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Theoretical and Methodological Foundations of Inquiry-Based Teaching: Considering the Potential of Materials for Interaction and Intellectual Work

Fundamentos Teóricos e Metodológicos do Ensino por Investigação: Considerando o Potencial dos Materiais para a Interação e o Trabalho Intelectual

Fundamentos Teóricos y Metodológicos de la Enseñanza por Investigación: Considerando el Potencial de los Materiales para la Interacción y el Trabajo Intelectual

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Abstract

Inquiry-Based Science Education, as a pedagogical approach, is not linked to a specific activity or content; rather, it is enacted through interactions between students and teachers, mediated by materials, norms, knowledge, and practices. This theoretical article examines the relationship of students and classroom materials as a catalyst for constructing meaning around established scientific knowledge. By discussing the role of materials in scientific practice and their subsequent adaptation to school settings - across both experimental and non-experimental activities - these study a shift in how we view materials. Specifically, it highlights their dual roles: alternating between technical objects (tools ready for use) and epistemic objects (objects under investigation) as a defining characteristic of Inquiry-Based Science Education. This proposition does not contradict the view of "the problem" as a primary driver of interaction; instead, it demonstrates how material uncertainty is essential for intellectual engagement. The implications suggest that instructional design for Inquiry-Based Science Education must explicitly account for the ways students interact with, utilize, and deliberate upon materials throughout the investigative process.

Keywords: pedagogical approach, materiality, epistemic object, technical object

Resumo

O ensino por investigação como uma abordagem didática não se vincula a uma atividade ou a um conteúdo em si, mas se consolida pelas interações entre estudantes e professor, sustentada por materiais, normas, conhecimentos e modos de agir. Este artigo teórico explora a relação dos estudantes com materiais em sala de aula como forma de promover a construção de entendimentos sobre os conhecimentos já legitimados pelas ciências. Para tanto, apresentam-se discussões sobre o papel dos materiais na ciência e suas transposições para os contextos escolares, considerando atividades experimentais e não experimentais, o que permitiu propor a transição dos papéis dos materiais, ora como objetos técnicos (objetos prontos para o uso), ora como objetos epistêmicos (objetos que estão sob análise), como uma característica do ensino por investigação. Essa proposição não rivaliza com a consideração do problema como elemento promotor da interação, mas demonstra como momentos de incerteza acerca dos materiais são necessários para o trabalho intelectual. Como implicações, sugere-se que o planejamento do ensino por investigação considere os modos de interação de estudantes com os materiais, bem como de seu uso e debate nos processos investigativos.

Palavras-chave: abordagem didática, materialidade, objeto epistêmico, objeto técnico

Resumen

La enseñanza de las ciencias basada en la indagación, como enfoque pedagógico, no se limita a una actividad o contenido específico, sino que se articula mediante las interacciones entre estudiantes y docentes, mediadas por materiales, normas, conocimientos y prácticas. Este artículo teórico examina la relación de los estudiantes con los materiales en el aula como un catalizador para la construcción de significados en torno al conocimiento científico. Para ello, se analiza el papel de los materiales en la práctica científica y su transposición a los contextos escolares, abordando tanto actividades experimentales como no experimentales. El análisis permite proponer una transición en los roles de los materiales, los cuales alternan entre su función como objetos técnicos (herramientas estabilizadas para el uso) y objetos epistémicos (objetos bajo indagación), siendo esta dinámica una característica distintiva de la indagación. Esta propuesta no invalida la centralidad del problema como motor de interacción;por el contrario, demuestra que la incertidumbre material es esencial para el compromiso intelectual. Como implicación para el área, se sugiere que el diseño instruccional de la enseñanza de las ciencias basada en la indagación contemple explícitamente las formas en que los estudiantes interactúan, utilizan y deliberan sobre el material en los procesos investigativos.

Palabras clave: enfoque pedagógico, materialidad, objetos epistémicos, objetos técnicos

Introduction

Inquiry-Based Science Education (IBSE) is a didactic approach that seeks to engage students in planned activities, aligned with the objectives and specificities of school environments, but resembling the practices of members of scientific communities during the process of constructing scientific knowledge (Carvalho, 2018; Duschl, 2008; Kelly, 2008; Sasseron & Duschl, 2016), which involves creating conditions for students to "think, considering the structure of knowledge; speak, evidencing their arguments and constructed knowledge; read, critically understanding the content read; write, demonstrating authorship and clarity in the ideas presented" (Carvalho, 2018, p. 766).

Presenting IBSE as a didactic approach reinforces the idea that it is not merely a set of strategies, but rather is grounded in theoretical principles, both from the epistemology of sciences and from the educational field, which guide science teaching[1]. Grounded in these principles, the approach should aim to promote student agency and enable their own forms of interaction and participation (Moraes & Taziri, 2019). Thus, the planning process of IBSE should be guided not only by the sequence of teaching steps but by a commitment to the socialization of students in a legacy that goes beyond the conceptual knowledge of sciences (Kelly, 2013).

1 In this text, we will use the word Sciences, with an uppercase initial letter, when referring to the school subject. The word sciences, with a lowercase initial letter, will be used to refer to the area of knowledge.

Considering this intention, the planning and implementation of IBSE should enable dialogue and practices that guide discussion and problem-solving (Solino & Gehlen, 2016) through investigative processes that involve the formulation and analysis of hypotheses, evaluation and socialization of results (Zômpero & Laburú, 2011), modeling, argumentation, data interpretation, and reflection for constructing evidence-based explanations (Campos & Scarpa, 2018; Cardoso & Scarpa, 2018; Franco & Munford, 2020). With these practices, in addition to enabling students and educators to discuss the products of sciences, the aim is to construct understandings[2] of how they function (Sasseron, 2015), that is, to create conditions for students to understand the knowledge produced by various scientific fields, as well as the ways of constructing scientific knowledge (Carvalho, 2018).

In this sense, studies in the field of Science Education have shown that teaching about scientific processes, describing their practices, or even conducting experiments in the classroom that confirm scientific concepts do not necessarily result in students appropriating the epistemic legacy of sciences (Franco & Munford, 2020), that is, do not result in the intended learning. For the effective implementation of IBSE, it is essential to create opportunities for students to participate in processes of constructing understandings about phenomena of the natural world or situations that involve aspects of sciences. Although there are divergences regarding the paths to plan learning situations, studies converge on the centrality of the problem in this approach (Munford & Lima, 2007; Carvalho, 2011; 2013; Sasseron, 2015; Solino & Gehlen, 2015; Campos & Scarpa, 2018; Franco & Munford, 2020; Sasseron, 2021).

In IBSE, the definition and confrontation of problems promote curiosity and constitute learning challenges for students (Pedaste et al., 2015). At the same time, they guide pedagogical work towards the meaning-making about scientific knowledge articulated with investigation (Cardoso & Scarpa, 2018), while students develop alternatives in the investigative process to solve them (Carvalho, 2018; Sasseron, 2018).

In this context, the activities proposed in IBSE, based on the presentation and confrontation of problems, may allow teachers and students to raise and test hypotheses, mobilize theories and scientific models (Sasseron, 2015), develop action plans (Carvalho, 2011), collect and analyze data that give meaning to the information obtained (Pedaste et al., 2015), argue and justify the ideas presented (Sasseron, 2015), and communicate new explanations constructed (Zômpero & Laburú, 2011).

This set of practices, which are epistemic because they involve movements for understanding, among others experienced in the classroom and resembling the work of scientific communities, indicates that a variety of teaching strategies can be utilized in IBSE, based on the proposition of problems, taking into account the particularities of each investigative situation (Scarpa & Silva, 2013).

2 The expressions "meaning-making" and "construction of understandings in the classroom" were used because it is understood that, unlike scientific knowledge already legitimized by the scientific community, what students construct in the classroom are meanings and comprehensions of that knowledge. According to Mortimer and Scott (2003), scientific knowledge is a socially stabilized product and, therefore, the process of teaching and learning does not consist of constructing knowledge for the first time, but rather in the meaning making by students as they are introduced to scientific culture.

These strategies, according to Carvalho (2013, p. 9, our emphasis), can be systematized in planned sequences "from the perspective of the **material** and didactic interactions, aiming to provide students with conditions to bring their prior knowledge to initiate new learning, have their own ideas, and be able to discuss them with their peers and with the teacher". The focus of the planning is to allow students to manipulate materials, observe variables, test hypotheses, and experience other situations that support the meaning-making in science classes.

It is not intended, therefore, to equate the centrality of the material with that of the problem in activities based on IBSE, nor to approach the mistaken idea that this didactic approach is limited to practical or experimental activities (Munford & Lima, 2007), but it advocates the importance of offering theoretical considerations about the role and potential of interaction with materials in the classroom as a way to support the meaning making and bring students closer to scientific practices.

These practices, according to Kelly (2008, p. 99), are "a patterned set of actions, typically performed by members of a group based on common purposes and expectations, with shared cultural values, tools, and meanings". They therefore involve the ways in which members of scientific communities create, adapt, and use tools to support scientific work (Stroupe, 2015), with these tools being "used for collection and analysis, from artifacts to constructs for organizing information and results" (Silva & Sasseron, 2021, p. 10).

When considering the school context from the perspective of scientific practices, it is understood that materials contribute "to the intentional mediation in the discussion about already systematized and existing knowledge" (Sasseron, 2015, p. 52, our translation). Beyond this contribution, materials impact the results found by students and can underpin the process of understanding and confronting problems, as presented by Santana and Sedano (2021, p. 389, our translation), indicating that materials should be carefully planned in investigative classes, as

> they directly influence the results, and their characteristics can underpin students' hypotheses. Thus, to analyze a given problem in investigative classes, each aspect belonging to the investigation can favor the construction of hypotheses regarding the possible answers to the addressed problem, and this includes the manipulation of materials.

From the works reviewed, we perceive that, although the planning and use of materials in IBSE do not occupy a central role in the publications of the field, this theme has been discussed in some works that address aspects such as the scarcity of resources, the limitations of textbooks, or the planning difficulties faced by teachers and pre-service teachers. Thus, even though these studies do not center their discussions on the specificities of interactions with materials, the focus of the present article, they bring contributions to the theoretical debate that is intended to be made about the role and potential of students' relationship with materials in the classroom.

As examples, some of the studies found focus on identifying the practices with which students engage when interacting with materials during investigative classes. In these studies, activities such as problem-solving (Moraes & Taziri, 2019), data classification, and experiment recording (Barros et al., 2023; Bertola & Moraes, 2021), observation and verification of regularities (Ferreira Junior et al., 2020), construction of scientific explanations based on evidence and reasoning (Santana & Sedano, 2021), and evidence-based argumentation and hypothesis testing (Roldi et al., 2018) are mentioned.

One point that stands out from these articles refers to the engagement of students with materials as they carry out investigative activities, which enhances the confrontation of problems and the work with hypotheses. In a study conducted in a Science Club, Siqueira and Silva (2020), after analyzing a group from the 6th grade of Elementary School during the execution of an Investigative Teaching Sequence (ITS), observe that the episode[3] in which students manipulated the materials while attempting to solve the problem was the most relevant, evidencing a greater frequency of cooperation and collaboration. "At this stage, it was also possible to perceive greater engagement from the students in collective work, as everyone wanted the opportunity to test their hypotheses (p. 186, our translation)".

Similarly, Roldi et al. (2018), after observing interventions in a science museum, indicate that interaction with the materials available in the collection, during a monitored visit with investigative characteristics, allowed high school students to articulate scientific theories and observable evidence, bringing them closer to scientific practice. Furthermore, the authors emphasize the use of field notes to complement the hypotheses raised from previous theoretical studies, with interaction with the collection and the records used as a basis for argumentation.

Still regarding engagement, in a study conducted with two classes from different social contexts and distinct prior experiences with IBSE, Moraes and Taziri (2019) observed the participation and initiative of the students, as well as their interest and curiosity regarding the materials while dealing with the problem proposed by the teachers[4]. However, they highlight that, in one of the classes, familiarity with similar

3 The episode analyzed in the article by Siqueira and Silva (2020, p. 179) begins with the "problem: How can one color the leaf of the Swiss chard without applying dye to it? To solve the problem, the students were organized into two groups, using water, dye, Swiss chard leaves, plastic containers, and paper towels. All materials were low-cost and easily accessible". At this moment, according to the authors, the students shared the objects, cooperated with each other, established agreements with a view to a common goal, and collectively decided how to use the materials.

4 The episodes analyzed in the article occurred in a class familiar with IBSE and in another without prior experience with the approach. Both episodes begin with the presentation of the materials necessary for the activity, namely "a bucket of water, sheets of paper, paper towels, smooth and transparent disposable plastic cups, with holes made in the bottom of some (...)". The proposed problem was 'How to place the paper inside the cup and submerge the cup in the water without wetting the paper?' (Moraes & Taziri, 2019, p. 77, our translation). According to the authors, not all students engaged in the presentation of materials and in proposing the problem; however, while manipulating the materials, "they exhibited excitement during attempts to solve the proposed problem (...)". A large portion of the students demonstrated 'dedication' through enthusiasm while making attempts, as evidenced by the happiness shown through smiles and facial expressions of surprise upon solving the challenge" (Moraes & Taziri, 2019, p. 80, our translation). Moreover, "everyone took the initiative to attempt the activity and followed the proposed rules in an organized manner. Emotions were present throughout, in the body language and the expressions manifested" (Moraes & Taziri, 2019, p. 81, our translation).

activities apparently increased engagement, while in the other, the euphoria and difficulty in understanding an atypical activity compromised involvement with the materials.

Another relevant point in studies discussing materials in IBSE is the role of the teacher in transitioning from manipulative action to intellectual action mediated by interaction with the materials. In an analysis of an ITS, Barros and collaborators (2023) discuss how teachers' questions guide records and the development of understandings in the classroom, creating opportunities for students to reflect on their experiences and "distinguish the relationship between the materials, the effects caused, the actions they had on the materials, the observed reactions, in addition to listening to their peers and expanding their knowledge and ideas in the search for answers to the problem (p. 226, our translation)".

In a similar study, Ferreira Junior and collaborators (2020) observed an investigative class in Adult Education and found that the teacher's role was crucial for advancing the discussion, allowing students to justify their observations by promoting "the raising of hypotheses and, through observation of the experiment and small questions, encouraged students to move from observational action to intellectual action mediated by argumentation among peers and the teacher" (Ferreira Junior et al., 2020, p. 19, our translation).

Still regarding this aspect, in the context of early years of elementary education, Santana and Sedano (2021) observed students interacting with materials throughout investigative processes, highlighting that the teacher guided and encouraged student participation through questioning, creating opportunities for the class to engage in epistemic practices.

From these studies, several points arise that will be discussed, such as the ways in which materials can support engagement in investigative processes; the possibilities of materials to sustain and complement theoretical debate; and the transition from interaction and reference to materials to their use in effectively addressing the problem. Thus, the objective is to theoretically explore the role and potential of the relationship between students and materials in the classroom, as a means to support intellectual work and the meaning-making about the themes and processes of science.

As this is a theoretical text, the methodological path outlined is structured based on the argumentative line developed, which starts from the discussion of the material aspects of scientific activity to possible transpositions to the school contexts in which inquiry-based teaching is considered a didactic approach. To this end, this study relies on the contributions of Pickering (1995; 2025) regarding agency, the notion of epistemic object (Rheinberger, 1997; Knorr-Cetina, 2001), the theoretical construct of domains of scientific knowledge (Duschl, 2008; Stroupe, 2014), and the discussions and analyses that arise from these ideas for science education.

Does the Material Possess Agency? Some Contributions from Andrew Pickering

The natural sciences are intrinsically linked to our interaction with the material world, as both ontology (what we understand as nature) and epistemology (how we understand it) are shaped by our relationship with material objects (for example, living and non-living beings, devices, equipment, laboratory samples, representations) (Tang, 2024). However, this interaction is not a direct and neutral contact with matter, but is mediated by the conceptual and epistemic structures that scientists mobilize to understand the world (Stroupe, 2014). It is in this interdependence between what we think and what the object allows us to do that scientific knowledge is constructed (Pickering, 1995). The complexity of this interaction was explored by Andrew Pickering, a physicist and doctor in Scientific Studies, who proposed the concept of "mangle", a metaphor used to demonstrate the uniqueness between human and non-human elements in the production and development of scientific knowledge (Pickering, 1995).

Mangle is a machine used to twist clothes and consists of rollers connected by a gear and operated by a crank. When properly using the mangle, the clothing is twisted and excess water is extracted, but improper use can damage the fabric or the machine itself. This simple device illustrates how human action (turning the crank) and materials (the rollers, the gear, and the clothing) work together[5] to achieve a specific result (Pickering, 1995; Silva & Sasseron, 2025a). The reference to the machine highlights the importance of human action in carrying out scientific activity, as it is necessary to know how to operate it effectively. This includes how to position the clothing properly and adjust the speed of the crank, as maintaining this synergy that occurs between human and non-human aspects is what Pickering refers to as tuning, which involves human skill and the availability of appropriate materials in any scientific activity (Silva & Sasseron, 2025a).

Your ideas are grounded in a performative image of science, considering it from two interrelated perspectives. First, "in doing things" and, second, in "performing with the world" (Pickering, 2025). The "doing things" shifts the focus from science merely as representation to science as practice (Pickering, 1995). The "performing with the world" introduces the idea that the material world is not a passive receiver of human action, but an active agent whose properties and resistances perform and shape the process of knowledge construction. Thus, this differentiation reveals that science is not only what scientists do, but what emerges from the mutual interaction between them and the materials (Pickering, 2025).

5 Working together means that human action and material coordinate and limit each other to achieve a specific result. In this process, human intention does not govern the material absolutely; rather, it is constantly reconfigured by the resistances—which occur due to physical and/or chemical properties—of the materials involved (Pickering, 1995; Silva & Sasseron, 2025a). For example, if the clothing gets caught in the roller (material resistance), the intention changes. Therefore, for Pickering (1995), the material is not merely a "consequence"; the resistance it offers can reconfigure human intention.

For Pickering (1995; 2025), there is an analytical symmetry between human and material agencies. Although they differ in nature, human agency is guided by intentionality and plans, while material agency manifests through resistances (Pickering, 1995; 2025), both are equally determinative in scientific practice. In this sense, materials act by imposing resistances that compel humans to constantly reconfigure their intentions. Thus, to say that materials act does not mean that they possess intentions or will of their own, but that their physical and/or chemical properties produce effects that cannot be ignored by human agency. For example, the waters of a river, when blocked, will overflow. However, the overflow is not merely a "consequence", but is the manifestation of the agency of water that imposes limits on the human intention to prevent it from following its natural course. The overflowing river does not "want" to flood, but its physical action (resistance) compels humans to change their plans, to rebuild the dam, or to flee. This capacity to produce a difference in the world is what defines material agency. Therefore, it is in this "tuning" (mangle) that knowledge is constructed.

Exploring this performative image of science, Pickering (1995) proposes the metaphor of the "dance of agencies". In it, scientists, driven by their intentions (human agency), construct a new machine (which may be an instrument, an experiment, a model, a hypothesis, a representation) (Manz, 2015). After this intervention, scientists adopt a monitoring posture, awaiting the manifestation of material agency (Pickering, 1995; Manz, 2015), which

> may be conceptualized in their resistance to being sped up, slowed down, halted altogether, or even reversed, but nevertheless these processes occur in a more active manner than the simple resistance of a rock lying in the way. These processes happen, in a way, in their own time[6] (Böschen et al., 2015, p. 261).

This phase of capture does not imply inactivity or a mechanical scaling between "thinking" and "doing"; on the contrary, it is part of a continuous process of tuning. However, when the capture of material agency fails to correspond to the intentions of scientists, Pickering (1995) defines it as resistance. Thus, resistance would indicate the failure of capturing material agency, and the dynamics of tuning change. Then, the scientist abandons the monitoring posture and assumes human agency in an effort to accommodate. This phase involves the reconfiguration of instruments, models, or practices, aiming to circumvent material resistance and allow a new attempt at capture (Pickering, 1995; Manz, 2015; Böschen et al., 2015). Accommodation is a human strategy in response to resistance, which may reconfigure objectives and intentions, a general characteristic of scientific practice (Pickering, 1995; Silva & Sasseron, 2025a). It is in this process that unexpected material resistances force the scientist to revise their original plans, in an uninterrupted flow of resistance and accommodation (Manz, 2015). According to Pickering (1995; 2025), this uninterrupted flow of tuning reveals that knowledge is not merely imposed by humans, but emerges from a necessary reaction to the performances of the material world.

6 The expression "in its own time" refers to the temporal autonomy of certain material processes, such as radioactive decay or bacterial growth. They possess intrinsic rhythms that do not entirely submit to chronology or human will. In these examples, material agency manifests itself in the resistance to being accelerated or interrupted, causing scientists to shape their practice according to this temporality (Böschen et al., 2015).

Thus, "Pickering conceptualizes science as a dance of human and material agency, encompassing iterations of resistance and accommodation" (Manz, 2015, p. 90). Manz (2015) clarifies what Pickering (1995) refers to as the "dialectic of resistance and accommodation":

> Scientists enact their agency by developing hypotheses, procedures, machines, and measures, which they apply to material phenomena. The world responds by doing something, generally something unexpected and somewhat mysterious; it resists its capture by human agency. Scientists then engage in accommodation, developing new goals, practices, and understandings. An entailment of this view is that practices and understandings are tuned and stabilized in relation to each other. When experiments do not perform as expected, scientists reconsider both their material procedures (e.g., experiments or measures) and their conceptual accounts, that is, their understanding of the phenomenon and how the experiment represents it. Producing a scientific finding involves making procedures, conceptual accounts, and results hang together. Therefore, material puzzles are essential aspects of science: They destabilize both practices and ideas, establishing a need to reconsider each in light of the other (p. 90).

The existence of a certain resistance of materials to human intentions does not mean that material agency exists on its own, but is intertwined with human agency (Böschen et al, 2015). It is important to emphasize that, from the perspective of the mangle, material agency cannot be confused with intentionality; for while human agency occurs based on intentions and goals, materials act performatively. Manz (2015) uses the expression "the world responds" considering the physical and/or chemical resistance that materials impose on experimental designs, forcing the scientist into a process of tuning. Pickering (1995) also does not reduce material agency to isolated effects of materials, for they do not merely serve as a passive object to human actions, but shape the production of meanings and constitute social practices (Silva & Sasseron, 2025a). For example, the use of a microscope is not merely an accessory for visualizing a cell; it is part of a social practice of observation that shapes what we understand about that cell. The lenses (material agency) limit or expand what can be visualized, defining the criteria of evidence and truth within the scientific community. If the lens distorts the image, the scientist needs to accommodate their practice, creating cleaning or adjustment protocols that come to constitute the social practices of that laboratory.

Thus, for Pickering (2025), we do not understand how the world works solely through cognition, for it emerges from an intertwining that involves action and performance. Therefore, action and performance are intrinsically linked to the centrality of materials in scientific practice, for it is the material properties that impose resistances to human intentions (Pickering, 1995; Manz, 2015; Böschen et al., 2015; Silva & Sasseron, 2025a). In this way, the material ceases to be an accessory to become central in the investigation process, for it is from the performance (resistance) of the material that the scientist is compelled to reflect, revise their knowledge, and reconfigure their actions

(Manz, 2015; Silva & Sasseron, 2025a). Therefore, the centrality to which we refer lies in the fact that knowledge is not merely "about" the world, but "with" the world (Pickering, 2025), in a process in which materiality defines the limits and possibilities of scientific practice.

This centrality of materials that Rheinberger (1997) and Knorr-Cetina (1999; 2001) explore with a focus on laboratories contributes to our understanding of how epistemic objects (research materials in their state of investigation) are active in the processes of production and development of scientific knowledge and are incorporated into scientific practices (Knorr-Cetina, 2001; Nerland & Jensen, 2010). While Rheinberger (1995) argues that laboratories are sites for experimentation and negotiation of materials, where scientists manipulate and transform materials to produce new knowledge, Knorr-Cetina (1999) explores the social, material, and cultural dimensions of laboratory work, emphasizing the ways in which scientists' identities, values, and practices shape the production of scientific knowledge (Silva & Sasseron, 2025a). In this context, for Knorr-Cetina (1999; 2001) and Rheinberger (1997), science does not "discover" a reality that was already there waiting; it "manufactures" knowledge in laboratories. This means that knowledge ceases to be understood as a neutral and universal representation of reality and is conceived as a situated and contingent product, marked by the social and material negotiations that originated it. Thus, science is a human and material construction; therefore, it is not neutral.

Rheinberger (1997) argues that scientists do not deal with isolated experiments, but with complex experimental systems that allow for the construction of new knowledge, encompassing the various aspects involved in scientific research. For him, these systems cannot be conceived as a system of concepts, but as a process that is also mediated and supported by materials for the creation and development of knowledge; including "instruments and measurement apparatus, preparation arrangements of different kinds, the necessary skills to use them in meaningful ways, the research objects, and not least the spaces in which these moments are brought to interact with each other in productive and creative arrangements" (Rheinberger, 2011, pp. 310–311).

Considering these elements that constitute experimental systems, research objects, also referred to as epistemic objects, are essential not only for understanding the active role that materials play in science but also for when and how they shape scientific practices.

The Notion of Epistemic Object in Science and Science Education

Epistemic objects[7] are entities and material processes under investigation, as they are theoretically indeterminate and under which scientific interest is directed (Rheinberger, 2021). They possess the characteristic of being mutable and incomplete in nature (Knorr-Cetina, 2001), because they "are as much defined by what they are not

7 We opted for the term "epistemic object" (Rheinberger, 1997; 2011; 2016; Knorr-Cetina, 2001) instead of "research object" for a conceptual distinction and because it is the term used by Rheinberger; while the latter is often treated as a passive object, the former emphasizes materiality in its state of "becoming" (Rheinberger, 1997; Knorr-Cetina, 2001). Thus, it is not passive, but assumes a dynamic centrality in the investigative process, as from the resistances and uncertainties it imposes, it becomes the focus of interest for a group (Rheinberger, 2016).

(but will, at some point have become) than by what they are" (p. 182). Thus, epistemic objects possess a historicity; that is, they can emerge, transform, or evolve, revealing new aspects about themselves (Chang, 2011) and the experimental systems they constitute.

As an example of this historicity of epistemic objects, Rheinberger (2008) explores the case of the fruit fly mutants (*Drosophila melanogaster*). For a long time, they were used as a model organism (instruments) with which genes—the epistemic objects in question—could be located and their positions fixed on chromosomes. With the advancement of Genetic Biochemistry, they became epistemic objects, as their characteristics became the subject of investigation, rather than merely locators (Rheinberger, 2008). This example also serves to illustrate the mutability of the roles of objects (Rheinberger, 1997). If epistemic objects are indeterminate, on the other hand, technical objects involve the equipment, instruments, and tools that are already well known and serve as support for epistemic objects. We can assert that the indeterminacy of epistemic objects does not refer merely to a temporary theoretical gap, but primarily to their capacity for transformation over time (Rheinberger, 2022). According to this author, an object is not "epistemic" by nature, but rather by the function it occupies in an experimental system[8] in a specific historical moment of science.

Another characteristic of epistemic objects is that they become the focus within a specific knowledge community, which Knorr-Cetina (1999) defines as epistemic cultures. In these communities, objects are constructed and shaped interactively through specialized practices (Knorr-Cetina, 2001; Sellberg & Solberg, 2024). However, this perspective should not be confused with a closed conception of science. Although the initial production occurs in situated contexts within specific communities, epistemic objects possess the capacity to transit between different domains and networks of practices, influencing and being reconfigured by new contexts of application (Rheinberger, 2022). Thus, depending on the field of investigation, epistemic objects can take on very different forms; for example, they can be a fly, a rock, equipment, a chemical structure, an absorption spectrum in the infrared region, and even a model or a simulation (Rheinberger, 2025; Silva & Sasseron, 2025a). Thus, what will define the emergence of an epistemic object in the course of scientific investigation is the uncertainty regarding that object, which can pertain to both its structure and its function (Rheinberger, 2021; 2025). It is important to highlight that this uncertainty regarding the emergence of an epistemic object is not merely a subjective doubt of the researcher, but the material and conceptual indeterminacy of the object during the course of the investigation (Rheinberger, 1997; 2021).

Although originally formulated for the context of scientific activity, the notion of epistemic object proposed by Rheinberger has been transposed to educational contexts (for example, Kalthoff & Rohel, 2011; Sasseron, 2021; Silva & Sasseron, 2025a; Ramos et al., 2026). In this transposition, the focus falls on the ways in which students position

8 According to Rheinberger, the experimental system is the functional unit of scientific activity, described as a "machine for making the future", that is, generating questions rather than answers. It is the complete scenario where the investigation occurs, consisting of local, social, technical, institutional, and epistemic aspects. It is the space where epistemic things, epistemic objects, and the set of technical objects interact and mutually transform.

the materials; the object becomes epistemic not due to its absolute novelty in relation to science, but due to the possibilities for it to be investigated and the potential for unfolding during the teaching and learning process. The objects used in classes are transformed into epistemic objects through discursive processes, incorporating the knowledge that must be learned and need to be at the center of attention, but cannot be taken as defined, as it will be up to the teachers to shape them as such (Kalthoff & Rohel, 2011). In this sense, activities in which students perform tasks defined in scripts do not promote their contact with epistemic objects, and there is a need for teachers to allow students to investigate the materials (Sasseron, 2021).

For their intellectual work to be possible, students need to experience activities that involve uncertainty, reasoning, and transformation of ideas (Stroupe, 2014; 2015). These activities are supported by the use, creation, and reconfiguration of tools, technologies, and materials (Stroupe, 2014). In this perspective, Silva and Sasseron (2023) proposed the use of epistemic objects to characterize the way students relate their intellectual work to the materials, whether they are concrete (for example, reagents, prisms, anatomical parts) or abstract (for example, the chemical structure of a substance, graphs, tables). At some point, the materials under study need to be positioned as epistemic objects during teaching situations.

Pre-service Chemistry teachers[9] positioned visual representations (the chemical structures of the reactants and products involved in a chemical reaction) as epistemic objects, assisting them in exploring their knowledge about organic reactions and facilitating learning (Silva & Sasseron, 2025b). In the context of the discussion developed in this article, it can be exemplified from Silva and Sasseron (2025b) that visual representations in an expository teaching of organic reaction serve merely as an illustration of a final product, that is, they are positioned as technical objects. On the other hand, in inquiry-based teaching, the representation is positioned as an epistemic object, requiring the student to explore it to predict reactive centers (nucleophiles and electrophiles) and understand the flow of electronic density that characterizes the transformation (reaction mechanism). In this sense, the reaction mechanism—mediated by the use of curved arrows—ceases to be a mere illustration of a chemical equation to become a consequence of an analysis of the chemical structures and the conditions of the organic reaction under study.

This positioning characterized the use of these representations as an epistemic practice[10], necessary for the construction of knowledge in Organic Chemistry (Silva & Sasseron, 2025a). Also, in the field of teacher training in Chemistry, Ramos et al. (2026) demonstrated how socio-scientific texts can be treated as epistemic objects. This occurs when the text is used to generate conflicts and uncertainties, rather than providing closed conclusions, acting through its material resistance to engage teachers in initial training

9 Just as for the word Sciences, the word Chemistry and its variations will be used with initial capital letters when referring to the school subject and with lowercase letters when the reference is to the area of knowledge.

10 Epistemic practices are understood as social practices that lead to the construction of new knowledge and new modes of action (Sasseron et al., 2025; Knorr-Cetina, 2001; Silva & Sasseron, 2025a).

in epistemic practices of argumentation. In inquiry-based teaching, for example, there is a greater possibility for a text to be positioned as an epistemic object, as the student needs to investigate the nature of a given conflict or evaluate how this evidence supports the resolution of a problem. In contrast, in expository teaching, the student often uses the text only for the passive extraction of information, positioning it as a technical object[11].

It is considered that working with materials is not disconnected from the problem to be solved. In inquiry-based teaching, materials cannot be seen merely as technical objects, as they are characterized by resistances and uncertainties that drive intellectual work; it is in this interaction that doubt about the problem transforms into the outcome. Therefore, the manner in which materials are approached is decisive for the investigative process, as the problem guides whether the material will be positioned as an epistemic or technical object. In summary, the transposition of the notion of epistemic object to the teaching of Sciences implies that didactic materials are not merely supports for studying theory, as they need to be investigated, requiring a shift in perspective regarding their didactic function, including in experimental activities.

The Materials and Experimental Activities

Studies on the role of practices in the teaching of Sciences make it possible to recognize different objectives of working with them in the classroom (Borges, 2002; Carvalho, 2006; 2018; Sasseron et al., 2025). The relationship between the use of practices in didactic proposals and educational objectives is also recognized, as well as the mobilization of practices based on teaching and science conceptions (Sasseron et al., 2025).

Experimentation, understood as a teaching practice, is highlighted as an important element for the approach to natural sciences and, in some cases, linked to perspectives derived from John Dewey's proposals regarding the relevance of experience in education (Zômpero & Laburu, 2011). In summary, the three main moments and modes of using experimentation in science teaching situations are highlighted.

First, in the 1950s and 1960s, teaching projects developed in different countries featured experimentation as a significant component, and we can recognize the effort to provide students with situations in which, in contact with experimental apparatus, they can verify and confirm concepts and laws theoretically addressed in classes (Osborne, 2016). Beyond mechanical execution, the objective was to allow students to understand the concrete manifestation of the law and its universal validity, starting from prior statements to understand how they assert themselves in the dynamics of reality. However, experimentation involved the execution of pre-established procedures (Osborne, 2016). For example, in the observation of onion epidermis cells under the microscope, the biological material serves merely as a support to confirm what is already presented in

11 Unlike epistemic objects, technical objects are characterized by being defined, closed, known, and well understood by their users. As an example, Silva and Sasseron (2025b, p. 616) explain that, "In the case when visual representations are conceived as a finished product, presented to learners as complete, they are considered technical objects. On the other hand, when they are conceived as part of a process, wherein one seeks to understand their production context, and their necessity to perform a function is evaluated, they are considered epistemic objects".

the textbook. The "answer" already exists before the experiment begins, and it is up to the students to identify and draw the structures of the cell (cell wall, nucleus, and cytoplasm). The microscope and the slide are positioned as technical objects, and the objective of the experiment is confirmation.

Second, in the 1980s and 1990s, experimentation began to occur with a focus on the problem, thus shifting attention to the subjects' relationship with the processes to solve it (Borges, 2002; Osborne, 2016). For example, the teacher proposes a problem: "How does the concentration of salt in the medium affect the physical structure of the onion cell?" The student needs to plan the experiment: prepare different saline solutions, observe the cells, and record the phenomenon of membrane wilting (plasmolysis). The cell begins to be problematized, and the focus is on the processes (observation, control of variables, recording). In this situation, the focus shifts from confirmation to the process. However, the result is still expected and linear.

Third, in more recent years, especially from the 2010s onward, criticism has assumed a central role in science teaching, and for experimentation, this results in student engagement with epistemic practices to evaluate situations and seek ways to understand and justify the perspectives under construction (Osborne, 2016; Kelly & Licona, 2018). For example, students investigate plant tissues under suspicion of contamination by pesticides; for this, they also use onion epidermis cells as a model. When faced with anomalous behaviors (for example, cells that do not undergo plasmolysis under conditions that should induce it or that exhibit structural deformations), students realize that the material does not behave according to the classical model of a healthy plant cell. In this context, the cell becomes an epistemic object because it imposes resistances, ceasing to be an "absolute truth" from the textbook and becoming an unknown. The student encounters questions of various kinds: "Why did this cell resist plasmolysis?", "Is the data reliable or is it a technical error?", "Is the model sufficient to explain this case, or has the presence of the contaminant altered the physiology of the samples in such a way that a new justification is required?" The student engages in processes of evaluating the results, and the image from the microscope ceases to be merely an "illustration" and becomes evidence that needs to be legitimized by the group. Intellectual work consists of coordinating these material data with the problem of contamination to construct and validate explanations.

Changes in the uses of experimentation can also be identified through the analysis of how students interact with the experimental materials linked to the activity.

Practices more focused on the execution of procedures are usually associated with predefined experimental arrangements, whose manipulation is planned to achieve the desired effect, that is, for the phenomenon studied theoretically to be proven or verified. In this context, the concern falls on the effectiveness of the experimental apparatus, rather than on the investigative action of the students. When restricted to following rigid scripts, students do not position the experimental apparatus as an epistemic object, since the materiality is presented as a defined technical entity that does not allow for uncertainties or resistances (Pickering, 1995; Rheinberger, 1997). From this, there are practices that do not concern themselves with creating space for student action, whether in proposing new experimental arrangements or in making decisions during the process. The student action is limited to the mechanical execution of previously defined steps, which restricts the manipulation of the material to its status as a technical object (Rheinberger, 1997).

When the problem takes center stage, work with the materials can occur in different ways. One of the possibilities is situations where the experimental arrangement[12] is presented ready to the students along with the problem. In these situations, students raise hypotheses and organize ways of working to solve this problem; in this context, the materials are positioned as technical objects, as they are used as support and their function is merely to assist in solving the problem. Thus, the very structure or functioning of these materials is not questioned. On the other hand, situations may arise where, in the face of the problem, students need to construct the means to resolve it. In contexts like this, the very experimental arrangement is under analysis and questioning; consequently, the materials take on the character of epistemic objects (Rheinberger, 1997), as they cease to be supports and become part of the investigative process, since students need to deal with the resistance and uncertainties of the materials themselves (Pickering, 1995; Rheinberger, 1997). Consequently, the modes of interaction of students with the materials (as technical or epistemic objects) are defined by the design of the experiment. This implies the articulation between the nature of the problem and the level of openness of the experimental arrangement, which determines whether the student will act by executing previously defined procedures or by investigating the material uncertainties and resistances.

From this perspective, it becomes relevant to consider the emerging agencies that arise during the investigation and are not entirely predictable in advance. Pickering (1995) discusses scientific practice based on established, broken, or modified links within a network of cultural elements, which encompasses theories and social norms as well as the materials themselves. The relationship between researchers and objects is described by the concept of performativity and agency (Pickering, 1995). Performativity means that science is not conceived merely as a space of representation; it is also a space of action, where the scientist acts and the material responds by imposing resistances and uncertainties (Pickering, 1995; Rheinberger, 1997). In this context, agency is understood as action and its unfolding, manifesting in three forms: human agency (the intentions and plans of scientists), material agency (the resistances and uncertainties imposed by materials), and social agency (the alignment between human intentions and material possibilities) (Pickering, 1995). The interaction between human and material agencies occurs through the "dialectic of resistance and accommodation": resistance emerging in situations where the functioning of the material occurs outside of what was expected,

12 From the transposition of Rheinberger's concept (1997) to Science Education, the experimental arrangement is understood as the determined material and procedural support that allows for investigation. It is constituted by the set of technical objects–instruments, equipment, organisms, reagents, representations, and models–and procedural skills that serve as a basis for understanding what is being investigated (epistemic object).

challenging human intentions; and accommodation being expressed through human response, aiming to deal with the unforeseen (Pickering, 1995). This process of tuning is the manifestation of social agency, in which scientists recognize the potential of the material and shape practice so that knowledge is constructed.

Considering that the positioning of materials in an activity responds to a specific pedagogical intentionality, it becomes essential to reflect on how this choice determines the dynamics of human and material agencies in the classroom. Depending on how teachers organize the experimental arrangement, the material may be positioned as a technical object or as epistemic. When the material is positioned as an epistemic object, space opens for the "dialectic of resistance and accommodation" (Pickering, 1995), in which the tuning between students' objectives and the resistances and uncertainties of the material allows for the manifestation of social agency. On the other hand, in activities where this tuning does not occur, human agency (in the form of a script with predefined steps for students to merely follow and the teacher's intention) prevails, and the material is reduced to a support from which only the previously anticipated result is extracted.

In didactic situations where students execute predefined procedures to verify laws and concepts, human agency interacts with the object, and this object manifests its physical and/or chemical properties. Thus, the resistances and uncertainties (material agency) inherent to the materials involved in the phenomenon under study are minimized or anticipated by the instructions. Although interaction occurs, the encounter does not promote the perception of what the material is capable of doing (resistances and uncertainties), since the use of that material in a certain way was established a priori by the instructions regarding the activity, which does not imply recognition by the students of why they engaged in such interaction with the object.

In experimental activities where a problem is presented to students, the experimental arrangement is made available to students as a field of possibilities for conducting the activity, but without prescribing a script with the procedures to be followed. In this context, human agency mobilizes the object with a specific intentionality (the resolution of the problem), requiring the confrontation of material resistances and uncertainties. This confrontation leads to an understanding of how the object behaves, that is, an understanding of its material agency. As a result, students' intentions adjust to the object's responses, establishing the tuning between human and material agency, which allows for the emergence of social agency.

There are still didactic situations where the problem is presented, but the materials are not provided organized as a pre-established experimental arrangement. In this case, the arrangement is not the starting point, as the materials that constitute it are in a state of "indeterminacy", requiring students, through their human agency, to analyze, select, and test which objects to mobilize. The experimental arrangement emerges from the investigation itself, requiring the recognition of the potentialities of materials and tuning, as it is the measured use and adjustment between the students' intentions and the resistances and uncertainties of the objects that will allow for the transformation of a dispersed set of materials into a functional experimental arrangement to solve the problem.

In light of this, it is understood that it is possible to perceive the emergence of agencies (human, material, and social) in different didactic situations. Understanding how these agencies coordinate allows for the planning of didactic activities based on inquiry-based teaching to focus not only on content but also on the dynamics of interaction between students and objects. To this end, it is essential that the planning articulates the conceptual, epistemic, social, and material domains of scientific knowledge, as this approach values the intention and plans of the students (human agency), the confrontation of the resistances and uncertainties of the objects (material agency), and the dialogical processes (social agency), thus revealing the necessary tuning for the construction of understandings in the classroom.

Domains of Scientific Knowledge: The Role of Materials in Supporting Intellectual Work

The domains of scientific knowledge are a theoretical construct used to analyze which elements are addressed in teaching and learning situations in the sciences (Duschl, 2008; Stroupe, 2014; Franco & Munford, 2020; Lino & Sasseron, 2024; Silva & Sasseron, 2025a). Initially, Duschl (2008) proposed three domains of scientific knowledge: the conceptual domain (CD), which is frequently mobilized in the classroom through the approach of concepts, laws, theories, and forms of scientific reasoning; the epistemic domain (ED), characterized by the modes or structures used to propose and evaluate knowledge or a proposition; and the social domain (SD), revealed by the processes and contexts that shape how knowledge is proposed, evaluated, and legitimized. Stroupe (2014) added the material domain (MD) of scientific knowledge, presenting it as the physical and intellectual tools that assist in the development of scientific work.

As some examples of these domains, one can refer to the analysis by Silva and Sasseron (2023) in an Organic Chemistry class, where the CD is identified by the teacher's presentation of the studied content, by the mobilization of concepts to address the class's questions, or by the teacher's effort to elicit students' prior knowledge; the MD is identified by the use of representations to support explanations or by the use of experimental materials to conduct reactions in the laboratory; the SD is identified by the establishment of norms in Organic Chemistry regarding the use of representations for recording experimental data or by the presentation of criteria to be used by students when choosing representations; while the ED is identified at the moment when the teacher organizes the understanding of organic reactions and explains the rationale behind this organization.

Still aiming to exemplify the occurrence of the domains in the classroom, we revisit the analysis of a laboratory class on Electricity (Lino & Sasseron, 2024) that identified the CD in moments when students revisit studied content to solve problems or to construct understandings about an experimental phenomenon they observe; the MD in moments when students discuss the experimental apparatus and its suitability for the data collection they require; the SD in moments when students revisit claims made by another colleague to review their own ideas throughout an investigation; and the ED in moments of negotiation for the collective construction of valid hypotheses and explanations.

Research has discussed how the domains of scientific knowledge can be considered in didactic planning (Franco & Munford, 2020; Sasseron et al., 2025; Nascimento & Silva, 2025; Sasseron & Orofino, 2025), as well as their role in learning situations (Lino & Sasseron, 2024; Silva & Sasseron, 2025a), and therefore, it is understood to be important to identify how these domains can be considered in light of the materiality that is constructed or enabled in didactic activities based on inquiry-based teaching. In this approach, the domains are considered in an integrated manner in didactic planning (Franco & Munford, 2020; Sasseron et al., 2025; Nascimento & Silva, 2025; Sasseron & Orofino, 2025). In learning situations, the material domain emerges as the "anchor" for mobilizing the others: the social domain emerges in the collective negotiation regarding how to act in the face of the resistances and uncertainties of the objects, while the epistemic domain reveals itself in the criteria used to interpret these material responses, leading to the construction of the conceptual domain (Silva & Sasseron, 2025a). However, it is important to highlight that, according to Stroupe's definition (2014), the material domain does not refer solely to manipulable physical objects in experimental or didactic exploration situations; it also materializes from the intellectual constructions that aid in understanding a situation, for example, the organization of information through graphic records, the construction of tables and graphs, or the establishment of an algebraic construction that allows for the description of a phenomenon.

As previously discussed, the ideas surrounding inquiry-based teaching have evolved over the years, driving new ways to plan and implement didactic proposals. At this moment, it is proposed to evaluate the actions associated with inquiry-based teaching whose purpose is to engage students in practices similar to those of the sciences in order to propose knowledge claims and to conduct their evaluation and support through justifications. In this context, the presence of the domains of scientific knowledge should occur through interactions among students, between students and the teacher, and their interactions with phenomena, objects, and knowledge through processes and practices of investigation, argumentation, and modeling (Jiménez-Aleixandre & Crujeiras, 2017).

During investigation processes, students encounter a problem and, to analyze it, they engage in planning actions for the investigation in which they can observe, measure, explore, and experiment, collecting information that aids in solving the problem. It is presented that these situations tend to be conducive to the mobilization of the epistemic, social, and material domains of scientific knowledge since they involve problem-solving processes that need to be close to the ways in which the sciences conduct similar analyses and require the organization of information obtained throughout the processes. In these situations, the conceptual domain does not emerge as the cause of the actions but as a consequence of them, resulting from the work with the other domains. Furthermore, the mobilization of these domains allows for contact with the ways of constructing knowledge, which does not mean an identical transposition of scientific activity into the school context, but rather an approach that values dialogical processes and the action and participation of students.

Argumentation situations, whose planning must consider the mobilization of the conceptual, epistemic, material, and social domains, premise the evaluation of the relationship between indications, evidence, and propositions presented or under construction, as the arguments regarding the construction under evaluation may address already established or proposed concepts. These are analyzed from critical evaluation modes concerning both the knowledge itself and the materials used to support it, in accordance with the practices inherent to the sciences.

In modeling activities, the explanation of the phenomenon is at the center of the process. In this case, the aim is to develop, test, and refine explanatory models, requiring imagination and reasoning that lead to the construction of hypotheses and predictions. Therefore, modeling tends to enable the mobilization of the conceptual, epistemic, and material domains of scientific knowledge, as it is expected that generalizable ideas to explain a situation can be debated, providing support for the understanding of a concept, law, or scientific model, achieved through analyses of propositions based on collected and organized data.

As observed, the material domain is inseparable and constitutive of the practices of investigation, argumentation, and modeling. However, beyond its mere mention, the active role of these materials in supporting the intellectual work of students indicates an interdependence between discursive processes and the work with these materials. This reveals that discursive processes not only comment on the manipulation of materials but are also shaped by them. For example, the resistances and uncertainties manifested by the materials impose the reconfiguration of intentions, revision of arguments, and refinement of models. Thus, it becomes necessary to discuss the relationship between materials and the domains of scientific knowledge, exploring them as objects and agencies in the context of investigative activities.

Materials and the Domains of Scientific Knowledge: Objects and Agencies

In the pursuit of discussing the role of materials in science education and their relationship with the conceptual (CD), epistemic (ED), social (SD), and material (MD) domains of scientific knowledge, the following discussion is based on the work of Sasseron and Orofino (2025) regarding the progression of mobilization of the domains of scientific knowledge in elementary and secondary education, with special attention to the material domain. The prior analysis of this proposal allowed for the recognition that for the grouping “Elementary Education: 1st to 3rd grade”, the aspects of physical materiality (MD) are not explicitly detailed, with descriptions focused on other domains prevailing. Thus, in Figure 1, a segment of the proposal by Sasseron and Orofino (2025) is presented, emphasizing only the progression of the MD of scientific knowledge, and a brief alteration for the mentioned grouping has been proposed.

Table 1

Progression of the material domain of scientific knowledge in elementary and secondary education, prepared by the authors based on Sasseron and Orofino (2025)

School level	Progression of the material domain of scientific knowledge
Fundamental Education 1st to 3rd grade	Transform observations into graphic records: drawings, writings, or tabulations (learning what a literary inscription is). *Conduct tests on materials to solve a problem.*
Fundamental Education 4th to 5th grade	Organize records that relate collected variables; Utilize materials and equipment with the purpose of implementing the defined methodology.
Fundamental Education 6th to 9th grade	Use or develop methods to solve a methodological problem based on collected or available information; Organize collected data to demonstrate patterns to be used as evidence.
High School	Evaluate the existence of anomalous data in relation to the type of material and procedures used for the investigation; Establish algebraic expressions that synthesize the explanation of a phenomenon.

Note. In italics, the insertion was made for the purposes of this study considering the proposal of Sasseron and Orofino (2025).

Figure 1 provides information that allows for the identification of the MD of scientific knowledge based on the two main instances: physical materiality and intellectual materiality.

Considering physical materiality, the progression of the MD exposes the possibility for students to conduct tests on materials to solve a problem (for example, students need to filter dirty water and have cloth, paper, and cotton available). They test the different materials to observe the flow rate and the color of the water in each material individually, before deciding which is the best combination for the filter); utilize materials and equipment with the purpose of implementing the defined methodology (for example, after deciding on the material to be used for the filter layer, they assemble the system in a cut PET bottle and use a stopwatch to record the time it takes for the water to pass through the system); use or develop methods to solve a methodological problem based on collected or available information (for example, while conducting the filtration, students observed that the water is coming out clean, but at a very low speed (in drops). Based on this data of time and flow rate, they decide to alter the methodology, reducing the layer of sand to optimize the process without losing the quality of filtration); and evaluate the existence of anomalous data in relation to the type of material and procedures used for the investigation (for example, one group of students observes that their water came out cloudier than that of the other groups, despite using the same methodology). Upon evaluating the material, they realized that the sand used had not been washed beforehand (information about the material) and that this generated an anomalous data point (extra turbidity), invalidating the direct comparison with the other groups). Therefore, the progression indicates the realization of tests and the use of materials and equipment as central elements in the implementation of a given methodology for analyzing a situation.

In terms of intellectual materiality, the progression of the MD establishes contact for students with the transformation of observations into graphic records through drawings, writings, or tabulations (for example, the student, after placing hot water in a ceramic cup and in a metal cup, touches the walls of the cup and observes that the metal cup is warmer). He creates a drawing of the two cups, using arrows to represent the heat "emanating" from the metal cup and not from the ceramic one; the organization of records that relate collected variables (for example, the student places his finger in the water inside the cups and marks the time he can keep his finger there, measuring the temperature every 2 minutes). He constructs a table with two columns: on the left, the time (minutes); on the right, the temperature (°C) for each measurement of the water in the different cups; the organization of collected data to demonstrate patterns to be used as evidence (for example, the student transposes the data from the table to a line graph). Upon observing the two lines on the graph, he realizes that the line of the metal cup "drops" much faster than that of the ceramic one; and the establishment of algebraic expressions that synthesize the explanation of a phenomenon (Sasseron & Orofino, 2025) (for example, the student analyzes that the variation in temperature depends on the mass of the water and the type of material of the cup, as indicated in the equation $Q = m.c.\Delta T$).

Considering that the MD is mobilized when materials cease to be merely supports and begin to sustain the intellectual work of students (Stroupe, 2014), the role of these materials cannot be restricted to their mere manipulation or the application of prior information about their use as a "recipe". In this perspective, considering that the MD assumes distinct forms, whether physical or intellectual, its characterization is linked to the epistemic object (Silva & Sasseron, 2023). The MD emerges from situations in which students problematize the materials, either by the function they perform or as objects of concern in the process of meaning making about the themes and processes of science (Silva & Sasseron, 2023; 2025a). In this sense, the problematization of function is linked to the uncertainty manifested by the materials, while its role as an object of concern emerges from the material resistance encountered, requiring the student to construct new understandings to continue the investigative path.

In this perspective, epistemic objects shape and are shaped by practices, understood as collective actions that lead to the incorporation of new knowledge to transform themselves and the entities formed in this relationship (Knorr-Cetina, 2001). In our interpretation, these entities can be concepts, models, representations, or even an instrument. Therefore, for the author, these social practices are epistemic and differ from practices that are routine and normative. In other words, the collective actions that lead to the incorporation of knowledge through the relationship with epistemic objects, thus generating something that did not exist before, are epistemic practices. From this understanding, the mobilization of the MD proves to be constitutive for the emergence of epistemic practices, as it is the intellectual engagement with materials that drives the production of new meanings.

Thus, the MD is mobilized by students when materials are positioned as epistemic objects (Silva & Sasseron, 2023; 2025a). However, this does not mean that this positioning endures throughout the entire investigative process or that a technical object does not become an epistemic object and vice versa. It is important to emphasize that investigation is not static; the transition between epistemic and technical objects is, in our defense, a characteristic of IBSE. Even though this transition may seem inherent to investigative approaches, we understand that, in general, in school contexts, materials are restricted to technical objects, conditioned by rigid scripts. We argue that investigation indeed resides precisely in the transition between technical and epistemic objects: the material, by manifesting uncertainties and resistances (epistemic object), challenges the group so that, once understood, it can be positioned as a technical object, serving as a basis for new problems. Without this material centrality and this transition, investigation is limited to a mechanical manipulation devoid of intellectual engagement.

Silva and Sasseron (2025a) argue that positioning materials exclusively as technical objects may suppress investigation. In this study, it was demonstrated that the students positioned the chemical structure of the compound as an epistemic object by questioning the functional groups and the possible reaction conditions. Once the group validates the reagents, this structure is positioned as a technical object. When the students realize that the validated reagents may lead to unforeseen developments, new questions arise, and the structure is once again positioned as an epistemic object. Thus, the transition between epistemic and technical objects is not a trivial event, but rather the very mark of the progress of the investigation, allowing consolidated understandings to support the investigative process.

From this perspective, in classes involving experiments, it is maintained that the use of scripts with information presenting all materials ready for use and the manner of utilizing them for a given purpose results in the manipulation of technical objects, which does not favor investigation. This occurs because there is an elimination of the uncertainty necessary for intellectual work, as the student becomes merely an operator of instructions. The criticism of these scripts does not suggest that students should not receive guidance, but proposes that materials be positioned as epistemic objects, allowing for actions such as "conducting tests on materials", "using materials and equipment for the purpose of implementing the methodology", and "evaluating the existence of anomalous data related to the type of material and procedures used" (Sasseron & Orofino, 2025). For example, "conducting tests on materials" serves not only to identify the best material for executing the experiment but also to understand how its properties and limits drive or restrict the investigated phenomenon. Thus, materials cease to be merely a support of a list to become an epistemic object (Silva & Sasseron, 2025a), whose function must be coordinated by the students to enable the implementation of the methodology and data analysis (Sasseron & Orofino, 2025).

In these situations, although the physical material (for example, beakers, scales, reagents, etc.) may predominantly function as a technical object, it assists the students in performing a task, manipulated with a clear and predefined purpose by human agency (Stroupe, 2014; Pickering, 1995). Thus, when these materials, positioned as technical objects, begin to perform a function or become the focus of the group's interest, leading to the meaning making about what is being investigated, these materials must be positioned as epistemic objects. In this process, agency primarily falls upon the students, who decide how and why to use the material to implement the experimental design (Sasseron & Orofino, 2025; Pickering, 1995). Such a decision mobilizes the ED, as it requires evaluating the knowledge involved in that decision. Furthermore, this decision regarding which material to use may demand an analysis of how this experimental design will be carried out, also mobilizing the SD, implying that the understanding produced was not given beforehand but negotiated by the group. Thus, the CD emerges from this negotiation so that the group reaches a consensus on the use of the material, as students are required to provide concepts that justify their material choices.

Working with intellectual materiality highlights the role of material in the ED, as, for example, "transforming observations into graphical records", "organizing collected data to demonstrate patterns", and "establishing algebraic expressions" (Sasseron & Orofino, 2025) reveal that the product of physical manipulation transforms into a new type of material: data, graphs, tables, and models, for instance. In such occasions, material agency manifests, as the material—now in the form of a graph or table—ceases to be a passive recipient of human action (Stroupe, 2014; Pickering, 1995). Although it is the student who performs the reading, the materiality of the graph imposes contours and resistances to reasoning; the visual pattern resulting from the data limits possible interpretations and "forces" the individual to confront their expectations with the physical evidence (Pickering, 1995). Thus, this graph or table may be positioned as an epistemic object, as it can perform a function and/or become the focus of interest (Rheinberger, 2016; Silva & Sasseron, 2023), leading to the meaning-making by the students, thereby also mobilizing the MD. In this work with intellectual materiality, the pattern observed in a graph or the failure in a constructed model provokes reasoning, fostering the mobilization of the ED to evaluate and argue about what the material is "revealing." Furthermore, the SD can also be mobilized from the analysis of how this graph or model was constructed and evaluated. Material agency, therefore, resides in the mediation process of constructing understandings, imposing restrictions or suggesting directions that, in turn, reconfigure human agency (Stroupe, 2014; Pickering, 1995). Thus, it means that material agency manifests itself in the process of meaning making through the resistance that materials (the actual data) impose on students' hypotheses, compelling them to accommodate their reasoning and reconfigure their human agency to make sense of the phenomenon. This reconfiguration allows for the construction of new understandings and their relationships with those already established, culminating in the mobilization of the CD.

Although the discussion in the previous lines has been based on an activity involving an experiment, there is a diversity of materials in the classroom that can be positioned as epistemic objects, that is, materials that cease to be merely supports of information to become the target of problematization and the construction of meanings; ranging from the blackboard, a text, and even a representation.

The blackboard, for example, can play an important role, as by incorporating it into the discourse in the classroom, it can be transformed into an epistemic object (Kalthoff & Roehl, 2011). For the authors, it is necessary to recognize that materials can be socially constructed through interaction, discourse, and the networks they can create. In this way, through the mediation of teachers, materials need to be discursively introduced and transformed into an epistemic object so that they can assist in the construction of an understanding (Kalthoff & Roehl, 2011). Therefore, in this mediation, epistemic objects are not merely present in the classroom, but they are actively incorporated into the dialogical process of the lesson, allowing or restricting discourse in the classroom.

An example of this dynamic occurs in the construction of a graph on the blackboard. The way in which the teacher conducts the discourse renders the representation and the support inseparable as an epistemic object, as the graph is not an abstract entity. It is the chalk on the blackboard. If it is used merely to display points and curves without questioning, it remains a technical object. However, it consolidates as an epistemic object when this materiality is discursively inserted into a structure of uncertainty. This occurs because the graph becomes the target of investigation when the classroom discourse begins to problematize it, focusing on predicting trends or interpreting anomalies (Kalthoff & Roehl, 2011). The intellectual work of students reveals itself in the uncertainties and material resistances that the object imposes. Imagine a discussion that requires a three-dimensional representation: the blackboard, being two-dimensional, imposes a resistance to reasoning. Material agency manifests itself in this limitation, forcing students to accommodate their thinking. If, for example, a student suggests positioning a pencil perpendicularly to the blackboard to represent the third axis, a reconfiguration of human and material agency occurs: the pencil is incorporated into the agency to overcome the resistance of the original support, allowing for the construction of new understandings.

In a similar perspective, a text, when understood as a material object, can support the exploration, evaluation, and resolution of a problem (Tanner et al., 2017). Ramos and colleagues (2026) demonstrated in a teacher training course for Chemistry that a text, when positioned as an epistemic object by the preservice teachers, fostered argumentative processes. In this study, these preservice teachers were expected to use the text as support to resolve a socio-scientific issue. However, the text provided for resolving this issue presented a source, considered reliable, but its content revealed some uncertainty. In one of the investigated groups, the mention of the source used to construct the text led one of the members to suggest a resolution to the socio-scientific issue. On the other hand, another member, perceiving the uncertainty of the text, disagreed and questioned the information, which culminated in an argumentative process among the group members.

Frequently, representations such as chemical structures have been treated as mere illustrations of what is being discussed, which ultimately generates various learning difficulties (Taskin & Bernholt, 2014; Silva et al., 2021). When understood as illustrations, they are positioned as technical objects because: (i) they are provided in advance, (ii) they are seen as a product, (iii) they do not affect future events, (iv) they reaffirm accepted theories or already accepted experimental data, and (v) they do not justify more in-depth studies (Silva & Sasseron, 2025b). For them to be positioned as epistemic objects, it is necessary for students to: (i) question their function, (ii) seek new information about them, (iii) develop curiosity about the phenomena from their use, (iv) connect them to future results, (v) understand them as a way to challenge accepted theories or experimental data, and (vi) feel motivated to study them more deeply (Silva & Sasseron, 2025b).

The mobilization of the domains of scientific knowledge depends on a continuous interaction between human and material agencies. The human agency manipulates the technical object, generating data and/or information that, when becoming an epistemic object, exerts its material agency, challenging and guiding the human agency in constructing understandings about the themes and processes of the sciences.

Final Considerations and Implications

In this study, the aim was to theoretically reflect on the role and potential of students' relationships with materials in the classroom as a means to support the meaning making and intellectual work. When understanding inquiry-based teaching as a didactic approach, one can defend the idea that it is realized through the interaction between students and teachers.

This interaction is triggered by the generation of questions, culminating in the need to solve problems, which may be of a conceptual nature or, more broadly, even involving social aspects. However, the interaction is not restricted solely to the construction of this problem; it also involves the way we work with the materials during the resolution process. If these are always treated as technical objects, which are previously known and used to apply information from a script, the interaction that fosters intellectual work will not occur. On the other hand, if at any moment, even if it is just one of the materials, it is positioned as an epistemic object, it will become the focus of the group. Its uncertainty generates more questions than answers, which triggers the interaction. This process may lead to the transformation of this epistemic object into a technical object, well known by the group, resulting in the success of this investigative process, as the group resolves uncertainties regarding the material or phenomenon, constructing new understandings that may generate new and more complex investigations.

Thus, both in experimental and non-experimental activities, the materials need to be explored by the group, whether for the function they perform or for the reason that they become the focus of the group. It is clear that it is not being argued that all materials should be positioned as epistemic objects, as this could hinder the resolution of the problem and suppress the possibilities of interaction, since the students would not know where to begin to reflect and plan any action for the construction of understanding. It is therefore maintained that the roles of these materials should be transformed throughout the investigation, alternating between technical objects and epistemic objects. This alternation is necessary because the investigation of an epistemic object (uncertain and incomplete) requires technical objects (known and complete). Technical objects and the understandings already constructed allow the group to become interested in and investigate the epistemic object. Without technical objects, the uncertainty of the epistemic object would be an obstacle to the investigation, as the students would not have support, for example, to interpret the data or coordinate their investigative actions.

Understanding the transformation of the roles of materials in experimental activities allows us to reconsider the conception that the experiment "went wrong" and therefore needs to be redone or adjusted to align with what was expected. This conception is typical of experimental activities that are more directly aimed at the verification or confirmation of a concept, as the failure to achieve the expected result is understood as a procedural failure. In the proposed context, the "error" is not a problem, but a regular and expected event in investigative processes. If, for example, when attempting to demonstrate the buoyancy of an egg in saltwater, the egg remains submerged, the expected result does not occur. Thus, these materials (the egg and saltwater) cease to be technical objects and become epistemic objects. The "error" shifts the group's focus, as the interaction ceases to be about the confirmation of a concept and becomes about investigating the causes of the material resistance manifested. Thus, the adjustment of the experiment or the reconfiguration of the procedures is not an attempt to "force" the result to align with the textbook, but rather to respond to the resistances that the materials presented. It is in this process of transformation of the roles of materials that the student needs to deal with uncertainties and resistances, which fosters intellectual work. Thus, the inquiries become deeper and new understandings are consolidated.

As implications of this study for the field of research in Science Education, regarding the ways in which materials can support engagement in investigative processes, it is suggested that proposals for the IBSE plan forms of interaction with the objects and how these will be taken into account by the students during the investigation, based on the presented problem and the provision of experimental arrangements and materials.

This planning should foresee the articulated mobilization of the domains of scientific knowledge, so that teaching is developed beyond mere technical manipulation or the application of ready-made instructions. From this articulation, materials can be positioned as epistemic objects, understood here as objects that, by presenting uncertainties and resistances, provoke inquiries and become the focus of intellectual work and the meaning making by the students.

Thus, in experimental or non-experimental activities, scripted or open, we consider that the guiding intentionality of the interaction between students and materials in the classroom can be planned with the perspective of producing opportunities for the materials to not only be referenced but, in fact, mobilized to support the construction of explanations and intellectual work.

In the field of research, this may unfold into analyses of planning and practices in scientific education that allow for the identification of directions, content, materials, and methods that favor interaction with materials to address problems.

From a theoretical perspective, the continuity of the effort to bridge the frameworks of inquiry-based teaching and those that seek to understand science as a social practice marked by critical interaction is considered relevant, as well as those that start from the performative image of science and address the active role that materials play in the processes of knowledge construction.

Authors' Contribution

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Data Availability Statement

All dataset were generated or analyzed in the current study.

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Manifestation of Attention to Good Scientific Practices and Exemption from Interest and Responsibility

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