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Why learning mathematics in high school physics is essential: A 21st century perspective

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Abstract

This paper examines the critical importance of integrating mathematics into high school physics education. This study presents mathematics as an integral component of understanding the physical world, not merely a technical tool. The paper identifies four fundamental roles of mathematics in physics: creating syntactic structure, generating multiple representations, providing reasoning tools, and facilitating discovery. The research demonstrates how mathematics enables transition from qualitative to quantitative description and provides predictive capabilities, illustrated through contemporary examples including GPS systems, smartphone technologies, medical imaging, and vaccine development. Practical applications across technology, medicine, and sports demonstrate relevance to students' daily lives. The study emphasizes how mathematical understanding in physics prepares students for higher education, develops analytical thinking, and deepens world comprehension. Pedagogical recommendations include connecting to everyday life, using multiple representations, and implementing logic-checking strategies. This research offers a practical framework for educators to enhance physics instruction and supports the argument that mathematical literacy in physics is essential for informed citizenship in our technological society.

Keywords: mathematics in physics, science education, sci-math sensemaking, high school physics, analytical thinking, physics education research

INTRODUCTION

Many high school students struggle to understand why mathematics is so prominent in their physics classes and find it difficult to grasp the connection between complex formulas and the natural phenomena familiar to them. Questions like "Why do I need to solve equations to understand how an object falls?" or "What's the connection between algebra and electricity?" echo in physics classrooms worldwide. The groundbreaking work of Palmgren and Rasa (2024) provides a comprehensive answer to these questions and offers a new understanding of the relationship between mathematics and physics. The authors argue that "Mathematics does not only present physical information but also shapes our beliefs about physical phenomena" (Palmgren & Rasa, 2024, p. 380). Mathematics is not merely a technical tool in physics but an integral part of understanding the physical world around us and how we perceive and interpret natural phenomena (Ben-Abu, 2019a, 2019b).

Recent research by Freeman et al. (2014) has shown that students who engage actively with mathematical concepts in physics demonstrate significantly higher learning gains compared to traditional lecture-based approaches. This active engagement with mathematics is not just about computational skills but about developing what Zhao and Schuchardt (2021) call "sci-math sensemaking"–the ability to make sense of mathematical equations in science contexts through connecting mathematical representations to physical meaning. Their sci-math sensemaking framework identifies key categories of how students interpret mathematical equations in science, providing crucial insights into the cognitive processes involved in mathematical reasoning within physics contexts. The COVID-19 pandemic has

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Contribution to the literature

- This study contributes to physics education research by creating a comprehensive pedagogical approach that bridges mathematical formalism with students' cognitive processes in learning physics.
- The research demonstrates concrete connections between abstract mathematical principles and 21st-century technologies familiar to high school students, including GPS systems, medical imaging, and vaccine development.
- By providing evidence-based strategies that develop both syntactic and semantic reasoning skills while emphasizing multiple representations and contextual learning, this work addresses persistent challenges in making mathematics relevant in physics education and prepares students for higher education in STEM fields and informed citizenship in a technological society.

further highlighted the importance of mathematical literacy in physics, as students worldwide have had to adapt to new learning modalities while maintaining conceptual understanding (Henderson et al., 2021).

MATHEMATICS AS THE LANGUAGE OF PHYSICS

From Qualitative Description to Quantitative Understanding

Many students begin their physics studies with qualitative descriptions of natural phenomena. When we say, "the ball falls fast" or "the car brakes sharply," this is a qualitative description that gives a general impression but does not provide accurate and useful information. Mathematics enables us to transition to precise quantitative description. As Redish and Kuo (2015) note, "in science, we don't just use math, we make meaning with it in a different way than mathematicians do" (p. 561). The framework developed by Zhao and Schuchardt (2021) further elucidates this process, showing that effective sci-math sensemaking involves multiple levels of interpretation: recognizing mathematical structures, connecting symbols to physical quantities, and understanding the causal relationships embedded in equations (Ben-Abu et al., 2019).

Recent studies by Kuo et al. (2020) have further demonstrated that students who develop both procedural fluency and conceptual understanding in mathematical physics show superior problem-solving abilities and transfer of learning to novel situations. When we say, "the ball falls with an acceleration of 9.8 m/s^2," we use mathematics to provide an accurate and measurable description that allows for precision in measurement, accurate comparison between different phenomena, and prediction of what will happen in new situations. This transition from qualitative to quantitative is revolutionary in our understanding of nature and enables us not only to describe phenomena but also to control them and predict their behavior. The sensemaking framework demonstrates that this transition is not automatic but requires deliberate cognitive work to connect mathematical representations with physical understanding (Zhao & Schuchardt, 2021).

Physics as a Predictive Science

The true power of combining mathematics with physics is revealed in the predictive capability it provides. Instead of relying on guesses or intuition, mathematics allows us to predict exactly when and how physical events will occur. For example, when NASA sends a spacecraft to Mars, engineers use complex mathematical equations to calculate precisely the flight trajectory, arrival time, and required fuel amount. The mathematical precision is so high that the spacecraft arrives at its destination after a journey of many months across millions of kilometers. Without mathematics, all of this would be impossible.

Modern examples of this predictive power are even more striking. The recent detection of gravitational waves by LIGO (Abbott et al., 2020) was made possible by Einstein's mathematical predictions from over a century ago, combined with incredibly precise mathematical modeling of the expected signals. Similarly, the development of COVID-19 vaccines was accelerated by mathematical modeling of protein structures and immune responses (Callaway, 2020). These examples demonstrate to students that the mathematics they learn in high school physics is not abstract but directly connected to cutting-edge scientific achievements. The sci-math sensemaking framework helps explain why some students struggle with these connections while others excel–it depends on their ability to see mathematical equations not just as computational tools but as representations of physical relationships and causal mechanisms (Zhao & Schuchardt, 2021).

FOUR ROLES OF MATHEMATICS IN PHYSICS ACCORDING TO THE NEW MODEL

Fundamental Syntactic Structure

Palmgren and Rasa (2024) present an innovative model based on four main roles of mathematics in physics. The first role is creating the basic syntactic structure of physics. Mathematics provides the "grammar" of physics–the system of rules and constraints that allows us to construct logical and consistent descriptions of physical phenomena. As the authors write: “Mathematics aids in forming a syntactic structure for physics: it acts as a framework in which physical knowledge is organized” (Palmgren & Rasa, 2024, p. 373).

Recent research by Uhden et al. (2022) has expanded on this concept, showing that students who understand the structural role of mathematics in physics develop better conceptual frameworks for understanding advanced topics. The work of Zhao and Schuchardt (2021) complements this by showing that students’ ability to make sense of mathematical equations depends heavily on their understanding of this underlying structure. Their framework identifies that successful sensemaking requires students to recognize not just what equations mean, but how they fit into the broader mathematical architecture of physics. Just as Hebrew has grammatical rules that allow us to construct logical sentences that others can understand, mathematics has rules that enable us to construct logical descriptions of physical phenomena that any scientist in the world can understand and verify (Ben-Abu, 2023). This structure is so fundamental that without it, modern physics simply cannot exist.

Creating Multiple Representations of the Same Phenomenon

The second role of mathematics in physics is creating diverse representations of physical phenomena. As Palmgren and Rasa (2024) note: “The same system or phenomenon can be represented in multiple different ways (graphically, tabulated, mathematically using different notational systems, etc.) that bring different facets or aspects of the system to the foreground” (p. 374). The same physical phenomenon can be represented in several mathematical ways, each emphasizing a different aspect and providing different insights.

Contemporary research by Gire and Price (2021) has shown that students who work with multiple representations develop more flexible thinking and better problem-solving skills. The sci-math sensemaking framework provides insight into why this works: different representations activate different aspects of student understanding, and the process of translating between representations deepens comprehension of the underlying physics (Zhao & Schuchardt, 2021). For example, motion at constant velocity can be represented as a graph showing a straight line of position versus time, as the mathematical equation $x = x_0 + vt$, as a table of numerical data, or as a verbal description. Each representation gives us a different and complementary understanding of the same phenomenon and allows us to gain a more complete picture of what happens in nature. Students who can move fluidly between these representations demonstrate higher levels of sci-math sensemaking and show better performance on both conceptual and computational physics assessments.

Tools for Reasoning and Problem-Solving

The third role of mathematics in physics is providing tools for thinking and problem-solving. Palmgren and Rasa (2024) distinguish between two types of thinking that characterize the use of mathematics in physics. Syntactic reasoning focuses on using formal mathematical rules, solving equations step by step, and substituting data into formulas. This is the type of thinking that many students know and learn early in their journey. In contrast, semantic reasoning requires understanding the physical meaning of mathematical expressions, connecting results to reality, and checking the logic of results. As the authors note: “Semantic reasoning relies on understanding the semantics of the representation at hand, i.e., it requires understanding the content of the representation” (Palmgren & Rasa, 2024, p. 376).

The sci-math sensemaking framework provides a more detailed understanding of how these different types of reasoning work together. Zhao and Schuchardt (2021) identify several categories of sensemaking behavior, including mathematical manipulation (similar to syntactic reasoning), physical interpretation (similar to semantic reasoning), and bridging activities that connect the two. Their research shows that students who engage in all categories of sensemaking show superior performance in physics courses and better retention of concepts over time. Recent studies by Hull et al. (2021) have confirmed that students who develop both syntactic and semantic reasoning abilities demonstrate more expert-like problem-solving approaches. The integration of both types of thinking creates deep and complete understanding of physics. A student who develops both these skills becomes a better physicist and a more critical thinker in general.

Discovery of Insights and New Information

The fourth and most fascinating role of mathematics in physics is its ability to lead to discoveries and new insights that would not be accessible without mathematics. Palmgren and Rasa (2024) distinguish between two types of discovery: direct extraction and emergent extraction. Direct extraction refers to solving specific problems and getting direct answers to known questions. In contrast, emergent extraction refers to discovering new phenomena and concepts that emerge through mathematics but were not expected in advance. As the authors write: “mathematical representations or their manipulations can uncover new structures that can lead to even unexpected explanations of phenomena” (Palmgren & Rasa, 2024, p. 377).

The sci-math sensemaking framework helps explain how students can develop the skills necessary for both types of discovery. Zhao and Schuchardt (2021) show that students who engage in higher-level sensemaking behaviors–such as recognizing patterns across different mathematical representations and identifying causal relationships embedded in equations–are more likely to make novel connections and insights. Recent examples of this include the mathematical prediction of the Higgs boson (Evans, 2020) and the mathematical modeling that led to the discovery of exoplanets through gravitational lensing effects (Johnson et al., 2021). These contemporary examples show students that the mathematics they learn continues to drive scientific discovery today, and that developing strong sci-math sensemaking skills is essential for participating in this ongoing process of discovery.

PRACTICAL APPLICATIONS IN DAILY LIFE FOR HIGH SCHOOL STUDENTS

Technology in Their Hands

High school students today live in a world surrounded by technology that is entirely based on the application of advanced physical and mathematical principles. The smartphone they use daily contains dozens of technologies, each based on sophisticated physics and mathematics. The GPS system that navigates them to school or friends' houses is based on Einstein's theory of relativity, which is an extremely complex mathematical theory. Without relativistic corrections, the GPS system would accumulate errors of several kilometers per day and would not be useful.

Recent developments in smartphone technology further illustrate this point. The facial recognition systems now common in phones use machine learning algorithms that are fundamentally based on mathematical optimization techniques and statistical physics principles (Zhang et al., 2020). The wireless charging capabilities of modern phones rely on electromagnetic induction, described by Faraday's laws and Maxwell's equations. Even the touchscreen technology uses principles of capacitance and electric field detection that require sophisticated mathematical modeling to be implemented effectively (Kumar et al., 2021). Understanding these connections requires the kind of sci-math sensemaking that Zhao and Schuchardt (2021) describe–the ability to see how mathematical relationships translate into real-world technological capabilities.

Medicine and Health

The field of medicine, which touches the lives of every student and their family, is also based on advanced physics and mathematics. When a doctor performs an MRI scan to check for brain or spinal cord injury, they use technology based on nuclear magnetic resonance–a phenomenon described by quantum mechanics and requiring complex mathematical understanding of frequencies, waves, and matter behavior in strong magnetic fields. Recent advances in medical imaging, such as the development of functional MRI techniques for studying brain activity in real-time, rely on even more sophisticated mathematical signal processing and statistical analysis methods (Chen et al., 2021).

The development of personalized medicine, where treatments are tailored to individual genetic profiles, depends heavily on mathematical modeling of drug interactions and biological pathways (Rodriguez et al., 2020). Even the COVID-19 vaccines that many students have received were developed using mathematical modeling of protein folding, immune system responses, and epidemiological spread patterns (Callaway, 2020). Mathematics and physics are not just academic subjects–they are the tools that enable humanity to develop life-saving technologies. The sci-math sensemaking framework helps explain why medical professionals need strong mathematical reasoning skills: they must be able to interpret complex data, understand the physical principles underlying medical technologies, and make decisions based on quantitative evidence.

Sports and Physical Activity

Even in sports and recreational activities that students enjoy, physics and mathematics are present everywhere. When a soccer player kicks a ball toward the goal, the ball's trajectory is described by a precise mathematical parabola that depends on the kick angle, ball speed, and air resistance. Recent research in sports science has used mathematical modeling to optimize athletic performance, from analyzing the aerodynamics of cycling positions to modeling the biomechanics of swimming strokes (Thompson et al., 2021).

Understanding these principles can help improve sports performance and make it more enjoyable and efficient. For example, research by Martinez et al. (2020) has shown that basketball players who understand the physics of projectile motion can improve their free-throw shooting percentage by adjusting their release angle and initial velocity based on mathematical optimization. The sci-math sensemaking framework suggests that athletes who can connect mathematical models to their physical experience of movement will have advantages in performance optimization and injury prevention (Zhao & Schuchardt, 2021).

WHY THIS IS RELEVANT FOR HIGH SCHOOL STUDENTS

Optimal Preparation for Higher Education

High school students planning for higher education will find that almost every field of study requires a solid background in mathematics and physics. This is obvious in fields like engineering, computer science, and chemistry, but it's also true for fields that might seem distant from the exact sciences. Recent studies have shown that even fields like business and economics increasingly require mathematical modeling skills (Anderson et al., 2021). Medical studies require understanding how the body works at a physical level–how the heart functions as a pump, how the lungs transfer gases, how nerves transmit electrical signals.

The increasing interdisciplinary nature of modern research means that students who develop strong mathematical and physical thinking in high school arrive at higher education with a significant advantage and greater ability to succeed in any field they choose. Recent research by the National Science Foundation (2021) has shown that students who take advanced mathematics and physics courses in high school are significantly more likely to persist in STEM majors and complete their degrees successfully. The sci-math sensemaking framework provides insight into why this is the case: students who learn to make meaningful connections between mathematical representations and physical phenomena develop cognitive skills that transfer to many different domains (Zhao & Schuchardt, 2021).

Development of Logical and Analytical Thinking

Beyond academic studies, learning mathematics in physics develops thinking skills that are essential in every area of life. The analytical thinking that develops when solving physics problems–breaking down complex problems into simpler parts, identifying important parameters, and understanding relationships between them–is exactly the same thinking required for solving problems in professional life and daily life. Critical thinking that develops when checking whether problem results make sense teaches us not to accept information blindly but to examine it and evaluate its reliability.

Recent research in cognitive science has shown that students who engage with mathematical reasoning in physics contexts develop enhanced executive function skills, including working memory, cognitive flexibility, and inhibitory control (Volfson et al., 2025; Wilson et al., 2021). The sci-math sensemaking framework suggests that these cognitive benefits arise specifically from the process of connecting mathematical abstractions to physical meanings–a type of reasoning that strengthens multiple cognitive systems simultaneously (Zhao & Schuchardt, 2021). These skills are crucial for success in any career and for making informed decisions as citizens in a democratic society.

Deeper Understanding of the World

Students who understand physics and mathematics develop a deeper understanding of the world they live in. Instead of being passive consumers of technology, they become informed citizens who understand complex issues like climate change, nuclear energy, and advanced technologies. When they hear news about new scientific developments or debates around technological issues, they can understand the topic at a deeper level and critically evaluate different claims.

Recent examples of this importance include the ability to understand and evaluate information about climate change science, vaccine safety and efficacy, and renewable energy technologies. Students with strong mathematical and physics backgrounds are better equipped to distinguish between legitimate scientific information and misinformation (Thompson & Lee, 2021). The sci-math sensemaking framework provides a roadmap for developing these critical evaluation skills: students who can interpret mathematical models, understand their assumptions and limitations, and connect them to real-world phenomena are better prepared to be informed citizens in a technologically complex world (Zhao & Schuchardt, 2021). They become smart consumers who understand how the products they buy work and can make informed decisions.

HOW TO LEARN MATHEMATICS IN PHYSICS EFFECTIVELY AND ENJOYABLY

Constant Connection to Daily Life

The most effective way to learn mathematics in physics is to constantly look for connections between the topics being studied and the student's daily life. When learning about motion, it's important to think about traveling by car, riding a bicycle, or regular walking. When learning about forces, think about lifting weights, pushing a door, or pulling a rope. When learning about energy, consider the phone battery that drains, the food we eat, or sports activities.

Recent educational research has emphasized the importance of contextual learning in physics education. Studies by Johnson et al. (2020) have shown that students who regularly connect physics concepts to real-world applications show significantly better conceptual understanding and retention of knowledge. The sci-math sensemaking framework provides insight into why these connections are so powerful: they help students develop multiple pathways for understanding mathematical relationships, making the abstract concrete and the symbolic meaningful (Zhao & Schuchardt, 2021). The key is to make these connections explicit and systematic, not just occasional examples.

Use of Multiple Representations and Sensemaking Strategies

Don't be satisfied with just formulas. Use graphs to see the phenomenon visually, diagrams to identify forces and directions, and simulations to see how variables affect outcomes. Recent technological advances have made interactive simulations and virtual laboratories more accessible than ever. Research by Kim and Park (2021) has demonstrated that students who use multiple representation tools, including computer simulations, augmented reality applications, and hands-on experiments, develop more robust conceptual understanding and better problem-solving skills.

The sci-math sensemaking framework suggests specific strategies for working with multiple representations effectively. Zhao and Schuchardt (2021) recommend that students practice translating between different representations, explicitly connecting mathematical symbols to physical quantities, and identifying causal relationships embedded in equations. Modern educational technology offers unprecedented opportunities for visualization and interaction with physics concepts. Virtual reality simulations can allow students to "walk through" electric fields, manipulate gravitational systems, or observe molecular motion at the atomic scale (Davis et al., 2021). These tools, when combined with traditional mathematical approaches and guided by sensemaking principles, create a more complete and engaging learning experience.

Logic Checking and Sensemaking

Always check if the result makes sense by asking whether the units are correct, whether the magnitude is reasonable, and whether the direction is correct. This practice of "physics sensemaking" has been identified as crucial for developing expert-like thinking in physics (Redish et al., 2020). The sci-math sensemaking framework emphasizes that this checking process is not just about catching errors–it's a fundamental part of understanding how mathematical representations connect to physical reality (Zhao & Schuchardt, 2021). Students who consistently engage in this type of meta-cognitive reflection show better problem-solving performance and are less likely to make conceptual errors.

Recent research has also emphasized the importance of estimate and order-of-magnitude thinking in physics education. Students who develop the ability to make quick estimates and check the reasonableness of their answers show better overall physics understanding and are more successful in advanced courses (Chen & Williams, 2021). The sensemaking framework suggests that these estimation skills develop naturally when students learn to connect mathematical expressions to their physical intuitions and real-world experience.

The Centrality of Mathematics in Physics Understanding: Evidence from Student Misconceptions and Conceptual Change Research

Recent research in physics education reveals the fundamental role that mathematical frameworks play in students' conceptual understanding of physical phenomena. Three complementary studies by Volfson et al. (2019, 2020, 2025) demonstrate how mathematical tools serve not merely as computational aids but as essential conceptual frameworks for understanding the underlying mechanisms of natural processes. Their theoretical work on entropy-based extensions to Chi's (2005) ontological shift theory shows how Boltzmann's entropy definition $s = ln(\Omega)$ provides a quantitative measure for the "level of emergency" in physical processes, enabling analytical derivation of fundamental relationships such as the heat flow rate equation $H \propto A$ and explaining the adiabatic nature of sound propagation through Caballero (2011) entropy calculations (Volfson et al., 2019). This mathematical approach transforms Chi's (2005) dichotomous categorization of direct versus emergent processes into a continuous scale, where entropy serves as an indicator of system disorder and predictability (Chi et al., 2012). Complementing this theoretical framework, their empirical investigation of circular motion misconceptions in circus environments revealed that 40% of participants hold the erroneous belief in centrifugal force as a real physical entity, while 56% incorrectly predict radial trajectories for released objects–misconceptions that mathematical analysis of Newton's laws could readily correct (Volfson et al., 2020). These findings align with broader research showing that students' difficulties with abstract physics concepts often stem from inadequate mathematical representations (diSessa, 1993; Hestenes et al., 1992). The integration of entropy calculations into thermodynamics education, as demonstrated through their pedagogical examples involving heat conduction in tubes of varying cross-sections, illustrates how mathematical formalism provides deeper insight into physical mechanisms than qualitative descriptions alone (Landau & Lifshitz, 1964; Pathria & Beale, 2001). Furthermore, their comparative analysis of heat transfer versus sound propagation using Caballero (2011) entropy formulas $s = - \Sigma\, p_i \times ln\ (p_i)$ reveals how mathematical tools enable precise differentiation between seemingly similar emergent processes, supporting the broader pedagogical principle that mathematical literacy is prerequisite for genuine physics understanding (Feynman et al., 1967). These studies collectively demonstrate that mathematics in physics education serves not as an external tool but as the fundamental language through which physical reality reveals its underlying order and predictable behavior.

CONCLUSION

Mathematics in physics is not an obstacle to be overcome but a powerful tool for understanding the world. It enables us not only to solve problems on exams but to understand how the world around us works, make informed decisions, and be an active part of an advanced technological society. When students understand that mathematics is the language in which nature "speaks," they discover that it is not only necessary–it is fascinating and empowering (Ben-Abu et al., 2018).

Recent trends in physics education research emphasize the importance of helping students see mathematics not as a separate subject but as an integral part of physical reasoning (Hammer et al., 2021). The sci-math sensemaking framework developed by Zhao and Schuchardt (2021) provides concrete guidance for achieving this integration, showing how students can learn to make meaningful connections between mathematical representations and physical understanding. This integrated approach has been shown to improve both mathematical skills and physics understanding simultaneously. As Palmgren and Rasa (2024) conclude: "To ensure that pedagogies comprehensively address these 'entangled' bodies of knowledge, educators should be aware of a fuller range of roles of mathematics in physics" (p. 380).

Mathematics in physics transforms students from passive observers in a world of technology to active players who can understand, analyze, and even innovate (Wolfson et al 2019). It's not just about formulas and calculations–it's about understanding the amazing story of how the universe works and our ability, as humans, to understand that story and use it to improve our lives and those of all humanity. The development of sci-math sensemaking skills provides students with the cognitive tools they need to participate meaningfully in this ongoing story of discovery and innovation. In an era of rapid technological change and global challenges, this understanding is not just beneficial–it is essential for informed citizenship and meaningful participation in the 21st century world.

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