When physics becomes abstract, analogies emerge: Examining the characteristics and pedagogical quality of analogies in high school physics textbooks

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(Received 5 January 2026; accepted 26 June 2026; published 31 August 2026)

This study examines the pedagogical quality and instructional adequacy of analogies included in high school physics textbooks (grades 9–12) in Türkiye. The analogies extracted systematically from 15 physics textbooks revealed a significant imbalance in their use across grade levels. The vast majority of the analogies were concentrated in the 10th grade textbooks, while their occurrence in other grades remained quite limited. A similar imbalance was also observed in subject focus: most of the analogies were allocated to the conceptually challenging and highly abstract topic of electricity, while other fundamental physics topics were largely neglected. In terms of pedagogical quality, all of the analogies were classified as either moderate or good according to Glynn's teaching-with-analogies model. However, most of the analogies reviewed lacked a step for identifying their limitations, thereby increasing the risk of misalignment and the development of misconceptions. The analogies were also predominantly of the concrete-abstract type, which helps students connect abstract physics concepts to concrete examples from daily life, and were largely based on functional similarity, meaning they focus on how the concept works rather than its structural features. Furthermore, the increased emphasis on the relevance of analogies to learners' backgrounds reflects a positive trend toward enhancing the contextual richness of analogies. To address the quantitative insufficiency of analogies and the imbalance across subject areas, it is essential that curriculum developers position analogical thinking as a required pedagogical tool for textbook authors.

DOI: 10.1103/ch6t-qvz6

I. INTRODUCTION

Physics is a scientific discipline that seeks to explain physical phenomena through fundamental laws and principles. Accordingly, the secondary physics curriculum contains many highly abstract and complex concepts that students cannot observe directly through their daily experiences [1,2]. These abstract concepts are sometimes counterintuitive, especially in areas such as electromagnetism and quantum physics, and students often struggle to relate them to their prior knowledge and past experiences [2,3]. Failing to connect these concepts to prior knowledge can hinder meaningful learning and potentially lead to persistent misconceptions among students [4]. One effective pedagogical tool used in science education to overcome these challenges has been the use of analogies. Analogies serve as a bridge between a concrete or familiar idea or phenomenon already known to the student (commonly referred to as the analog or source domain) and a new and probably abstract concept being learned (commonly referred to as the target domain) [4–6]. Analogies help to make the abstract aspects of scientific knowledge more concrete and easier for learners to understand [1,7]. Analogies also support mapping new knowledge onto existing knowledge structures, thereby facilitating students' conceptual change [8,9]. Moreover, analogies possess epistemic value beyond being merely a didactic tool by supporting understanding of the nature of science and scientific processes [10]. Throughout the history of science, analogical thinking has been instrumental in many important scientific discoveries and the formulation of explanatory models [11].

In many countries, textbooks play a central and indispensable role in shaping science teachers' lesson planning and classroom practices [12,13]. In Türkiye's highly centralized education system, textbooks also serve as the primary reference source of the curriculum for teachers as well as students [14]. Thus, the pedagogical characteristics of the analogies included in science textbooks can directly impact the conceptual science learning of the entire student population in K-12 classrooms. However, the literature clearly shows that analogies are a *double-edged sword* [1,4]. Misleading or insufficiently elaborated analogies in textbooks may cause students to transfer dissimilar or irrelevant features of the analog to the target concept, resulting in deep conceptual misconceptions [15].

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Analogies are powerful cognitive and instructional tools that play a central role in science education, especially when learning complex, abstract concepts in physics. At the core of analogical reasoning is the process of mapping a concrete or familiar system or phenomenon (i.e., source domain) onto a new, unknown concept (i.e., target domain) [4–6]. This cognitive process not only supports meaningful learning but also possesses an epistemic dimension, being critical to model building and the representation of scientific knowledge [10,11]. However, the instructional effectiveness of analogies is highly dependent on their systematic and careful design [6]. Unstructured analogies risk transferring nonshared features, as demonstrated by studies where specific analogy characteristics were incorrectly imported into explanations of target concepts [16]. Past research on high school science textbooks in various countries such as England, Wales, and Türkiye has identified significant shortcomings, such as the prevalence of simplistic presentations and a failure to explicitly address the limitations of analogies, thereby increasing the risk of student misconceptions [1,17,18].

To maximize the pedagogical effectiveness of analogies and minimize the development of misconceptions, systematic planning and implementation are necessary [19]. One of the most important guidelines developed for this purpose has been the teaching-with-analogies (TWA) model developed by Glynn [20,21]. This research-based model offers a practical set of instructional steps, which involve introducing the target concept, activating an analog familiar to learners, mapping similar features, and also emphasizing where the analogy fails (i.e., limitations). The final step of explicitly stating limitations is fundamental to why analogies are described as a double-edged sword, yet previous studies examining Turkish physics textbooks have revealed that failing to indicate the limitations was a common deficiency [17,22]. This lack of specificity in presenting limitations of analogies, together with the broader pedagogical shortcomings identified in prior research on analogies in K-12 science education, constitutes the primary research problem of the present study and underscores the necessity for a systematic, theory-informed evaluation of analogies used in high school physics textbooks.

Given their central role in the applied curriculum, the pedagogical quality of analogies presented in textbooks significantly impacts student learning [5]. In response to the need for a systematic, theory-informed evaluation, this study aimed to examine the analogies used in Turkish high school physics textbooks in terms of their instructional adequacy and pedagogical effectiveness. By adopting Glynn's TWA model [21] as the analytical framework, supplemented with additional criteria derived from the literature and developed by the authors, this study provides a structured examination of instructional design elements of analogies found in physics textbooks and critically explores the potential role of textbook analogies in supporting or hindering students' conceptual physics learning. Overall, this study aimed to examine the extent to which analogies are included in Turkish high school physics textbooks for grades 9 through 12 and how they are constructed and presented. Specifically, the study analyzes the pedagogical and structural characteristics of analogies in these textbooks in order to understand how analogical thinking and reasoning are addressed in physics education in Türkiye. Guided by these aims, the following research questions were formulated:

1. What are the characteristics of the analogies presented in Turkish high school physics textbooks?
2. How can the analogies used in Turkish high school physics textbooks be classified according to their level of pedagogical quality (e.g., poor, moderate, good) when evaluated through the TWA model?

A. Significance of the study

Textbooks represent the applied curriculum. Teachers and students rely heavily on textbooks as their primary instructional resource in many countries [13]. As a result, the content of textbooks directly shapes what and how subjects are taught in the classroom. Within this context, the pedagogical quality of analogies presented in K-12 science textbooks may significantly affect student learning. Poorly constructed or pedagogically inadequate analogies can lead to misconceptions, whereas well-designed analogies can clarify abstract physics concepts and facilitate learning [19]. Therefore, a systematic evaluation of analogies in physics textbooks is essential for determining their pedagogical quality and their potential to support students' conceptual understanding. Despite the well-documented role of analogies in science education, studies systematically examining the pedagogical quality of analogies in high school physics textbooks remain limited (e.g., [2,14,17]).

II. METHODOLOGY

A. Research design

This study employed document analysis as its research method. According to Bowen [23], document analysis is a systematic procedure for reviewing and evaluating printed materials in order to elicit meaning, gain understanding, and develop empirical knowledge. Because K-12 physics textbooks are formal educational materials developed and published according to a specific curriculum, document analysis is a particularly suitable approach for systematically analyzing their content.

B. Study context

Türkiye has a very centralized public education system where the K-12 curricula for all subject areas are prepared by the Ministry of National Education (MoNE).

TABLE I. Distribution of the analogies identified in the reviewed textbooks.

Grade level	Curriculum (2018 or 2024)	Publisher	The number of analogies
9th grade	2018	Hecce Publishing [38]	2
	2018	MoNE Publishing [39]	0
	2018	SDR Publishing [40]	2
	2024	MoNE Publishing [34]	1
10th grade	2018	MoNE Publishing [41]	1
	2018	Ekoyay Publishing [42]	2
	2024	MoNE Publishing [36]	18
11th grade	2018	Anka Kuşu Publishing [43]	0
	2018	MoNE Publishing [44]	1
	2018	ATA Publishing [45]	2
	2018	MoNE Publishing [46]	1
12th grade	2018	Başak Publishing [47]	0
	2018	MoNE Publishing [48]	1
	2018	Yıldırım Publishing [37]	0
	2018	MoNE Publishing [49]	0
Total		15 textbooks	31

In addition, K-12 curricula for all subject areas are generally updated every 5 to 6 years by the MoNE in order to keep up-to-date with the recent developments in pedagogy and subject-specific topics. The last major update on the K-12 curricula took place in 2024 [24], which replaced the curricula introduced in 2018 [25]. Regarding high school, the implementation of a newly introduced curriculum starts with the ninth grade level and progresses toward the higher grades in each successive year. As such, the recent physics curriculum, which was released in 2024 [24], is currently being implemented in grades 9 and 10 at the time of conducting this study, while the previous physics curriculum (i.e., 2018 curriculum) is still in place for grades 11 and 12 [25].

There are generally multiple publishers of K-12 textbooks in Türkiye, including private companies and the MoNE itself. The MoNE provides general guidelines for textbook publishers and also evaluates and authorizes textbooks published by private companies to be used in schools. In other words, more than one officially approved textbook may be available for the same subject and grade level. Since this study aimed to comprehensively examine analogies in Turkish high school physics textbooks, the researchers decided to include all high school physics textbooks published for both the new 2024 curriculum and the previous 2018 curriculum. A total of 13 physics textbooks for grades 9 to 12 were available from different publishers, including the MoNE for the 2018 [25] curriculum, while only two textbooks (one for grade 9 and one for grade 10), which were prepared and published by the MoNE, were available for the 2024 curriculum [24]. The corpus included all physics textbooks for grades 9 ($n = 4$), 10 ($n = 3$), 11 ($n = 4$), and 12 ($n = 4$). The complete list of these 15 textbooks analyzed in this study can be seen in Table I.

In order to provide a contextual background for the textbook analysis, it is also important to briefly outline the main instructional subjects covered in the Turkish high school physics curriculum for the 2018 and 2024 versions. These subject areas include Force and Motion, Fluids, Energy, Electricity and Magnetism, Waves, Optics, the Nature of Matter, Simple Harmonic Motion, Heat and Temperature, Atomic Physics, and Modern Physics. These subject areas are distributed across grade levels in a spiral structure, meaning some subjects are revisited with increasing depth at multiple grade levels.

C. Data collection

Regarding data collection, first, this study identified analogies and established inclusion and exclusion criteria to ensure transparency and reproducibility. All 15 textbooks examined were read from cover to cover by the first author in order to identify analogies. As in the study by Körhasan and Hıdır [1], each analogy was considered as the unit of analysis.

Similar to the related studies in the literature, to identify an analogy to be included in the analysis, statements in the textbooks that refer to or imply an analogical relationship, such as comparisons between a known thing (i.e., analog) and an unknown thing (i.e., target), have been searched and examined (e.g., [1]). To clearly distinguish genuine analogies from statements that merely resemble them, the following cases were excluded from the analysis:

1. Mythical explanations of concepts (e.g., in ancient times, it was believed that the reason for the

movement of the planets in the sky was a divine will that moved them in perfect circular orbits)
2. Daily life examples of a scientific concept (e.g., explaining the sport of skydiving in terms of speed and air resistance)
3. Illustrative examples and formal scientific models (e.g., presenting the Bohr atomic model as a scientific model of atomic structure)
4. Conventionalized metaphorical scientific terminology (e.g., the term "current" is a conventionalized term with metaphorical origins that refers to electrical flow)
5. Metaphorical expressions in daily language (e.g., referring to meteor showers as "shooting stars")

To ensure the reliability of the data collection process, the two authors started from a randomly selected unit in a randomly selected textbook, identified and extracted analogies independently, and reached 100% agreement in the first stage.

D. Data analysis

This study used the content analysis method to identify and classify analogies in high school physics textbooks, evaluating their characteristics based on the TWA model previously developed by Glynn [20,21]. Content analysis is defined as the systematic analysis, counting, and creation of meaningful categories in textual and visual materials to answer a specific research question [26]. The rationale for choosing this method was that it is the most appropriate technique for systematically and reliably analyzing written documents, such as textbooks, in a way that reveals underlying patterns.

E. Rubric development

The analytical rubric used in this study was developed by the authors based on the established frameworks in analogy research literature. It consists of two main sections. The first section evaluates the pedagogical adequacy and characteristics of analogies. It was adapted from Glynn's [20,21] TWA model, which provides a systematic framework for examining how analogies are introduced, mapped, and concluded during instruction. The second section of the rubric examines the structural characteristics of analogies used in the textbooks. The categories in this section, including the subject area in which the analogy is provided (e.g., electricity and magnetism), the nature of the analogical relationship between the analog and the target (e.g., functional), the presentation format of the analogy (e.g., verbal or verbal-pictorial), and level of abstraction (e.g., concrete-abstract: analog as a concrete concept and target as an abstract concept), were informed by prior studies analyzing analogies in science textbooks (e.g., [10,27,28]). These categories enabled a holistic analysis of the structural features of the analogies found in the textbooks. In addition to the literature-based categories, the rubric includes a category developed by the authors called the "Relevance of Analogy." This dimension examines the extent to which the analogy is familiar and meaningful in relation to the everyday experiences of the target student group. This category was included based on scholarly discussions in the analogy literature that emphasize the importance of students' familiarity with the source domain for effective analogical reasoning (e.g., [29,30]). The rubric development process involved several stages. First, the relevant theoretical frameworks and classification approaches in the analogy literature were reviewed, and an initial rubric was constructed. Second, a subset of the dataset was coded as a pilot to evaluate the clarity and applicability of the rubric categories. During this stage, analogies were coded independently by the researchers and an external coder to test the adequacy of the rubric and the coding scheme. The pilot coding revealed that the rubric categories and the coding scheme were clear and applicable in systematically analyzing analogies; therefore, no further revisions were made. Additionally, expert opinions from science education scholars were obtained to evaluate the conceptual appropriateness of the rubric. The experts confirmed that the rubric provided a suitable analytical framework for examining the pedagogical and structural characteristics of textbook analogies and recommended no modifications. The full details of the rubric were presented in Supplemental Material [31]. The following two subsections provide additional explanation of each main category in the rubric, namely: 1. Pedagogical Characteristics based on Glynn's TWA model and 2. Structural Characteristics.

1. Pedagogical characteristics based on Glynn's TWA model

Glynn's [20,21] TWA model criteria have been used to evaluate the pedagogical characteristics of analogies found in the included textbooks. These criteria were structured based on the six fundamental steps defined in the TWA model (Fig. 1), and each criterion was addressed through two complementary indicators to reveal whether the analogy contained the relevant feature. In analogical presentation, the introduction of the target concept prior to the analogy and the activation or probing of students' prior knowledge about the analog (i.e., source domain) were evaluated within the first criterion, *the Pretopic Orientation*. Then, *the Level of Enrichment* of the analogy was addressed by examining the extent to which similar features between the analog and the target concept were matched in a clear and systematic manner. In this context, the identification and mapping of relevant characteristics were also considered. Finally, *the Limitations of the Analogy* (i.e., where the analogy breaks down) were evaluated by determining whether the differences between the target concept and the analog were clearly stated and

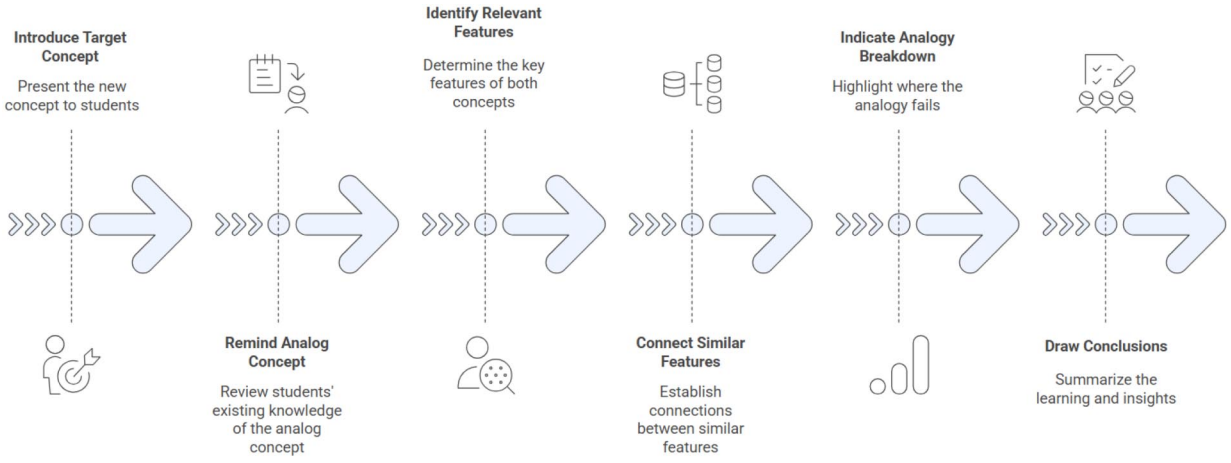


FIG. 1. The TWA instructional model adapted from Glynn [32]. The model presents six sequential steps for the effective pedagogical use of analogies.

whether appropriate conclusions were drawn based on these differences.

2. Structural characteristics

To reveal the contextual and structural characteristics of analogies, the Structural Characteristics category was created based on the criteria commonly used in the literature [10,27,33]. Accordingly, each analogy was first examined in terms of its content and then classified according to the subject area in which it was presented in the textbooks (e.g., mechanics, electricity, and optics). The nature of the analogical relationship was evaluated by focusing on whether the similarity established between the analog and the target concept was structural, functional, or both. If the shared attributes between the analog and target systems included only structural features (e.g., shape, appearance, or physical configuration), the analogy was coded as *structural*. If the shared attributes included only functional features (e.g., behaviors, operations, or interactions among components within a system), the analogy was coded as *functional*. In addition, if the analog and target systems shared both structural and functional attributes, then the analogy was coded as *structural-functional*. Next, we determined the presentation format of each analogy identified in the textbooks, examining whether it was presented verbally only or with both verbal and visual components. In addition, the level of abstraction of the analogy was addressed by considering the relationship between the concrete or abstract nature of both the analog and target concepts. For example, if the analog was inherently concrete (e.g., the flow of water through pipes) and the target was an abstract concept (e.g., electric current in a circuit), then it was coded as concrete-abstract. Finally, the relevance of analogies was examined by evaluating how well the analogs aligned with the daily life experiences of high school students. This criterion was added to the analysis framework by the researchers to reflect the literature's emphasis on the contextual and age-appropriate use of analogies.

F. Scoring of analogies

First, to evaluate the pedagogical quality of analogies, we examined the six fundamental criteria of the TWA model (Fig. 1) separately. Each criterion was given a score of 1 if it was explicitly identified in a given analogy and a score of 0 if it was missing. The total TWA score an analogy could achieve ranged from 0 to 6. Then, analogies were classified into three quality levels (i.e., poor, moderate, and good) based on their total score by following Körhasan and Hıdır's [1] study. Those with a total TWA score between 0 and 2 were considered poor; those with a score of 3 or 4 were considered moderate; and those with a score of 5 or 6 were considered good. Additionally, each of the following categories in the Structural Characteristics part of the rubric was evaluated independently and analyzed using a binary coding method: Subject Area, Nature of Analogical Relationship, Presentation Format, Level of Abstraction, and Relevance of Analogy. A score of 1 was given if the relevant feature for the target category was present in the analogy, and a score of 0 was given if it was not. Overall, this binary coding approach employed in applying the analytical rubric provided a transparent, replicable scoring procedure and facilitated interrater agreement analyses.

1. Illustrating the application of the rubric

To demonstrate how the analytical rubric was applied during the data analysis process, the following analogy from the 10th grade electricity unit [34] has been selected as an example. This analogy has been used as an illustrative example to show how the pedagogical and structural characteristics of an analogy were coded by the researchers:

> Despite using different materials and types of energy, plumbing systems and simple electrical circuits operate on fundamentally the same principles. Both contain an energy source, a flow path, and a control mechanism. This similarity provides a useful model for understanding simple electrical circuits. The pump that enables water to move through pipes in plumbing systems corresponds to the energy source in simple electrical circuits, such as batteries and generators. However, electrons in a circuit behave differently than water in a pipe. While water moves from one end of a pipe to the other with the help of a pump, electrons do not move this way within a conductive wire. A potential difference applied to the circuit causes electrons to oscillate within the conductive wire and travel short distances. During these oscillations, the electrons transfer energy to each other and slowly drift, creating an electric current. A valve, which controls the flow in plumbing systems, functions similarly to a switch in an electrical circuit [33] (p. 203).

In terms of pedagogical characteristics and design quality, the analogy was classified as "good" overall because it met five of the six fundamental criteria of the TWA model. First, the analogy clearly introduces the target concept of a simple electrical circuit, identifies the common components of both systems (energy source, flow path, and control mechanism), and establishes clear correspondences between these components (pump-generator and valve-switch). Furthermore, the analogy explicitly highlights that the movement of electrons differs from the movement of water in a pipe. It clearly states the limits of the analogy, thus aiming to prevent potential misconceptions. An explanation of how electric current is generated is provided at the end of the analogy, leading to a structured conclusion. The only shortcoming of this analogy is that it does not explicitly remind students of the analog (i.e., activate relevant prior knowledge about plumbing systems) before establishing the correspondences. To address this limitation, the analogy could begin with a brief introductory sentence such as: "Before considering electrical circuits, let us recall how water moves through a household plumbing system: a mechanical pump pushes water through pipes with different diameters, and valves regulate the flow." Adding such an introductory reminder would allow the analogy to satisfy all six criteria of the TWA model.

When evaluated in terms of structural characteristics, the content of the analogy relates to the subject of electricity in physics. Since the analogy establishes structural correspondences between the components of two systems (e.g., pump vs battery and valve vs switch) while also emphasizing similarities in how the systems function (e.g., mechanical pump pushes water flow vs the battery provides energy for electric current), the analogical relationship was coded as both structural and functional. In addition, the presentation format consists solely of textual narration without any accompanying visuals, so it was coded as verbal. The analogy's abstraction level is concrete-abstract because it uses a concrete system commonly encountered in everyday life, such as plumbing and water flow, to explain the abstract concept of electric current. Finally, using concepts based on students' everyday life and experiences shows that this analogy is highly relevant to learners.

G. Reliability of the present study

To ensure the reliability of the coding process, the first author coded all of the analogies extracted from the reviewed textbooks. Then, 20% of the corpus, which were selected randomly, were coded independently by the second author. Cohen's kappa (κ) coefficient was calculated to measure the agreement level between the two authors' coding. The calculation resulted in an intercoder reliability coefficient of $\kappa = 0.98$ ($p < 0.001$), with a percent agreement of 99%, indicating almost perfect agreement. This indicates that the overall coding procedure was highly reliable [35].

III. FINDINGS

A. Analogies in textbooks

In this study, a total of 15 physics textbooks at the 9th, 10th, 11th, and 12th grade levels were examined, and a total of 31 analogies were identified. The distribution of analogies by grade level indicates that their use is not balanced across grades and textbooks. Accordingly, 68% of analogies ($n = 21$) were found in the 10th grade textbooks, while the use of analogies was quite limited in the 9th grade (16%; $n = 5$), 11th grade (13%; $n = 4$), and 12th grade (3%; $n = 1$) textbooks (see Table I). Notably, the 10th grade MoNE textbook [36] contained 18 analogies, accounting for the large majority of all analogies. In contrast, multiple 11th and 12th grade textbooks were examined, yet four of them included no analogies at all (e.g., [37]). These findings demonstrate that the use of analogies in Turkish high school physics textbooks varies substantially by grade level and publisher.

As illustrated in Fig. 2, the subject of Electricity significantly outweighs all other subjects, accounting for a total of 24 analogies (78%). In contrast, Waves included a much smaller portion (13%), while the subjects of Energy, Fluids, and Heat and Temperature each comprised only one analogy (3% each). A closer qualitative examination of the identified analogies showed that electricity concepts were predominantly explained through analogies drawn from water systems, transportation systems, and everyday experiences. For example, electric current and

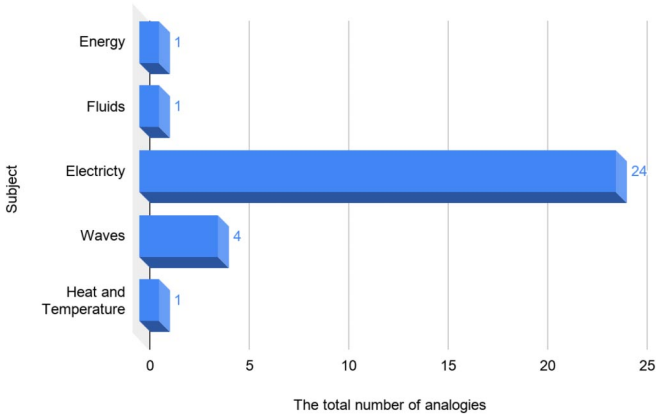


FIG. 2. Distribution of the number of analogies across physics subject areas.

resistance were explained through highways and traffic systems, water flow in pipes, and water slides, whereas electric field lines and equipotential surfaces were explained through contour maps and topographic representations. Similarly, capacitance was associated with everyday notions of "capacity" and filling cupped hands with water, while wave propagation was explained through Mexican wave activities and water ripple movements. The complete qualitative overview of all 31 analogies, including their target concepts, source analogs, instructional purposes, pedagogical quality scores, and missing components according to Glynn's TWA model, is presented in Supplemental Material [31]. Overall, these findings suggest that the use of analogies in the reviewed textbooks is concentrated predominantly in the subject of Electricity rather than being distributed evenly across the subject areas. This pattern indicates that textbook authors rely more heavily on analogies in conceptually abstract topics such as Electricity, where students often need additional instructional scaffolding, whereas in less abstract subject areas in physics such as Mechanics, analogies may be viewed as less necessary. However, the absence or very limited use of analogies in other highly abstract topics such as Energy and Modern Physics indicates that abstractness and conceptual difficulty alone do not fully explain the imbalanced use of analogies across subjects.

B. Pedagogical quality of analogies according to Glynn's TWA model

The results of the analysis showed that none of the analogies found in the examined textbooks were classified as "poor," meaning that all analogies identified in the textbooks met at least three out of six criteria of Glynn's TWA model (see Table II). According to Table II, 68% ($n = 21$) of the analogies were classified as "good," and 32% ($n = 10$) were classified as "moderate." While the absence of poorly designed analogies was a positive finding, a significant portion of the analogies only partially met the pedagogical steps outlined in the TWA model. The analogies classified as good were predominantly related to electricity concepts and generally involved familiar everyday contexts such as water flow systems, plumbing systems, water slides, and traffic systems, whereas the moderate analogies frequently lacked explicit discussion of the limitations of the analogy and activation of students' prior knowledge.

Moreover, all of the analogies classified as moderate (32%, $n = 10$) received a total score of 4 out of a maximum of 6 according to Glynn's TWA model. This indicates that they included most of the necessary pedagogical steps for constructing an effective analogy in science but missed two critical steps. According to the analysis results, the two missing elements in the moderate analogies that resulted in a moderate classification are failure to explicitly state limitations and lack of prior knowledge activation. In essence, these moderate analogies executed the core steps of introducing the target, presenting the analog, and mapping similarities, but they critically failed to include the necessary steps for activating the students' background knowledge on the analog and acknowledging the limitations. For example, analogies comparing electric current with highway traffic systems, water flow in pipes, and neural signaling systems were generally classified as moderate because they introduced the target concept and mapped similarities effectively, yet failed to activate students' prior knowledge about the analog and explicitly identify the limitations of the analogy. In contrast, analogies explaining electric potential difference through water reservoirs, resistance through water flow in pipes, and wave propagation through connected flow systems fulfilled all six criteria of Glynn's TWA model and were therefore classified as high-quality analogies.

The examination of the nature of the analogical relationships employed in the identified analogies revealed that 45% of them ($n = 14$) contained only functional similarities, while 39% ($n = 12$) consisted of analog and target concepts with both functional and structural similarities, and only 16% of the analogies examined ($n = 5$) involved just structural similarities. Overall, these results suggest that analogies in the textbooks primarily explained how concepts work, with less emphasis on conveying structural features. For instance, water flow systems were often used to explain electric current, charge flow, resistance, and potential difference through analogies involving pipes, valves, reservoirs, plumbing systems, and water slides. Similarly, highway traffic systems were used to explain electric current flow and circuit control elements. Neural signaling systems, on the other hand, were employed to explain the transmission of electrical signals in circuits. Contour maps, on the other hand, were used to explain electric field lines and equipotential surfaces by emphasizing spatial and structural correspondences. Sea urchin

TABLE II. Structural and pedagogical characteristics of analogies in Turkish high school physics textbooks: categorical distribution of analogies in textbooks ($n = 31$).

Criteria	9th grade (n)	10th grade (n)	11th grade (n)	12th grade (n)	Total (n)	Total percentage (%)
I. GLYNN'S TWA CRITERIA						
Poor	0	0	0	0	0	0%
Moderate	0	10	0	0	10	32%
Good	5	11	4	1	21	68%
II. STRUCTURAL CHARACTERISTICS						
Subject area						
Electricity	3	17	4	0	24	78%
Waves	0	3	0	1	4	13%
Fluids	1	0	0	0	1	3%
Energy	0	1	1	0	2	3%
Heat and temperature	1	0	0	0	1	3%
Nature of analogical relationship						
Structural	3	1	1	0	5	16%
Functional	1	9	3	1	14	45%
Structural and functional	1	11	0	0	12	39%
Presentation format						
Verbal	1	9	1	0	11	35%
Verbal-pictorial	4	12	3	1	20	65%
Level of abstraction (analogy-target)						
Concrete-abstract	3	21	3	0	27	87%
Abstract-concrete	0	0	0	0	0	0%
Abstract-abstract	1	0	1	1	3	7%
Concrete-concrete	1	0	0	0	1	6%
Relevance of analogy						
Yes	4	17	1	0	22	71%
No	1	4	3	1	9	29%

spines were used to illustrate the radial distribution of electric field lines around point charges. Additionally, the analogy between the nautilus organism and submarine systems explained buoyancy control and ballast mechanisms through structural and functional similarities.

When analogies were evaluated in terms of their presentation format, the verbal-pictorial format was predominant. While 65% of analogies ($n = 20$) were presented in a verbal-pictorial format, 35% ($n = 11$) were presented in a verbal format only. This finding indicates that analogies were largely presented with visual aids in order to facilitate students' conceptual understanding processes during analogical reasoning. For instance, analogies involving contour maps, sea urchin spines, plumbing systems, water slides, wave movements, hydrophones, and whirlpools were typically accompanied by figures, diagrams, or visual representations that illustrated the relationship between the analogy and the target concept. In contrast, some analogies, such as those involving greenhouse structures, train transportation systems, and electrical energy transmission between cities, were presented verbally without visual aids.

The analyses of abstraction levels showed that the vast majority of the analogies were identified as concrete-abstract in nature. Eighty-seven percent of analogies ($n = 27$) involved a transition from a concrete analog to an abstract target concept. In contrast, the abstract-abstract analogies represented only 7% ($n = 3$) and the concrete-concrete analogies represented only 6% ($n = 1$). No analogies with an abstract-concrete structure were found. This finding clearly demonstrates that the basic function of most analogies identified in the reviewed textbooks was to explain abstract physics concepts using concrete examples drawn from everyday life and nature. For instance, electric current and charge flow were explained using water flow in pipes; electric potential difference, using water reservoirs and pumps; resistance, using narrow pipe systems and water slides; capacitance, using cupped hands to hold water and the everyday notion of capacity; and wave propagation, using Mexican wave activities and water ripple movements. In contrast, abstract-abstract analogies included explaining equipotential surfaces through contour maps and electrostatic interactions through comparisons with gravitational interactions between celestial bodies.

The only concrete-concrete analogy identified in the textbooks was the one between the nautilus organism and submarine systems, which was used to explain buoyancy control mechanisms.

From a relevance perspective, the results indicated that 71% ($n = 22$) of the analogies were relevant to students' everyday experiences. For example, electrical circuits were explained using analogies involving highways and traffic systems (e.g., traffic lights) in the 10th grade electricity topic. This would help students relate some fundamental concepts in electric circuits, such as current and resistance, to familiar phenomena and experiences in their everyday lives. Since concepts such as highways, vehicles, and traffic lights are directly related to students' daily experiences, this analogy was considered relevant. Conversely, 29% ($n = 9$) of the analogies did not sufficiently correspond with students' daily lives. For example, in the topic of Fluids in the ninth grade textbook [34], the concept of buoyant force was explained through the nautilus, a marine creature, and submarine systems. While the scientific functionality of the analogy between the nautilus's chambered shell structure and submarine ballast tanks is undeniable, it would not be considered relevant because the examples are highly distant from most students' daily life experiences in Türkiye and probably in many other countries that are not expected to be directly familiar with contexts such as the nautilus and submarines. Finally, the majority of the relevant analogies were found in the 10th grade textbooks, while the proportion was much lower in the 9th, 11th, and 12th grade textbooks. Other examples of relevant analogies included explaining electric current and resistance through water flow in pipes, explaining capacitance through everyday notions of capacity and filling cupped hands with water and explaining wave propagation through Mexican wave activities and water ripple movements, all of which are closely connected to familiar daily experiences. In contrast, analogies involving contour maps for equipotential surfaces, hydrophone systems, eddy currents represented through water whirlpools, and electrostatic interactions compared with gravitational interactions between celestial bodies were considered less relevant because these contexts may not be sufficiently familiar to many students in their everyday lives.

IV. DISCUSSION

The findings of this study contribute significantly to the related literature by examining the occurrences, pedagogical quality, and structural characteristics of the analogies found in high school physics textbooks. Most analogies were found to be provided in the subject of electricity across the textbooks for grades 9–12. This underscores one of the primary purposes of analogies, which is to help students understand and bridge abstract or complex concepts and thereby facilitate conceptual learning. The related literature indicates that analogies in science education have served as an effective bridge, particularly for conceptually difficult, abstract, and potentially misleading topics (e.g., atomic structure, chemical bonding, and electricity) [27]. However, the highly limited use of analogies in other fundamental physics topics across the reviewed textbooks, such as fluids and energy (only one analogy for each), suggests that analogies were greatly underutilized in these areas. The findings indicate that analogies in general appear less frequently in relatively more concrete physics topics such as mechanics compared to other subject areas. One possible explanation for this emerging pattern is the nature of the subject itself. For example, many mechanics concepts are closely connected to students' everyday physical experiences (e.g., motion, acceleration, force, and friction). Because these phenomena are often directly observable or experienced in daily life, textbook authors may rely more on real-world examples and concrete situations rather than constructing explicit analogies. In such contexts, the physical phenomena themselves may serve as a reference point for understanding the target concept, reducing the perceived need for analogical explanations. Given this, textbooks should extend the use of analogies to other abstract physics topics, such as quantum mechanics [2,50] and electromagnetism [3].

The overwhelming dominance of analogies incorporating functional similarities between analog and target concepts indicates that physical principles were explained by focusing on "how they work" (i.e., their functional characteristics). However, the relatively lower use of analogies focusing on structural similarities suggests that gaps may exist in the mapping of the relational system between the parts of the analogy and the target. Gentner [51] stated that the power of analogy increases when the structural system is transferred to the target domain. To deepen their conceptual understanding, students must understand not only the function of a concept but also its structure [28]. Therefore, enriching analogical relationships by giving more attention to structural similarities, in addition to functional ones, in textbooks may significantly contribute to conceptual understanding. These findings also support the role of analogies as scientific models, which serve as starter models [19] for more complex concepts. The dominance of the concrete-abstract type of analogies across the textbooks shows that analogies fulfill this modeling function. This function facilitates meaningful learning by building a bridge between students' prior knowledge and unknown scientific goals [10,52].

The results of this study show that none of the analogies fell into the poor category, and 68% are at the good level. However, a relatively high proportion of analogies classified at the moderate level suggests that the TWA model's critical step of clearly articulating the limitations (i.e., nonaligning attributes between analog and target) of

analogies is not being fully addressed in practice. Glynn *et al.* [53] and Treagust [54] emphasized the importance of identifying the characteristics of an analogy and mapping both the similarities and the limitations systematically for successful use of analogies. Omitting these steps, especially identifying limitations, increases the potential risks of the analogy. Indeed, Dagher [4], Thiele and Treagust [27], and Körhasan and Hıdır [1] demonstrated that shortcomings in this area could cause students to transfer an analogy's irrelevant features to the target concept, potentially leading to unintended misconceptions.

The literature acknowledges that analogical reasoning involves mapping features from a familiar source onto an unknown target concept [20]. However, this mapping process is far more sophisticated and dynamic than a simple one-to-one transfer, as it requires complex cognitive processing of information such as selecting relevant relational attributes of both systems, suppressing irrelevant features, and adapting the source schema to fit the constraints of the target concepts. In this context, the conceptual blending framework in cognitive science [55,56] offers a more detailed explanation of this complexity. It suggests that mapping is not limited to two input spaces (i.e., source and target) but instead creates a third "blended space" that selectively integrates features from both. In this new space, "emergent structures" can be dynamically constructed. These structures may not necessarily be present in the original inputs. They are constructed through the processes of completion and elaboration [55,56]. Regarding the analogies, the lack of explicit articulation of an analogy's limitations (a critical step in the TWA model) may potentially foster the formation of undesirable emergent structures in the blended space that are inconsistent with the target scientific concept. These structures can then be reflected back to the student's understanding. This cognitive mechanism implies that the mere presence of an analogy is not sufficient. The absence of clearly stated limitations is the main reason why the analogies classified as moderate in the Turkish physics textbooks have the potential to unintentionally create or reinforce students' alternative conceptions. In this context, a systematic and comprehensive application of the TWA model by textbook authors will enhance the pedagogical impact of analogies while minimizing the risk of conceptual misunderstandings. Conversely, the dominance of verbal-pictorial presentation (65%) is consistent with literature showing that visual support contributes to conceptual understanding and mapping similarities [9].

Seventy-one percent of the analyzed analogies were found to be relevant to learners' daily life experiences, suggesting that care was taken to ensure the selected analogies were appropriate for the local context, particularly in classes where the new curriculum is being implemented (10th grade). This is because the extent to which an analogy overlaps with a student's daily life directly increases its effectiveness in promoting learning and motivation [27]. Heywood [7] and Thiele *et al.* [28] stated that analogies increase students' interest and participation in lessons beyond cognitive transfer. The high level of relevance in classrooms where the curriculum is implemented increases the potential for these analogies to spark greater interest, curiosity, and satisfaction among students. These findings support the conclusion that everyday life experiences are critically important to the selection of analogies by textbook designers.

The study findings suggest that textbook authors should be more mindful of the pedagogical functions, advantages, and limitations of analogies and incorporate them into their textbooks. While analogies can facilitate understanding, they can also lead to misunderstandings if they are not structured properly or if their limitations are not clearly stated. However, since producing effective analogies is a pedagogically complex process that requires careful matching of structural relationships between concepts rather than relying on superficial similarities, systematic support is needed for textbook authors and teachers in this process. Providing examples and guidelines for analogy design during preservice teacher training and in in-service teacher professional development settings could address this need to some extent. Additionally, it is crucial for textbook authors to have subject-specific knowledge and pedagogical content knowledge related to analogy-based teaching strategies in order to design analogies that are conceptually accurate, pedagogically meaningful, and appropriate for students' prior knowledge and cultural backgrounds.

V. CONCLUSION

The findings of this study revealed important insights about the use of analogies in high school physics textbooks. While the analyzed analogies were generally found to be of adequate pedagogical quality, insufficient numbers of analogies employed in the textbooks and quantitative imbalances across the grade levels and subject areas were identified as key areas for improvement.

This study has important implications for the development of curricula and textbooks based on the findings about the nature and distribution of analogies in high school physics textbooks. The results regarding the pedagogical function of analogies, the topics in which they were used, and their structural characteristics provide guidance for designing analogies more effectively and for enhancing their instructional value in high school physics textbooks. Moreover, curriculum designers should prioritize introducing analogies in topics where they were found to be sparse and should encourage structurally enriched analogies that make the mapping between source and target explicit. Finally, teachers also play a crucial role in effectively facilitating the use of incomplete analogies

provided in textbooks. They must be equipped with the knowledge and skills to identify ill-prepared analogies and supplement them with additional information, so that students can benefit from analogies better.

The use of analogies should not be limited to traditionally challenging topics such as electricity. Analogies should also be used in a balanced manner in other areas with a high level of abstraction where there is a risk of conceptual misunderstanding in learning, such as modern physics topics (e.g., quantum mechanics) and thermodynamics (e.g., entropy). This approach will enable students to relate complex concepts to their concrete prior knowledge and past experiences, allowing for a deeper understanding [2]. The study also highlights an important pedagogical implication that the prevalent functional similarities in the analogies identified should be systematically enriched with their corresponding structural attributes. Analogies should reveal not only "how concepts work" but also "how they come together" and the relational system between these parts. This will help students go beyond superficial similarities and grasp the integrity of conceptual understanding [28].

In terms of pedagogical quality, it can be recommended that textbook authors must thoroughly implement Glynn's TWA model by identifying and explicitly acknowledging the limitations of analogies. Maintaining the dominance of the concrete-abstract structure of analogies and promoting verbal-pictorial presentation continue to be key elements in supporting conceptual understanding. However, clearly stating the potentially misleading aspects of analogies is critical to reducing the risk of conceptual misunderstanding. In line with findings on the relevance of analogies to learners' backgrounds, analogies used in textbooks should closely align with the daily life experiences and contexts of the target audience. Using relevant analogies can in turn increase students' interest in the subject and improve retention [9].

While this study provides valuable insights into the use of analogies in high school physics textbooks, there are limitations to consider when interpreting the findings. The most significant limitation is that the study relied solely on text analysis methods, failing to evaluate the actual classroom usage patterns of analogies or their conceptual effectiveness in eliminating misconceptions and improving academic achievement. Therefore, the findings reflect the potential pedagogical quality of analogies, but they do not allow for direct conclusions about their effects in the classroom.

The findings and limitations of this study suggest new areas of research on the use of analogies. Larger-scale and cross-cultural comparative analyses covering physics textbooks from different publishers and different countries are recommended. Additionally, experimental studies on the effectiveness of different types of analogies in eliminating conceptual misconceptions and improving student achievement would be beneficial [4,8]. Based on the relevance of analogy category highlighted in this study, a formal analytical framework can be developed to guide the systematic construction or selection of analogies that are most appropriate to learners' daily life and contextual backgrounds, rather than relying on *ad hoc* or random choices. The framework may also include components to evaluate how relevant analogy use might influence students' interest and learning outcomes. Finally, qualitative research examining how teachers use, transform, or generate analogies found in textbooks will contribute to a better understanding of the discrepancies between textbook content and classroom practice [57].

DATA AVAILABILITY

The data that support the findings of this article are not publicly available because of legal restrictions preventing unrestricted public distribution. The data are available from the authors upon reasonable request.

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