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Angaben zur Veröffentlichung / Publication details:

Schleicher, Manuel, and Olaf Krey. 2026. “Diving into quantum physics: challenging the constraints of knowledge transfer through engaging school lab units.” *Journal of Physics: Conference Series* 3203 (1): 012029. https://doi.org/10.1088/1742-6596/3203/1/012029.

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To cite this article: Manuel Schleicher and Olaf Krey 2026 *J. Phys.: Conf. Ser.* **3203** 012029

4th World Conference on Physics Education 2024 IOP Publishing
Journal of Physics: Conference Series **3203** (2026) 012029 doi:10.1088/1742-6596/3203/1/012029

Diving into Quantum Physics: Challenging the Constraints of Knowledge Transfer Through Engaging School Lab Units

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Abstract. The Transregional Collaborative Research Center (TRR360) conducts cutting-edge research in the field of constrained quantum matter (ConQuMat). Its associated outreach initiative aims to bridge the gap between school-level physics knowledge and the foundational concepts necessary to understand quantum matter. In this paper, we present students' conceptions of magnetism, drawing on a brief literature review. Based on these insights, we developed experiment-based learning environments that form the core of our initial learning module for grades 7 and 8. This unit introduces key concepts such as diamagnetism, paramagnetism, and antiferromagnetism, along with an "arrow model" designed to visualize magnetic phenomena. We argue that this arrow model offers several advantages over the traditional elementary magnet model, particularly in fostering a more accurate and intuitive understanding of magnetic behavior. The origins of magnetic moments are introduced through the framework of Bohr's atomic model. Finally, we outline our future research directions and plans for expanding the learning module.

1. Introduction

Magnetism is a phenomenon familiar to everyone – every child enjoys playing with magnets, yet few understand the underlying principles. Although magnetism is included in the secondary school curriculum in most nations, students have little science-based understanding of the concepts of magnetism or how magnets work, regardless of grade level or education. In general, there is little understanding of magnetism outside of the scientific community. Even physics students know surprisingly little about magnetic concepts [1]. The fundamental principles of magnetism are inherently complex and counterintuitive, as they originate in quantum physics. However, this very complexity presents a unique opportunity: developing a coherent conceptual understanding of magnetism can serve as a gateway to grasping other abstract scientific ideas—such as semiconductor behavior or crystal structure analysis via X-ray diffraction—topics that are included in advanced physics curricula at the regional level [**?**]. Moreover, magnetism provides a natural entry point into the research conducted within TRR360, as its foundational concepts resonate deeply within the study of quantum materials. To address these challenges, to foster scientific curiosity, and to harness the educational potential of magnetism, we developed a school-based laboratory unit that integrates inquiry-based learning with insights from current research.The following section presents students' conceptions of magnetism, informed by a brief literature review. We subsequently describe the design of our laboratory unit (work in progress) and conclude with an overview of future research plans.

2. Students' conceptions on magnetism

Magnetism is a topic rife with conceptual challenges, likely attributable to its inherently quantum-physical nature. The coexistence of both attraction and repulsion—phenomena that defy everyday intuition—further complicates understanding [3]. A particularly persistent difficulty lies in grasping the concept of the magnetic field, which lacks direct sensory perception and thus resists intuitive modeling.

When constructing mental models, learners simplify complex phenomena by focusing on salient features and selectively representing objects and their interactions to form personally meaningful interpretations [4]. Research on students' conceptions of magnetism has been conducted internationally—primarily in the United States – spanning from primary school to university level. Despite extended instruction, many students retain naive preconceptions even after years of formal education [5].

At the nanoscale, magnetic behavior is governed by a complex interplay of chemical composition, particle size, thermal energy, and interactions that are negligible at macroscopic scales. This necessitates a higher level of cognitive abstraction and mental imagery than is typically required for more concrete physical concepts [5, 6, 7]. Bridging magnetic phenomena across different scales offers rich opportunities for deepening conceptual understanding. Novick (1981) [8] investigated students' understanding of the particulate nature of matter and found that even older learners struggled with fundamental cognitive challenges. Although children may be aware of atoms and molecules as discrete entities, they often still conceive of matter as continuous or believe that substances *contain* molecules rather than *being composed of* them [9]. A robust understanding of magnetism thus depends on a solid grasp of the particulate model of matter and the influence of thermal energy on particle dynamics.

One of the most widespread misconceptions is the conflation of magnetic effects with electric charge [1, 5, 10, 11]. In Maloney's study, high school students equated magnetism with electric charge, viewing one pole of a magnet as positively charged and the other as negatively charged, or assuming that electrically charged objects are attracted to magnets [10]. Even a third-year physical science student attributed the adhesion of a paper clip to a magnet to electrostatic charge [6]. This misconception is not limited to students; many teachers also associate magnetism with electric charge or polarization, underscoring its deep entrenchment in common understanding. Consequently, any instructional or research approach to magnetism must explicitly address and dismantle this persistent misconception.

Given the heavy reliance of learning and teaching about magnetism on visual and spatial representations, assessing students' mental models through drawings and sketches is particularly insightful. Visual representations play a crucial role in scientific learning and communication [12, 13]. Drawing-based assessments complement traditional verbal methods by revealing implicit conceptual frameworks. Meyer (1991) [14] identified three primary mental models among students: the *"pulling model"*, which describes magnetic effects as direct pulling or sucking forces without reference to mechanism; the *"emanating model"*, in which invisible rays or energy streams are emitted from the magnet to act on distant objects, with barriers (e.g., thick plastic or wood) blocking the force; and the *"enclosing model"*, in which the magnet generates an invisible, persistent field of influence - akin to gravity - where forces only manifest when magnetic materials enter the field. This model also incorporates the barrier concept. Meyer further observed developmental differences: younger students (4th grade) often failed to distinguish between the poles of a magnet, while older students (7th grade) demonstrated greater awareness of polarity and began to consider distance as a relevant factor, indicating a growing conceptual sophistication. This example once again demonstrates the importance of knowing about age specific students' conceptions.

These findings were corroborated and extended in studies involving pre-service and in-service teachers, who also exhibited confusion between magnetism and gravity, the belief that all metals are ferromagnetic, or that magnetization is an inherent, unchangeable property of materials [1]. Some teachers even proposed that magnets must overcome resistance from air to exert their force. Borges and Gilbert (1998) [5] further categorized magnetic mental models into five types: the pulling model, magnetism as a cloud, magnetism as electricity, magnetism as electric polarization, and the field model.

More recent studies in the U.S. and Finland have deepened our understanding of students' conceptual development. Sederberg (2009) [15] analyzed students' conceptions of the magnetization process, while Cheng (2012) [16] investigated the reflective reasoning process through which students construct explanatory models. In a scaffolded intervention, both fully and partially scaffolded groups were presented with magnetic phenomena and tasked with developing consistent models—iteratively refining their understanding. Most recently, Kahkonen (2020) [17] examined students' conceptions of magnetic poles and magnetization before and after a research-informed teaching unit. The intervention, grounded in prior findings, proved effective in advancing students' conceptual understanding.

A further challenge lies in the issue of consistency [18]. The meaning of scientific terms evolves with age and experience. Younger learners often rely on intuitive, experience-based interpretations, while older students may apply specific rules to particular situations without recognizing broader conceptual connections. This suggests that learning progressions in conceptual sophistication depend on age, prior experience, and the ability to classify phenomena meaningfully and analyze relationships across contexts. Nevertheless, certain misconceptions about magnetism—such as the charge-magnetism equivalence—persist across all levels of scientific education and remain fundamentally incompatible with established scientific knowledge [15].

In summary, the existing body of research on students' conceptions of magnetism is predominantly focused on ferromagnetism. This narrow emphasis may contribute to a persistent misconception: the view of magnetism as a property exclusive to a limited subset of materials, particularly ferromagnetic ones, rather than as a universal phenomenon inherent in all matter. This limited perspective likely stems from a lack of understanding of magnetism as a fundamental aspect of atomic and electronic structure, rather than a characteristic confined to specific materials. Addressing this conceptual gap is essential for fostering a more comprehensive and scientifically accurate understanding of magnetic phenomena across different scales and material types. Our school laboratory unit, introduced in the next section, is specifically designed to address this gap and foster a more comprehensive understanding of magnetism as a universal phenomenon.

3. School Lab Unit

The lab unit is currently in development and will be evaluated and refined using a design-based research approach. The version described here is the second draft, following a first round of evaluation and refinement.

3.1. Organization of the Unit

The school laboratory unit is designed as a half-day program with a total duration of four hours, targeting students in grades 8 and 9 of secondary school. At this stage, magnetism is introduced briefly at the beginning of the physics curriculum, where students learn that magnets possess two poles, that like poles repel and unlike poles attract, and that a magnet can be split into smaller magnets. The elementary magnet model is then introduced to explain this behavior, portraying a magnet as a composite of many small, discrete "elementary magnets."

While this model provides a useful starting point for understanding basic magnetic phenomena, it has several limitations. It lacks applicability to more advanced magnetic effects and often leads to misconceptions, particularly due to the misleading similarity between macroscopic and microscopic representations. Furthermore, the model's conceptual autonomy — its independence from other scientific models — hinders integration into a broader conceptual framework [19]. The absence of spatial constraints for the elementary magnets also contributes to cognitive challenges, as students struggle to visualize their arrangement and behavior [20]. To address these issues, a new theoretical model has been developed, specifically designed to be closely aligned with other scientific models and to support coherent, interconnected understanding. This model is described in detail in Section 3.2.

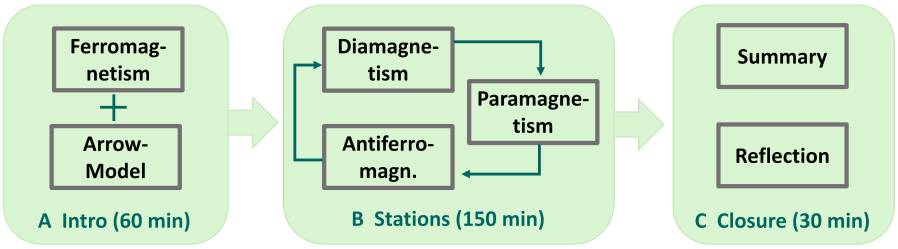

Figure 1. Procedure of the school lab unit "The other magnetism".

The structure of the teaching unit, organized into distinct phases, is illustrated in Fig. 1. The unit begins with a brief historical overview of magnetism, designed to spark curiosity and generate questions that are addressed throughout the intervention. This is followed by a short diagnostic quiz to assess students' prior knowledge of magnetism. Students are then divided into pairs and proceed to the *Station Ferromagnetism*, which serves as the initial phase for activating and reinforcing prior knowledge while introducing foundational concepts through familiar, everyday phenomena.

The core of the unit consists of three stations, each dedicated to a distinct form of magnetism:

- Diamagnetism
- Paramagnetism
- Antiferromagnetism

At each station, students engage in hands-on experiments, interactive models, and educational videos to explore the respective magnetic behavior. A key focus is the clear distinction between these new phenomena and the more familiar ferromagnetic effects. Central to the instructional approach is the use of the *arrow model*, which provides a consistent and visually intuitive framework for representing magnetic moments and their interactions. Worksheets are employed as a traditional yet effective medium to support constructive learning and scaffold conceptual development.

The unit concludes with a creative role-play activity, in which students embody magnetic moments and physically enact the different forms of magnetism. By organizing themselves according to the alignment rules of each magnetic state and responding to simulated external magnetic fields, students actively apply their understanding in a kinesthetic and collaborative context. This approach aims to consolidate theoretical knowledge and promote deeper conceptual integration. The intervention ends with a post-unit questionnaire and a final quiz, which evaluate learning outcomes, guide further refinement, and help students see their own progress.

3.2. Underlying theoretical model

Given the advanced nature of the physics content in the unit, the primary focus of this design description lies in the simplification and elementarization of core concepts. The choice of visual representation plays a decisive role in making abstract magnetic phenomena accessible. To bridge the gap between observable phenomena and theoretical understanding, a model has been developed that is both visually intuitive and amenable to sketching. At its foundation are magnetic moments, which are introduced through a simplified version of Bohr's atomic model. [1] In this model, the atom is conceptualized as a nucleus surrounded by electrons in defined orbits. *Crucially, the electron is not represented as a particle moving along a path, but as the orbit itself.* The direction of orbital motion is interpreted as spin, and magnetic moments arise from the vectorial alignment of these orbital contributions. On a theoretical level, this allows for a clear explanation of how paired electrons moving in opposite directions cancel each other's magnetic effects, while unpaired electrons result in a net magnetic moment.

The stepwise visualization of this model is illustrated in Fig. 2, using the example of an unpaired electron. Starting from the atomic level, the model progressively reduces complexity to yield a simple, symbolic representation: a single arrow. This "arrow model" serves as a powerful didactic tool to link observable phenomena with underlying theoretical principles and a mircoscopic description.

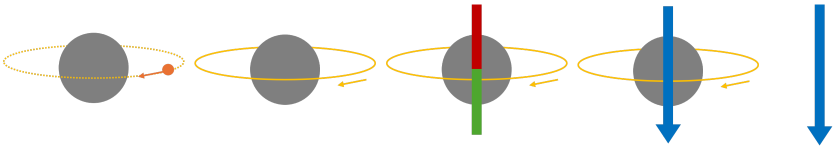

Figure 2. From an unpaired electron to an arrow: a stepwise visualization of the permanent magnetic moment using the "Arrow Model" based on a reduced atomic model.

The theoretical model is then used to introduce key concepts such as *magnetic order and domains*, *thermal motion of magnetic moments*, and *magnetization under external magnetic influence*. These concepts are essential for establishing connections between the different types of magnetism in this uni (diamagnetism, paramagnetism, anti-ferromagnetism, and the already known ferromagnetism) and for understanding their distinct characteristics. By explicitly referencing these concepts across all three stations, the unit enables a systematic comparison and supports the development of a coherent conceptual framework.

Importantly, we must emphasize that this model is not scientifically accurate and would not be accepted by the physics community. In fact, it oversimplifies and misrepresents quantum mechanical principles. However, for young learners who are eager to connect observations with explanations, this model provides a valuable scaffold for building an organized, meaningful knowledge structure. Thus, the model is introduced as a descriptive and heuristic aid, especially in response to students' inquiries for deeper explanations, with an emphasis on connecting observable phenomena to microscopic descriptions and supporting visual reasoning. The arrow model is not intended as a literal representation of reality, but as a bridge to support conceptual development in an age-appropriate and engaging way.

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[1] We use the term "Bohr's model" here for didactic convenience, although historically this is not accurate. The model and particularly its visual representation do not originate from Bohr, but is a simplified (and scientifically inaccurate) interpretation of his atomic theory.

4. Learning Stations

The learning process unfolds within a station-based instructional model, in which students engage in hands-on exploration and collaborative inquiry. This dynamic, student-centered environment significantly enhances the influence of the provided instructional materials, creating opportunities for deeper conceptual engagement. However, such an approach also demands careful scaffolding to support learners in navigating complex ideas, ensuring that inquiry remains productive and accessible.

Introductory station: The Arrow Model for Describing Ferromagnetism

This station builds upon students' prior school knowledge and aims to establish a shared conceptual foundation for all participants. It follows the initial magnetism quiz and is completed simultaneously by all groups. The primary objective is to introduce and implement the theoretical arrow model by connecting familiar concepts of *ferromagnetism* with this new representational framework. In doing so, key ideas are revisited, consolidated, and extended to support a more coherent understanding of magnetic phenomena.

The principles of the arrow model are introduced through an instructional video, which provides a clear and visual explanation of its core components. A corresponding worksheet guides students' attention to the essential features: the length, direction, and position of the arrow, which together represent the magnitude, orientation, and spatial location of magnetic moments. (See the textbox for asssumptions of the arrow model.) Students first reproduce these concepts through guided tasks before progressing to increasingly complex applications. The model is systematically introduced, explicitly linked to prior knowledge, and gradually extended to incorporate advanced ideas such as magnetic domains and magnetic coupling.[2]

Core Assumptions of the Arrow Model

- Atoms are considered the smallest units that carry magnetic properties. Each atom is assigned a magnetic (net) moment, represented by an arrow.
- If the magnetic moments of two bodies are oriented in the same direction, i.e., the arrows in the model point the same way, the bodies attract each other.
- If the magnetic moments of two bodies are oriented in opposite directions, i.e., the arrows in the model point in opposite ways, the bodies repel each other.
- The magnetic effect of a body increases with the strength of the magnetic moments (the length of the arrows) and with the number of magnetic moments aligned in the same direction (the more arrows pointing the same way, the stronger the effect).
- Magnetic moments (arrows) can be coupled to neighboring magnetic moments (arrows), represented by a dashed line between them. Coupled arrows mutually influence each other's orientation.
- Magnetic moments (arrows) respond to an external magnet by aligning with it.

Once this foundational understanding is established, groups proceed to the three subsequent stations dedicated to diamagnetism, paramagnetism, and antiferromagnetism in a flexible, self-directed order. This transition allows students to apply their newly acquired conceptual tools to explore different forms of magnetism in a meaningful and interconnected way.

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[2] The choice of the arrow model is grounded in its alignment with students' prior experiences: arrows are already used to represent vectors in mechanics, e.g. velocity.This conceptual continuity not only alleviates cognitive load but also enhances the model's transferability and relevance across physics domains, where further vector quantities can be explored and understood.

Station Diamagnetism

The station opens with a pendulum experiment designed to provoke curiosity. Students investigate the behavior of diamagnetic materials such as bismuth, pencil lead (graphite), and (water within) grapes when brought near a strong magnet. Their observations are contrasted with those of a ferromagnetic material, highlighting anomalies that students cannot yet explain at this stage: for instance, grapes are repelled by *both* poles of a magnet, regardless of orientation. This counterintuitive result challenges intuitive expectations and sets the stage for deeper inquiry.

Students then represent their findings through sketches based on the arrow model. They are guided to use the *length* of the arrows as a visual indicator of the strength of magnetization and the *orientation* of the arrows, either aligned or opposing, to account for attraction or repulsion. This visual encoding supports the development of a coherent mental model.

The station concludes with an explanation of the diamagnetic effect, supported by a self-made educational video. Using the arrow model in conjunction with a simplified version of Bohr's atomic model, the video illustrates the phenomenon at the atomic level (see Fig. 3). An external magnetic field induces a change in the orbital motion of paired electrons, depending on their spin direction. As a result, the orbital radius increases or decreases accordingly. This perturbation disrupts the perfect cancellation of magnetic moments in paired electrons, leading to a net magnetic moment that is oriented *opposite* to the applied field—thus explaining the observed repulsion. *** A pendulum experiment is used as an opener. The behaviour of diamagnetic materials such as bismuth, pencil lead (graphite) and grapes, when approached with a strong magnet, is investigated. The observations are contrasted with the behaviour of a ferromagnetic material and attention is drawn to the abnormalities that the students cannot explain at this stage (Magnets repel grapes, regardless of which pole of the magnet is approached). The students then depict their experimental findings in sketches based on the arrow model. Putting the focus on length as an indicator of strength of magnetization and a opposing or aligning orientation of the arrows to account for repulsion or attraction. The station concludes with an explanation of the cause of the diamagnetic effect supported by a self-made educational video. Using the arrow model in combination with the atomic model of Bohr, an illustration of the diamagnetic effect at the atomic level is given (Fig. 3). The external magnetic field induces a change in electron movement of the paired electrons depending on the spin. The orbital radius becomes larger or smaller depending on the direction of rotation (spin). The cancellation of the magnetic effect of paired electrons does not persist, resulting in a net magnetic moment. Which is directed against the external field.

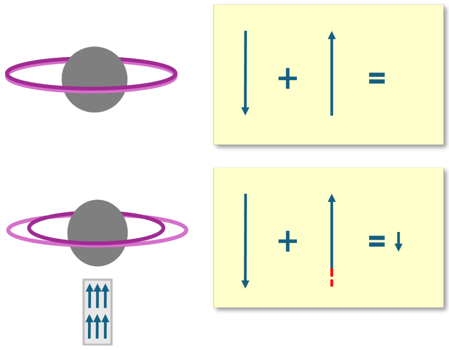

Figure 3. Illustration of the explanatory approach for the diamagnetic effect used in the educational video, demonstrated with two paired electrons in a simplified atomic model.

Station Paramagnetism
To experimentally discover paramagnetism phenomena the station involves a pendulum experiment with sample pieces made of iron and brass. Brass, being paramagnetic, is attracted much more weakly than iron. Furthermore, students are tasked with magnetizing an iron nail and a brass nail. By repeatedly stroking them with a strong magnet and then testing their magnetization by lifting a paperclip. Only the ferromagnetic iron nail retains its magnetization after the magnet is removed and can exert a magnetic force on the paperclip. Once again, appropriate representations of the microscopic behavior are created using the arrow model. The focus here lies on the distinction between strongly aligned magnetic moments in ferromagnetic materials and the slight disorder that persists in paramagnetic materials, even in the presence of a magnetic field. A more detailed insight into the thermic influence is given by an educational video and revised with corresponding exercises.

Station Antiferromagnetism
Due to the lack of direct experimental approaches, this station begins with an instructional video that introduces the fundamentals of antiferromagnetic ordering. Worksheet exercises are used to revise the newly acquired information. A haptic model is introduced to make the concept of the alternating arrangement of magnetic moments more tangible. The model is shown in figure 4 and constructed using permanent cylindrical magnets. Every magnet represents a magnetic moment and magnetic attraction represents the antiferromagnetic coupling. The orientation of the magnetic moments in the thought model are marked with sticky arrows (figure 4b) alternating between left and right. Also the representation of the two state orientation by visibility of the point (screw hole) from top was introduced to the students. In the next step a triangular version of the haptic model is used to experience magnetic frustration (figure 5) as no configuration of alternating orientation is possible. This became clear either by the point visibility or the use of sticky arrows. To further discuss the model the limitations and the differences between this representation and a scientific representation of antiferromagnetism were also discussed.

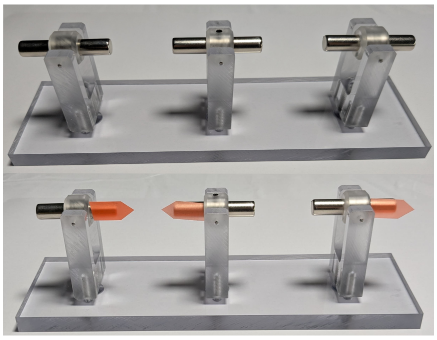

Figure 4. Linear haptic model of antiferromagnetism. The upper image depicts the alternating orientation by the point visibility, the lower one additionally represents the orientation with a sticky arrow.

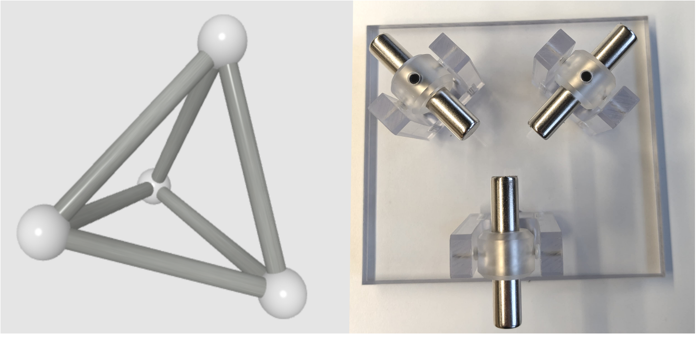

Figure 5. Triangular haptic model of antiferromagnetism. The left image shows a possible arrangement of atoms in a tetrahedral crystal which exhibits frustration. The right image shows the corresponding haptic model.

The station concludes with the behavior of antiferromagnetic materials in external magnetic field. This is addressed with a short video and corresponding exercises.

5. First Results of an Evaluation Study and Future Research Directions

Preliminary results from the pilot implementation indicate that students were able to comprehend the abstract concepts of magnetism and apply the arrow model with confidence. No evidence of conceptual conflict between the arrow model and the already known elementary magnet model was detected. Despite its abstract nature, the arrow model proved effective in enabling students to reason about the microscopic causes of magnetic phenomena. The initial results indicate that the arrow model is a promising didactic instrument for advancing students' conceptual understanding of magnetism. Additionally, the integrated learning environments, featuring experiential experiments, explanatory videos, and guided worksheets were found to support meaningful learning processes, enabling students to engage with abstract phenomena in a tangible and coherent way.

Nevertheless, a deeper investigation is required to elucidate the conceptual knowledge students develop when engaging with the learning materials. Current literature on students' understanding of magnetism is predominantly restricted to ferromagnetism and electromagnetism (2). There is a notable absence of research on students' mental models of *diamagnetism*, *paramagnetism*, and *antiferromagnetism*. This study seeks to bridge this gap by integrating prior findings on ferromagnetic conceptions with new data on these less familiar magnetic phenomena. Qualitative analysis of students' drawings, combined with interpretive analysis of accompanying written and verbal responses, will provide insight into the development of their conceptual understanding.

This study will examine the mental representations of students in grades 8 and 9 after completing the school laboratory unit. To explore the evolution of conceptual understanding across educational levels, we will also interview students in physics bachelor's and master's programs. Master's students, having completed an advanced lecture on magnetism, are expected to demonstrate a mature and coherent understanding of magnetic phenomena. Bachelor's students, assessed after a foundational course, may exhibit more fragmented or incomplete conceptions. By comparing these groups, we aim to investigate how exposure to mathematically rigorous instruction influences the development of visual and conceptual models. Given the dominant focus on formalism in university physics, we anticipate notable differences in the use and coherence of visual representations, offering insights into the challenges of bridging symbolic and visual modes of understanding. In particular, we aim to explore how the arrow model may serve as a valuable cognitive scaffold for students in higher education, particularly when grappling with abstract magnetic phenomena.

6. Conclusion

We present a development project aimed at bridging the gap between school-level physics education and advanced concepts in magnetism by offering students in secondary school the opportunity to explore paramagnetism, diamagnetism, and antiferromagnetism within an school laboratory setting.

To support this goal, we introduce the *arrow model*, a visual and conceptual tool that enables students to represent microscopic magnetic states in a coherent and accessible way. By linking these microscopic descriptions to observable phenomena, the model facilitates a deeper understanding of magnetic behavior. While the arrow model is not a scientifically accurate representation of quantum mechanical reality, it is consistent with core scientific principles at an introductory level and serves as a valuable heuristic. When students inquire about the origin of magnetic moments, we connect them to electron motion and provide a plausible, albeit simplified, explanation grounded in a modified version of Bohr's atomic model. This explanation is introduced only when students seek deeper understanding, with a deliberate focus on fostering visual reasoning and coherent conceptual linking.

This approach reflects the principle of *epistemic fidelity*, where the model is not intended as a literal representation of reality but as a pedagogically effective tool for building coherent conceptual understanding. The use of arrows—already established as representations of vectorial quantities like velocity and force—provides a strong conceptual continuity across physics topics. This alignment reduces cognitive demands and enhances the model's transferability, supporting students in making connections between diverse physical phenomena.

The project is currently underway as a design-based research study. We have presented an overview of our current development phase, including the structure of the laboratory unit, the integration of the arrow model, and the use of hands-on experiments, educational videos, and worksheets.

Having established the general functionality of the teaching approach, we now shift our focus toward a deeper investigation of students' conceptual development. In particular, we aim to analyze how visual instruction influences learners' conceptions of magnetism at the secondary school level. Furthermore, we will compare these findings with those from university students - both bachelor's and master's level - after they have undergone formal, mathematically rigorous instruction in magnetism. This comparative analysis will help us understand how different modes of instruction shape mental models and how visual tools like the arrow model can support learning across educational stages.

Ultimately, our goal is to develop a flexible, research-informed teaching framework that supports the progressive development of scientific understanding from intuitive, visual reasoning in school to more formal, abstract thinking in higher education.

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Acknowledgments

The project TRR360 is funded by the German Research Foundation (TRR 360 – 492547816).