex forms of knowledge associated with the intensive use of symbolic representations, such as mathematical equations.

David Griffiths (1994) uses only three levels of SD (5, 4, and 3) in the first section of his book, entitled *The Schrödinger Equation*, with level 5 (Symbolic) accounting for 67% of the text. The author introduces the section by presenting a classical problem to be solved, namely, determining the position of a particle (which accounts for the use of 100% classical physics at level 3, Conceptual, of SD). He compares this issue with quantum mechanics, which, according to him, addresses the same problem in a different way by seeking the particle's wave function.

The sections that present the mathematical equation of the wave function, referred to in this study as the more "mathematized" sections, are predominantly characterized by the highest level of SD, the Symbolic level, across all three texts. In the texts by Eisberg and Resnick (1974) and Griffiths (1994), the proportion exceeds 60%. In the section of the book by Feynman, Leighton, and Sands (1964) that presents the mathematical form of the wave function equation, 41% of the text is at level 5, Symbolic, while levels 3 (Conceptual) and 2 (Narrative) account for 45%. The authors achieved a distribution across the other levels (3 and 2), indicating that even in a section presenting an equation, it is possible to present mathematical formulations with lower levels of SD.

VII. Discussion and Final Considerations

The study presented an analysis of SD in six sections from three quantum mechanics textbooks, all of which contain a definition of the wave function, with the aim of deepening the understanding of the knowledge made available in quantum mechanics teaching materials for higher education. The sections from the book by Feynman, Leighton, and Sands (1964) predominantly employ quantum physics, whereas Eisberg and Resnick (1974) define the wave function predominantly using classical physics. Griffiths (1994) alternates between these approaches, using only quantum physics in one section and predominantly classical physics in another. This methodological choice, particularly when introducing the Schrödinger equation through a classical problem, highlights a strategy that remains under debate in physics education. In this field, there is no consensus as to whether the teaching of quantum mechanics should begin with concepts from classical physics (Gil; Solbes, 1993; Greca; Freire Júnior, 2003; Ireson, 2000; Sinarcas; Solbes, 2013). This is related to one of the difficulties associated with learning quantum mechanics: its conceptual structure conflicts with the intuitions derived from everyday experience (Greca; Herscovitz, 2011; Greca; Moreira; Herscovitz, 2001; Ke; Monk; Duschl, 2005; Levrini; Fantini, 2013; Lin; Singh, 2010; Müller; Wiesner, 2002; Olsen, 2002; Pospiech, 2003; Singh; Marshman, 2015). Relying on concepts from Classical Physics in the teaching of Quantum Mechanics may lead students to resort to classical interpretations when analyzing quantum phenomena, thereby constituting a potential obstacle to understanding the specificities of Quantum Mechanics.

Regarding the organization of knowledge, the analysis of the graphs made it possible to construct semantic profiles of the sections, revealing not only the degree of complexity of the knowledge but, above all, how this knowledge is organized and mobilized throughout the discourse. It was observed that these profiles vary significantly across the works analyzed, particularly with regard to the presence or absence of semantic waves, as well as their regularity and amplitude. In some sections, such as "Introduction" in Eisberg and Resnick's *Quantum Physics* (1974), "The Statistical Interpretation" by David Griffiths (1994), and "The Schrödinger Equation" by Feynman, Leighton, and Sands (1964), well-defined semantic waves were formed, with alternation between high and low levels of SD, revealing movement across different degrees of conceptual complexity. In other sections, such as "Plausible Arguments Leading to the Schrödinger Equation" (Eisberg; Resnick, 1974), semantic waves appeared only locally, at the beginning and end of the section, indicating limited semantic variation throughout the text. In the section "The Meaning of the Wave Function" (Feynman; Leighton; Sands, 1964), this movement was restricted to specific passages and did not occur continuously throughout the exposition.

The semantic waves formed in the graphs reflect movement between different levels of complexity, alternating between high and low SD (Maton, 2014). The amplitude of the waves shown in the graphs is analytically relevant: higher-amplitude waves, which connect more distant levels of the semantic scale, for example, between metacommentary (1) and symbolic (5), increase the potential for articulating simpler and more complex forms of knowledge. On the other hand, lower-amplitude waves, for example, between the narrative (2) and conceptual (3) levels, which are close levels with less variation in density, limit the mobilization of knowledge by restricting variation in complexity and abstraction. Another element highlighted by the semantic profiles is the presence of flat lines, which occur prominently in sections characterized by a predominance of the symbolic level (5). In these cases, prolonged permanence at the symbolic level (5) can be observed, indicating extensive use of formal mathematical representations. Profiles with low semantic variation tend to make access to knowledge more difficult, as they restrict the unpacking movements necessary to make meanings more accessible. This pattern can be observed, for example, in David Griffiths's (1994) section "The Schrödinger Equation", as well as in the section "Plausible Arguments Leading to the Schrödinger Equation" in Eisberg and Resnick's *Quantum Physics*, in which the emphasis on mathematical representations contributes to reduced semantic variation throughout the exposition. According to Maton (2014), the presence of semantic waves reveals movement across different levels of abstraction and complexity, structuring knowledge in ways that enable students to master theory and apply it in less complex contexts. Graphs that do not display semantic waves, by contrast, show plateaus without variations in density, suggesting that knowledge remains isolated at either highly complex levels (high density) or excessively simple levels (low density), without alternation between them. Semantic waves are fundamental to knowledge building because they enable students to move between complex and simpler meanings, promoting deeper and more transferable understanding (Maton, 2013, 2014).

Eisberg and Resnick (1974) present, at the end of each section of their book, questions of a conceptual nature aimed at revisiting the conceptual issues of quantum mechanics. However, the highest SD levels (Symbolic and Theoretical) predominate in the two sections that present the Schrödinger equation. In the section in which they present plausible arguments for arriving at the Schrödinger equation, all of the arguments are mathematical, and the authors use level 5, the highest density level (Symbolic), in 65% of the text. The most conceptual section of this work is the only one among those analyzed in which there is a significant presence of level 1, Metacommentary, since it is an introductory section intended to guide the reader on how the study of the wave function will be developed, what will be presented later in the book, and what the reader needs to know to continue with the reading. It is also the book that makes the greatest use of classical physics to introduce the wave function. Nevertheless, it is only when referring to the de Broglie postulate as a fundamental step in the development of Schrödinger's theory that the authors refer to the old quantum mechanics to introduce the Schrödinger equation.

Richard Feynman, Robert Leighton, and Matthew Sands (1964) present more narrative-oriented sections in the analysis, which can be attributed to the fact that the work resulted from two years of lectures at Caltech. In other words, the book is, in part, a transcription of those lectures and tells a narrative of these classes to the students. The order in which concepts are presented differs from that of the other books: the wave function is addressed in the final chapter of the volume on quantum mechanics, and the work follows neither a historical nor a traditional sequence. The meaning of the wave function is only fully elaborated in the final chapter, despite having been used in previous sections without any more detailed explanation. Another difference between this book and the others is that the authors choose to discuss the meaning of the wave function without using any mathematical equations. This is the only book that does not use level 5 (Symbolic) at all to present the wave function conceptually. Nevertheless, Feynman, Leighton, and Sands (1964) use 100% quantum concepts in the section in which they explain the meaning of the wave function.

David Griffiths (1994) has two sections in which he presents predominantly mathematical equations and descriptions, consistent with his argument in the book's preface that problem-solving is a means of understanding quantum mechanics. The more conceptual section is presented in his work after the section on the mathematical treatment of the wave function and is predominantly characterized by level 3, Conceptual. In this conceptual section, there is a weakening of SD in comparison with the other sections, along with the exclusive use of quantum concepts. The section in which the author presents the actual mathematical Schrödinger equation has 67% of its content at level 5, Symbolic. Another characteristic of the semantic wave generated in this section, as well as in the section *Plausible Arguments Leading to the Schrödinger Equation* by Eisberg and Resnick (1974), is the presence of an extended plateau spanning the entire graph, showing that the text remains predominantly at level 5 and exhibits little variation in SD (with more than 60% of the text at the Symbolic level 5). Remaining at a high SD level (high knowledge complexity) throughout a substantial portion of the text is not ideal for knowledge building. These sections do not exhibit significant variations in density and, consequently, in the complexity of knowledge, which may make the text more difficult for students to read and understand, as they remain at Symbolic level 5 without sufficient variation.

The study aimed to deepen the understanding of the knowledge made available in higher education quantum mechanics textbooks concerning the definition of the wave function. Textbooks play a prominent role in students' academic education and in teachers' pedagogical practice, since they influence not only what and how students learn, but also how teachers teach. Many teachers consider textbooks to be their only source of reference; in practice, textbooks become the curriculum, particularly for inexperienced teachers (Ogan-Bekiroglu, 2007). The analysis revealed that the books approach the concept of the wave function in different ways, and this variation directly influences how concepts are presented and understood by students, thereby affecting the effectiveness of learning. The analysis of SD aims to identify the potential of quantum mechanics teaching materials in supporting students' understanding and learning.

The sections that presented semantic waves, with greater variation in SD, allow readers to move between more abstract and complex theoretical meanings and more simplified concepts, an aspect considered central by Maton (2014) to knowledge building. Conversely, sections with little semantic variation, which remain for long stretches at symbolic levels, indicate excessively dense texts that may hinder knowledge appropriation and restrict conceptual understanding.

We consider that this research, conducted on the most widely used quantum mechanics textbooks and drawing on the Legitimation Code Theory framework in its semantic dimension, with an emphasis on the concept of semantic density, reveals important facets of these books that have the potential to explain some characteristics of the teaching of quantum mechanics to university physics students. We believe that determining the other variable of the semantic dimension – gravity, which refers to the degree of relationship between meanings and their contexts (Maton, 2014) – is a natural extension of this research and will be undertaken in future work.

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