Dynamic Equilibrium in Science Education: Cross-Disciplinary Perspectives and Representations in Israel and United States Standards and Textbooks

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Abstract: The study examines how Dynamic Equilibrium (DE) is represented in science national standards and textbooks for high-school biology, chemistry, and physics in the US and Israel. DE, a crucial concept in understanding dynamic systems, is inconsistently represented across educational materials and students encounter difficulties learning about DE. Analyzing 17 textbooks and national standards, the research combines quantitative and qualitative content analysis to assess the frequency and nature of presentation of DE-related phenomena. The study identifies 256 DE-related phenomena, comprising 14% of all phenomena that are studied in science. The primary systems approach used is System Dynamics, which focuses on stocks and rates of flow at one description level. The main representational format is verbal, and computational models are scarcely used. Differences across disciplines and between countries were found. These findings emphasize the need for powerful representations of DE to enhance students' understanding of dynamic systems and improve science education.

Introduction, theoretical perspectives, and research goal

In this paper, we focus on Dynamic Equilibrium (DE) in science standards and textbooks, which we are considering as a structuring concept across the sciences in high-school learning. DE is a central concept for understanding patterns in dynamic systems and specific to this work, in the natural sciences. In fact, any semi-stable pattern in nature might be a result of DE. A system that exhibits DE is in a stable state where opposing influences continuously balance each other, resulting in no net change to the system (Biology Dictionary, n.d.). DE is usually described through the ongoing processes within the system, which return the system to equilibrium, after it is perturbed. Familiar examples are homeostasis in biology, ecological systems, and chemical equilibrium.

Despite the importance of this concept, DE is a challenging concept for students at all educational levels, even in universities. A major difficulty stems from the apparent contradiction between the system's stable appearance and the dynamic processes underlying it (Sarıçayır et al., 2006). For instance, students often misconceive stability solely in terms of constancy or resistance to disturbance and fail to relate it to energetic states, such as the system's tendency toward a minimum potential energy. In chemistry, students incorrectly interpret equilibrium as the complete cessation of reactions rather than a dynamic balance between opposing rates (Nakhleh, 1992; Özmen, 2008). Biology students similarly confuse stability with stasis, for example, viewing homeostasis as a fixed, unchanging state rather than an active process of regulation (Zion & Klein, 2015). Moreover, understanding equilibrium as an emergent phenomenon poses additional challenges. Students struggle to recognize the relationship between micro-level interactions and macro-level system properties. Instead, they tend to adopt a deterministic-centralized mindset, attributing system-level patterns to individual components or leaders, as observed in misconceptions about chemical diffusion and traffic flow (Wilensky & Resnick, 1999; Chi et al., 2012). The Samon & Levy (2017) have shown that across with respect to gases, the more different the properties of the two levels are, the more challenging it is for students to understand them.

DE can be described in terms of *System Dynamics* (SD; Forrester, 1961). SD models are used to analyze complex relationships within systems, focusing on how systems evolve over time at one level of description. It employs stocks, flows, and feedback loops to understand dynamic changes and interdependencies. *Structure-Behavior-Function* (SBF; Hmelo-Silver & Green Pfeffer, 2004) models are normative models of complex systems that represent three core aspects: structure (the components of the system), behavior (the causal mechanisms or processes within the system), and function (the purpose or roles of the system and its components). SBF models are widely used for analyzing, designing, and teaching about complex systems by focusing on how these three elements interact to define system operation and purpose. *Agent-Based Modeling* (ABM; Wilensky & Rand, 2015) models examine systems through the perspective of multiple agents engaging in dynamic interactions over time and within a spatial context. These models focus on understanding how simple and local interactions among the components of a system at the micro-level lead to complex and sometimes unpredictable behavior at the macro-level. DE is particularly important in the fields of teaching and learning science, as it forms the foundation for understanding a wide range of scientific phenomena. In the NGSS US science education standards, the last of the seven crosscutting concepts is directly related to DE: Stability and Change, denoting conditions for stability and determinants of rates of change (NGSS, 2013). Proper instruction on DE enables students to develop systems thinking and a deep understanding of complex dynamic processes, linking different levels of representation—from the micro to the macro—in both natural and artificial systems ((Wilensky & Resnick, 1999; Dickes et al., 2016).

This study is part of a larger international project aimed at developing new representations for DE that help resolve the above-described difficulties. Cross-national comparisons are crucial for understanding cultural and educational influences on the representation of scientific concepts (Valverde et al., 2002). This study compares high school science education systems in Israel and the United States, highlighting fundamental structural differences. In Israel, students study all science subjects concurrently at a slower pace until tenth grade, after which those who specialize in science continue through twelfth grade. In contrast, U.S. high school students typically study one science discipline per academic year (e.g., biology, chemistry, physics). These differing approaches provide a valuable opportunity to examine how educational frameworks shape students' understanding of DE phenomena. The theoretical approach undertaken involves restructuration, a construct developed by the Wilensky & Papert (2010) to denote fundamental changes to representations that can transform both the scientific generativity of the representation and public understanding by making them more general and understandable. Thus, our approach to designing possibly better representations is to investigate various perspectives that can inform this process: students' concepts, scientists' concepts, and in the case of the present paper – mapping out where and how DE shows up in high school science curricula. Our sense was that there are many more DE-related phenomena beyond homeostasis and chemical equilibrium, which are not explicitly presented as DE; as DE describes any dynamic system that holds certain important variables relatively constant. For example, constant velocity in physics or the neutralization reaction between an acid and a base, resulting in a stable pH of 7, are both phenomena where DE is present but not traditionally emphasized as such in educational contexts. This research aims to examine how the concept of DE is presented and represented in the national science standards and textbooks in Israel and in the US. The research questions guiding this study are: How does the content of high school in biology, chemistry, and physics compare between Israel and the US? What DE phenomena are present in the standards of both countries, and which unexpected phenomena were identified as related to DE despite not being explicitly defined as such? What representational formats are used (e.g., graphs, illustrations, diagrams, computational models) in the textbooks, and what are the differences in the use of representations across subjects and countries? Which system frameworks (SD, ABM, SBF) are most prevalent in explaining DE phenomena, and how does their use vary between the curricula of Israel and the US?

Methodology

This study analyzed the content and scientific representations related to DE in the main textbooks and national standards (Israel Ministry of Education, 2024; US NGSS, 2013; US National Research Council, 2012). 17 popular textbooks were selected based on expert teachers' and researchers' recommendations and verified by reading teachers' forums. A qualitative analysis examined the content of the curricula in the two countries and aligned them to examine the degree of similarity. A mixed-methods content analysis (Krippendorff, 2019; Schreier, 2012) involved recording the frequency of DE-related phenomena and their related representations, categorizing them into seven format types: verbal, equation-based, graphical, tabular, photographic, illustrative, diagrams, and computational, such as simulations. Further analysis examined the systems approach to describing DE. The coding by these two lenses – representational format and systems approach – are described and compared between subjects and between countries. It is important to highlight that analyzing this corpus of data does not reflect the complete learning environment that students experience, which may include laboratories, problem-solving exercises and external resources.

Findings

Content of the curricula

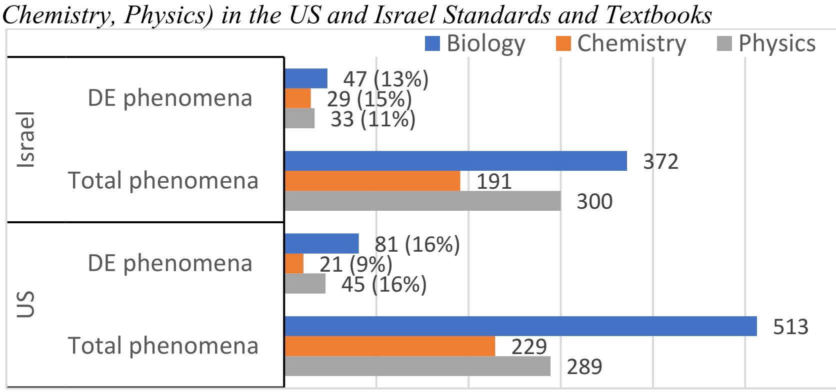
An overview of the high school science curricula in the two countries was made to establish whether the content overlaps and can be compared. The standards and the textbooks' list of topics were compared and aligned with each other until a manageable set of categories could be used to group the topics, and the total number of phenomena in each discipline in both countries was counted (see Figure 1). In biology, while both curricula address cell structure, molecular processes, and ecology, Israel's curricula emphasize organ systems, whereas the US materials focus on biodiversity and evolution as distinct topics. In chemistry, there is common ground in areas like the structure of matter, chemical reactions, energy, and chemical equilibrium. However, Israeli learning units prioritize types of reactions and their relation to food energy, whereas the US curricula highlight kinetics and enthalpy's effects on natural systems. In physics, the main topics are mechanics, forces and interactions, electricity and magnetism, radiation, energy, and the structure of matter, with minimal country differences.

Identification and counting of DE-related phenomena

Subsequently, we focused on identifying phenomena that embody the principle of DE in the standards and textbooks, beyond those explicitly defined as DE phenomena. The total number of phenomena and the DE-related phenomena are presented by disciplines (biology, chemistry, and physics) for both countries (see Figure 1).

Figure 1

Frequency of All Phenomena and DE-Related Phenomena Across Disciplines (Biology, Chemistry, Physics) in the US and Israel Standards and Textbooks



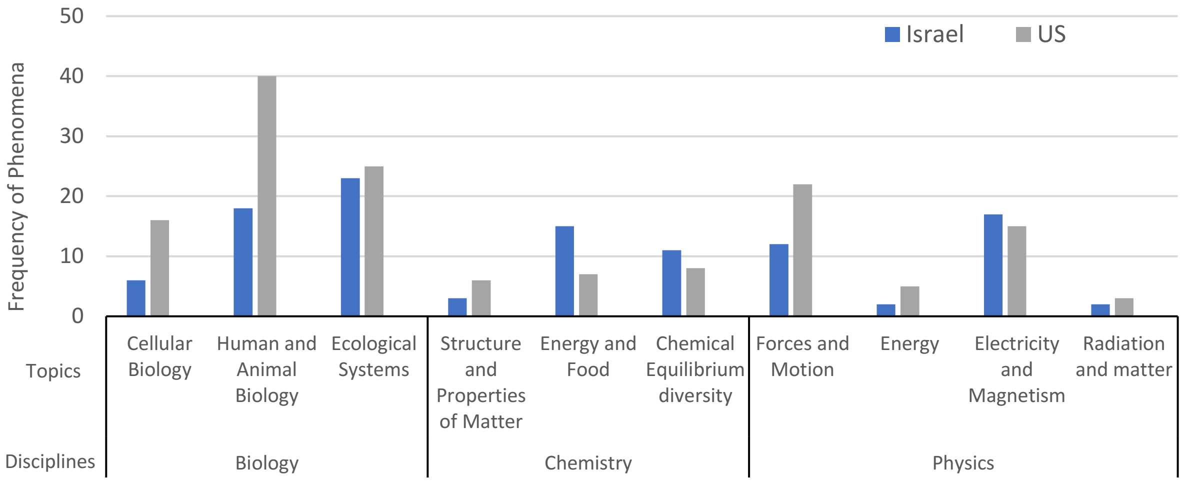
Overall, there are 256 DE-related phenomena across the three disciplines. Of these, 147 phenomena were identified in the US, accounting for 14% of all phenomena described in the standards. In Israel, 109 DE-related phenomena were identified, representing 13% of all phenomena described in the standards. When comparing among the disciplines, both the total number of phenomena and DE-related phenomena are most pervasive in biology, followed by physics, and then chemistry. In physics and chemistry, the total number of phenomena is similar between the two countries, but the overall number of phenomena across all disciplines is significantly higher in the US compared to Israel. The proportion of phenomena describing DE is greater in the US than in Israel across biology and physics. However, in chemistry, the percentage of DE-related phenomena is higher in the Israeli curriculum than in the US curriculum.

Distribution of DE-related phenomena

We focused on identifying phenomena that embody the principle of DE in the standards and textbooks, beyond those explicitly defined as DE phenomena. The distribution by discipline and topic of DE-related phenomena is presented (see Figure 2).

Figure 2

Distribution of DE-Related Phenomena Across Disciplines (Biology, Chemistry, Physics) and Topics in the US and Israel High School Textbooks



When comparing among the DE-related phenomena for both countries by topics, the two countries are similar regarding half (five) of the ten topics. However, the US curriculum includes significantly more DE-related phenomena in the topics of forces and motion in physics, as well as cellular biology and animal biology in biology. Conversely, the Israeli curriculum places greater emphasis on DE-related phenomena in the topics of energy and food, and chemical equilibrium in chemistry.

Among the 256 phenomena examined, there were some we expected, as they are generally associated with DE, although they are not explicitly defined as DE in the textbooks. For example, 11 phenomena describe chemical equilibrium, 27 deal with homeostasis, and 13 describe ecological systems. These phenomena are familiar as being related to DE, so that did not surprise us. However, 205 other phenomena, which represent 80% of all DE-related phenomena and 11% of all phenomena described in the standards of both countries describe DE processes for topics and phenomena that had not been previously defined as related to DE.

DE representations' format

In future steps of this project, we will create and investigate new computational representations for DE. Thus, we were interested in the prevalence of the different kinds of representations: verbal representations refer to the use of written or spoken words to describe scientific phenomena, which facilitate the communication of complex ideas (Knecht, 2007). Mathematical representations involve the use of mathematical symbols and equations to model and describe relationships and changes within a system (Pincock, 2011). Graphs are visual representations that display quantitative data and relationships, commonly used to illustrate trends or patterns in the data (Khine & Liu, 2017). Tables present data in an organized grid format, allowing for easy comparison of variables (Slough et al., 2010). Photograph representations capture real-world images of phenomena, providing a concrete visual reference (Lee, 2010). Illustrations are hand-drawn or digitally created visuals that clarify or enhance the understanding of scientific concepts (Lee, 2010). Diagrams are structured visual representations that combine spatial, symbolic, and textual elements to illustrate relationships, processes, or systems in a clear and concise manner (Tang, 2023). Computational representations, including simulations and models, use computational methods to simulate dynamic processes and visualize the behavior of systems over time (Humphreys, 2002). The format of the textbooks' representations of DE-related phenomena is described in Table 1. Only the main conclusions from the table are presented for brevity.

Table 1
Format of Representations of DE-related Phenomena According to Textbooks in the US and Israel

Discipline	Country	Phenomena (N)	Representation Format (% of N)							
			Model	Diagram	Illustration	Photograph	Table	Graph	Equations	Verbal
Biology	UA	81	18	26	48	13	1	5	6	100
	Israel	47	0	42	38	27	22	27	9	100

Chemistry	US	21	0	25	63	17	8	25	79	100
	Israel	29	3	0	11	0	24	29	34	100
Physics	US	45	0	20	76	20	4	31	73	100
	Israel	33	0	8	82	10	8	13	62	100

Overall, verbal representations were present in any textbook section that included DE-related phenomena. The frequency of representational formats observed in the study follows the order: verbal > illustration > mathematical > diagram > graphical > table > computational model. The frequency of representational formats varies across disciplines. In physics and chemistry, mathematical representations are frequent, but rarely used in biology. Illustrations are common in both biology and physics, but less so in chemistry. Diagrams are more frequent in biology, with less usage in physics and chemistry. The least used format is computational models, which appear primarily in biology, to a small extent in chemistry, and not at all in physics.

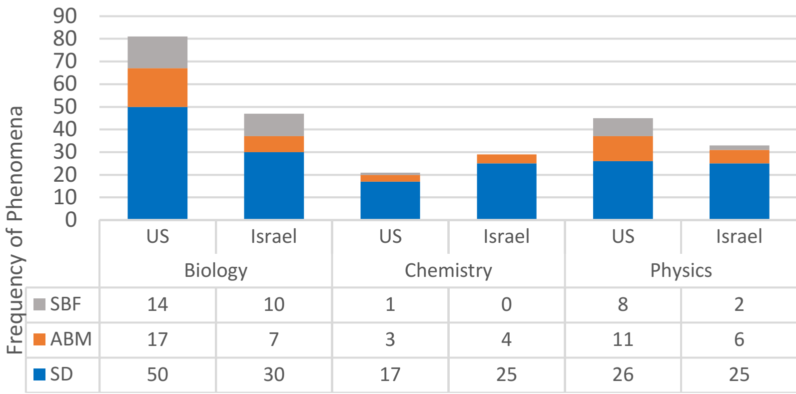
Comparison between countries shows a similar distribution shape among the representational formats, with the US having a greater number of illustrations and mathematical representations, and Israeli textbooks using more tables. Very little use of the computational models is made, and only in the US. The results show differences in the frequency and distribution of these representations across disciplines and between the two countries. In the field of biology, Israeli textbooks display a wider range of representational formats: six out of eight types of representations appear in at least 20% of the textbooks, compared to only three out of eight in US textbooks. In physics, however, US textbooks show six types of representations in at least 20% of the textbooks, while Israeli textbooks only include three types of representations at this level.

Regarding the use of illustrations, findings show that US chemistry textbooks include illustrations at a significantly higher rate than Israeli textbooks (63% versus 11%). However, in physics and biology, the use of illustrations is similar between the two countries. Israeli textbooks were found to use tables more frequently than US textbooks, especially in chemistry and biology. Furthermore, in biology, photographs are more common in Israeli textbooks than in US textbooks, while photographs are rarely used in Israeli chemistry textbooks. Additionally, diagrams are more common in Israeli biology textbooks compared to US textbooks; in chemistry, diagrams do not appear in Israeli textbooks at all, while in the US, they are found in about 25% of the textbooks. In biology, the use of graphs is more widespread in Israel, while in chemistry, graph usage is similar across both countries. In physics, graphs are used more extensively in US textbooks than in Israeli textbooks. For mathematical representations in chemistry, US textbooks include these representations at a significantly higher frequency than Israeli textbooks (79% versus 34%), whereas in physics and biology, the frequency of mathematical representations is similar in both countries.

Representations' systems framework

As we plan to create new dynamic computational representations for DE, the structure of DE explanations was examined through the lens of systems' frameworks: System Dynamics (SD), Structure-Behavior-Function (SBF) and Agent-Based Modeling (ABM). The following analysis examines the prevalence of represented phenomena through these frameworks, across the science fields, with a comparison between textbooks from the two countries. We coded the explanation of each DE phenomenon according to seven dimensions, which we expected to distinguish between the different frameworks: behaviors and properties of individual components (described in ABM and SBF, but not in SD); randomness or chance (only in ABM); interactions between individual components (described in ABM and SBF, but not in SD); functions of parts or the system as a whole (only in SBF); heterogeneity of micro-level entities (characteristic of SBF); and stocks and rates, which describe the speed of change and accumulation within the system (more typical of SD). These dimensions provide a structured approach to identifying the frameworks in explanations of DE phenomena (see Figure 3).

Figure 3
Frequency of System Frameworks (SD, ABM, SBF) Representing DE-Related Phenomena Across Disciplines (Biology, Chemistry, Physics) and Countries.



The overall findings indicate that the SD approach is the most prevalent, with a total of 173 phenomena. The ABM approach is less common, appearing in 48 phenomena, and the SBF approach is the least frequent, appearing in only 35 phenomena. When analyzed by discipline, the SD approach is the most dominant framework across all fields. In biology, SD is used most frequently, followed by the Agent-Based Modeling (ABM) and Structure-Behavior-Function (SBF) approaches, which appear with similar frequency. In chemistry, SD is again the most prevalent, with ABM appearing in a few cases and SBF being almost absent, especially in the Israeli curriculum. In physics, SD remains the most commonly used framework, with ABM being more prominent than SBF. A comparison between the countries reveals that the US relies heavily on the SD approach across all disciplines, while also incorporating ABM and SBF in a more balanced manner. In contrast, Israel predominantly uses the SD approach, with much less frequent use of ABM and even fewer instances of SBF. Notably, the SBF approach is entirely absent in chemistry within the Israeli curriculum.

Discussion

This research is part of an international project focused on developing representations for Dynamic Equilibrium, one of the big ideas in science, describing how stable patterns form in a dynamic system, with the goal of improving students' understanding of DE-related phenomena. The significance of our research lies in its potential to improve science education by enhancing students' comprehension of complex scientific concepts like DE, which is crucial for understanding dynamic systems in various scientific fields. The present research focuses on examining the representation of the concept of DE in science national standards and textbooks at the high school level in the US and Israel.

The main objective of the study is to compare the content of curricula in various fields of biology, chemistry, and physics, and to investigate how the concept of DE is presented and represented in the educational materials of both countries. Additionally, the study explores the extent and prevalence of DE phenomena in the curricula and how these phenomena are represented in textbooks through graphs, illustrations, computational models, and more, as well as the differences in the use of these representations across different disciplines and countries. The research also addresses the use of systems approaches (SD, ABM, and SBF) in explaining DE phenomena, and the differences in their application between the curricula of the US and Israel. It is also important to clarify that this study does not aim to provide a definitive answer regarding the differences between the countries but rather serves as a starting point for future research. The project examines two key sources of knowledge: explicit scientific knowledge of DE, ensuring alignment with current science and learners' intuitive knowledge, shaped by personal experiences and out-of-school learning. By combining these sources, the project aims to create new systems representations of DE, using agent-based models (ABM) but going beyond them, to make DE more comprehensible for learners. The current study plays a crucial role in the project by providing the school-based perspective by comparing curricula, exploring the representations of DE-related phenomena, and identifying how different educational tools and models can support better understanding of DE among both students and teachers.

It is important to note that this study analyzed standards and textbooks. While this analysis represents to some extent what students learn in class, there are additional components of the learning environment that are not considered, such as laboratories, websites and problem-solving exercises. When findings show one country or discipline having "more" of something, it doesn't necessarily reflect the amount of learning. For example, in one discipline or country, there may be more laboratory work, where students experience the phenomena and use the relevant concepts at greater depth. The enduring conflict of depth versus breadth (Schwartz et al., 2009) in determining what should be learned in schools creates differences we have not accounted for. Thus, the findings only focus on the phenomena selected for teaching, and not the overall learning environments that students experience. In order to investigate how the concept of DE is represented in the standards and textbooks of both countries, the study begins by comparing the content of the science curricula across the disciplines of biology, chemistry, and physics. A comparison of the curricula reveals that the content is largely similar; however, notable differences exist, particularly in the teaching of evolution and biodiversity in biology. In the US, there is a strong emphasis on topics such as biological diversity and evolution, whereas in Israel, these topics are generally excluded from the curriculum. These differences are influenced by social, religious, and, at times, teacher training factors. In the US, evolution education is a cornerstone of biology instruction, especially in states that have adopted the Next Generation Science Standards (NGSS), which highlight evolution as a foundational scientific theory. The adoption of these standards has led to advancements in evolution education, including improved teacher training and teaching methodologies. However, there are still states where resistance to fully adopting these standards persists, leading to gaps in evolution education due to ongoing cultural and political opposition (Plutzer et al., 2020). Additionally, differences in topics within chemistry reflect distinct educational approaches between the two countries.

One of the key findings of this study is that phenomena related to DE constitute approximately 14% of all phenomena taught in biology, chemistry, and physics across both countries. This is particularly significant, as it highlights the widespread presence of DE-related phenomena in high-school science curricula and emphasizes the importance of understanding DE in complex and dynamic systems. However, it should be noted that a significant proportion of these phenomena are not explicitly defined as DE-related within the curricula, underscoring the need for broader recognition and emphasis on this concept. Based on these findings, several recommendations are proposed. First, there is a need to raise awareness of the importance of DE-related phenomena in the learning process. These phenomena provide students with a deeper understanding of the principles underlying complex systems, making it essential to integrate them more systematically and intentionally into science curricula. Second, teacher training should be enhanced to include a focus on DE-related phenomena, particularly those identified as unexpected in this study. Professional development initiatives can support teachers in effectively and comprehensively incorporating these topics into their instruction. Furthermore, continued research into the unexpected phenomena identified in this study is crucial for understanding their potential in science education and expanding the existing body of knowledge on this topic.

"Stability and Change" is one of the cross-cutting concepts emphasized in the NGSS standards (NGSS, 2013). These concepts span scientific disciplines, helping students draw connections between different domains. For example, "stability and change" is evident in ecosystems, where fluctuations in species populations can contribute to long-term stability, and in chemical reactions, where equilibrium reflects a stable dynamic state. Building on this, we recommend investigating whether explicit instruction on dynamic equilibrium as a unifying concept across phenomena and disciplines enhances student understanding. Finally, future research and design efforts should aim to define DE in a way that supports mechanistic reasoning, linking dynamic processes to stable outcomes. Based on the findings of this study, there is a clear connection to the objectives of the international project aimed at developing new representations of DE. The results underscore the significance of both visual and verbal representations, especially in relation to the lack of mathematical representations in biology textbooks across both countries. This absence limits the understanding of dynamic relationships between variables. As highlighted in previous studies, mathematical representations are vital for understanding complex biological phenomena, such as population dynamics and genetic processes, as they not only enhance comprehension but also improve problem-solving skills (Treagust & Tsui, 2013).

The difficulties in understanding the concept of DE stem from grappling with the complex dynamics of interactions between components at different levels within a system. Previous studies (Wilensky & Resnick, 1999; Friedler et al., 1987) suggest that students struggle to understand how interactions at the microscopic level (e.g., molecules or particles) are related to macroscopic phenomena (e.g., concentrations or acidity) in the system as a whole. The main issue lies in recognizing the interactions between components and being able to describe the dynamics that lead to changes in equilibrium states. Often, students perceive equilibrium as a static state where no changes occur and fail to grasp that dynamic processes continue to operate at different levels within the system. The aim of our project is to address these challenges by developing new representations that focus on enhancing students' systemic and dynamic understanding of DE, using computational models. These models will allow for the representation of the system's dynamics, demonstrate interactions between its components at different levels of description, and will also display global variables and rates in real time. The current research indicates that the use of computational models is scarce in both countries, highlighting the need for increased emphasis on their use. These models can enhance understanding of dynamic processes and provide students with tools to explore the system in real time and construct a comprehensive systemic understanding of DE.

The approaches of System Dynamics (SD), Agent-Based Modeling (ABM), and Structure-Behavior-Function (SBF) are central theoretical frameworks for understanding complex systems across various scientific fields. According to the results of the study, the most prevalent approach in describing DE phenomena in textbooks is SD. This approach focuses on understanding the system as a whole over time, emphasizing feedback loops, stock-and-flow structures, and time delays. However, it does not include spatial information, and it works at one description level of the system; and is thus more limited in enabling students to make sense of the mechanisms underlying a phenomenon. It is particularly suited for phenomena when they are described as quantitative relationships between variables, such as concentrations and reaction rates in chemical equilibrium, and velocity and energy conservation when a body is going down a hill. SD allows for the creation of relatively simple models that can be quantitatively analyzed and used to predict the whole system's future behavior. In scientific research and high school science learning, understanding how phenomena occur often requires examining multiple levels of description. This study identifies a significant gap in system representations, despite prior research emphasizing the critical role of agent-based modeling (ABM) in understanding relationships between system levels (Wilensky & Resnick, 1999). The study's findings indicate that the SD approach to systems is the most commonly used method for describing phenomena, though it primarily focuses on a single level of description. In contrast, ABM enables the simulation of collective behavior emerging from simple agent interactions governed by basic rules, offering insight into "bottom-up" phenomena, such as population dynamics in biology or electric charge interactions in physics. By distinguishing between at least two levels of system description and incorporating spatial information, ABM helps students understand how micro-level behaviors shape macro-level patterns. Given its importance, we recommend a more prominent integration of ABM representations in science education to strengthen students' ability to connect system levels. Additionally, the use of computational models to illustrate dynamic processes should be encouraged, as they have been shown to enhance both understanding and engagement among learners (Blikstein & Wilensky, 2009).

In conclusion, this study underscores the importance of developing a unified and universal representation of DE in science education. The current diversity of representations across disciplines can create confusion and hinder students' understanding of DE. A unified representation, adaptable to different scientific fields and systems, could serve as a solid foundation for learning, ensuring consistency while allowing flexibility. This representation should be both simple and clear, yet rich enough to capture the complexity of dynamic systems, including feedback loops and multi-level processes (microscopic and macroscopic). By providing such a universal framework, we can address existing challenges in both research and practice, enhancing the ability of students and teachers to grasp complex scientific phenomena. Future research should explore additional dimensions of DE and investigate how it can be integrated with other scientific concepts. This could lead to new insights into the interconnections between system dynamics and other subjects. Furthermore, expanding research into areas beyond biology, chemistry, and physics—such as mathematics, social sciences, and geography—presents an opportunity to apply the DE concept to other dynamic systems, offering new perspectives and broadening its educational impact.

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