

The physics-mathematics nexus: Connecting formalism, meaning, and classroom practice

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INTRODUCTION

Mathematics gives physics much of its explanatory and predictive power. For learners, however, connecting a mathematical expression with a physical situation is an achievement that requires deliberate instruction. A student may manipulate an equation correctly yet struggle to explain what it says about the physical world. This gap between mathematical manipulation and physical interpretation presents a central challenge in physics education (Planinic et al., 2019). Making these connections requires students to interpret the quantities in an expression, recognize the physical assumptions underlying a mathematical relationship, and judge whether a result is meaningful in the situation under consideration.

This educational challenge is rooted in the broader relationship between physics and mathematics, which has long been a subject of philosophical inquiry, historical analysis, and educational research. Mathematics serves as the language of physics, shaping both its theoretical frameworks and practical applications. However, integrating mathematical reasoning and physical meaning in instruction remains a persistent challenge for educators (Lehavi et al., 2017). Addressing this challenge requires insights from history and philosophy, theory, and practice.

Historically, many ground-breaking advances in physics—such as Planck's formulation of blackbody radiation—were deeply rooted in mathematical reasoning (Branchetti et al., 2019). Understanding the historical development of mathematical and physical ideas can illuminate their interconnected nature and enhance pedagogical approaches (Galili, 2018; Tzanakis, 2016). From a philosophical perspective, the structural conception of mathematics in physics involves complex questions of representation and applicability that go beyond simple instrumentalism. The bidirectional process of mathematization and interpretation that students must navigate raises fundamental questions

about how scientific knowledge is constructed and communicated in educational settings.

In the classroom, research has highlighted the crucial role of teachers' pedagogical content knowledge in bridging physics and mathematics. Educators who explicitly integrate both disciplines tend to foster deeper student comprehension, as evidenced by studies on instructional strategies and classroom discourse (Lehavi et al., 2017). Innovative approaches such as blended teaching (Kämpf & Stallmach, 2024), inquiry-based learning, and interactive simulations have demonstrated significant potential in reducing cognitive barriers and supporting meaningful connections between mathematical models and physical reasoning (Patero, 2023). Recent research has also sought to diagnose the cognitive sources of students' difficulties in navigating the physics-mathematics nexus, offering valuable insights for targeted interventions (Levi et al., 2024).

This special issue brings together theoretical and empirical contributions addressing how that relationship can be understood and strengthened. Its nine papers examine the issue across secondary education, university courses, and teacher education. Read together, they suggest three connected themes concerning epistemological and theoretical frameworks of the phys-math interplay; cognitive barriers, student difficulties and misconceptions; and innovative curricular and instructional design.

EPISTEMOLOGICAL AND THEORETICAL FRAMEWORKS OF THE PHYS-MATH INTERPLAY

The foundational role of mathematics in structuring physical thought forms the first major theme of this special issue. Ben-Abu (2026a) highlights mathematics not merely as a computational tool, but as a core structural model vital for understanding complex phenomena in biophysics. Extending this epistemological view to secondary education, he outlines four essential roles of mathematics in physics

(Ben-Abu, 2026b): providing syntactic structure, generating multiple representations, serving as a reasoning tool, and acting as an engine for scientific discovery. These roles collectively enable the transition from qualitative observation to predictive, quantitative understanding. Similarly, Kuske-Janßen and Pospiech (2026) focus on how educators mediate this mathematical-physical connection through classroom discourse. They propose a multi-level verbalization model to categorize how teachers translate highly condensed mathematical formulas into educational and everyday language, noting that instruction frequently overemphasizes technical calculation at the expense of structural meaning-making.

COGNITIVE BARRIERS, STUDENT DIFFICULTIES, AND MISCONCEPTIONS

The second theme addresses the practical and cognitive challenges students encounter when navigating the physics-mathematics nexus. Levi, Merzel, and Lehavi (2025) diagnose phymatic difficulties by identifying distinct thinking approaches—ranging from purely mathematical to context-oriented—that influence how high school students apply arithmetic operations and interpret the applicability of formulas across different real-world contexts. In higher education, Urrutia et al. (2026) document the specific obstacles engineering students face when transitioning between algebraic and graphical representations of non-constant acceleration. Their phenomenographic analysis reveals a persistent confusion between mathematical functions and kinematic concepts, indicating a reliance on rote procedures over physical interpretation. Isacson et al. (2026) further explore the temptation of inertial forces, such as the centrifugal force, in circular motion contexts. They argue that invoking the weak equivalence principle can help bridge students' embodied, everyday experiences of acceleration with formal Newtonian mechanics, addressing long-standing controversies and misconceptions.

INNOVATIVE CURRICULAR AND INSTRUCTIONAL DESIGN

The final theme presents novel educational strategies and curricular designs aimed at overcoming these barriers. Lippiello et al. (2026) detail the implementation of interdisciplinary worksheets on vectors, derivatives, and integrals developed within a teacher learning community. Their exploratory quantitative findings suggest closer alignment between students' confidence and performance. Teachers reported that the worksheets and the accompanying teacher learning community supported interdisciplinary planning and helped them translate connections between mathematics and physics into classroom implementation.

Focusing on teacher preparation, Kämpf et al. (2026) report on a blended learning course designed to build preservice physics teachers' understanding of Gauss's law of electricity. The intervention successfully bolstered students' calculation confidence, though it also illuminated the stubborn nature of certain conceptual misconceptions. Finally, Tóth and Bitzenbauer (2025) introduce a minimalist, photon-polarization-based sequence for teaching quantum computing at the secondary school level. By deliberately circumventing complex matrices and complex numbers, their approach is designed to make advanced concepts like quantum superposition, entanglement, and cryptography accessible, illustrating how formalism can be selected and sequenced around students' prior knowledge of photon polarization.

SUMMARY AND FUTURE DIRECTIONS

The contributions to this special issue collectively underscore that the interplay between physics and mathematics is far more complex than the mere application of formulas to physical problems. Mathematics shapes the very epistemic structure of physical theories, yet this structural role is often lost in translation within the classroom, leading to algorithmic "plug-and-chug" behaviors.

Looking forward, the authors identify critical limitations in current research and outline a clear roadmap for the future of phys-mathic education, starting with the need to broaden the empirical scope and deepen cognitive probing. Many studies acknowledge the constraints of small, localized sample sizes, such as findings restricted to specific engineering cohorts, prompting calls to extend research across broader educational and cultural settings (Urrutia et al., 2026). To empirically validate integrated teaching frameworks, there is a pressing need for cross-cultural adaptations, longitudinal studies, and randomized controlled trials (Ben-Abu, 2026a). Furthermore, researchers highlight the limits of standard questionnaires or test scores in capturing internal cognitive processes. To address this, future research must employ deeper qualitative methodologies—such as in-depth clinical interviews, trace-based data, and think-aloud protocols—to better disentangle how instructional design, teacher mediation, and student engagement interact (Levi et al., 2025; Lippiello et al., 2026).

Moving from diagnosis to targeted remediation, the collection emphasizes the necessity of developing specific instructional interventions and expanding content boundaries. Authors advocate for creating targeted materials that support students in seamlessly integrating algebraic and graphical representations (Urrutia et al., 2026), as well as adaptive resources that prioritize the structural, rather than merely technical,

interpretation of physics formulas (Kuske-Janßen & Pospiech, 2026). There is also a strong push to expand this pedagogical lens across a wider spectrum of physics topics. For instance, future research must examine how students navigate complex, modern domains like quantum physics, requiring deeper analyses of students' mental models and comparative studies on the educational impact of specific protocols, such as B92 versus BB84 (Kuske-Janßen & Pospiech, 2026; Tóth & Bitzenbauer, 2025). Within classical mechanics, researchers advocate for systematic reviews of how textbooks and exams treat topics like circular motion, ensuring that assessments genuinely challenge conceptual understanding rather than simply prompting rote numerical insertion (Isacsson et al., 2026).

Finally, the integration of advanced technological tools and cross-disciplinary partnerships represents the final frontier for this research. There is a strong potential in using digitally supported solutions, such as AI-powered platforms, digital tutors, and simulations, to automate technical calculations. This technological integration can free up cognitive space for students, allowing them to focus on content-related discussions and critical reflections on a formula's validity within interdisciplinary educational frameworks (Ben-Abu, 2026b; Kuske-Janßen & Pospiech, 2026). Additionally, it is necessary to examine the unique phys-math challenges students face when interfacing with diverse, online programmable devices, such as quantum computers (Tóth & Bitzenbauer, 2025). Ultimately, bridging these instructional and cognitive gaps will require formalized, interdisciplinary collaborations—particularly between physics and mathematics educators—to develop joint learning paths that address proportional reasoning and the physical contextualization of mathematical symbols (Kuske-Janßen & Pospiech, 2026).

Taken together, these contributions highlight a shared educational priority: giving students sustained opportunities to explain what mathematical representations mean, justify their use, and evaluate their physical implications. Such opportunities can help learners use mathematics to ask questions, construct explanations, and judge claims about the physical world. We hope this special issue encourages closer collaboration between physics and mathematics educators in designing tasks, examining students' reasoning, and making the physics-mathematics nexus an explicit focus of everyday teaching.

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