DISSERTATION | DOCTORAL THESIS

Titel | Title

Students' understanding of emergent processes in physics within the context of the particulate nature of matter

verfasst von | submitted by

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1. Introduction

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or the atomic fact, or whatever you wish to call it) that all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied (Feynman et al., 2006).

The idea that everything we can touch is made out of very small, non-visible particles is one of the most profound and fundamental concepts in science. Educating students on the particulate nature of matter (PNM) can facilitate their comprehension of a multitude of physical and chemical phenomena. Nevertheless, as evidenced by previous research, the PNM is challenging for students to grasp (Hadenfeldt et al., 2014). A situation that I repeatedly encountered in my teaching of that topic served as the starting point for my dissertation project: When asked what happens to the particles of a liquid in a thermometer when the temperature rises students often reply that the particles expand causing the expansion of the liquid. Students apply the same properties to particles as to macroscopic objects. Wilensky and Resnick (1999) refer to this students' conception as "level confusion".

During my initial literature search, I came across a concept that was new to me at the time and quickly caught my attention: emergence. Emergence is not a term specifically related to physics, but describes various phenomena that are based on the same underlying mechanism: the sum of the behavior of the components of a system (agents) determines the properties of the system as a whole. For example, when many individual birds follow the same set of simple rules, they collectively act as a flock. There is no "leader" bird that instructs the others how to form a swarm; rather, the swarm emerges from the collective action of all the birds at the same time. In physics, emergence can be defined as follows: "*An emergent behavior of a physical system is a qualitative property that can only occur in the limit that the number of microscopic constituents tends to infinity"* (Kivelson & Kivelson, 2016, p. 1).

How does this relate to the original problem of students' misconceptions about the PNM? Following the definition of emergence in physics, we can say that most phenomena related to the PNM are emergent in nature. When we describe the macroscopic systems we encounter in our daily lives, the number of microscopic components always tends to infinity. Even a single drop of water consists of about 100,000,000,000,000,000,000,000 molecules. The behavior of this vast number of molecules determines the properties of water. For example, the faster the molecules move, the higher the temperature of the water. Thus, teaching the PNM always means teaching students about emergent phenomena. Therefore, science education research should focus on finding new ways to teach the PNM that incorporate the idea of emergence.

The main goal of my research project was to find a way to teach the PNM that focuses on the emergent properties of matter. I studied different approaches by interviewing students and documenting their reactions. This allowed me to draw conclusions about what might help or hinder students' learning of the PNM. In addition to finding these theoretical implications, my goal was also to create a concrete teaching-learning sequence that could be used in practice. This approach - contributing to research and practice - reflects my position as both a teacher and a science education researcher.

The purpose of this paper is to provide an overview of the research process and to present my findings. I begin by discussing the theoretical framework for my research. Then I present the research questions that guided the research process. At the heart of the dissertation are the papers that I have written during my project. Most of them have already been published in national and international journals. I conclude with a discussion of these papers, highlighting the main findings and implications for future research and classroom practice, as well as the limitations of my research.

2. Theoretical framework

The starting point for the doctoral research project was the difficulties students had in learning the PNM. In order to gain a better insight into what exactly is challenging students in their engagement with the PNM, the literature on students' conceptions of the PNM was reviewed.

A. Students' conceptions on the PNM

Although the majority of students are familiar with terms such as "atom" or "molecule", they tend to view matter as continuous (Harrison & Treagust, 2006). When they apply particles to their explanation, they often transfer the properties of macroscopic objects to submicroscopic particles (Albanese & Vicentini, 1997; Derman et al., 2019; Griffiths & Preston, 1992). For instance, students often believe that the expansion of water vapor is caused by an expansion of water molecules (Boz, 2006; Lee et al., 1993; Nakhleh, 1992). Additionally, students frequently transfer other properties of objects, such as color or shape also are transferred to particles (Albanese & Vicentini, 1997). As they tend to conceptualize continuous substances, students also encounter difficulties in envisioning the existence of empty space between the particles, a phenomenon known as "horror vacui" (Novick & Nussbaum, 1981; Peuckert, 2006). Additionally, Harrison and Treagust (2006) argued that some of students' misconceptions might be attributed to the use of inappropriate representations of particulate models in science textbooks. In general, atoms and molecules are represented by small colored spheres (Bunce & Gabel, 2002), which might lead students to believe that atoms and molecules are small colored spheres. In contrast, Wiener et al. (2015) proposed typographical representations, representing particles with letters and words to emphasize the model character of these depictions.

A more elaborate explanation for the origin of students' conceptions can be found in conceptual change theories (Posner et al., 1982). For instance, students applying the same properties for particles as for macroscopic objects might result from the blending of scientific knowledge with everyday experiences. Because students simultaneously try to make use of newly learned information while still relying on their intuition derived from experience this conception can be classified as "hybrid" (Vosniadou, 2019). One illustrative example would be students arguing that the particles of salt have a cubic shape because salt crystals always form cubes.

A even more in-depth explanation of students employing the same properties for particles as for tangible objects can be found in the *ontology framework* proposed by Chi (2005, 2013). This framework is based on the premise that misconceptions frequently arise due to students reasoning within the wrong ontology. For example, students may conceptualize heat as a tangible substance rather than as energy. Chi et al. (2012) argue that students utilize a *sequential ontology* rather than an *emergent ontology* when explaining scientific phenomena such as diffusion or heat transfer. This is due to the fact that in everyday life emergent processes are rarely observed, whereas causal processes, where one thing directly leads to another are more prevalent. Using the wrong ontology results for example in students explaining the process of heat transfer by the object losing "hot particles". This "narrative-like" explanation feels more familiar to students (Henderson et al., 2017). To provide an accurate explanation students must first be taught the *emergent ontology*.

B. Design-based research

The primary objective of the doctoral research project was the design and evaluation of a teaching-learning sequence (TLS). As defined by Méheut and Psillos (2004) *a TLS "is both an interventional research activity and a product, like a traditional curriculum unit package, which includes well-researched teaching–learning activities empirically adapted to student reasoning*" (Méheut & Psillos, 2004, p. 517).

Over the past few decades numerous frameworks have been developed in the field of TLS design and research (Psillos & Kariotoglou, 2016). This research project was situated within the methodological framework of design-based research (DBR), which has gained increasing popularity in educational contexts (Tinoca et al., 2022).

DBR takes problems from the practice of teaching and learning as its focus, aiming to contribute to both theory and practice (Bakker, 2019; Brown, 1992). The goals of DBR are twofold: to develop a TLS for classroom practice and simultaneously generate local theories about teaching and learning the respective content (Haagen-Schützenhöfer & Hopf, 2020). To achieve these objectives several iterative "cycles of design, enactment, analysis and redesign" (Design-Based Research Collective, 2003, p. 1) are conducted. The design phase commences with the formulation of a preliminary version of the TLS and the formulation of hypotheses regarding theoretical aspects. Subsequently, the draft version of the TLS is evaluated; either through individual interviews with students or in a classroom setting using questionnaires or video recordings of the instruction. In the final phase of each cycle, data is analyzed in accordance with the type of evaluation. The findings from the initial cycle of the DBR project can then be used to inform the redesign of the TLS at the outset of the second cycle. This cyclical approach is typically repeated several times (Haagen-Schützenhöfer & Hopf, 2020). Figure 1 illustrated the various stages of the DBR project.

The process of DBR is guided by theory-driven design principles (Anderson & Shattuck, 2012; Euler, 2017). Design principles transform general theories of teaching and learning into guidelines applicable to a certain topic (here: the PNM). As DBR aims at contributing to theory and practice these guidelines should not only inform science education researchers but also be a useful tool for practitioners. As outlined by Haagen-Schützenhöfer and Hopf (2020), there are two distinct types of design principles: general and domain-specific.

General design principles are those that define theoretical aspects of teaching and learning in general, which are of particular important for the DBR project. The general design principles employed in this study are as follows: 1) the development of the TLS is based on students' conceptions, 2) conceptual change is triggered by using an ontological conceptual change strategy rather than by cognitive conflict, 3) learners are seen as active participants in the learning process, 4) learning starts with students' subjective perceptions and leads to abstract scientific concepts, and 5) the use of learner-friendly representations.

Domain-specific design principles in this DBR project specifically refer to teaching and learning the PNM. These principles relate to one or more of the general design principles and are based on implications derived from theory. Domain-specific design principles can be interpreted as a hypothesis guiding the research process; they can be refined, revised, or discarded in the light of new evidence (Haagen-Schützenhöfer & Hopf, 2020). The development of the domain-specific design principles in the DBR project is described in Chapter 5A.

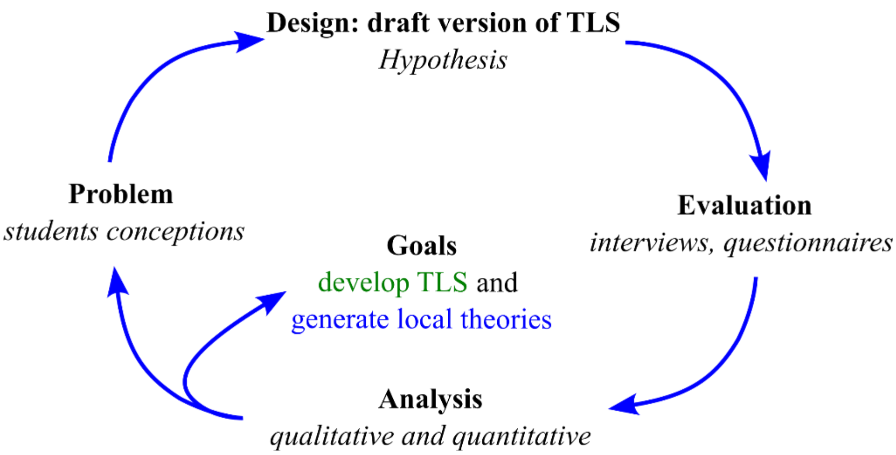

Figure 1: Design-based research process
(source: own illustration adapted from Haagen-Schützenhöfer & Hopf, 2020)

3. Research questions

The methodological framework of DBR was employed to facilitate the completion of several cycles of design, evaluation, and analysis. Figure 2 provides an overview of the iterations that were conducted throughout the DBR project.

The following question served as a guideline for the research process throughout the doctoral project:

RQ 1: How can students' understanding of emergent properties within the context of the PNM be improved?

In order to evaluate this question, an initial set of domain-specific design principles was developed: 1) the use of experiments as the starting point for the introduction of the PNM (Fischler & Rothenhagen, 1997; Hofmann & Erb, 2018), 2) the use of the term "building block" instead of "particle" (Pfundt, 1981) and, 3) the use of typographic representations instead of spherical representations of atoms and molecules (Wiener et al., 2015). This resulted in the formulation of two more research questions, which are related to RQ 1 and respectively focus on a specific aspect of teaching the PNM:

RQ 2: What experiments convince students of the applicability of the particulate nature of matter?

RQ 3: Do typographic representations promote scientifically appropriate ideas about the particulate nature of matter?

Based on the domain-specific design principles the method of educational reconstruction was applied (Kattmann et al., 1996). Educational reconstruction brings together content knowledge with students' conceptions regarding that content. This approach allows for the structuring of content knowledge in a way that specifically takes students' conceptions into account, thereby making it more accessible to students. This structure is given by *key ideas* representing the core concepts to be learned by students in a specific order. In the initial design phase of the DBR project (see Figure 1) two key ideas were formulated, which were then further developed and expanded throughout the doctoral research project.

To assess students' understanding of the key ideas they were transformed into an interview protocol according to the probing acceptance method (Jung, 1992; Wiesner & Wodzinski, 1996). This method comprises four consecutive steps: 1) the interviewer explains the key idea, 2) the student rating the acceptance of the key idea, 3) the student paraphrasing the key idea, and 4) the student solving at least one task related to the key idea. The data from these interviews was then analyzed using evaluative qualitative content analysis (Kuckartz & Rädiker, 2023). For the analysis, I specifically focused on students' use of the PNM. Accordingly, three categories based on students' mental models of matter (Johnson, 1998) were used for coding: "continuous model", "hybrid model" and "particulate model". The results of the analysis regarding students' views toward different experiments on the PNM were published in Budimaier and Hopf (2022) and can be found in chapter 4. Moreover, the analysis of students' views on different representations of matter was published in Budimaier and Hopf (2023a) (see Appendix C).

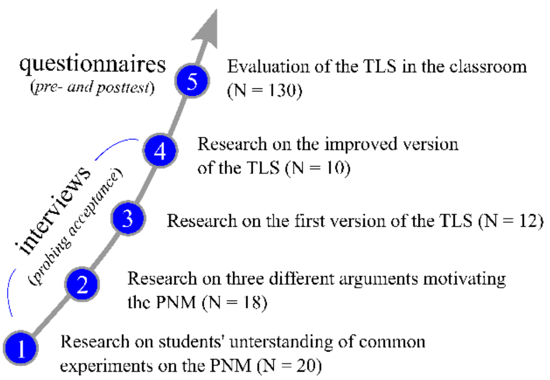

Figure 2: Iterations in the DBR project (source: own illustration adapted from Haagen-Schützenhöfer & Hopf, 2020

Data from the initial cycle in the DBR project suggest that students have great difficulties when attempting to comprehend both an experiment and the PNM simultaneously. Consequently, I concluded that experiments are not the most effective method of introducing the PNM to students and the first design principle was discarded. In search of an alternative I considered other arguments motivating the fact that everything is made out of non-visible particles. The most promising approach appeared to be the use of crystal structures (Ebenezer, 2001; Franzbecker & Quast, 1975; Smithenry, 2009). For comparison, I decided to also use another common approach: images created by a scanning tunneling microscope (STM) (Furlan, 2009; Margel et al., 2004). Moreover, many students in the interviews appeared to possess a "hybrid model" of matter, integrating the idea of particles with a continuous perception of matter. Because of that, I decided to emphasize the emergent aspects of the PNM more explicitly. Following the redesign phase at the beginning of cycle 2 the domain-specific design principles were as follows: 1) using crystal structures as the starting point for the introduction of the PNM, 2) using STM images as the starting point for the introduction of the PNM, 3) using the term "building block" instead of "particle", 4) emphasizing the emergent aspects of the PNM, and 5) using typographic representations instead of spherical representations of atoms and molecules. This led to the formulation of another research question:

RQ 4: Does learning about crystal structures serve as an effective context for developing a conceptual understanding of the relationships between macroscopic and submicroscopic levels of matter?

The domain-specific design principles were again employed to formulate key ideas based on the method of educational reconstruction. In cycle 2 of the DBR project, four key ideas were evaluated with students using the method of probing acceptance. In contrast to the approach taken in cycle 1, where students were presented with a series of experiments, this time three different arguments were employed to introduce them to the PNM. These were: 1) the formation of snow crystals, 2) the formation of salt crystals, and, 3) an STM image of graphite. The data indicate that students were able to connect the macroscopic and submicroscopic levels of matter in the context of the snow and salt crystals but not with the STM image of graphite. However, all three arguments fostered students' use of a particulate model more than experiments.

As a result, I decided to use crystal structures for the introduction on the PNM in my TLS and discarded the idea of using STM pictures. Furthermore focusing on the emergent aspects of the PNM seemed to have paid off as students' overall performance increased in comparison to cycle 1. Therefore the TLS is based on the following design principles: 1) using crystal structures as the starting point for the introduction of the PNM, 2) using the term "building block" instead of "particle", 3) stressing the emergent aspects of the PNM, and 4) using typographic representations instead of spherical representations of atoms and molecules. Following the framework of DBR, two additional cycles of interviews were conducted to further refine the TLS. The results of cycles 2 to 4 in the DBR project were published in (Budimaier & Hopf, 2023b) and can be found in chapter 4.

The final step in the doctoral research project was to evaluate if the feasibility of the TLS in a classroom setting compared to interviews with individual students. This led to the final research question:

RQ 5: Is the developed TLS, based on empirically evaluated design principles, effective in promoting students' use of the PNM?

To address this question, teaching materials were developed for classroom instruction. These materials included students' worksheets, teacher demonstrations and presentations, small hands-on activities, and 3D-printed crystal structures. To assess students' utilization of the PNM before and after instruction, a pre- and posttest was employed. Several teachers participated in the study with their classes. The results were submitted for publication in *Physical Review Physics Education Research*.

4. Articles written within the scope of the doctoral thesis

This chapter presents the three articles that were written within the scope of the doctoral thesis. Articles A and B are already published, and article C is submitted for publication in *Physical Review Physics Education Research*.

All articles were written by the first author, who is also the author of this doctoral thesis. This included literature research and creating materials for the research project as well as data gathering and analysis. Furthermore, the first author acted as the corresponding author for all articles and handled the submission and revision of the manuscripts.

The supervisor's contribution consisted of giving recommendations regarding research questions, literature, and methods as well as reading all manuscripts and repeatedly providing feedback and suggestions for improvement.

A. Budimaier, F. & Hopf, M. (2022). Students' Ideas on Common Experiments About the Particulate Nature of Matter. *Journal of Baltic Science Education*, 21(3), 381–397. https://doi.org/10.33225/jbse/jbse/22.21.381 - **published**

B. Budimaier, F. & Hopf, M. (2023). Development of a new teaching-learning sequence on the particulate nature of matter using crystal structures. *Physical Review Physics Education Research*, 19(2). https://doi.org/10.1103/PhysRevPhysEducRes.19.020169 - **published**

C. Budimaier, F. & Hopf, M. (submitted). Evaluation of a new teaching-learning sequence on the particulate nature of matter using crystal structures. *Physical Review Physics Education Research.* – **submitted (April 26th, 2024)**

Budimaier, F. & Hopf, M. (2022). Students' Ideas on Common Experiments About the Particulate Nature of Matter. Journal of Baltic Science Education, 21(3), 381–397. https://doi.org/10.33225/jbse/jbse/22.21.381

STUDENTS' IDEAS ON COMMON EXPERIMENTS ABOUT THE PARTICULATE NATURE OF MATTER

Abstract

Research on students' thinking about the particulate nature of matter has shown that students find it difficult to connect the macroscopic with the sub microscopic world. Although they have heard about atoms, students stay within a continuous model of matter or attribute macroscopic properties to particles. The research presented focuses on the arguments students make, when they have to explain experiments on a sub microscopic level. The question is if experiments convince students of the applicability of the particulate nature of matter. Therefore the researchers conducted twenty interviews according to the method of probing acceptance with students from lower and upper-secondary school. Every interview featured one of five experiments, commonly used in teaching. The goal was to see if the experiments helped students to successfully apply the particulate model of matter. Students' answers were coded using qualitative content analysis. The results of this research show, that explaining experiments on a sub microscopic level proves a great challenge for students. None of the five experiments seems to be a good starting point when engaging students with the particulate nature of matter for the first time. Therefore further research should focus on other ways of introducing this difficult topic to students.

Keywords

classroom experiments, conceptual change, particulate model, probing acceptance

Introduction

In the physics classroom, experiments are commonly used to teach scientific phenomena. The empirical evidence of the experiment should convince students of the underlying scientific idea. Fostering conceptual change in the context of the particulate nature of matter, students should become convinced of the idea, that numerous scientific phenomena can be explained through interactions of atoms and molecules. While scientists and science teachers may be comfortable applying this idea to observable phenomena, the question remains if experiments can easily convince students to do likewise. Learning via experiments means that one needs to have the skills to interpret the observations made in the experiment in the light of scientific theories.

Students face great difficulties when learning about the particulate nature of matter because their experiences from everyday life are based on a continuous perception of matter (Albanese & Vicentini, 1997; Flores-Camacho et al., 2007; Harrison & Treagust, 2006; Johnson, 1998). However, an established understanding of the particulate nature of matter forms an important basis for many scientific concepts, like states of aggregation, diffusion, or heat transfer. Therefore it is considered to be a key concept in science education (National Science Teaching Association, 2017; OECD, 2019) and science education research has offered much effort in documenting students' ideas about the particulate nature of matter (Hadenfeldt et al., 2014; Özmen, 2013; Talanquer, 2009).

Students' Conceptions on the Particulate Nature of Matter

Students exhibit a wide range of conceptions that often interfere with intended learning about the particulate nature of matter. Students often misunderstand even what counts as "matter" (Babai & Amsterdamer, 2008; Krnel et al., 2005). For example, many students do not classify gases as matter but rather associate them with properties of energy forms (Lee et al., 1993; Stavy, 1991). Students in secondary school know words like "atom" and "molecule" and can even describe how these two terms relate. They can tell you that atoms are the smallest portions of matter. Nevertheless, they attribute the same properties to atoms and molecules as to the substance they compose (Albanese & Vicentini, 1997; Derman et al., 2019; Griffiths & Preston, 1992; Lee et al., 1993; Nakhleh, 1992). As an example, many students assume that the size of water molecules changes during phase transitions (Boz, 2006; Griffiths & Preston, 1992; Lee et al., 1993; Nakhleh, 1992). Furthermore, some students show what is known as "horror vacui", the idea that "nature abhors vacuum" (Harrison & Treagust, 2006). This idea goes back to the Greek philosopher Aristotle, who opposed Democritus' Atomism, which also included the conception of a vacuum. Like Aristotle, students seem to abhor the idea of a vacuum, consequently describing matter as continuous.

Students' thinking about the particulate nature of matter can be categorized into different mental models (Flores-Camacho et al., 2007; Johnson, 1998; Margel et al., 2008). Novices tend to see matter as continuous, having no or very limited ideas connected to the particles. Students on intermediate levels are more aware of the presence of particles, but they attribute the same macroscopic properties as the substance they compose. Naïve ideas like the size of molecules changing during phase transitions fall in this category. Scientific ideas, like the states of aggregation resulting from the collective properties of molecules, are only featured on the highest level.

Changing Students' Conceptions

Science education research has developed various approaches to rectify the students' conceptions discussed above. Therefore, researchers have tried to find the underlying structures of students' reasoning. They describe students' ideas about science either as loose fragments (1993; diSessa, 1993; diSessa et al., 2004), synthetic models (Vosniadou et al., 2001; Vosniadou, 2012, 2019; Vosniadou & Skopeliti, 2014; Vosniadou & Verschaffel, 2004) or an incorrect evaluation on the ontological level (Chi, 2005; Chi et al., 2012; Chi, 2013; Henderson et al., 2017). Making use of multiple perspectives on conceptual change might allow gaining further insight into students thinking about the particulate nature of matter (Chiu & Chung, 2013; Harrison & Treagust, 2001; Stamovlasis et al., 2013).

diSessa (1993) argued, that the answers students give depend strongly on the specific context of the question, concluding that student ideas about science can be seen as loose fragments, that are applied flexibly depending on the situation. The *knowledge-in-pieces* approach assumes that people in general have a set of simple rules they use when making an argument. These rules, referred to as *phenomenological primitives (p-prims)*, are generated from everyday experiences and have proven themselves many times in different contexts. The different p-prims are not structured like scientific concepts but are often loosely connected or even inconsistent with each other. An example would be *Ohm's p-prim*: to reach something in life you have to overcome resistance, the higher the resistance the more effort you have to take to reach your goal. According to Smith et al. (1994), student conceptions originate from applying *p-prims* to new situations, in a way that is not compatible with scientific reasoning.

Vosniadou (2012), on the other hand, argued that students construct *synthetic models* when connecting their existing ideas with scientific explanations. While trying to add the new scientific information to their prior knowledge, students construct a hybrid model that features aspects from everyday experiences as well as scientific ideas. For example, as mentioned above, students try to integrate molecules into their continuous conception of matter, by thinking of the molecules as suspended in another substance. Therefore, this misconception can be described as a synthetic model. As Vosniadou (2012) pointed out, "traditional instruction does not provide students with the necessary background information" (p. 9) so that they can acquire new ontological categories.

Chi (2005) also discussed that problem and drew attention to the fact that many misconceptions are based on an improper evaluation of the ontological level. For example, substance-based conceptions are evidenced across various topics in physics. Force, heat, or light are seen as substances that can be used to change something while being used up in the process (Reiner et al., 2000; Sanmarti et al., 1995). Accordingly, a conceptual change aimed at changing the ontological category could be promising in many contexts. Learners would first need to be made aware that there are two different types of processes called *sequential* and *emergent* (Chi et al., 2012). Following the definition by Kivelson and Kivelson (2016), an "emergent behavior of a physical system is a qualitative property that can only occur in the limit that the number of microscopic constituents tends to infinity" (p. 1). For example, the distinct differences between phases of matter occur only when the system contains a huge number of molecules. Chi (2013) concluded that students do not have these ideas about emergence, because they cannot observe them in their everyday lives. Therefore, it is necessary to add this missing emergent schema to students thinking, by clearly separating it from the direct schema used to explain sequential processes. This might be done by illustrating this distinction with everyday examples and natural phenomena, for example, the construction of a skyscraper as a sequential process and the swarm intelligence of fish as an emergent process (Chi et al., 2012; Henderson et al., 2017).

Learning About the Particulate Nature of Matter with Experiments

Only a few studies regarding student learning via experiments in the context of the particulate nature of matter have been conducted so far. When evaluating the degree of coherence found in students' conceptions, Gómez et al. (2006) used three simple experiments to demonstrate certain aspects of the particulate nature of matter. Hofmann and Erb (2018) asked undergraduate university students to rate the persuasiveness of experiments on the particulate nature of matter. Other studies focused on digitalized experiments in a software framework (Snir et al., 2003) or with interactive videos (Glatz et al., 2020). However, none of the research above compared secondary students' views on experiments commonly used to convince them of the particulate nature of matter.

Research Question

Research on students' conceptions has shown, that although students have already heard of atoms, molecules, and particles, they do not apply this knowledge properly. For example, when students are asked to explain their observations of an experiment, they often use macroscopic properties to explain what happens to particles. Different frameworks on conceptual change allow for different interpretations of this problem. Students might lack an emergent schema necessary for the correct interpretation of experiments demonstrating the particulate nature of matter. There might be an underlying p-prim, that is activated during the presentation of such an experiment. Finally, it is possible that teaching about the particulate nature of matter results in students constructing a synthetic model during their explanation.

Addressing this problem, the research presented focused on students' reasoning while explaining experiments commonly used to convince them of the particulate nature of matter. This research aimed to find guidelines for teaching, how the particulate nature of matter should be presented to students so that they might recognize it as a useful tool for explaining scientific phenomena. The question was if students, whose interpretations are often made based on everyday conceptions, have the necessary skill-set to correctly interpret experiments, designed to convince them of the particulate nature of matter. This led to the following research question:

> *What experiments convince students of the applicability of the particulate nature of matter?*

The research results were analysed within the framework of conceptual change theories.

Research Methodology

General Background

According to the research question, an intervention based on experiments was designed. The main criterion for these experiments was that one should only be able to fully explain the observed phenomena by correctly applying the idea that everything is made out of particles. Experiments fulfilling the above criterion were searched in science education literature (Fischler & Rothenhagen, 1997; Gómez et al., 2006; Harrison & Treagust, 2006; Hofmann & Erb, 2018; Jadrich & Bruxvoort, 2010; Sieve, 2016; Wilms, 2011).

A detailed list of all experiments taken from the literature is available in the Appendix. Some of them might in part be explained on a macroscopic level, but when looking into further detail still need the particulate nature of matter.

There are different arguments to support the idea of a particulate model of matter (Fischler & Rothenhagen, 1997; Hofmann & Erb, 2018). For each of these arguments, an experiment that is commonly used in teaching was chosen for the study. A field emission microscope, for example, is a complex experimental setup that is not available in every school, which is why it was not considered in the context of this research. Table 1 gives an overview of the five experiments and the arguments that are supported by them. A more detailed description of the experiments is available in the Appendix.

Table 1

Experiments on the Particulate Nature of Matter

Experiment	Argument	Reference
Observation of Brownian motion under a microscope	Particles are in constant motion	(Fischler & Rothenhagen, 1997)
Distillation of a coloured solution	First-order phase transitions can be explained using the particulate model	(Fischler & Rothenhagen, 1997)
Volume change of a food pouch during heating and cooling	There is empty space between particles	(Sieve, 2016)
Propagation of an oil droplet on a water surface	Particles have a certain size	(Harrison & Treagust, 2006)
Egg floating in saltwater	Particles can form chemical bonds	(Harrison & Treagust, 2006)

Sample Selection

Several factors were taken into account for the sample selection. The researchers only focused on students from secondary school. Conducting the research in Austria, the national curriculum sets the topic of the particulate nature of matter in the sixth and tenth grades. Because several misconceptions on the particulate nature of matter are reported in the literature to prevail even at the level of upper secondary school (Adbo & Taber, 2009; Novick & Nussbaum, 1981; Osborne & Cosgrove, 1983; Treagust et al., 2010), a comparison between lower- and upper-secondary school was of interest.

The selection of the students was influenced by the Covid-19-pandemic, which made it impossible to visit schools due to restrictions by the federal government. However, the first author being a teacher in a secondary school in Vienna made it possible to carry out the study in this school. The school is located in a district with very high socioeconomic status and students, in general, are highly supported in their learning by their parents. Twenty students from four different classes (sixth and tenth grade) volunteered to take part in the interviews. The sample was equally divided into students in the sixth and tenth grades. Students in both groups already were instructed about the particulate nature of matter in their previous physics classes.

According to regulations in Austria, an ethics committee approval was not necessary for this study. Nevertheless, necessary precautions regarding data collection were taken care of. The headmaster of the school, where the interviews took place, approved the implementation of the study. Before participating in the interviews, students received a letter to their parents, which shared the most important information about the study. At the end of the letter, the researchers asked for the parents' consent, allowing their child to participate in the study. Only students who handed in a signed declaration of consent, participated in the study. No personal data was collected from the students during the interviews.

Instruments and Procedures

Examining students' reasoning with the five experiments listed in Table 1, interviews were conducted according to the method of probing acceptance (Jung, 1992; Wiesner & Wodzinski, 1996). This method features a combination of a micro-teaching session and a one-on-one interview. Instead of just asking the students questions, the interviewer presents an explanation, intending to find educational obstacles within the topic being presented. Probing acceptance always features three consecutive steps: 1) rating the acceptance of the explanation, 2) paraphrasing the explanation, and 3) solving at least one task, where the student has to make use of the explanation.

Interviews started with the demonstration of one of the five experiments listed in Table 1. At first, the interviewer did not mention particles, atoms, or molecules but just asked the student, if they have an explanation for what had just happened in the experiment. After the student answered, the interviewer then explained the experiment by making use of the idea, that everything that can be touched is imagined to be composed of very small, non-visible building blocks. After having heard the explanation, the student was asked to tell the interviewer if the student found the explanation to be sensible and plausible. After that, the student was asked to paraphrase the explanation. This paraphrase indicated what part of the information seemed most relevant to the student and if they had integrated scientific terminology into their explanation. If the student had difficulties, the interviewer tried to lead the student into reconsidering the problem by asking further questions. Ensuring that the student understood the explanation, the interviewer then gave them two tasks, where they had to apply their knowledge of the idea to a new problem. In order to see if the student had been convinced by the idea that everything is composed of very small building blocks, the interviewer asked if the student is also composed of them. Furthermore, the interviewer asked why an inflated balloon shrinks over time, to get an insight into students' perception of empty space between particles. Table 2 shows one of the interview guidelines.

Each interview lasted for 15 to 25 minutes. The interviews were recorded with a voice recorder and subsequently transcribed.

Table 2

Interview Guideline for the Experiment "Brownian Motion"

Experiment start	*First, I want to show you an experiment. I mixed water and milk and put a little drop of that mixture under the microscope. If you now look through the microscope, you can see little circular fat droplets moving around in water. Can you explain to me, why these fat droplets are moving?*
Explanation	*Everything that can be touched is imagined to be composed of very small, non-visible building blocks. This experiment gives evidence of that because we assume, that the fat drops move due to the movement of the building blocks of water. The building blocks are too small to see, but without them being there and moving around, we cannot explain the movement of the fat droplets.*
Acceptance	*What do you think about it? Do you think this idea makes sense?*
Paraphrase	*Please repeat in your own words what I have just explained to you.*
Task 1	*If everything is composed of very small non-visible building blocks, does that also mean that you are composed of them?*
Task 2	*Why does an inflated balloon shrink over time?*

Data Analysis

The researchers analysed the interviews using evaluative qualitative content analysis (Kuckartz, 2018). At first, the six items listed in the interview guideline (Table 2) were coded with a deductive approach. For the first question, students' answers were coded whether they were able to explain the experiment on a macroscopic level. Concerning student acceptance of the explanation, three deductive categories were used: "fully accepted", "accepted with restriction" and "not accepted". For the other items, students' answers were coded based on their use of a particulate model of matter, similar to other studies (Haidar & Abraham, 1991; Williamson et al., 2004). Based on their mental model of matter, students' answers were coded as "particulate model", "hybrid model" or "continuous model". The code system for one of the items had to be refined by an inductive approach. When asked if the human body is also composed of particles, some students reacted by showing negative emotions. Since these students still accepted the particulate nature of matter, there was no clear correlation between negative emotions and any of the three deductive codes. Consequently, the coding system for this question was altered, to include students' emotional reactions.

Table 3 shows an overview of the coding scheme including an explanation of which codes were applied in which circumstances. An overview of the coded data material is provided in the form of a code matrix in Table 4. This type of representation was derived from other physics education research studies (Burde, 2018; Haagen-Schützenhöfer, 2016; Wiener et al., 2015; Zloklikovits & Hopf, 2021). Intercoder reliability was also determined by having a colleague from the authors' research group code ten percent of the interviews. Results were compared with the coding of the researchers and Cohens-Kappa was calculated to be $\kappa = 0.74$. According to Landis and Koch (1977), this represents substantial intercoder-agreement.

Table 3

Coding System

	2	1	0
Experiment macro	The student correctly explains the experiment on a macroscopic level.	The student explains the experiment in part correctly on a macroscopic level.	The student can not explain the experiment on a macroscopic level.
Experiment micro, paraphrase, task 2	The student uses terms such as atom, molecule, particle, etc. Furthermore, phenomena on the macroscopic level are correctly traced back to the behaviour of particles.	The student uses terms such as atom, molecule, particle, etc. There is the idea that the particles are within a continuous medium and/or properties of substances (e.g. volume, density, temperature, ...) are transferred to particles.	The student does not use terms such as atom, molecule, particle, etc. but rather terms describing macroscopic quantities (e.g. volume, density, temperature, ...).
Acceptance	The student rates the explanation of the interviewer positively without any restrictions.	The student rates the explanation of the interviewer positively but also mentions some restrictions.	The student rates the explanation of the interviewer negatively.
Task 1	The student describes the idea with positive adjectives (e.g. cool, good, interesting).	The student describes the idea with neutral adjectives (e.g. comprehensible, useful).	The student describes the idea with negative adjectives (e.g. creepy, awkward, scary).

Research Results

Students found it very difficult to link the behaviour of the particles with the observations of the experiment. Only three out of 20 students used "particle" or a similar word when explaining the experiment when it was first shown to them at the beginning of the interview. None of the participants explained the experiment by correctly linking observable phenomena to the behaviour of particles. However, some of the interviewees were able to explain the experiment (in part) at this point on a macroscopic level without mentioning particles. That was especially the case for the experiments "distillation of a coloured solution" and "volume change of a food pouch". As mentioned before, it is to some extent possible to explain the experiments on the macroscopic level; the power of the particulate nature of matter is that it allows for a deeper level of understanding. Students' acceptance of the idea that "everything is made out of non-visible building blocks" was overall positive. However, when looking at the paraphrases of the explanation of the experiment (see Table 4), only six of the students were able to reproduce the explanation correctly.

The following analysis provides a more detailed insight into students' learning difficulties when confronted with one of the five experiments. At first, the "Acceptance" and "Paraphrase" are discussed, followed by the answers to the two tasks. Because there were only a few clear differences between the responses of the 6th-graders and those of the 10th-graders, responses from both groups are discussed together; at points where differences were observed between the two groups, this is indicated.

Table 4

Coding Matrix

	Distillation				Brownian motion				Food pouch				Oil patch				Egg & saltwater			
Grade	**6th**		**10th**		**6th**		**10th**		**6th**		**10th**		**6th**		**10th**		**6th**		**10th**	
Participant	**O2**	**R2**	**F2**	**G2**	**L3**	**M3**	**A3**	**B3**	**C4**	**S4**	**I4**	**J4**	**N5**	**U5**	**D5**	**T5**	**H6**	**V6**	**K6**	**Q6**
Exp. macro	1	1	1	2	0	0	0	0	1	2	1	1	0	0	0	0	0	0	2	0
Exp. micro	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Acceptance	2	2	1	1	1	2	2	0	2	2	2	1	2	2	2	0	2	2	2	2
Paraphrase	1	2	1	2	0	2	1	1	2	2	1	1	1	1	1	0	1	1	2	1
Task 1	1	1	0	1	2	2	2	0	0	2	1	0	0	1	1	0	1	1	1	1
Task 2	1	0	2	0	0	2	1	2	2	0	2	2	0	1	0	1	1	0	0	2

Note. Participants are ordered in the sequence the interviews were conducted (A being the first interview, V the last interview). Numbers indicate the experiment demonstrated in that interview, for example the "Brownian motion" experiment being number three. Two interviews had to be removed, to ensure an equal distribution of participants throughout the experiments.

Distillation of a Coloured Solution

All four students were able to explain the experiment without mentioning particles, the scientifically most appropriate explanation being the following:

> *Well, I suppose that the water (.) when it boils evaporates, so that evaporates and the colour powder is probably (.) very dissolved but will probably not evaporate with it and remain in the glass (ok) and the water vapor just goes over the tube into the test tube on the other side.* (G2:2)

Two of the students fully accepted the idea of particles, stating it as being "cool" (O2:14) or "a good explanation" (R2:12). The other two were coded as only "accepting with limitation" because although they in general accepted the idea, they added something that was disturbing them. For one student, there was the problem that "it always goes smaller somehow, it always goes smaller, smaller, smaller" (F2:12) and they, therefore, had the feeling that there is never a stop to the particles still becoming smaller. The second student found the idea to be "so very different from what we know of our world" (G2:11).

Looking at student paraphrases there can be found that the student, with the most appropriate explanation, in the beginning, added the idea of particles making the following statement:

> *[…] so the water particles were mixed with the colour particles, so with the particles of the dye and when boiling, just the water particles (.) have become gaseous and have evaporated (.) and risen through the tube and the water particles do not and they have remained in the vessel (.) and that, the the water is then just clear again when it is on the other side.* (G2:15)

Therefore, one might assume that understanding the experiment on a macroscopic level provides a basis for a more profound understanding of the experiment on a sub microscopic level.

Two of the four student paraphrases were coded as representing a hybrid model. These paraphrases did not make use of the particulate nature in full, but just described the experiment having as "something to do with particles":

> *Because of the particles, as you said, just this water particle comes so it evaporates in there, and then it condenses in there and the red liquid just remains.* (O2:20)

This example showed that the student remembered the interviewer talking about particles and thought that this piece of information should therefore be part of the paraphrase as well. However, despite using the word "particle", the student did not apply conceptual knowledge about the particulate nature of matter in the paraphrase, suggesting that they did not understand how the observations made in the experiment are connected to particles.

Observation of Brownian Motion

Each of the four students participating in the interview with the Brownian motion experiment seemed to interpret what they observed in the microscope differently. When asked to explain the observable phenomenon, in the beginning, they came up with a variety of explanations for the movement of the fat droplets. For example, one student had the idea that there is air between the fat droplets allowing them to move around. Another mentioned bacteria as the reason for the movement. Only one of the students used the word "molecules" for the explanation, but in explaining the fact that the fat droplets do not mix with water. In general, the students seemed to be more fixated on the formation of the fat droplets than on their movement. This fixation persisted even after the students had heard the explanation by the interviewer, as the following example demonstrates:

> ***I:*** *Okay well, how would you explain that again in your own words, what's happening. Could you repeat that again? [...]*
> ***R:*** *So milk and water have a different density, and water is not as dense as milk and in milk, there are also fat droplets, fat, fat inside and water is yes, (.) like this word there is in chemistry this lipo, liponis, lipo, yes never mind then you also see that that, that water and milk, milk? milk! can't mix because they just have a different structure and water just this lipo, lipid, or what it's called, is just fat repellent.*
> ***I:*** *Lipophobic*
> ***R:*** *Yes, exactly, lipophobic. Water is just fat repellent, and they just can not mix and that they are constantly in motion can be seen just by these (...) circles on the moving things as you have already said and that is just I think, I do not know, so because of the air and the particles are still in constant motion and in irregular and yes* (A3:19-22)

Although the student went into detail about why fat and water do not mix, the explanation for the movement of fat droplets continued to be based on the idea that the droplets move through air. Furthermore, it remains unclear, if the student was using the word "particles" just as a synonym for "fat droplets" or if the student was thinking about the water molecules constantly moving around. Another student also stated that it is "the main idea that water and oil, fat somehow, do not mix somehow and then all the time they push each other apart" (B3:28). So in the case of this experiment, the most salient idea for students seemed to be that a constant force due to the lipophobic nature of water caused the fat droplets and the water to repel each other. Although this idea of lipophobic repulsion could be connected to the idea of water particles pushing fat particles, these students gave no evidence to suggest that it was for them. Their explanation was entirely macroscopic in nature. Another student also had an idea based on repulsion, although it was less elaborated: "Well, maybe because the one (...) has magnets in it? So, the one plus magnet, the other a minus and they just repel sometimes somehow" (L3:22). Only one student mentioned the idea, that the fat droplets move because "they are pushed by small particles" (M3:12).

Volume Change of a Food Pouch During Heating and Cooling

All of the four students were able to explain this experiment to some extent on a macroscopic level at the beginning of the interview. One of them showed surprisingly good (albeit macroscopic) scientific reasoning even at this early point: "Because the methylated spirits that are inside, they heat up because the water is so hot, and that causes them to expand and inflate, and that causes the package […] there to inflate" (S4:6). Another explained that the food pouch expanded because "the air expanded" (C4:14). One of the four students mentioned particles to explain the fact that the food pouch expands when put into the hot water. However, the explanation was still coded as a "hybrid model" because properties of substances were transferred to particles:

> *Through the methylated spirits, so I have no idea, but it, the particles, which yes, when it gets warmer, particles normally always expand and as I hold it in the water, in the hot water, the particles that are in this squeeze expand, that's why it opens up and then when I put it back in the cooler, they contract again* (J4:2).

This student stuck to this conception even after hearing the explanation from the interviewer. The student also added another aspect to the paraphrase, that had not been mentioned by the interviewer:

> ***I:*** *How, how would you describe that?*
> ***R:*** *We put the methylated spirits in it and since particles expand and move in the warm water (..) it spreads, so this (.) bag fills with air or the with? Yes, with air and when I cool it down again, then it contracts again.*
> ***I:*** *Okay, and how would you say it fills with air, how does the air get in? I have closed it tightly at the top, screwed it shut, and it has no other hole.*
> ***R:*** *(.) Maybe it absorbs through the water, I don't know* (J4:7-10).

While in the first explanation the student used the expansion of the particles to explain why the food pouch expands in hot water, they then thought that the pouch also fills with air. It seems that this student had what is often referred to as "horror vacui", the fear of the absence of matter. It seems likely that the student was uncomfortable with the idea from the interviewer, that there is vacuum between the molecules of the methylated spirits and hence imagined that somehow air was getting inside the pouch and causing its expansion. In other words, this seems to be a concept the student spontaneously constructed during the interview, as opposed to something they had already thought about beforehand. When asked by the interviewer how the air might have gotten into the pouch, the student admitted to not know, but came up with the new idea, that the air might have been absorbed through the water.

Two of the four students progressed from their first explanation of the experiment to the paraphrase they gave after hearing the explanation of the interviewer. One student first explained that the food pouch expanded because "the air expanded" (C4:14). In the paraphrase, this student then stated that "depending on the temperature, the distance and the particles themselves change" (C4:32). Although it seems the student was transferring properties of substances to properties of particles when specifically asked if the particles themselves change their temperature the student answered: "No, I rather suspect the velocity and the energy of the particles increases" (C4:36). Therefore, it can be assumed that the student obtained at least a rough idea of the emergent nature of the increasing volume in the experiment. The second student also initially gave a correct explanation at the macroscopic level. After the interviewer told the student about the particulate nature of matter and explained the experiment, the student correctly included that information into the paraphrase, stating that the "particles that make up the methylated spirit move faster and thus the distance between them increases" (S4:16).

Propagation of an Oil Droplet on a Water Surface

As can be seen in Table 4, this experiment seemed to be the most difficult one for the students in this study. None of the four students used "particle" or a similar word in their explanation at the beginning, nor were any of the students able to explain the phenomenon on a macroscopic level. Although three of the students accepted the explanation from the interviewer, none of them were able to paraphrase it correctly.

Seeing an experiment and hearing an explanation seemed insufficient to enable students to use the particulate nature of matter when they gave an explanation. These students did not obtain more than a rough idea about how the experiment has something to do with particles, as demonstrated by the following exchange:

> ***Interviewer:*** *Could you repeat what I have just explained to you about this experiment and also try to explain it in your own words.*
>
> ***Respondent:*** *So oil spreads in water only for example in so, there is a stain, and (...) it forms such atoms. Did you mean atoms yes? And (...) that's all I understood.*
>
> ***I:*** *Ok. Yes, because you said with the atoms, yes? What do you know about that or why, what does that have to do with atoms here?*
>
> ***R:*** *There are different atoms, for example like (..) H or O for example yes (..) hydrogen and oxygen*
>
> ***I:*** *Very good, there are different elements (yes) but what does this experiment have to do with atoms so to speak?*
>
> ***R:*** *Because (...) yes, for example, water atoms do not mix with oil, or what are the atoms called? These with, which are with oil, so together, they simply can not mix* (U5:13-18).

On the one hand, this student had some prior knowledge about atoms and elements, and they could connect this knowledge with the topic being presented in the interview. On the other hand, the student noted that the only thing understood from the explanation given by the interviewer was that atoms are "formed" and the student failed to elaborate what that might mean. In trying to make sense out of the first explanation from the interviewer prior knowledge of the student about the existence of different kinds of atoms, was activated. With this extra information that had not been mentioned by the interviewer, the student concluded that "water atoms" and "oil atoms" do not mix and was thereby content with an explanation for why the oil drop in the experiment did not mix with the water. However, this was not the aim of the experiment; rather, the experiment intended to show that the oil drop only forms a finite area on the water surface. The student had completely missed the point, walking away only with a vague idea that the experiment "has something to do with particles".

Egg Floating in Saltwater

None of the four students used "particle, "atom" or a similar word in their explanation of the experiment at the beginning of the interview. However, one of them gave a scientifically correct explanation on the macroscopic level:

> *Because the, so through the salt content in the water, the density of the water has become even tighter, so even denser, the water is denser and there the egg can now swim […]* (K6:6).

After hearing the explanation of the interviewer all of the four students fully accepted the idea, that everything is "composed of very small, non-visible building blocks". When paraphrasing the explanation given by the interviewer, they tried to include the underlying concept of a particulate model of matter, as the following two examples illustrate:

> *So it became from the salt with the water non-visible so to speak particles. So because of the salt, the water became a little, a little denser and that's why the egg could float upwards* (V6:12).
>
> *So because of these particles, small particles. The salt has just mixed with the water and has therefore not increased by these 30 millilitres, I think, but only by about ten and the density has just (...) changed and it is just I do not know any smaller or larger than that of the egg* (Q6:12)?

These two examples showed that, although the students both used the word "particles", they still seemed to lack a basic understanding of the concept of the particulate nature of matter. Their arguments can once more be summarized by "it has something to do with particles". However, the students were not sure how this idea might be useful to explain the phenomenon in the experiment. Only the student, who had already given a correct explanation on the macroscopic level was able to paraphrase the explanation correctly, trying to connect particulate ideas with the prior statement:

> *So that, the salt was dissolved in the water and is, has increased the density of the water, because the atoms of salt have mixed with the atoms of the water, so to speak, and have made the water denser and now the density of water was greater than the density of the egg, therefore, the egg can now float* (K6:10).

The case of this student favours the trend observed so far, that if someone already understood the experiment on a macroscopic level, it is possible to use knowledge to develop a correct sub microscopic explanation of the phenomenon.

Solving Tasks 1 and 2

Although one might assume paraphrasing to be a pretty easy task, the results presented above showed that this was not the case for students. Even more difficult than paraphrasing was the application of the key idea to new contexts. When asked about the shrinkage of a balloon filled with air (Task 2 in Table 2), seven answered according to the particle model, four within the hybrid model, and eight according to the continuum model. Most students did not mention air molecules diffusing through the membrane of the balloon. They mentioned that air goes out through tiny (but macroscopic) holes in the balloon or through the knot, which is not entirely tight. One alternative conception that also could be observed was the idea that the motion of the air molecules slows down and finally comes to a stop after some time, as the following answer of a student shows:

> *So at first they are very fast, so it is so big, after a few days it shrinks a little bit because the because the particles just do not move so fast. And then after a few days, they move slower, slower, slower, and then it shrinks completely* (O2:34).

Indeed, were the balloon to be put into a freezer, this student's mapping of volume to particle motion would be appropriate. This might serve as an example of the general difficulty students face in handling the many variables in the ideal gas equation simultaneously. Another idea, that also was observed when students tried to explain the food pouch experiment, was the expansion and contraction of particles:

> *No, the air also consists of small particles, and the particles expand or contract and it depends on this whether the balloon expands or contracts, but there is always the same amount of air in there* (T5:16).

It seems that most of the students could not apply the particulate model of matter to a new task. Comparing the results of different students in the coding matrix shown in Table 4, if or if not one of them can give a right answer seems more or less randomly distributed. Some of them, who already gave a correct answer when paraphrasing the explanation of the experiment, then again had problems in solving the task. On the other hand, some of the students whose paraphrase was situated in a "hybrid model" then were able to give a correct answer. Of the seven students who stayed within the same model in the paraphrase and task 2, only two gave a correct answer in both cases.

The first task, where students were asked if they also are made out of particles themselves, seemed to be challenging on an emotional rather than a cognitive level for students. The idea, that there is lots of empty space between the nuclei of two neighbouring atoms seemed strange to some students. For example, one of them said that: "then you had to imagine that you would have holes on yourself in which nothing would be and that is somehow creepy." (J4:14) This is supported by another student who "once heard that we basically consist of I don't know 90 percent of nothing" (F2:20). Another student also found that idea to be strange and frightening. They compared particles with toy bricks, that can be put together to form something new, but then also be taken apart again. Consequently, the student asked out loud what might happen, if the particles in their hand are taken apart: “will it be like this then, that I am bleeding?” (B3:30). Overall, it could be observed, that emotional reservations were much stronger within the group of 10th-grade students than within the 6th-grade students. The younger students more often showed positive emotions regarding the particulate nature of matter, in comparison to students from 10th grade. Of the 6th-graders only two had negative emotions about the idea that they themselves are also made of particles, while four of the 10th-graders strongly disliked the idea.

Discussion

Former research in this field has shown that students tend to view matter as continuous because that is in line with their everyday experiences (Flores-Camacho et al., 2007; Johnson, 1998; Margel et al., 2008; Talanquer, 2009). This study is consistent with those findings, as only three out of 20 students used “particle” or a similar word when trying to explain the experiment at the beginning of the interview. Furthermore, none of these three students could offer an explanation that links the observations in the phenomenon correctly to the behaviour of particles.

A variety of studies (Albanese & Vicentini, 1997; Derman et al., 2019; Griffiths & Preston, 1992; Lee et al., 1993; Nakhleh, 1992) observed students attributing macroscopic properties to atoms and molecules. Likewise, the majority of students in this study voiced that kind of “hybrid model” of matter when paraphrasing what had just been explained to them by the interviewer following the experiment. For example, when trying to explain the observation, that a food pouch filled with several drops of methylated spirits expands in hot water, students said that the particles of the methylated spirits expand and therefore cause the expansion of the pouch. These findings are in line with the model of student ideas proposed by Chi (2005). Students do not differentiate between the macroscopic and the microscopic level because they lack the emergent schema that is necessary for explaining these phenomena (Chi et al., 2012).

There were also cases in which students used words like “particle”, “atom” or “molecule” but did not integrate the idea that everything is composed of particles into their explanation. This was observed in all of the five experiments that were presented to students in the study and is in line with the study of Nakhleh et al. (2005). These findings can be explained well with the theoretical framework of Vosniadou (2012). Students tried to integrate the idea of the particulate nature of matter into their conception of matter being continuous and therefore generated a synthetic model.

Students who showed good scientific reasoning at the beginning of the interview were able to adapt their existing explanation to incorporate the particulate nature of matter. As it can be seen in Table 4, five students (R2, G2, C4, S4, K6) could explain the experiment (in part) on a macroscopic level and then also correctly paraphrase the explanation by the interviewer. Similar results have been reported by Snir et al. (2003). On the other hand, only one of these students (C4) underwent some kind of permanent conceptual change, as this student also gave a correct answer in task 2. The remaining four students were not able to answer task two correctly. It remains open to question, why task 2 was more difficult for the students than paraphrasing the experiment, although both are based on the same underlying understanding of the particulate nature of matter.

Applying multiple frameworks of conceptual change to students’ ideas provided further insight into student thinking, as it has also been reported in other studies (Chiu & Chung, 2013; Harrison & Treagust, 2001; Stamovlasis et al., 2013). It appears that when trying to explain an experiment on the particulate nature of matter, some students constructed synthetic models (Vosniadou, 2012) because they lacked an emergent schema necessary for a scientifically correct explanation (Chi et al., 2012).

Limitations

Comparing the five experiments with each other, based upon only limited data, the oil patch experiment seems to be the least effective, while the distillation of a coloured solution or the expansion of a food pouch seems to be easier to grasp for students. As Löfgren and Helldén (2008) reported, this might be because students tend to see the particulate model as useful as long as something visible is turning into something invisible (for example when the coloured liquid turns into invisible water vapor). It remains an open question if experiments other than those used in this study would generate a better acceptance of the particulate nature of matter, or if experiments, in general, are not suitable for introducing this topic to students. As shown in the Appendix, there are many more experiments that could also have been investigated. Primarily because of the limited number of respondents, only five experiments were carefully chosen. Even so, the fact that each experiment was discussed with only four interviewees is an additional limitation. Especially considering the range of student reactions to the experiments, subsequent research should involve a larger sample to see if the research results are representative or only idiosyncratic.

Bias might also result from all students coming from the same school and being taught by the same physics teacher. According to this teacher, most of the students, who volunteered to take part in an interview had good grades and high interest in physics. If students would have been randomly selected by the researchers, they might have performed more poorly than the sample investigated. Considering the difficulties students had solving the two tasks or even paraphrasing what the interviewer had just told them, the possibility needs to be considered, that experiments commonly used in the classroom do little good in helping students understand the particulate model of matter.

Conclusion and Implications

Much research has already been conducted regarding student understanding of the particulate nature of matter. This study builds upon existing work and helps to fill a gap in the literature by exploring the learning efficacy of five popular experiments which aim to convince students of the particulate nature of matter. Results indicate that using experiments for introducing the particulate nature of matter to students might not lead to the desired outcome. It seems that observing an experiment, even when it is explained by the teacher, does not convince students of the particulate nature of matter. Therefore, common ways of teaching that topic should be revised and new perspectives examined.

In contrast to other studies examining experiments in the context of the particulate nature of matter, common theories of conceptual change have been applied to students reasoning about the experiments. It seems that most of students' conceptions that have been documented within the research results are best described as synthetic models, like for example the conception, that the experiment "has something to do with particles". For a more detailed and scientifically accurate description of what happens in an experiment on a sub microscopic level, students would need to acquire an emergent schema. Therefore, future research might focus on framing experiments on the particulate nature of matter with the necessary information so that students can acquire this new ontological category.

The qualitative approach of this study enabled an in-depth analysis of students thinking about common experiments used in the physics classroom. The highlighted learning obstacles for each of the five experiments might inform teachers to find new and better ways to explain these experiments to students, increasing the learning outcome. For instance, when showing the experiment "Brownian Motion" it is important to focus students' attention on the fact, that the lipophobic nature of water is not the reason for the particles moving around.

Another possible implication for teaching is that trying to explain an experiment that is new to the student in a way that emphasizes the particulate nature of matter leads to a cognitive overload within students' thinking. This would in turn suggest that students should first understand the experiment on a macroscopic level before being exposed to the explanation on a sub microscopic level. The students in the study who paraphrased the explanation the most adequately (with a particle-based explanation) were the ones who began with a correct macroscopic explanation for the experiment.

This study emphasized specific difficulties students face when having to explain common physics experiments on a sub microscopic level. Research results indicate that due to this topic being very difficult to learn, even well-chosen experiments are not easily accepted as a convincing argument for the particulate nature of matter by students. This might inform physics education researchers as well as teachers, to develop new ways of convincing students of the particulate nature of matter

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Appendix

List of Experiments on the Particulate Nature of Matter

Experiment	Description	Reference
Molecular sieving	Only some coloured solutions can penetrate a membrane. This depends on the molecule diameter.	Wilms (2011)
Evaporation and condensation of water	When water evaporates and condenses, its properties change. However, no mass is lost. This can be explained when looking at the physical states on a molecular level.	Wilms (2011)
Volume reduction when mixing water and alcohol	If water and alcohol are mixed, the total volume is less than the sum of the two individual volumes. This is due to attractive forces between the molecules.	Lichtfeldt and Peuckert (1997)
Egg floating in saltwater	Eggs normally sink in water, but in saltwater, they float. The salt dissociates in water, meaning that the molecules split up into two parts. Therefore the density and buoyancy of the solution increase.	Harrison and Treagust (2006)
Forming and dissolving salt crystals	Under the microscope, the crystal structure of salt can be seen. If the salt is dissolved in water and the water then evaporated, salt crystals of the same shape are formed again.	Fischler and Rothenhagen (1997)
Melting	During melting, the temperature of a substance does not change because the energy supplied is used to break intermolecular bonds.	Fischler and Rothenhagen (1997)
Observation of Brownian molecular motion	Looking at an emulsion of fat and water under the microscope, you will see moving fat droplets. This movement results from the thermal motion of the water molecules.	Fischler and Rothenhagen (1997)
Evaporation of an aromatic liquid (e.g. perfume)	If you put an open jar of perfume in a corner of a room, the smell will spread throughout the room over time. The cause is the thermal movement of the air molecules.	Fischler and Rothenhagen (1997)
Diffusion	If you layer a coloured solution at the bottom of a water glass, the water also becomes coloured over several days. The cause is the thermal movement of the water molecules.	Wilhelm (2018)
propagation of an oil droplet on a water surface	A small drop of oil on a water surface forms a circle of finite diameter since the thickness of the oil layer must be at least equal to the diameter of an oleic acid molecule.	Fischler and Rothenhagen (1997)
Surface tension of water	Small objects (e.g. paper clips) whose density is greater than that of the water can be placed on a water surface. This is due to intermolecular forces.	Fischler and Rothenhagen (1997)
Osmosis with a cherry in water	If you put a cherry in water, it will burst after a few hours because water molecules diffuse into the cherry and increase the pressure inside.	Fischler and Rothenhagen (1997)
distillation of a coloured solution	If a coloured solution is distilled, the distillate is colourless, since only the liquid water evaporates, but not the solid pigment. This is because the forces between water molecules are weaker so that they can spread out when their kinetic energy reaches a certain level.	Fischler and Rothenhagen (1997)
Compressing air and water in a syringe	A syringe filled with air can be compressed, but one filled with water cannot. The reason is the much greater distance between the air molecules.	Gómez et al. (2006)
Balloon in the bottle	Some water is heated in a round bottom flask, which is then sealed with a balloon. When the heat supply is removed, the balloon begins to pull into the flask as a vacuum is created. The appearance of a vacuum only makes sense in a particular model of matter.	Collin and Flint (2019)

Diffusion in a balloon filled with CO2	An inflated balloon in a bell jar filled with CO_2 will inflate within an hour until it bursts because CO_2 molecules diffuse into the balloon faster than air molecules diffuse out.	Jadrich & Bruxvoort, 2010
Volume change of a food pouch	An emptied food pouch filled with a few drops of methylated spirits expands greatly in hot water because the distance between the molecules increases greatly as the liquid evaporates.	Sieve (2016)
Mass increase when inflating a soccer ball	If you put a soccer ball on a scale and pump it up, its mass increases. In addition, pressure and temperature change according to the ideal gas model, which is based on a particular model of matter.	Harrison and Treagust (2006)
Field emission microscope	The field emission microscope shows the atomic structure of a very thin needle (usually made of tungsten) in high magnification.	Hofmann and Erb (2018)
Electrolysis and oxyhydrogen reaction	Electrolysis can separate water into hydrogen and oxygen. If the two substances are brought together, the oxyhydrogen reaction produces water again. This can most effectively be explained by hydrogen and oxygen being two kinds of particles, that make up water.	Hofmann and Erb (2018)

Detailed Description of the Experiments used in the Study

1. **Observation of Brownian Motion under a Microscope**
A mixture of milk and water is put under a microscope. When observed, an irregular movement of the fat droplets is revealed, although the amplitude of movement is very small. The movement of the fat droplets can be explained as a result of the constant thermal movement of the water molecules surrounding them. The water molecules hit the fat droplets and set them in random motion.

2. **Distillation of a Coloured Solution**
A coloured solution is put on a stove and heated until it boils. The vapor is captured and sent into a glass tube standing in cold water. There the vapor condensates and a transparent liquid accumulates in the tube. It can be concluded that the pigment molecules do not combine with the liquid water; rather the pigment molecules distribute themselves between the water molecules. Once heated the liquid water evaporates while the pigment stays behind.

3. **Volume Change of a Food Pouch During Heating and Cooling**
An empty food pouch is filled with eight drops of methylated spirits. Thereby it is important to take care, that the air is pressed out of the pouch as much as possible. When placed in hot water, the pouch inflates, when removed from the hot water, the volume decreases again. This is because the methylated spirits boil in the hot water bath (boiling point of ethanol: 78 °C) and consequently the volume increases. When it cools down, the methylated spirits condense again and the volume of the pouch decreases. Since the pouch seemed to be otherwise completely empty before, students recognize that the volume can only come from the boiling of the methylated spirits. In the liquid state, however, the particles of the methylated spirits were very close together. For this reason, there can be nothing but empty space between the particles after the boiling of the methylated spirits. Air or other gases can therefore be excluded as a component between the particles.

4. **Propagation of an oil Droplet on a Water Surface**
A large container is filled with water and some lycopod is spread on the surface for better visibility. Since oil and water do not mix, the oil spreads evenly on the water surface due to its lower density. The key aspect of the oil patch experiment is, that a little drop of oil on a water

surface forms a circle of a finite area. This can be explained by assuming that everything is composed of particles: the thinnest layer of oil that might spread out on the water surface has about the thickness of one molecule of oil. Therefore a limited quantity of oil can only form a finite area. If, on the other hand, matter was continuous, even the smallest quantity of oil would spread out to the edge of the water container.

5. **Egg floating in saltwater**

Normally an egg sinks in water due to its higher density. This can be changed by adding several teaspoons of salt to the glass of water. Common salt (sodium chloride) dissociates in water into Na^+ and Cl^- ions. These are smaller than the H_20 molecules and can therefore fill gaps between them. The density of the solution increases because the volume does not increase uniformly with mass. The higher density creates greater buoyancy, which causes the egg to float. In a continuous model of matter, adding 30 ml of salt to 250 ml of water would have to result in 280 ml of saltwater. Therefore the density would not increase that far that the egg would be able to float. The fact, that the egg is floating in saltwater but not in normal water supports the particulate nature of matter.

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Development of a new teaching-learning sequence on the particulate nature of matter using crystal structures

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Abstract
When learning about the particulate nature of matter (PNM), students tend to attribute the same properties to both particles and to the substances they compose. It has been argued that this might be explained by them categorizing the wrong ontological category. To explain the relationships between submicroscopic and macroscopic levels of matter, students need to understand the concept of emergence. Building on prior work, the authors propose that crystal structures might be a suitable context for the introduction of the PNM. As there is a close connection between the behavior of the particles and the properties of crystals, students can learn the concept of emergence and therefore gain a deeper understanding of the PNM. This study investigates students' learning about the PNM within the context of crystal structures following the methodological framework of design-based research (DBR). The aim of the study is the development of a prototypical teaching-learning sequence (TLS) on the PNM and to help developing local theories for teaching that subject. Throughout several cycles of designing and refining the TLS, a total of 40 interviews were conducted using the method of probing acceptance. Evaluative qualitative content analysis led to new insights into students' thinking about the PNM and allowed for further development of the TLS. For example, we found that salt and snow crystals were a more effective learning context than an scanning tunnel microscopy (STM) image of graphite for students to come to understand the connection between macroscopic and submicroscopic levels of matter.

I. INTRODUCTION

The particulate nature of matter (PNM) proves to be a difficult topic for students in all age groups. Although most of the students have heard about atoms and molecules, they do not apply this idea to concrete scientific problems; rather, thy tend to view matter as continuous in such situations. Therefore, students need to be convinced of the fact that the PNM applies to a broad range of scientific contexts. Students should recognize that various phenomena, in science as well as in everyday life, can only be explained when making use of the idea that everything is composed of very small, non-visible building blocks.

Previous research has shown that students experience difficulties when engaging the PNM to explain experimental results [1]. Franzbecker and Quast [2] argued that students should be introduced to the PNM with phenomena that can be directly observed in nature. As opposed to experiments like the oil drop experiment or experiments demonstrating Brownian motion, they argued that studying the formation of crystals would be a more fruitful learning context for students. Our research aimed to test this hypothesis empirically; namely, our study investigates whether looking at crystal structures is an effective learning activity that promotes students' understanding of the PNM. Although there are several studies regarding the teaching of crystal structures (e.g. [3–6]) as well as regarding the teaching of the PNM (e.g. [7–10]), there are, to the authors' knowledge, no studies exploring student understanding of the PNM using crystal structures. To fill this research gap within the literature, we conducted our study to test this approach to teaching the PNM.

II. THEORETICAL FRAMEWORK

Students' everyday experiences are determined by interactions with the macroscopic world. Because of that, they generally prefer to view matter as continuous and, consequently, have difficulties in thinking in terms of its particulate nature [11–14]. However, the idea of everything being composed of atoms and molecules is a key concept in science and therefore also considered important in science education [15,16]. Science education researchers have put much effort into documenting students' conceptions on the PNM as well as finding ways to overcome them [17–19]. This section gives an overview of common students' conceptions as well as conceptual change theories and different approaches for teaching about the PNM.

A. Students' conceptions of the particulate nature of matter

Students in general are familiar with the word "atom" even before attending science class [13]. Although they describe it as the smallest portion of matter, this does not necessarily result in them perceiving matter as discrete. More often they think of atoms as very small pieces of a continuous substance and therefore apply the same properties to atoms as they do to substances [11,20–23]. For example, some students think that during thermal expansion, the size of the atoms also increases [21–24] or that atoms in a solid do not move at all [24–26]. Some students also experience difficulties when confronted with the idea that there is just empty space between particles [27]. Because of that they often think that there is air between the particles [28].

Students' difficulties in understanding the PNM are also related to their lacking ability in modeling. Each model is based on an idealization and therefore, its functionality for explaining scientific phenomena is limited [29]. Students, however, tend to see models as copies of the real world and cannot recognize their limitations [30]. Hence, Harrison and Treagust stress the importance of discussing the advantages and disadvantages of models for atoms and molecules with students and of encouraging students to use multiple models instead of focusing on what the most appropriate model could be [31].

Students, who view models as copies of the real world, also might construct flawed mental models when interpreting pictorial representations of the PNM. For example, charts in textbooks representing the different spacings of the particles in the three phases of matter often contradict the scientifically accepted view [32–34]. A study with Swedish high school students concluded that students' mental models of matter align with textbook representations [35]. Therefore, students think that in solids particles are in contact with each other, in liquids particles are about one particle apart from each other, and in gases, particles are about three to four particles apart from each other [34]. However, scientifically accepted ratios would be 1:1:10 for the spacing between the particles in solid, liquid, and gaseous state [36].

B. Changing students' conceptions

As stated above, one of the main issues when teaching the PNM is that students tend to use the same properties for atoms and molecules as they use for tangible objects. This can be classified as a "hybrid" conception, as it mixes intuitive understanding based on everyday experiences with scientific information [37]. Students try to make use of the newly learned information but simultaneously rely on their experiences. If the conception has explanatory power, Vosniadou [37] refers to the conception as a *fragmented conception*. Conceptions that are fragmented are not shortcomings in student reasoning, but rather they arise naturally in learning new scientific concepts [38].

Chi [39,40] offers another explanation for students' difficulties when learning about the PNM. Chi argues, that most concepts in science are *emergent* in nature. According to Kivelson and Kivelson, an "emergent behavior of a physical system is a qualitative property that can only occur in the limit that the number of microscopic constituents tends to infinity" [41] (p. 1). Hence, phenomena in thermodynamics like diffusion, heat flow, or temperature are emergent, meaning that the properties of the physical system emerge from the behavior of countless atoms and molecules. For example, the temperature of an object emerges from the mean kinetic energy of its molecules.

According to Chi et al. [42], students tend to confuse the properties of matter with the properties of atoms and molecules because they are not familiar with emergence. Instead, they apply a *direct-causal schema* to emergent processes. For example, students explain the process of heat transfer by the object losing "hot particles", because this "narrative-like" explanation feels more familiar to them [43]. In this *sequential ontology,* some particles intentionally leave the object to reach the goal of the object getting cooler. A proper explanation of the cooling process requires use of an *emergence ontology*. In contrast to the sequential ontology, all particles follow the same set of rules and there are no "special" particles that leave the object while the others remain. Given the fact that all particles on average slow down a little, a drop in the object's temperature emerges.

C. Different approaches for teaching about the particulate nature of matter

Based on well-known students' conceptions and conceptual change theories, a number of different approaches for teaching the particulate nature of matter has been researched. The most frequently researched methods are computer simulations [9,10,44–46], computer animations [47–50], multiple representations [51–53], conceptual change texts [54–56], or having students engaged in hands-on experiments [57–59]. Other methods utilize predict-observe-explain [8,57], anthropomorphic stories [60], or the imagination stretch strategy [7]. Roughly a third of these studies investigated lower secondary students' understanding of the PNM. Another third of the studies focused on upper secondary students while the rest of the studies investigated primary or university level students' understanding of the PNM.

The results of these studies reveal, that focusing on the interaction of the particles proves more successful than traditional approaches [18]. The PNM is traditionally taught using ball-shaped representations of atoms and molecules, which do not include important features like the interaction of the particles [53]. To gain a sound understanding of the PNM, students need to be aware of the connections between the macroscopic and submicroscopic levels of matter [18]. It has been proposed, that teaching the PNM in the context of crystal structures might foster students' understanding of the connections between the macroscopic and submicroscopic levels of matter [2,61]. Studies making use of crystal structures in a variety of educational contexts can be found at the university level [3–5,62], although they are not about teaching the PNM. There are, to the authors' knowledge, no studies exploring lower secondary students' understanding of the PNM using crystal structures.

D. Research Question

As discussed above, students face great difficulties when connecting the macroscopic level with the submicroscopic level of matter. Different teaching approaches have been developed to overcome these difficulties. Only some of them investigated lower secondary students understanding of the PNM. Although these approaches have already provided insights concerning the teaching and learning of the PNM, the PNM still proves to be a difficult topic for students to learn [17]. As the PNM is an important topic in lower secondary education, further development of curricular materials is a worthwhile goal for researchers in science education. These curricular materials should reduce common misconceptions and foster students conceptual understanding of the PNM. The aim of this study is to test an alternative approach to teaching the PNM in lower secondary school that - to the authors knowledge - has not been researched so far. According to Franzbecker and Quast [2] crystal structures might be a good starting point when engaging with the particulate nature of matter. This leads to the following research question:

Does learning about crystal structures serve as an effective context for developing conceptual understanding of the relationships between macroscopic and submicroscopic levels of matter?

Based on this research question, we developed an tested a new way of teaching the PNM in lower secondary school. We describe this teaching approach in the following section.

III. RESEARCH METHODOLOGY

A. General background

This study followed the structure of design-based research (DBR), a methodology commonly used in education to develop knowledge for classroom practice [63]. As DBR aims at making a contribution to both theory and practice [64], the research question must be relevant to problems that occur in practice and the research results should be of use for practitioners [65,66]. The research process follows several iterative "cycles of design, enactment, analysis and redesign" [67] (p. 1) to develop and evaluate content-related instruction as well as generate domain-specific instruction theories [68].

DBR is carried out in real life instead of in a laboratory setting, and there are several associated methodological implications. For example, in contrast to psychological experiments conducted in the researchers' laboratory, there can be many dependent variables in DBR of varying levels of importance to the researchers [69]. As such, DBR does not attempt to hold variables constant during research but rather aims at identifying all characteristics of the situation that might have an effect on the variables of interest [64,69]. Furthermore, there are no fixed procedures for the intervention; rather, materials and procedures are revised during the process depending on how successful they have proven to be in practice [69].

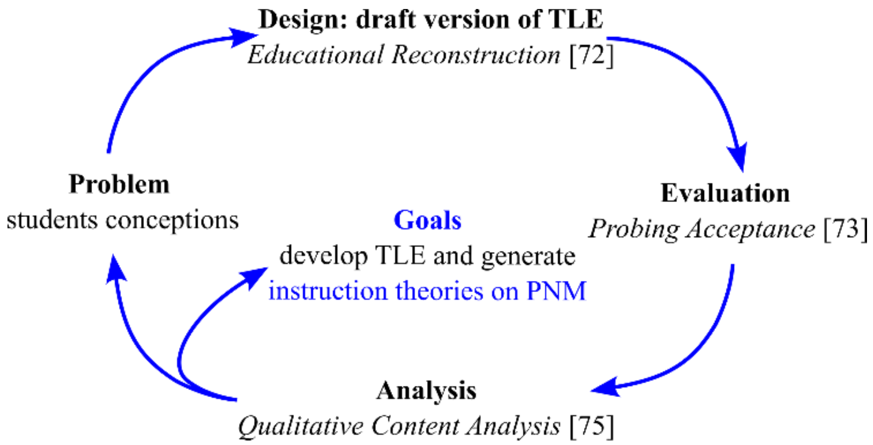

FIG. 1. Overview of the design-based research process. The terms in bold represent the steps of each cycle, beginning with the problem. The terms in italics represent the methods used in every step of the cycle (source: own illustration adapted from [68]).

Figure 1 shows the process of DBR followed in this study. The goals are to design a teaching-learning sequence (TLS) using crystal structures for teaching the PNM as well as to generate new theoretical findings on teaching the PNM. These two goals progress simultaneously throughout the DBR project. The starting point in our DBR process was the problem that the PNM is difficult to learn for most of the students. DBR aims at overcoming this problem by using theory-driven design principles that guide the research process [70]. These principles represent the transformation of general theories into guidelines, that inform teaching within a specific topic. Therefore, design principles should not only inform researchers, but also be an important tool for practitioners teaching a certain topic.

Haagen-Schützenhöfer and Hopf [68] distinguish between two categories of design principles: general design principles and domain-specific design principles. General design principles describe the general theoretical approach used in the curriculum design project. Examples of general design principles used in this study are: (i) the development of the curriculum is based on students' conceptions, (ii) the development of the curriculum is based on the use of an ontological conceptual change strategy, and (iii) learners are seen as active participants in the learning process. Based on the general design principles, there are also domain-specific design principles, which are related to the topic being taught (here: the PNM). An initial set of design principles was derived from findings on teaching the PNM and further developed throughout the process of the DBR project. A more detailed description of the domain-specific design principles can be found in section III.C.

As stated in the general design principles we chose to develop the curriculum based upon students' conceptions. Therefore, the next step in the design phase was the identification of well-known learning obstacles regarding the particulate nature of matter in science education literature. By means of bringing together students' conceptions and scientific content, a list of the most important *key ideas* on the PNM was compiled using the model of educational reconstruction [71].

Following the organization of the key ideas, we developed an interview protocol to use the method of probing acceptance [73]. According to Wiesner and Wodzinski [73], just asking students questions during interviews might lead to the problem of students generating ideas under the pressure of needing to find an answer. Although being plausible for the students at the time, these ideas tend to be inconsistent with scientific ideas. It is important to recognize that learning obstacles are not only created by the students, but are also influenced by researchers and teachers [72].

Instead of letting students find the answers themselves, Wiesner and Wodzinski [73] argue that students should be given an explanation and be asked if they find it sensible and plausible. In that way, the interviewer can evaluate students' answers and find the best possible explanation based on students' reactions. This explanation can further be used in teaching, bringing theoretical findings directly into practice. This method of probing acceptance can be used for the development of new teaching and learning environments, as it enables the researcher to find the most suitable explanation for a certain topic and to eliminate everything within the explanation that might hinder students in understanding the scientific concept. In this sense one can understand probing acceptance as a method of testing feasibility.

Probing acceptance combines a micro-teaching session with an one-on-one interview. For every key idea that should be explained to the students, the method follows four consecutive steps. First, the interviewer explains the key idea to the student. Second, the interviewer asks the student if the explanation was comprehensible. Third, the student is encouraged to paraphrase the explanation given by the interviewer, to see which parts of the explanation stayed in the students' minds. Fourth, the student is asked to solve at least one task where they have to make use of the explanation.

The interviews were analyzed using evaluative qualitative content analysis [74] (see section III.E). Results of the content analysis were then used to inform the redesign of the initial key ideas as well as the interview protocol. For example, if several students had difficulties when paraphrasing a specific explanation, then this part of the TLS needed to be revised. In the next cycle of probing acceptance, the researchers can then verify that the paraphrasing of their explanation has improved.

B. Sample selection

Due to an upcoming change of the national curriculum in Austria, only eighth-grade students (aged 13 to 14 years) learn about the PNM, so we restricted our participant sample to this age group. The researchers made sure that informed consent was given with every student participating in the study. Only students who handed in a consent form signed by their parents were allowed to participate in the study. The researchers did not collect any personal data from the students during the interviews.

The interviews took place at two schools in Vienna. The headmasters of both schools approved the implementation of the study. School A is located in a district with a very high socioeconomic status and most of the students are highly supported in their learning by their parents. School B is located in a district with comparatively lower socioeconomic status. A sample of two schools with different backgrounds was selected due to the goal of developing a TLS that can be used with Austrian eighth-grade students of different backgrounds. In cycle 1, conducting interviews at school B unfortunately was not possible due to COVID-19 regulations. Therefore, the researchers had to wait until cycle 2 to conduct interviews at this school. However, a systematic comparison of the two schools was not the goal of the research. Rather, our study is qualitative in nature, with the goal of testing if the TLS is feasible for students from two schools with different backgrounds.

Students in both schools already were instructed about the PNM in their previous physics classes. This was due to the changing national curriculum. As mentioned above, in the new curriculum the PNM should be taught in eighth grade, which is why only eighth-grade students were part of the study. However, in the current curriculum the PNM already is part of the sixth grade. Therefore, all students had been instructed about the PNM two years prior to their participation in the study.

Interviews were conducted during physics lessons of the class outside the classroom. In Austria, school lessons are 50 minutes long. To allow time for a short introduction to the study, we limited the interviews to a duration of 40 minutes. On average, one interview lasted between 30 and 35 minutes. The time constraint made it necessary to shorten the interview protocol to some extent. As a result, none of the 40 participants was taught the whole set of seven key ideas. Even if there had been more time, it is questionable if eighth-grade students would have been able to maintain their attention for the full amount of time needed for all seven key ideas.

Table I shows the most important facts of the sample. The different number of participants in each cycle resulted from the DBR process. The first cycle was more general and compared students' understanding with different examples. Cycles 2 and 3 were aimed to further improve the results from cycle 1. In these cycles a smaller number of participants was needed to see if the improvements showed the desired outcome.

TABLE I. A total of 40 students from two schools and four different classes participated in the study.

Cycle	Number of participants	School	Classes	Grade
1	18	A	2	8
2	12	B	1	8
3	10	A	1	8

C. Domain-specific design principles

As stated above, domain-specific design principles play an important role in the DBR project. The following set of principles was used in this study:

1. Using crystal structures as a starting point for the introduction of the PNM

In physics teaching and textbooks, the existence of atoms and molecules is often supported by demonstration experiments. However, only scarce research (e.g. [75–77]) has been conducted to determine if students understand those experiments and can draw the necessary conclusions, connecting their observations from the experiment with the PNM. Two recent studies noticed that students face great difficulties when trying to connect the macroscopic with the submicroscopic level when observing these experiments [1,78] Franzbecker and Quast argued that the best way to introduce students to the PNM is not to show them such experiments, but phenomena that can be directly observed in nature [2]. The fact that regularly shaped objects like crystals exist in nature, presents an open question for students. Using this question as a starting point for inquiry can lead the students to the idea that everything is composed of very small, non-visible[1] building blocks. This approach has, to our knowledge, not been researched so far. However, this study aims at closing this research gap.

2. Use of "building blocks" instead of "particles"

Pfundt [79] raised the question if the atom should be perceived as the "first building block" rather than the "last dividing piece". One could start from a continuum and approach the atom by breaking down things into smaller and smaller pieces or, on the other hand start with those pieces and compose reality by putting them together. Although the former approach is common in science education, it is very likely to lead to the idea that the atoms have the same properties as the objects they compose. For example, when cutting a piece of yellow sulfur in smaller and smaller pieces, it might seem obvious to students that the sulfur atoms are also yellow [80].

To contradict this way of thinking, the authors decided to use "building blocks" instead of "particles". As "particle" comes from "to part", the word suggests the idea of splitting things up, rather than putting them together. Furthermore, "particle" is also ambiguous and can be related not only to atoms and molecules, but also to specks of dust or grains of sand or salt [81].

3. Stressing the emergent aspects of the PNM

As explained in section II.B, students need to be aware that proper explanation with the PNM requires use an emergence ontology in contrast to a sequential ontology [39]. Everyday examples where the properties of the whole are not the same as the properties of the constituents were used to demonstrate the idea of emergence to students. For example, an image on a screen consists of very small rectangular pixels. While the image can show a dog, the pixels themselves are only very small rectangles.

The aspect of emergence then was connected with the PNM by explaining that the bonds between atoms determine the properties of the object. The cubic structure of a salt crystal for example emerges from the cubic crystal system of the sodium and chlorine atoms. On the one hand, the strength of a diamond is explained by the diamond cubic crystal structure of the carbon atoms. On the other hand, the same carbon atoms lead to totally different properties of graphite resulting from the stacking of graphene layers.

4. Using typographic representations instead of ball-shaped drawings of atoms and molecules

Harrison and Treagust [13] argued that misconceptions about the particulate nature of matter often result from flawed representations in textbooks. Atoms and molecules are depicted as circles of different sizes and are drawn within a continuous shape. Therefore, students might think that there is always something between atoms and molecules and that they look like little balls with different colors and sizes.[2]

To prevent that, Wiener *et al*. [83] developed and successfully tested typographic representations using only words and letters to depict atoms and subatomic particles. In this study, we adapted that idea and used the chemical symbols for atoms and molecules. In a previous study we found that the majority of students in the studied sample preferred typographic representations over ball-shaped and continuous representations of the structure of matter, even though the students were already familiar with the ball-shaped representations from their physics textbooks [84]. The only misconception that occurred in

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[1] We described building blocks as "non-visible" rather than "invisible" because some students might connect "invisible" with transparent materials like water or glass.

[2] Applying this ball-shaped model might also lead to further misconceptions. For example, let us consider an explanation for the decrease in volume when mixing ethanol and water. If water and ethanol are represented by balls of different sizes, than it seems obvious that the smaller water-balls fill in the gaps between the larger ethanol-balls and therefore the volume of the mixture decreases. Although this vivid explanation might be easy to grasp for students, it is scientifically flawed. The reason for the volume contraction is not the filling of the gaps between the molecules of ethanol with water molecules, but the change in length of the hydrogen bonds. These are formed between the partially negatively-charged oxygen atom of the ethanol molecule and the partially positively-charged hydrogen atom of the water molecule. Due to the hydrogen bonding, the distance between the molecules can decrease significantly below the van der Waals contact distance. As a result, the total volume of the mixture is reduced [82].

combination with the typographic representations was that some students imagined that the particles in solids are in contact with each other. To prevent that the drawings were altered in order to emphasize the empty space between the particles [see, e.g., Fig. 2(a)].

The idea of typographic representations was not only used in drawings, but also 3D-printed models. For example a three-dimensional model of the structure of molecules in ice was used to demonstrate how the molecules are bound to each other and how this is related to the hexagonal form of ice crystals. Normally within these models, atoms and molecules are represented by little balls. For this study, we decided to create our own models using a 3D printer. Instead of little balls, the atoms and molecules were represented by their chemical symbol; for example we printed “H_2O” for water molecules [see Fig. 2b].

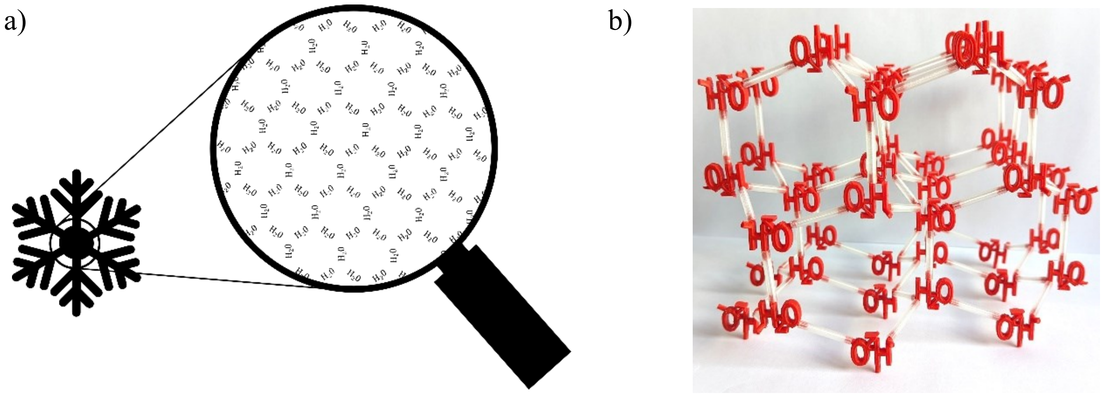

FIG. 2: (a) Typographic representation of ice I_h; (b) 3D-printed crystal structure of ice I_h. (source: own illustration)

D. Instruments and procedures

Based on the domain-specific design principles just discussed, key ideas for the PNM were developed, using the model of educational reconstruction [71]. The four key ideas which were presented to the students in cycle 1 can be seen in Table II.[3]

TABLE II: List of the key ideas in cycle 1.

Key ideas in cycle 1
KI 1: Everything that can be touched is imagined to be composed of very many, small, non-visible building blocks.
KI 2: The properties of a building block are not the properties of the object.
KI 3: The movement of the building blocks determines the temperature of an object.
KI 4: The bonding of the building blocks determines the properties of the object.

Before these four key ideas were discussed with the students participating in the first cycle, they were shown one of three examples which served as an introduction to the PNM: (i) salt crystals, (ii) snow crystals, and (iii) a scanning tunneling microscopy (STM) picture of graphite. That approach aimed to test two different examples of crystal structures as suggested by Franzbecker and Quast [2] in contrast with a third example that is not a crystal structure. The first two examples were chosen because they represent two crystal structures that appear in everyday life and therefore should be familiar to students.

[3] Here, we do not describe the key ideas and interview protocol from Cycles 2 and 3; rather, we describe them below in the Results section, just prior to the interview analysis for the corresponding cycle. This is in keeping with the DBR-based nature of our research, where the modified key ideas are themselves research products. The results of the previous cycle informed the method of the next cycle.

The third example, an STM image of graphite, was used because it represents another way of introducing the PNM commonly used in science education [85–87].

The explanation of the fourth key idea was also aided with three different 3D-printed models for the demonstration of the crystal structure of salt, ice and graphite. These models should demonstrate the connection between the submicroscopic and the macroscopic levels of matter to students. For example, a model of the cubic lattice structure of NaCl was shown to students and explained to them that salt crystals are shaped like cubes on a macroscopic scale due to the arrangement of the atoms.

E. Data analysis

The interviews were analyzed using evaluative qualitative content analysis [74]. Concerning students' acceptance of the explanation, three deductive categories were used: "fully accepted", "accepted with restriction", and "not accepted". The paraphrases were rated as "correctly reproduced", "partially correctly reproduced", or "incorrectly reproduced". For the tasks, students' answers were rated based on their use of a particulate model of matter, similar to other studies [88,89]. Based on their mental model of matter, students' answers were rated as "particulate model", "hybrid model", or "continuous model". Table III gives a detailed description of the rating scales.

TABLE III. Students' answers in the interviews were rated using the scales shown below (adapted from [1]). For every key idea, the interviewer asked the students if they accept the explanation, requested them to paraphrase the explanation and gave them at least one task. Each of these three steps were rated as follows: correct answers received 2 points, answers that were partly correct received 1 point, and wrong answers received 0 points.

Points	**2**	**1**	**0**
Acceptance	The student rates the explanation of the interviewer positively without any restrictions.	The student rates the explanation of the interviewer positively but also mentions some restrictions.	The student rates the explanation of the interviewer negatively.
Paraphrase	The student's explanation is consistent in content with the interviewer's explanation.	The student reproduces parts of the interviewer's statement, other parts are omitted or reproduced in an altered form.	The student's explanation does not agree in any part with that of the interviewer.
Task	The student uses terms such as atom, molecule, particle, etc. Furthermore, phenomena on the macroscopic level are correctly traced back to the behavior of particles.	The student uses terms such as atom, molecule, particle, etc. There is the idea that the particles are within a continuous medium and/or properties of substances are transferred to particles.	The student does not use terms such as atom, molecule, particle, etc. but rather terms describing macroscopic quantities.

The first author rated all of the interviews using the described guidelines. Inter-rater reliability was also investigated with other researchers from the second authors' working group. For each cycle, another researcher rated two interviews, which were then compared with the results from the first author. Cohen's Kappa was calculated for the first cycle to be $\kappa = 0.54$ for the second cycle to be $\kappa = 0.57$ and for the third cycle to be $\kappa = 0.74$. While the first two represent a moderate interrater agreement, the third represents a good interrater agreement [90]. Disagreement between the raters most of the time stemmed from the fact that the first author rated more harshly than the other researchers. As the aim of the research was to further improve the TLS the first author chose the harsher rating in cases of unresolved disagreement. Doing so ensured that every learning obstacle within the investigated group of students was taken into account when redesigning the interview protocol for the next cycle.

Results from the analysis of the individual interviews were gathered in the form of a multicolored matrix (see e.g. Fig. 3), a common type of representation among DBR projects (e.g. [91,92]). The points awarded to students answers of the individual items as presented in Table III are matched with a color to enhance readability. If an item was rated with full 2 points (meaning it reached the desired result), it was colored green in the matrix. When students' answers were rated 1 point (meaning they met the expectation only to some extent) a yellow color was applied. Zero points means that the student was not able to answer that specific item (colored red). Via the matrix, one can analyze the performance of singular students as well as the performance of all students on a certain item of the interview protocol. For example, if most of the answers on one item are rated green and only some of them yellow, one might assume that students in general can understand that explanation, or answer that question. However, if there are several red codes within the same item, then this explanation or question should be revised during the redesign phase of the next cycle in the DBR project.

IV. RESEARCH RESULTS

The presentation of the research results is structured by three cycles in the DBR project. The focus is on contrasting aspects that were generally accepted by students with learning obstacles that came to light during the analysis. In the results that follow, we provide detailed descriptions of individual students when doing so provides meaningful insights into students' thinking.

		Snow crystal							Salt crystal							STM image of graphite					
	Student	A1	B1	G1	H1	M1	O1		C2	D2	I2	J2	N2	P2		E3	F3	K3	L3	Q3	R3
	Example	0	0	0	1	0	0		0	0	0	0	2	0		1	0	1	2	2	2
Key Idea	Acceptance	2	2	2	2	2	2		1	2	2	2	2	2		2	2	2	2	2	2
	Paraphrase	2	0	2	2	2	2		2	2	2	2	2	2		1	1	2	1	2	1
	Task		1	0	1	2	0		0	2	2	2	2	2		2	2	1	2	2	1
Key Idea	Acceptance	2	2	2	2	2	2		0	2	2	2	2	2		2	2	1	2	2	1
	Paraphrase	2	2	2	2	1	2		1	1	1	2	1	2		2		1	2	2	2
	Task	2	0	1	1	0	2		2	2	1	2	2	2		2	0	2	1	2	2
Key Idea	Acceptance	1	2	2	2	2	2		2	2	2	2	2	2		2	2	2	2	2	2
	Paraphrase	2	2	2	2	2	2		2	2	1	2	2	1		1	0	2	2	2	2
	Task	2	1	2	2	1	2		2	1	2	2	2	2		2	0	1	2	2	2
Key Idea	Acceptance	2	2	2	2	2	2		2	2	2	1	2	2		2	2	2	2	2	2
	Paraphrase	2	2	2	2	2	1		2	2	2	2	2	2		2		1	1	2	2
	Task	1	2	2	2	2	2		2	2	2	2	2	2		0	0	1	0	0	2

FIG. 3. The results for each interview in the first cycle are depicted in a multicolored matrix. Green color (2 points) represents a correct answer, yellow (1 point) a partially correct answer and red (0 points) a wrong answer. Data suggest that students had difficulties with the first example as well as with most of the tasks.

A. Cycle 1

At the beginning of the interview, students were shown one of the following three examples: salt crystals, snow crystals and a scanning tunneling microscopy (STM) picture of graphite. This is represented by the three different sections in Fig. 3. Students were asked to explain the formation of salt crystals, the formation of snow crystals, or an STM picture of graphite.

As indicated by the abundance of red in the top row ("Example") in Fig. 3, interviewees generally did not use a particulate explanation when answering that first question. Rather, they explained the phenomenon using a continuous description of matter. In five out of six cases, students thought that the air was changing the form of the water as it freezes. One student thought that "*the air can change the water a bit, so the speed how fast it freezes"*[4] (O1:2)[5]. Another student used the idea of particles in combination with an influence of the air: "*Maybe because they somehow don't fall down at the same time and then the air shapes them a little bit differently or so, the air particles or so"* (H1:2). Similarly, students also explained the formation of salt crystals without particles. In their explanation, the cubic shape of the salt crystals is mainly caused by the surrounding rock or by water. For example, one student argued that *"because it was underground, it was squeezed by the rock and all kinds of other things, and that's how it got its shape"* (J2:2). Another student mentioned that *"the salt arranges itself in the rock so that it fits in the rock"*(C2:4). Besides being shaped by the rock, being shaped by water was also an argument that students used:

> *So just when, they are mostly in mountains inside and in these caves that there's often moisture. And with this moisture, it could happen purely theoretically that the whole gets a bit reshaped in the way and if that then happens for a long time, for years then that can probably, that looks like sanded by people* (D2:4).

In summary, students tended to explain the formation of salt and snow crystals with external factors like water or air and not with the PNM. This means that they applied a direct-causal schema to an emergent process. On the other hand, five out of six talked about particles of some kind when an STM picture was shown to them.

The second step in the interview was the explanation of the first key idea: "Everything that can be touched is imagined to be composed of very many, small, non-visible building blocks". Most of the students were able to paraphrase that idea, although the group that started with the STM image had the most difficulties. That seems surprising, as most of the students already talked about particles by themselves when the STM image was shown to them at the beginning. As the "task" associated with Key Idea 1, students were asked if light also consists of building blocks. Some of them had difficulties. One of them argued: "*Yes, because light, light moves through the air and the air also consists of many building blocks"* (G1:8). Another one mentioned that light "*consists of, of other building blocks but not of atoms, but with (..) ions, neutrons"* (K3:10). In general, when reminded that "everything that can be touched is imagined to be composed of building blocks" students agreed, that light cannot be touched and therefore is not necessarily composed of building blocks.

Some students' answers to the tasks showed that they were applying the properties of matter to particles: for example, when asked what happens to a single particle of the red liquid in a thermometer when the thermometer is placed into a cup of hot tea (*Key Idea 3* in Fig. 3), one student answered: "*Maybe it [the particle] would enlarge, that's why it rises probably. It would increase and so it then needs more space. So it always goes up" (*B1:32). Related to key idea 2 students were asked what would happen to a single particle of water if the water is placed into the freezer overnight. One student thought that at the beginning "*it still moves and then tomorrow it is frozen and no longer moves when it is ice"* (H1:20-21). Another student explained that the particle at the beginning is "*in its normal form, liquid"* (L3:24) but that "*it would freeze"* (L3:22).

At the end of the interview, students were shown a picture of pyrite and were asked why this crystal has a cubic shape. Students' answers strongly depended on the example they had been shown at the beginning of the interview. If they had begun with salt or snow crystals, the interviewee was able to connect the submicroscopic with the macroscopic level. One of them compared the bonds of the pyrite with the bonds in ice, that they have seen before: "*Probably because the atoms there enter a*

[4] All quotes have been translated by the authors from the German original.

[5] The citation of the participants has been carried out according to Rädiker and Kuckartz [74]. Before the colon comes an abbreviation for the participant. The letter represents the sequence of the participant in alphabetical order. The number relates to the three different examples used in the first cycle: 1) snow crystals 2) salt crystals and 3) STM picture of graphite. After the colon, the paragraph(s) in the respective transcript are indicated.

quadrangular bond and not a hexagonal bond as in water, and therefore if you make the squares together like this, a cuboid also comes out, I would say" (H1:38). Another student specifically stressed the fact that countless building blocks are necessary to form a visible object:

> *Just that again the building blocks connect with other building blocks billions and billions of times and then one has a cubic shape. So that they bind together with a cubic shape, so to speak, and that then becomes such a cubic shape at the end* (J2:40)

The students who started the interview with the STM image, on the other hand, again used external factors to explain the shape of the crystal, as this example illustrates: "*I believe that the pyrite has become so because of very high temperatures and that it has been formed by the surroundings because of the pressure that comes from the surroundings" (L3:38).* Another student argued similarly: "*And (...) yes by very high pressure just these layers were compressed and so the cube built up layer by layer"* (Q3:32). Our results seem to point to students learning to a use an emergent ontology when engaging with the salt or snow crystal but not with the STM image of graphite.

B. Cycle 2

Following the design-based research process, the interview guideline was refined according to the results from cycle 1. To make the description of the results comprehensible, these changes are described in the following subsection.

1. First redesign of the interview guideline

Based on the results from cycle 1, the STM image was not used anymore because students could not make a connection between the macroscopic and the submicroscopic level after learning the basic ideas about the PNM with that example (see Fig. 3). The other two examples, salt and snow crystals, both were demonstrated to students at the beginning of the interviews because they showed the desired outcome in cycle 1.

Furthermore some items were altered to make the interview protocol more coherent. Other items were not used anymore because students had difficulties giving correct answers: for example, the task for key idea 1 in cycle 1 asking students if light is composed of building blocks was removed. Changes were also necessary to be able to use the same rating scales in the qualitative content analysis for every key idea. Furthermore, the order of key ideas 3 and 4 was switched. This was also done to increase coherence, in particular because two new key ideas were added at the end of the interview guideline. Table IV lists all key ideas in cycle 2.

To aid the explanation by the interviewer, a presentation using typographic representations was shown to students. For example, with the explanation of key idea five came two different drawings showing the structure of the water molecules in solid and liquid state. Furthermore, 3D-printed models that were used in cycle 1 were further developed to fit with the typographic representations. Different 3D-printed models were used for the explanation of key ideas 3, 5 and 6. For key idea number 3, the a model of the cubic structure of salt was shown. To demonstrate the properties of a liquid on an atomic scale, flexible printing material was used to show that the bonds between the building blocks become more flexible in a liquid. For the demonstration of the behavior of molecules in a gaseous state, a model experiment consisting of a plastic bag with 3D-printed H_2O-symbols was used. When the bag is shaken, the symbols move around and demonstrate the distances between molecules in gaseous state to scale [93].

TABLE 2: List of the key ideas in cycle 2. Note that in comparison to cycle 1, the order of key ideas 3 and 4 has switched. Furthermore key ideas 5 and 6 were added.

Key ideas in cycle 2
KI 1: Everything that can be touched is imagined to be composed of very many, small, non-visible building blocks.
KI 2: The properties of a building block are not the properties of the object.
KI 3: The bonding of the building blocks determines the properties of the object.
KI 4: The movement of the building blocks determines the temperature of an object.
KI 5: At the melting point, the bond becomes flexible and the rigid structure disappears.
KI 6: At the boiling point, the bonding of the building blocks ceases and they move away from each other.

2. Findings in cycle 2

At the beginning of the interview, all students were shown two examples: salt crystals and snow crystals. Similar to cycle 1, students reasoned with external factors when trying to explain why these crystals are regularly shaped. This can be seen by the multiple red codes in the second line in Fig. 4 ("Example").

In the context of the snow crystals, one student again mentioned that "*maybe they kind of deform in the air or something"* (B:2). Another student focused more on the process of the snow crystals turning while falling:

> *I think when it, the water, freezes and falls down and turns then just so, then there are six because then it is not one ball, that just comes down so as snow, but it then flattens out more and more so and then it becomes a hexagon.* (J:2)

When arguing about the formation of the salt crystals, several students again focused on the surroundings where the crystals "*grow for example in a narrow place, so they have such an exact shape as they should grow"* (L:6). Some of these students also mentioned the origin of the salt in the mountains:

> *Maybe because somewhere in the stone, so maybe somewhere in the rock in such a mountain, sea salt, which was there at some time somehow settled. And then these crystals were for example maybe in the mountain, so a special form that looks exactly like that it is somehow in the stone so that it forms a rectangular shape.* (C:6)

These statements highlight that students were not familiar with an emergent ontology at the onset of the interview and therefore argued with a direct-causal schema.

Ten of the twelve students fully accepted the idea that everything consists of building blocks and there is nothing between these building blocks. However, one student seemed to be confused by the idea that there is nothing between particles:

> *So I believe, I am not so sure, because I don't know whether it really can be nothing there, but in the world somewhere in between there must be at least some matter, so that it is really such a substance, I don't know* (L:10).

	Student	A	B	C	D	E	F	G	H	I	J	K	L
	Example	0	0	0	2	0	0		0	0	0		0
Key Idea	Acceptance	2	2	2	2	2	2	2	1	2	2	2	0
	Paraphrase	2	2	2	2	1	1	2	1	1	1	2	2
	Task	2	1	2	2	2	0	2	0	0	2	2	0
Key Idea	Acceptance	1	2	2	2	2	2	2	1	1	2	2	2
	Paraphrase	1	2	2	2	2	1	2	1	1	1	2	2
	Task	0	2	2	2	0	0	1	0	2	0	2	2
Key Idea	Acceptance	2	2	2	2	1	1	1	1	2	2	2	2
	Paraphrase	2	2	2	2	2	2	2	1	2	1	2	1
	Task	2	2	2	2	2	1	2	1	2	2	2	2
Key Idea	Acceptance	1	2	2	2	2	2	2	2	2	2	2	2
	Paraphrase	2	2	2	2	2	2	2	1	2	2	2	2
	Task	0	0	0	0	2	0	2	0	2	2	2	2
Key Idea	Acceptance	1	2	2	1	2	2	2	2	2	2	2	2
	Paraphrase	2	2	2	2	2	2	2	1	2	2	1	1
	Task	2	0	2	2	2	2	2	2	0	2	2	2
Key Idea	Acceptance	2	1	2	2	2	1	2	2	2	2	2	2
	Paraphrase	2	2	2	2	2	2	2	2	2	2	2	2
	Task	2	2	2	2	2	2	2	0	2	2	2	2

FIG. 4. The results for each interview in the second cycle are depicted in a multicolored matrix. Green color (2 points) represents a correct answer, yellow (1 point) a partially correct answer and red (0 points) a wrong answer. Data suggest that students had difficulties with the first example as well as with some of the tasks.

Although ten out of twelve students accepted the idea that everything is composed of building blocks, only 7 of them gave an answer based on the PNM when asked about the composition of the snow crystals. The others still used external factors for their explanation. One student thought that the different form of the snow crystals is a result of light rays hitting them from different angles while they fall:

> *Maybe because it [the snow crystal] always turns, the [light] rays hit it always differently, so at one time the rays are always the same and in the air, it [the snow crystal] always turns a bit and the ice ball just always melts a bit.* (F:26)

Some of the students, who used particulate ideas, chose a different approach and tried to find the chemical composition of the snow crystal: "*So I think there will be hydrogen (right) and maybe I'm not sure oxygen?"* (L:20). Therefore, one might assume that using knowledge from chemistry education seemed more useful for the students than making use of the ideas they just heard of.

The second key idea showed some difficulties for the students, especially a task about colloidal gold, which can be also found in other studies [94,95]. Students were asked why a liquid containing small gold particles[6] has a red color, unlike the color of a gold bar. Some of the students argued that *"something chemical occurs"* (A:26) when gold and liquid are combined:

[6] These "gold particles" are in fact clusters of gold atoms with a diameter of 2 – 100 nm and not individual gold atoms.

In an experiment, if you mix a colorless thing and something blue and then all of a sudden it turns red, they can react with each other because just because it's colorless doesn't mean there's nothing in there that could change the other. (H:32)

These statements reveal that there are also misconceptions about color, which make this task especially difficult. Students do not think about the interaction of light and matter and therefore think of color as a property of matter instead of light. For example, another student argued that *"iron gives a red color to things it is mixed"* (E:22).

Key Idea 4 in general was not difficult for the students, as nearly all of them accepted the idea and were able to paraphrase it. However, half of the students did not use the PNM to solve the task at the end of the key idea. Their answers were right on the macroscopic level, but they did not see the necessity to get into a more detailed description on the submicroscopic level, although that was part of the explanation for the key idea they had just heard. Instead, these students again made use of external factors to explain why the size of a bridge might change with temperature:

Interviewer: Why does the size of the bridge change at all with temperature?
Participant: Yes, because the material expands a little, just a little.
Interviewer: And why does it expand? So how can one justify this somehow why it expands?
Participant: Maybe when the sun shines on it the whole day? Or the earth's core from below still makes a little bit [of an influence] perhaps. (F:83-86)

As presented in Fig. 4, only very few yellow and red codes appear for key ideas 5 and 6. Students did not have problems paraphrasing the key ideas and solving the tasks. Therefore, one might argue that most students did understand the emergent ontology at the end of the interview. The three red codes that appear in connection with the tasks can be explained by students not using the PNM. Although they were able to explain the phenomenon on a macroscopic level of matter, their answers were rated red, because for a yellow or green rating, they needed to mention particles in some way. Nevertheless, these two key ideas were well accepted and understood by most of the students.

A new finding in cycle 2 was that some of the students made use of substance-based wording although they showed conceptual understanding of the PNM. For example, they explained the bonding between the particles in the salt crystal but used the word "substances" instead of "particles" or "building blocks". It seems that for these students, the term "substances" is more familiar than "building blocks" or "particles". Being confronted with a lot of new ideas and terms during the interview, they fall back on using more familiar phrases.

C. Cycle 3

Following the design-based research process, the interview guideline again was refined according to the results from cycle 2. To make the description of the results comprehensible, these are described in the following subsection.

1. Second redesign of the interview guideline

Based on the results from cycle 2, several changes were made to the interview protocol. There was no initial question anymore because there was already enough data showing that students do not use the PNM by themselves. This decision was also made due to time constraints, as each interview had to fit into 40 minutes. For the same reason, key ideas 5 and 6 were not included again, as the positive results from cycle 2 showed that the key ideas can be used for the TLS without any further changes. Shortening the interview guideline was also necessary due to the fact that a new key idea had to be added. In cycles 1 and 2, the idea that there is just empty space between particles had been included as a very short note in the explanation of the first key idea. Given there were some difficulties with that specific point, it was made into its own key idea to be discussed with the students in greater detail.

To tackle the problem of students arguing with external factors when asked about the formation of crystals, two videos showing the formation of a salt crystal and a snow crystal were added. Both videos demonstrate the formation of a salt or snow crystal in a lab, where external factors can be excluded. These videos should convince students to focus on the PNM and were also used as inhibitive "stop signs" [96] later on in the interview.

Finally, the tasks that were either too difficult or where students did not use the PNM were changed. For example, the task about the color of colloidal gold was omitted because half of the students had not answered it correctly. For key ideas 1, 2 and 3, a second task was added, to gain further insight into students' understanding of each key idea. All tasks were optimized to require students to think about particles, making it impossible to be solved completely without particles. Concept cartoons were added to help students express their points of view. Table V lists the key ideas in cycle 3.

As in cycle 2 a presentation using typographic representations aided the explanation by the interviewer. The presentation was modified according to the findings from cycle 2 and the new interview protocol. For example, for key idea 2, students were shown different examples where the properties of a single constituent are not the same as the properties of the whole. For instance, students were shown the parts of a three-dimensional puzzle that all had different shapes while the puzzle as a whole is ball-shaped. This idea was then connected with the example of the salt crystal: the building blocks do not have the same cubic form as the crystal itself.

The 3D-printed models were further developed to fit the typographic representations even better. For example, with key idea 3 came two 3D-printed models showing the crystal structure of diamond and graphite. This should demonstrate to students that although diamond and graphite both solely are made of carbon, they have different properties. This shows that it cannot be the properties of the building blocks alone that determine the properties of the object; rather the bonding between the building blocks is also crucial to consider.

TABLE V: List of the key ideas in cycle 3. Note that key idea 5 is different than in cycle 2. Key ideas 5 and 6 from cycle 2 were not included any more because of time constraints.

Key ideas in cycle 3
KI 1: Everything that can be touched is imagined to be composed of very many, small, non-visible building blocks.
KI 2: The properties of a building block are not the properties of the object.
KI 3: The bonding of the building blocks determines the properties of the object.
KI 4: The movement of the building blocks determines the temperature of an object.
KI 5: There is nothing between the building blocks.

2. Findings in cycle 3

As can be seen in Fig. 5, there are only very few red codes in general and there is no item with more than one red code. The two red ratings for student R can be explained by this student having German as a second language and therefore having some difficulties in phrasing a coherent answer. Also, there might have been some words in the explanation of the interviewer that were difficult to understand for the student. The third red coding (student S) stemmed from the fact that the student's answer to the question did not include particles of any kind:

> *Yes because it is, so first of all the air is like that, has a gaseous, is gaseous. And the air distributes itself in the space everywhere and if you push it upward, upward until it can move no more and therefore develops pressure, a high pressure and one cannot move it, the air is, it has no more place at all to move* (S:84)

It seems that none of the key ideas generally caused problems for most of the students anymore. Students were focused on using the PNM instead of using external factors in their explanations. Therefore one can assume that the explanations in the interview helped most of the students to understand the emergent ontology and they consequently did not apply a direct-causal schema. However, there were some exceptions. For example, one student was very self-reflective about their conceptions on how snow and ice are formed:

I just used to imagine that snow crystals are not ice and I probably still have that in the back of my mind. I simply thought that snow [is made] from air and water and ice only with water and so air, cold, and water [equals] snow and ice just needs cold and water (T:56).

Student		M	N	O	P	Q	R	S	T	U	V
Key Idea 1	Acceptance	2	1	2	2	2	2	2	2	1	2
	Paraphrase	1	1	2	2	2	1	2	2	2	1
	Task 1	2	2	2	2	2	2	2	2		2
	Task 2	2	2	2	2	2	2	2	1	1	2
Key Idea	Acceptance	2	2	2	2	2	2	2	2	2	1
	Paraphrase	1	2	2	1	2	0	2	2	2	1
	Task 1	2	1	2	1	1	2	2	2	1	2
	Task 2	2	2	2	2	2	0	2	1	2	2
Key Idea	Acceptance	2	2	2	1	2	2	2	2	2	2
	Paraphrase	2	2	2	1	2	1	2	2	2	2
	Task 1	2	2	2	2	2	2	2	2	2	2
	Task 2	2	2	2	2	2	2	1	2	2	2
Key Idea	Acceptance	1	2	2	2	2	2	2	2	2	2
	Paraphrase	1	2	2		2	2	2	1	2	2
	Task	2	2	2	2	2	2	2	2	2	2
Key Idea	Acceptance	1	2	2	1	2	2	2	2	1	1
	Paraphrase	1	2	1	2	2	2	2	2	1	1
	Task	2	2	2	2	2	2	0	2	2	

FIG. 5. The results for each interview in the third cycle are depicted in a multicolored matrix. Green color (2 points) represents a correct answer, yellow (1 point) a partially correct answer and red (0 points) a wrong answer. Data suggest that students only had a few difficulties with paraphrasing the explanation and solving the tasks.

The student very explicitly described conceptual change during the interview. They questioned their former view and concluded to change something. However, this student still stuck to some misconceptions arguing that "*not every [...] water atom can have the same shape. Because otherwise, every snowflake would look the same* (T:66)".

Despite claiming to fully accept the first key idea, this students was not convinced that air also consists of particles:

Student T: *I know, so I know that they are very small, but it is, it comes to me, that one just for example when one inhales that, that they are similar things in our lungs. It is very, very small and fine but still, I can't imagine that there are atoms everywhere.*

Interviewer: *Okay, but that means where could you imagine that better than in the air? For example, from the things that surround us right now?*
T: *A plant (ok), this sign, glass, because they are just material things* (T:26-30)

However, after the explanation of key idea 2, the student stated that now "*I can also imagine it better with the air, that the air also has that [particles]"* (T:40). This is particularly interesting, as key idea 2 did not talk about air or gases in general.

D. Summary

Students in general showed a high acceptance of the key ideas throughout the study. Problems arose mainly when they had to solve a task connected to the key idea and in some cases also when they had to paraphrase the explanation given by the interviewer. Results from the first cycle suggested not to use STM pictures as an introductory example for the PNM. Rather, using snow or salt crystal formation as the opening example provided students an opportunity to recognize that a phenomenon they had previously considered to be direct-causal is better explained in terms of emergence. Therefore, the interview guideline on cycles 2 and 3 was exclusively based on crystal structures.

Another observation that could be made throughout the study was that some of the students preferred to use external factors to explain natural phenomena like the formation of crystals. However, in cycle 3, there are only very few examples of answers like that, as students made use of the PNM more frequently. Also, students applying the same properties to particles as they use for substances was observed less in cycles 2 and 3 than in cycle 1 (see Fig. 6b). Therefore, one can assume that especially in cycle 3 students were able to basically understand the emergent ontology.

Looking at the terms students used to describe atoms and molecules, it seems that the word "building block" was widely accepted by the students as they used it more often than the word "particle" (see Fig. 6a). Furthermore, students' use of the term "building block" increased throughout the three cycles from an average of 3.9 times per student in cycle 1 to 8.5 times per student in cycle 3. At the same time, students' use of the word "particle" was three times lower in cycle 3 than in cycle 1. Students also applied other more scientific terms like "atoms", "molecules" or "elements". Molecules were mainly mentioned in connection with atoms. However, some students repeatedly confused those three terms with each other. Some students, especially those in cycle 2 used the term "substances" when they were actually talking about the PNM, mixing a conceptual understanding based on particles with a wording based on a continuous perception of matter.

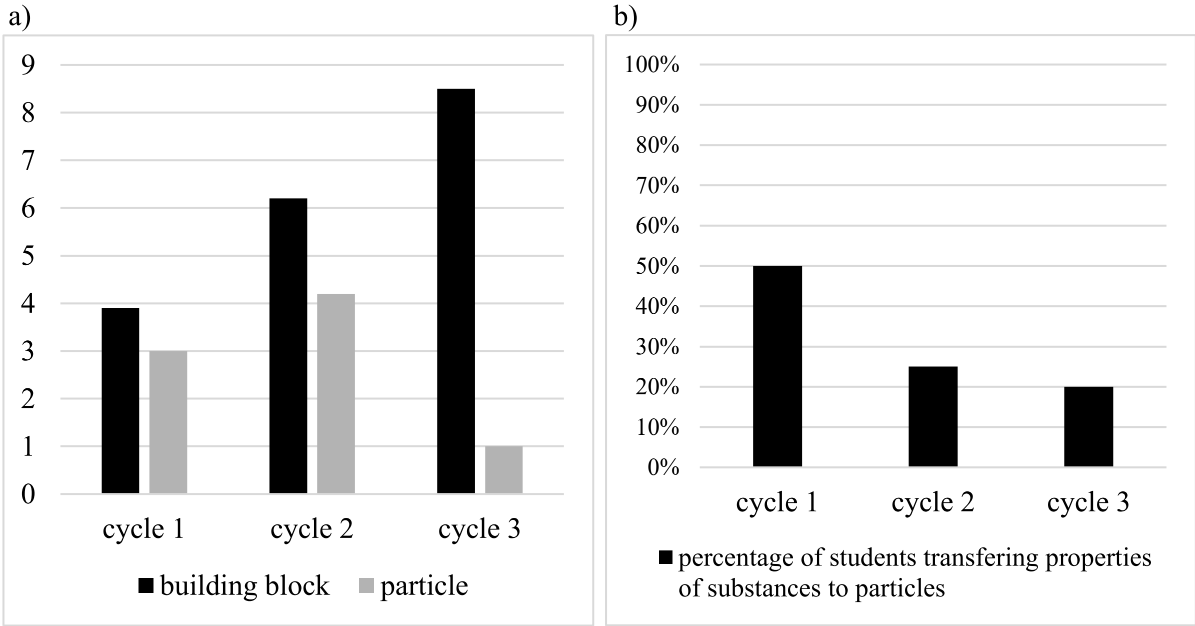

FIG. 6: a) Use of the terms „building block" and "particle" per student during the three cycles of interviews. b) Percentage of students applying the same properties to particles than to substances during the three cycles of interviews.

V. DISCUSSION

Previous research on students' understanding of the PNM showed that students tend to view matter as continuous [11–14]. This study confirms those findings, as most of the students did not use the PNM when they were asked to explain natural phenomena, such as the formation of crystal structures. Instead, they focused on external factors, like the influence of the surrounding rock on the formation of salt crystals. This may be explained with the ontologies framework of Chi *et al*. [42]. Students prefer to argue with external factors because they think within a *direct-causal schema* instead of an *emergent schema*.

Given this circumstance, one of the design principles in the DBR project was to illustrate the emergent schema to students. Due to further development of the explanations given in the interviews, the implementation of this design principle was most effective in the third cycle. This is reflected in the research result that students in cycle 3 very rarely used external factors in their reasoning. Although there was just a series of small changes made from cycle 2 to cycle 3, a huge difference in the outcomes was be observed. The use of design principles allowed these changes to be visible [68].

All but one of the students who were shown an STM picture in the introduction of the interview connected this image to particles. A positive effect of STM images on students recognition of particles was also documented by Margel *et al.* [87]. However, as Harrison and Treagust [13] pointed out, the fact that students know about atoms and molecules does not mean that they possess conceptual knowledge about the PNM. This has been confirmed by this study as most of the students who mentioned particles in connection with the STM image, did not make connections between the submicroscopic and macroscopic levels of matter. On the other hand, students who were introduced to the PNM with crystal structures were able to make this connection. This suggests that using crystal structures represents an effective design principle when introducing the PNM to students.

The ideas of students' discussed above can be classified as fragmented conceptions [37]: students tried to use the newly-learned information in the interview, but simultaneously relied on existing experiences and knowledge. Most of these ideas involve application of the same properties to both atoms and substances. Some students in this study described that when an object is heated and therefore expands, the size of the building blocks also increases. This result has also been found in other studies

[21–24]. Another well-documented students' conception [24–26] observed in this study was the idea that when something is frozen the building blocks do not move at all.

These so-called fragmented conceptions were less observed in cycle 3. This result again suggests that the implementation of design principles was most effective in the third cycle. It cannot be determined if either the improved 3D-printed typographic models or the increased focus on emergence was responsible for the changing results. However, design principles are not meant to function as generalized theories, but rather to work as a set of practical guidelines within the context they operate and serve as "local theories" [70].

The fact that some of the students used the word "substances" as a synonym for particles when talking about the PNM can also be interpreted as a fragmented conception. This conception was predominantly observed with the students in cycle 2. However, compared to the use of other terms in connection with the PNM, it occurred relatively seldom. Most of the students mentioned atoms, particles, or building blocks when talking about the PNM. In the first cycle, "atom" was the most common term, but "particles" and "building blocks" were also frequently used by the students. Over the three cycles the use of "building blocks" increased while students applied "particles" less often. This again suggests that the implementation of the design principles was most effective in the third cycle. Students had the highest performance in this cycle while at the same time they used "building blocks" most often and "particles" least often. This strengthens the hypothesis that using "building blocks" instead of "particles" might avoid misconceptions, as "particle" is ambiguous and can be interpreted as tiny parts of something.

A. Limitations

Only two examples of crystal structures, namely salt and snow crystals, were examined in this study. These two were carefully chosen because they appear in everyday life and are well-known to students. Nevertheless, many other examples could have also been investigated. Due to this study being qualitative in nature with only 40 participants, the focus was to determine students' thinking within these two examples. To gain deeper insight into students' ideas about crystal structures in general a larger sample can be explored with a more quantitative approach.

The selection of the students was solely based on their voluntary participation. All participants came from a total of four classes in two different schools. The selection of the students was to some extent influenced by the COVID-19 pandemic, which prevented the researchers from visiting a larger number of different schools because of restrictions by the federal government. Future work using a sample of randomly selected students from a wider range of schools might demonstrate increased variety of students' answers. A high proportion of the students participating in the study was described by their teachers as having high interest and good grades in physics. A randomly selected sample might show poorer results than the sample investigated. On the other hand, since all of the students received instruction on the PNM before the interview, it is possible that a randomized sample would have performed equally well.

Comparing the results from cycles 1 and 2, it seems as if the students performed better cycle 1. As the goal of DBR is to increase students understanding with every cycle, it raises the question of why the researchers did not succeed in that. A possible explanation might be that the items that were introduced from the first to the second cycle were too difficult. Also, students in these two cycles came from different schools and their performance might therefore not be comparable. However, the goal of the DBR project was not the comparison of different schools but the development of a new TLS on the PNM. Even if students' performance in cycle 2 was not as good as in cycle 1, the collected data still proved valuable insights for the redesign of the interview protocol and the construction of cycle 3. For example, that another key idea regarding to empty space between the particles had to be added.

At some point in the study, the interview protocol had to be shortened because of time constraints. Due to the interviews taking place during lessons of 50 minutes, it was not possible to test all of the seven key ideas at once. Therefore, none of the students was taught the whole set of key ideas. However, it is likely that students from lower secondary school would not have been able to focus on the topic of the PNM for the time necessary to discuss all seven key ideas.

VI. CONCLUSION AND IMPLICATIONS

Students' understanding of the particulate nature of matter has been extensively investigated by science education research. However, using crystal structures for the introduction of the PNM, as proposed by Franzbecker and Quast, had not been empirically tested prior to our work. Our study fills a gap in science education literature by exploring the feasibility of teaching the PNM in the context of crystal structures. Most of the 40 lower secondary students in the study gained a good understanding of the PNM by learning about the crystals structures of salt and ice. Those students who were shown the basic principles of the PNM via an STM image of graphite had difficulties connecting the submicroscopic with the macroscopic level of matter. Comparing the results from this study with our previous research suggests that within the investigated samples, crystal structures were better suited for the introduction of the PNM than commonly used experiments [1]. Therefore, the hypothesis by Franzbecker and Quast was verified, at least for these two examples. The results of this study seem to support the feasibility of teaching the PNM in the context of crystal structures.

Previous research reported that students tend to view matter as continuous. That was also observed in this study, as many students used external factors for the explanation of the regular shape of crystals. Within the ontologies framework of Chi, this can be explained by students using a *direct-causal schema* instead of an *emergent schema*. Therefore, it is necessary to explain the emergent schema to students and help them to understand the relations between macroscopic and submicroscopic levels of matter. This study contributes to that as it developed a way of teaching that fosters students' use of the PNM and inhibits their use of external factors to explain certain phenomena. This was made possible by the domain-specific design principles, according to which tasks were designed to better promote students use the PNM. We found that students' answers in the last cycle were based on the PNM more frequently than in the first two cycles; furthermore, there was less reasoning in terms of external factors. Finally, fragmented conceptions were observed less frequently in the cycle 3 compared to in the first two cycles and students more often used the term "building blocks" than "particles" in cycle 3.

Our research fulfilled both aims of DBR. New theoretical knowledge about student understanding of the PNM was generated in the form of the domain-specific design principles, e.g. the use of crystal structures for the introduction of the PNM. Data suggest that all of the four design principles used in this study had a positive impact on students' learning. Furthermore, this study contributes to the practical needs of teaching, as a teaching-learning sequence on the PNM was developed. The TLS should be investigated with a larger group of students, to strengthen the empirical basis of teaching students the PNM with crystal structures. This might encourage physics education researchers as well as teachers to use and further develop this way of teaching the PNM.

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Evaluation of a new teaching-learning sequence on the particulate nature of matter using crystal structures

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Abstract

Although there has been extensive research on students' understanding of the particulate nature of matter (PNM), there is still a lack of research on contexts that can be used to teach this challenging topic. In a previous design-based research study, the authors designed a teaching-learning sequence (TLS) on the PNM in the context of crystal structures. Data from individual student interviews suggested that the TLS positively influenced students' use of the PNM. To test whether the TLS also promotes students' use of the PNM in the classroom, a study of feasibility was conducted. In six 8th -grade classes in Vienna, students' use of the PNM was assessed with a pretest before they were taught the TLS during four lessons. After the intervention, students were given a posttest. Open-ended questions were coded using evaluative qualitative content analysis so that quantitative analysis could be applied. T-tests of students' mean scores on both tests show significant improvements in students' use of the PNM in the posttest. The context of crystal structures seems to be helpful to students, as most of them use the PNM when asked about crystal formation. In addition, in the post-test, students more often accepted the idea of empty space between particles and associated particle motion with temperature. However, when asked about phase changes, most students remained in a continuous conception of matter.

I. INTRODUCTION

The particulate nature of matter (PNM) is a key concept in science education in many countries. Consequently, it has already been extensively researched. Some of this research has focused on documenting students' difficulties and misconceptions in this field [1–3], while others have developed methods to overcome those difficulties [4,5]. Further research has described students' progressions when learning about the PNM throughout their school careers [6–8]. Nevertheless, there are still aspects of teaching and learning the PNM that require further investigation. Following a meta-analysis on the effectiveness of PNM-based intervention studies Çalik *et al.* [9] argued that research in this field should provide better contexts to teach the PNM. By better understanding the relationships between the context and the PNM, it might be possible to improve students learning.

In a previous study [10] the authors utilized the context of crystal structures to develop a teaching-learning sequence (TLS) on the PNM. A TLS is designed to enhance teaching and learning by integrating findings from educational research into practice [11]. Research indicates that the implementation of a TLS can be a significant factor in influencing teaching and learning in classrooms [12–14]. There is an ongoing discussion on the development of methodological frameworks to serve as guidelines for the development and evaluation of TLSs [12,15–17]. One such framework, namely design-based research (DBR), was used develop our TLS on the PNM using crystal structures.

The objective of this study was to ascertain whether the TLS is conducive to students' abilities to apply the PNM. Additionally, we sought to ascertain teachers' perceptions of the TLS, with a view to identifying any potential difficulties they may have encountered in implementing the TLS in their classrooms.

II. THEORETICAL FRAMEWORK

A. Teaching and learning the PNM

Given the significance of the PNM in science education, there is a substantial corpus of theoretical knowledge on teaching and learning the PNM in science education research. Consequently, we will limit our discussion to a few theoretical aspects that are particularly relevant to our work.

Research on students' conceptions on the PNM forms an important basis for understanding how students process new information on that topic. Although most students are familiar with terms like "atom" or "molecule", they tend to view matter as continuous [18–20], as this is more in line with their everyday experiences. When trying to make use of the PNM, students often apply properties of macroscopic matter to atoms and molecules [1,21,22]. For instance students believe that the volume of atoms increases when an object is heated because the size of the object itself increases [23,24]. This kind of conception is referred to as *hybrid*, as students integrate newly learned information while still applying non-scientific concepts [25]. This also results in students experiencing difficulties with the idea, that there is nothing between particles [26]. Although students accept the existence of particles, they tend to believe that these particles are embedded in a continuous substance. For example, they believe that there is always air between the particles because they perceive that everything is surrounded by air in their everyday experience [27].

Another significant area of research concerns different methodological approaches and their suitability for learning the PNM. Computer simulations [28–30], computer animations [5,31,32], or other digital learning environments [4] are frequently employed to illustrate interaction at the particle level. Regarding the connections between macroscopic and submicroscopic levels, approaches based on multiple representations have been investigated in particular [33,34]. Moreover, students should be persuaded of the veracity of the PNM through the observation of experiments [35–37].

In addition to different methodological approaches, various contexts for the introduction of the PNM have already been tested. Commonly encountered are phenomena from thermodynamics such as diffusion [30,38], the behavior of gases [39], and fire and ice [40]. Since a fundamental understanding of the behavior of particles is necessary for (statistical) thermodynamics, this context is particularly closely related to the learning objectives on the PNM. In contrast, other approaches attempt to demonstrate the importance of the PNM by presenting phenomena that cannot be explained without the assumption of atoms. For example, observations of images produced by scanning tunneling microscopes suggest the existence of atoms [41,42]. Natural phenomena, such as the regular geometric shape of salt crystals, can only be explained by assuming the existence of atoms [43–45].

Another relevant aspect of teaching the PNM is the consistent use of terms that connect to scientific language but avoid its complexity and partly historically-grown contradictions [46]. The term "particle" is not a clearly defined term in everyday language and can be associated with dust particles or grains of sand in addition to atoms, molecules, and subatomic particles [47]. Another argument against the use of the particle concept in teaching has been made by Pfundt [48]. According to her, the frequently used approach of mentally dividing matter further and further until indivisible particles remain at a certain point rather leads to the transfer of macroscopic properties to atoms. If, for example, a piece of yellow sulfur is divided into smaller and smaller particles, it is not surprising if students assume that these particles are also yellow [49].

Representations also play an important role in teaching the PNM. Since atoms and molecules are inherently invisible, visualizations are necessary in the classroom to illustrate their fundamental properties. However, the prevalent visualizations of atoms and molecules in the form of small spheres [50] can potentially lead to misconceptions [51]. Wiener *et al.* have therefore proposed the use of typographic representations as an alternative to spherical representations [46]. Their acceptance has already been investigated in the context of the atomic model and the PNM, and was received positively by students [52,53].

Additionally, insights into the design of a TLS on the PNM can be found in the field of conceptual change theories. For instance, Chi explains the challenges students face in comprehending the PNM due to misconceptions at the ontological level [54]. A multitude of phenomena associated with the particle model adhere to an emergent ontology, whereby the properties of the system emerge from the interaction of its components. The properties of the system are distinct from the properties of the components. Emergent phenomena occur in physics whenever the number of submicroscopic constituents tends to infinity [55]. This is exemplified by phenomena such as in temperature, pressure, heat transport, or diffusion. However, students are usually unfamiliar with emergence, as it does not play a role in their everyday experiences. Therefore, they interpret emergent phenomena with a *direct-causal* schema. For example, students tend to explain the cooling of an object by the release of "hot particles" because this "narrative-like" explanation is more familiar to them [56]. Consequently, Chi *et al.* [38] emphasize that students must first be familiarized with an *emergent ontology* to understand the PNM.

B. Development of a TLS within the framework of design-based research

How can these implications from theory be used in classroom practice? One answer to this question can be found in the development of teaching-learning sequences (TLS). "*A TLS is both an interventional research activity and a product, like a traditional curriculum unit package, which includes well-researched teaching–learning activities empirically adapted to student reasoning*" [15]. Over the past decades, several frameworks for developing TLSs have been developed [14].

One branch of the studies on TLS design and implementation uses design-based research (DBR) [57]. This methodological framework takes up problems from classroom practice and seeks theory-driven solutions through cyclical testing, evaluation, and further development of learning opportunities [58]. Given its focus on theory and practice [59], the goal of DBR is to develop instructional designs, as well as to generate local theories about teaching and learning the subject matter at hand [60]. Figure 1 shows the cyclical progression of a DBR project.

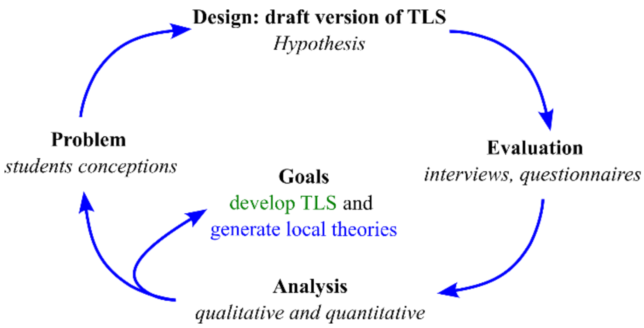

FIG. 3. Process of design-based research (source: own illustration adapted from [60]).

The concrete translation of theoretical findings into guidelines for classroom practice occurs through design principles that guide the research process [13]. Haagen-Schützenhöfer and Hopf [60] distinguish between general and domain-specific design principles. While the former primarily influence fundamental decisions about teaching and learning, the latter relate specifically to the learning of the subject matter (here: the PNM). Design principles are theory-driven and are continuously developed during the cyclical course of the DBR process.

C. Research Question

Despite great efforts in science education research, the PNM is still a difficult topic for students to learn and there is a lack of different contexts for teaching the PNM. Therefore, the authors aimed to develop and evaluate a TLS within the methodological framework of DBR. Several cycles in DBR have already been carried out to develop the instructional design. The present study is dedicated to the evaluation of the instructional design, which leads to the following research question:

Is the developed TLS, based on empirically evaluated design principles, effective in promoting students' use of the PNM?

III. TLS DESIGN AND EVALUATION

Following the framework of DBR a TLS on the PNM was developed through multiple iterations of design, evaluation, and analysis. Figure 2 shows the sequence of iterations in the DBR project.

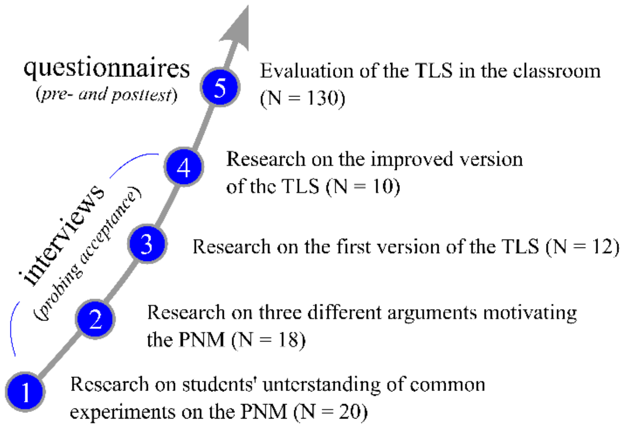

FIG. 4. Sequence if iterations in the DBR project. Results from cycle 1 are published in [36], results from cycle 2 to 4 in [10]. Cycle 5 is the present study (source: own depiction adapted from [60]).

A. Development of the design principles and key ideas

As a result of the first four iterations of the DBR project (see Fig. 2), four domain-specific design principles and seven key ideas were found to improve students' use of the PNM (see Tables I and II). We here describe these only briefly here, for a detailed report see Budimaier and Hopf [10].

TABLE III. Domain-specific design principles developed throughout the first four cycles of the DBR project.

Domain-specific design principles
DP 1: Using crystal structures as a starting point for the introduction of the PNM.
DP 2: Use of "building blocks" instead of "particles".
DP 3: Stressing the emergent aspects of the PNM.
DP 4: Using typographic representations instead of ball-shaped drawings of atoms and molecules.

The choice use of crystal structures as the context for introducing the PNM was based on the idea of Franzbecker and Quast [43]. Results from the DBR project suggested that crystal structures allow students to connect macroscopic and submicroscopic levels of matter [10]. Teaching them the emergent ontology [38] and emphasizing the emergent aspects of the PNM further helped students to make that connection. To avoid misconceptions based on flawed representations of atoms and molecules as small spheres [51], we decided to use typographic representations, based on the idea of Wiener *et al.* [46].

Based on previous research [48], we decided to use the term "building blocks" instead of "particles", to also avoid misconceptions based on the fact that "particle" is not well defined in everyday language [47].

The seven key ideas (see Table II) were also influenced by the domain-specific design principles. For example, atoms and molecules are always referred to as "building blocks", and the emergent aspects of the PNM are explained in key idea 2. The key ideas were not formulated all at once, but were developed over the first four cycles of the DBR project. New key ideas were added with each cycle to increase the explanatory power of the TLS and to respond to students' needs. For example, key idea number 6 was added after some students mentioned that they could not imagine that there is nothing between the building blocks. In addition, existing key ideas were adjusted when the results from the previous cycle showed that students were having difficulties learning that key idea. The order of the key ideas was also changed several times.

TABLE IV. Key ideas developed throughout the first four cycles of the DBR project.

Key ideas
KI 1: Everything that can be touched is imagined to be composed of very many, small, non-visible building blocks.
KI 2: The properties of a building block are not the properties of the object.
KI 3: The bonding of the building blocks determines the properties of the object.
KI 4: The movement of the building blocks determines the temperature of an object.
KI 5: At the melting point, the bond becomes flexible and the rigid structure disappears.
KI 6: There is nothing between the building blocks.
KI 7: At the boiling point, the bonding of the building blocks ceases and they move away from each other.

B. Development of the teaching materials

Given the overall satisfactory results in cycle 4, the TLS was considered ready to be tested on a larger scale in classrooms. To increase the likelihood that teachers would volunteer to participate in the study with one of their classes, the researchers decided to keep the number of lessons to a minimum. The goal was to incorporate all seven key ideas into four hours of instruction.

The domain-specific design principles and key ideas guided the creation of the instructional materials. Snow and salt crystals serve as the context for teaching the PNM because the formation of crystals can only be explained in terms of their atomic structure. Since the shape of the crystal results from the lattice structure and not from the shape of the individual atoms, students need to distinguish between the properties of substances and those of particles. To help students understand the underlying concept of emergence, several examples from everyday life, such as jigsaw puzzles or pixels on a screen, are used. When students see that the building blocks of a puzzle have a different shape than the puzzle itself, they can apply this idea to the building blocks of a salt crystal. To visualize this connection, 3D-printed models of crystal structures are used. To emphasize the different properties of particles and substances, atoms and molecules are represented by their chemical symbol. In this way, students are encouraged to understand the relationship between building blocks and matter, and to build their own mental model of matter. By the end of the TLS, they should be able to apply this model in small hands-on experiments, such as compressing air in a syringe and making assumptions about why this is possible.

To get students thinking about the PNM, several worksheets were created with tasks for students to complete alone, in pairs, or in groups. For example, in the first lesson, students should watch a video about the formation of salt or snow crystals and then explain what they saw in the video to a classmate. Students should use 3D-printed crystal structures to investigate how the crystals are formed. Over the course of the four lessons, students were given a total of seven worksheets, which covered everything they would later be asked to do in the post-test on a conceptual level.

Teachers who participated in the study received a manual that included a description of the key ideas, design principles, and detailed planning for the four lessons, including learning objectives and materials to be used. Teachers were free to use the lesson plans as they were or to adapt them according to their preferences or the needs of their classes. Teachers were also given a presentation file with several slides for each lesson. The slides included key ideas, illustrative graphics, and videos of simple experiments. There were also materials for teachers to demonstrate, such as small experiments or 3D-printed models to support the teacher's explanations.

C. TLS evaluation

A pre-post test format was chosen to examine students' performance. For the pretest and posttest, mostly the items from the interviews in cycles 3 and 4 were used, supplemented by some items from a German translation of the Chemistry Concept Inventory (CCI) [61]. There were both single-choice and open-ended items. The same items were be used for the pretest and posttest.

To evaluate the pretest and posttest items, a small pilot study was conducted. First, a test containing all items was administered to six students from a school where the first author teaches. All students had previously been taught the PNM. The students not only answered the questions, but were asked to explicitly tell the researcher if they had any problems or did not understand the questions. As the main problem, most of the six students thought that the test was too long. In addition, they did not use the PNM to answer the open-ended questions. To address these issues, the authors then met with other members of their working group to discuss possible revisions to the test. The discussion resulted in several changes being made to the pretest and posttests. One item required students to do a lot of reading because it consisted of 13 statements that students had to decide were true or false. The number of statements was reduced by more than half. To make it clearer to students how to answer the open-ended questions, each item explicitly stated that they should use the PNM for their answer. In addition, several minor changes were made to most of the items. The refined version of the pretest was then administered to a class of 23 students. Because some students still took a long time to answer the questions, one more item was removed from the pretest.

The final version of the pretest consisted of seven general questions about the PNM, which the students should already have known from previous instruction according to the national curriculum in Austria. The posttest consisted of eleven questions: the seven questions from the pretest and four questions more specific to the TLS.

Four teachers from three different schools in Vienna agreed to teach the TLS to an eighth grade class. The teachers' experience in teaching physics ranged from two to six years. All principals of the schools agreed to the implementation of the study. Informed consent was obtained from all parents of participating students. Teachers were also instructed on how to administer the pretest and posttests in a way that would not reveal the identities of the students. For 130 students a data set of pretest and posttest was gathered. An overview of the sample is shown in Table III.

TABLE V. Sample of students participating in the study.

School	Teacher	Class	Number of students
I	A	1	23
		2	22
	B	3	25
		4	22
II	C	5	20
III	D	6	18

Our aim in this study was to test the feasibility of the TLS in some classrooms. Therefore, students were not divided into experimental and control groups, i.e., this was not a randomized controlled trial (RCT). The use RCTs in education research is often criticized because students and teachers in a classroom do not follow causal natural laws [62]. Rather, the purpose of our study was to investigate whether the TLS would encourage students in the sample to use the PNM at all. Furthermore, it was of interest whether teachers were able to implement the TLS in a meaningful way. Therefore, each teacher was interviewed by the first author to get feedback on how the implementation of the TLS worked out. The interviews were semi-structured, each teacher was asked a minimum of five basic questions, but depending on the course of the conversation, the interviewer also asked additional questions to gain more insight. All interviews were recorded with the permission of the teachers and later transcribed for qualitative analysis.

For data analysis, student responses from the paper and pencil tests were transferred to a spreadsheet for enable further processing. The open-ended responses were coded using evaluative qualitative content analysis [63]. Categories for coding were based on students' different mental models of matter [18]. If students correctly applied the PNM, their response was coded as "particulate model". If the students used the same properties for particles as for macroscopic materials, their response was coded as "hybrid model". If students did not use particles at all in their explanation, their answer was coded as "continuous model". Thus, the coding focused specifically on students' use of the PNM. Students could answer correctly on a macroscopic level, but without using particles in their answer, the coding in that case would always be "continuous model". Interrater reliability was examined by two researchers from the authors' working group using ten percent of the data set. Cohen's kappa was calculated to be $\kappa = 0.73$. This represents a good interrater agreement [64].

Responses to the open-ended and closed-ended questions were than converted into scores for use in a quantitative analysis. Wrong answers to the closed-ended questions were coded as 0 points and correct answers were coded as 1 point. For the open-ended questions, students received 0 points if the answers were based on the continuous model, 1 point if it was based on the hybrid model, and 2 points if it was based on the particulate model. Therefore, all items are ordinally scaled. The analysis was performed in *JASP*, a free statistics program [65]. Because the data are ordinal scaled, only nonparametric tests can be used. The Wilcoxon singed-rank test was used to test whether the differences between students' responses in the pretest and posttest were statistically significant. To gain an insight into the overall performance of the students in the pretest and posttest, the sum of their scores on the seven identical questions from the two tests was compared. Therefore, a paired samples t-test was used to calculate *Cohen's d* for each class individually as well as for the sum of all participants.

The interviews with teachers were analyzed using structuring qualitative content analysis [63]. In contrast to the evaluative content analysis used with the open-ended questions from the pretest and posttest, the goal was not to find pre-existing categories in the data. Rather, teachers' ideas about the TLS were to be identified through an inductive analysis of the transcribed interview data.

IV. RESULTS

The results are based on the scoring of the pretest and posttest as well as the interviews. For comparison between the pretest and the posttest, the seven items that were part of both tests were used. Items that were only part of the posttest were analyzed separately.

A. Pre-post comparison

Overall students used the PNM more often in the posttest than in the pretest. As shown in Fig. 3a, about two-thirds of the students used the PNM more in the posttest. That is, they answered the three open-ended questions that were the same on both the pretest and the posttest more often using a hybrid or particulate model of matter. The Sankey diagram (Fig. 3b) shows how many students answered a question within the same mental model in both tests or changed their mental model from pretest to posttest. In the pretest, most of the students' answers can be described as a continuous model of matter, followed by a hybrid model and a particulate model. In the posttest, the continuous model is still the most prevalent, although fewer students' responses fall within that model. Fewer students use a hybrid model while students' use of the particulate model more than doubles. The most noticeable changes are students switching their answers from a continuous to a particulate model and students switching from a hybrid to a particulate model. However, most of the students' answers that were in the continuous model in the pretest remained in that model in the posttest.

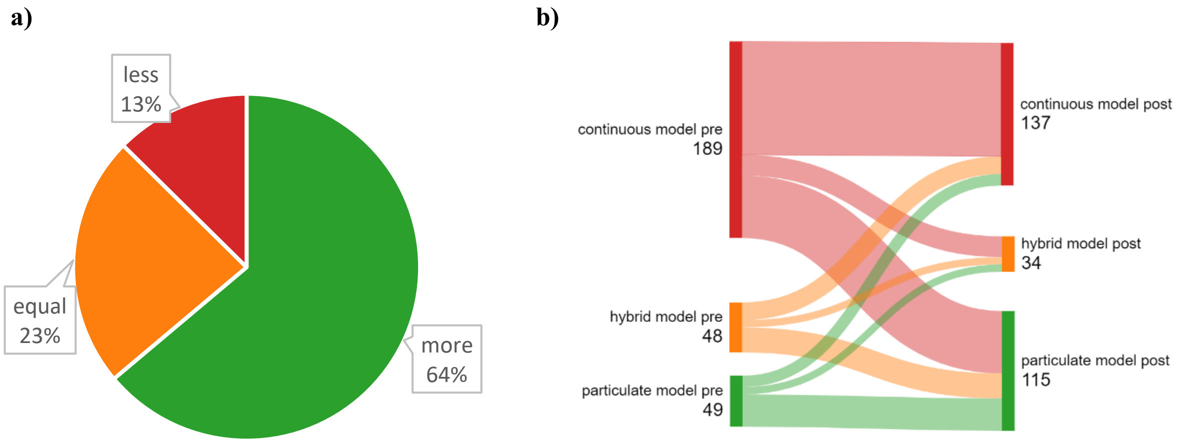

FIG. 3. a) Changes in the number of students using the PNM between pretest and posttest. b) Sankey diagram of students' mental models of matter before and after the intervention. Note that the numbers are pooled responses to the three open-ended questions that were the same on pretest and posttest. Students' answers to these questions were excluded from the analysis if they did not answer both the pretest and the posttest (source: own illustration using sankeymatic.com).

A paired samples t-test was conducted to compare students mean scores on the seven questions that were the same on the pretest and posttest. There was a significant difference in mean scores per student between the pretest ($M = 5.38$, $SD = 2.54$) and posttest ($M = 7.34$, $SD = 3.01$); $t(130) = -7.03$, $p < 0.001$. The effect size, measured by Cohen's d, was $d = -0.62$, indicating a medium effect [66]. The negative effect indicates a higher score on the posttest. Table IV shows different effect sizes for the six classes of students who participated in the study. Five out of the six classes scored significantly higher on the posttest than on the pretest. Cohen's d varies from small ($d_1 = -0.428$) to very large effects ($d_4 = -1.451$). Class 5 scored lower on the posttest than on the pretest ($d_5 = 0.033$).

TABLE IV. Comparison between pretest and posttest in different classes (paired samples t-test). For all tests, the alternative hypothesis specifies that the pretest is less than the posttest.

class	mean pretest	mean posttest	t	df	p	Cohen's d
1	5.826	7.043	-2.053	22	0.026	-0.428
2	4.182	6.773	-3.694	21	< 0.001	-0.787
3	6.240	8.520	-4.174	24	< 0.001	-0.835
4	4.136	8.273	-6.807	21	< 0.001	-1.451
5	5.250	5.150	0.149	19	0.558	0.033
6	6.722	8.056	-1.856	17	0.040	-0.437
all	5.377	7.338	-7.032	129	< 0.001	-0.617

To gain a better understanding of the differences between the six classes, an ANOVA was calculated. The results indicate that there are differences between the six classes on both the pretest ($F(5,124) = 4.224$, $p = 0.001$) and the posttest ($F(5,124) = 4.184$, $p = 0.002$). A post hoc comparison was used to differentiate between which classes had statistically significant differences. Tables V and VI show the results of the post hoc comparison including Tukey's test. Table V shows that there are four significant differences between the classes with a significance level of $p < 0.05$. These differences are due to the fact that classes 3 and 6 had the highest mean scores in the pretest and therefore are different from the other classes. Table VI shows that there are three significant differences between the classes in the posttest. These differences are all due to the fact that class 5 had the lowest score in the posttest.

Table V. Post hoc comparisons between classes in the pretest. P-value adjusted for comparing a family of 6.

		Mean Difference	SE	t	p_{tukey}	
1	2	1.644	0.715	2.299	0.202	
	3	-0.414	0.693	-0.597	0.991	
	4	1.690	0.715	2.363	0.178	
	5	0.576	0.733	0.786	0.969	
	6	-0.896	0.755	-1.187	0.842	
2	3	-2.058	0.701	-2.936	0.045	*
	4	0.045	0.723	0.063	1.000	
	5	-1.068	0.741	-1.442	0.702	
	6	-2.540	0.762	-3.333	0.014	*
3	4	2.104	0.701	3.001	0.037	*
	5	0.990	0.719	1.376	0.741	
	6	-0.482	0.741	-0.651	0.987	
4	5	-1.114	0.741	-1.503	0.663	
	6	-2.586	0.762	-3.393	0.012	*
5	6	-1.472	0.779	-1.890	0.413	

* p < .05

Table VI. Post hoc comparisons between classes in the posttest. P-value adjusted for comparing a family of 6.

		Mean Difference	SE	t	p_{tukey}	
1	2	0.271	0.846	0.320	1.000	
	3	-1.477	0.819	-1.802	0.468	
	4	-1.229	0.846	-1.454	0.694	
	5	1.893	0.867	2.184	0.253	
	6	-1.012	0.892	-1.134	0.866	
2	3	-1.747	0.829	-2.108	0.290	
	4	-1.500	0.855	-1.755	0.499	
	5	1.623	0.876	1.852	0.436	
	6	-1.283	0.901	-1.424	0.713	
3	4	0.247	0.829	0.298	1.000	
	5	3.370	0.851	3.962	0.002	**
	6	0.464	0.876	0.530	0.995	
4	5	3.123	0.876	3.565	0.007	**
	6	0.217	0.901	0.241	1.000	
5	6	-2.906	0.921	-3.154	0.024	*

* p < .05, ** p < .01

Table VII shows the results of the Wilcoxon signed-rank test for the seven identical items in the pretest and posttest. Since item 1 consisted of five questions asking students to rate whether a statement is true or false, the total number of measures compared was eleven. Table VII shows that for six of these eleven items, the difference between pretest and posttest is statistically significant as $p < 0.05$.

Three out of these six items are related to the idea that there is nothing between the particles (1b, 2, and 7). In item 1b, students were asked if they agreed with the statement "There is empty space between the building blocks". There was a significant difference in students' mean acceptance of this statement between the pretest ($M = 0.51$, $SD = 0.50$) and the posttest ($M = 0.70$, $SD = 0.46$); $z = -2.69$, $p < 0.001$. The effect size measured by the rank-biserial correlation is $r_B = -0.40$, which represents a medium effect [66]. In item 2, students were asked what is between two adjacent water building blocks when the water has evaporated. They could choose from three options: "air", "water vapor" or "nothing". In the posttest, significantly more students chose the correct answer "nothing" ($M = 0.43$, $SD = 0.50$) than in the pretest ($M = 0.20$, $SD = 0.40$); $z = -3.45$, $p < 0.001$. The effect size measured by the rank-biserial correlation is $r_B = -0.56$, indicating a large effect. In item 7 (11 in the posttest), students were asked why a sealed syringe filled with air can be compressed. They were also asked to use the PNM in their explanation. If they used the PNM correctly, their answer would receive 2 points. If they used the PNM but also applied misconceptions, their answer would receive 1 point. If they did not use the PNM, they would always receive 0 points. On the posttest, significantly more students gave answers based on the PNM ($M = 1.53$, $SD = 0.76$) than in the pretest ($M = 0.66$, $SD = 0.87$); $z = -5.36$, $p < 0.001$. The effect size measured by the rank-biserial correlation is $r_B = -0.89$, indicating a large effect. The data from these three items suggest that most of the students accepted the idea, that there is nothing between the building blocks in the posttest.

Table VII. Wilcoxon signed-rank test. Note that for all tests, the alternative hypothesis specifies that Pretest is less than Posttest. For example, 1a_Pre is less than 1a_Post. For the last three items the numbers do not align because the posttest had more items than the pretest.

pretest		posttest	W	z	p	Rank-Biserial Correlation	SE Rank-Biserial Correlation
1a_Pre	-	1a_Post	574.000	2.204	0.994	0.400	0.179
1b_Pre	-	1b_Post	549.000	-2.694	< .001	-0.400	0.147
1c_Pre	-	1c_Post	632.500	-0.947	0.139	-0.148	0.155
1d_Pre	-	1d_Post	627.000	-1.395	0.055	-0.214	0.152
1e_Pre	-	1e_Post	231.000	-0.617	0.243	-0.125	0.200
2_Pre	-	2_Post	280.500	-3.446	< .001	-0.560	0.161
3_Pre	-	3_Post	375.000	-2.362	0.003	-0.388	0.163
4_Pre	-	4_Post	400.000	-2.114	0.008	-0.347	0.163
5_Pre	-	8_Post	411.000	-3.301	< .001	-0.503	0.151
6_Pre	-	10_Post	242.500	-0.940	0.168	-0.185	0.194
7_Pre	-	11_Post	65.000	-5.364	< .001	-0.889	0.164

Two items with significant differences between pretest and posttest (3 & 5) are related to the idea that the temperature of an object is determined by the motion of the particles. In item 3, students were asked: "What happens to a single building block of water when water vapor is heated?". he students were presented with four options, which they could select according to their understanding of the phenomenon in question. These were as follows: a) "The building block's density decreases, b) "The building block expands", c) the building block slows down, and d) " The building block speeds up". In the posttest, a significantly greater number of students chose the correct answer, option d ($M = 0.61$, $SD = 0.49$) in comparison to the pretest ($M = 0.46$, $SD = 0.50$); $z = -2.36$, $p = 0.003$. The effect size measured by the rank-biserial correlation is $r_B = -0.38$, which represents a medium effect. In item 5 (item 8 in the posttest), students were asked: "An iron ball does not fit through an iron ring at room temperature. Describe what could be done to make it fit through. Justify your answer with the building blocks of matter!". Students' answers were coded the same manner as with item 7 above. In the posttest, a significantly greater proportion of students provided responses based on the PNM ($M = 0.79$, $SD = 0.92$) than in the pretest ($M = 0.46$, $SD = 0.72$); $z = -3.17$, $p < 0.001$. The effect size measured by the rank-biserial correlation is $r_B = -0.49$, representing a medium effect. The data from these two items indicate that the majority of students accepted the notion that the movement of the building blocks determines the temperature of an object.

The final item with statistically significant differences between pretest and posttest is item 4. n this item, students were presented with the following scenario: "A balloon filled with helium is pushed to the bottom of the swimming pool. It immediately becomes smaller. How can this decrease in volume be explained?". Students were than asked to choose from four different answers[7]. In the posttest, a significantly greater proportion of students provided responses based on the PNM ($M = 0.75$, $SD = 0.44$) than in the pretest ($M = 0.61$, $SD = 0.49$); $z = -2.11$, $p = 0.008$. The effect size measured by the rank-biserial correlation is $r_B = -0.35$, representing a medium effect. Students were less likely to chose option b, indicating that they less often used the same properties for particles as for substances.

[7] a) The cold water causes helium to become liquid; b) The helium building blocks are getting smaller; c) Helium building blocks migrate through the rubber skin of the balloon into the water; d) The distances between the helium building blocks become smaller.

B. Posttest analysis

In the TLS, the PNM was introduced via crystal structures. In the posttest, students were required to answer two single-choice questions. They were asked to select the statement in a concept cartoon that most closely aligned with their beliefs. The first question pertained to the formation of snow crystals. Three statements were presented to explain why all snow crystals possess six prongs (see Appendix). Each statement represented a person having a continuous, hybrid, or particulate mental model of matter. Sixty-six percent[8] of the students selected the statement representing a particulate model of matter (see Fig. 4a). The second question concerned the reason for the differing properties of diamond and graphite, despite both being composed solely of carbon atoms. Once again, three different statements were presented to explain this phenomenon, representing a continuous, hybrid, and particulate mental model of matter. In this item, 67 percent of the students selected the statement representing a particulate model of matter (see Fig. 4b).

a) Why do all snow crystals have six prongs?

b) How can diamond and graphite have different properties when they both solely consist of carbon?

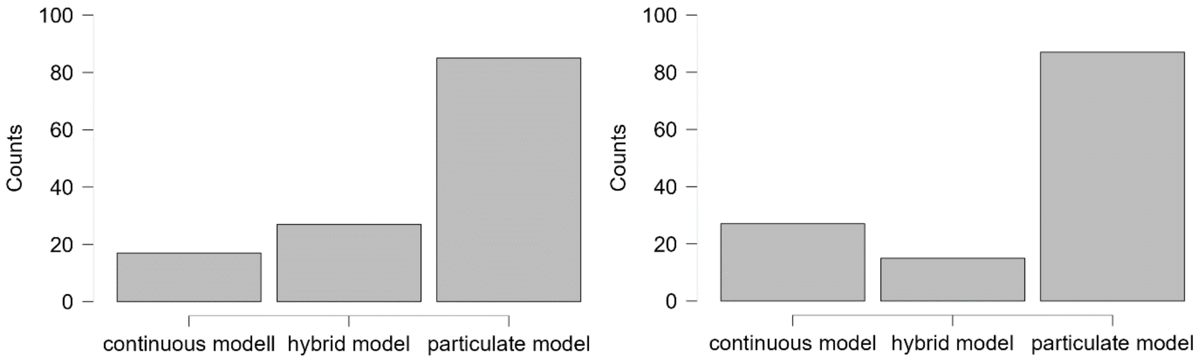

FIG. 4. Coded answers of students to questions in the context of crystals structures.

One of the most relevant challenges in teaching the PNM is that students tend to apply the same properties to particles as they do to macroscopic objects. Despite students demonstrating higher performance on the posttest, this misconception persisted in some cases. When asked about the statement: "A railroad track expands when heated because the iron building blocks expand" 55 percent of the students agreed. However, when asked: "What happens to a single water building block when water vapor is heated?" 61 percent of the students selected the correct response: "The building block speeds up". Only 14 percent selected the incorrect response: "The building block expands." This suggests that the phases of matter may influence whether students transfer the properties of macroscopic objects to submicroscopic particles.

When it comes to explaining melting and boiling point, students rarely utilize the PNM. In the posttest, only 17 percent of students in the posttest utilized the PNM to explain the differing boiling points of various substances. Of the valid responses, 70 percent were based on a continuous model of matter (see Fig. 5b). Furthermore, a smaller proportion of students employed the PNM when asked to explain why ice immediately melts over a flame while aluminum does not. A mere 12 percent of students employed a particulate model of matter to answer the question, while 82 percent applied a continuous model (see Fig. 5a).

[8] These are the valid percentages, missing answers were omitted from the analysis.

a) Why does an ice cube melt over a flame but not an aluminum can?

b) When heating salt water: why does the water evaporate but not the salt?

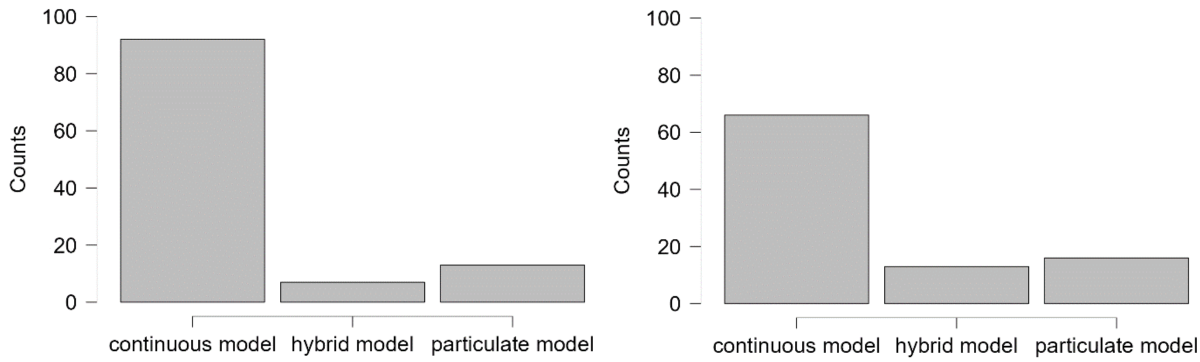

FIG. 5. Coded answers of students to questions in the context of melting point (a) and boiling point (b).

B. Teachers' perspective

In general, the feedback from the four teachers on the TLS was positive. They found the materials to be "good" and "helpful," and they described the implementation of the TLS in the classroom as "easy." Teachers generally liked introducing the PNM with crystal structures. However, two of them said that they would not discuss crystal structures in as much detail as suggested by the TLS, while teacher D said it would be beneficial to go even more into detail. All four teachers indicated that they would utilize the TLS again, although one teacher expressed reservations about doing so under certain conditions. Teacher A expressed a preference for not using the model experiment demonstrating the spacing between particles in the gaseous state, stating concerns that it lacked sufficient descriptive detail for students.

Some of the domain-specific design principles of the TLS were novel for the teachers. For instance, the use of "building blocks" instead of "particles" was unfamiliar to all of them. The teachers indicated that they were accustomed to the term "particles" and that the textbooks also employed this terminology. This may present a challenge, as teachers may encounter difficulties integrating their textbooks with the TLS. Additionally, the concept of utilizing crystal structures and 3D-printed models to teach the PNM was novel to some teachers. They noted that the handling of the 3D-printed model was challenging, especially the need for substantial storage space and the potential for breakage. Nevertheless, all of the teachers indicated that the models were well received by the students. The teachers' descriptions of the students' prior knowledge of the PNM differed. Teachers A and B expressed surprise at the limited recollection of the PNM by the students, whereas Teacher D observed that the students demonstrated a high level of familiarity with the topic due to their previous studies in physics and chemistry. This finding aligns with the observation that class 6 achieved the highest average score in the pretest. Teacher D additionally proposed that supplementary materials be included in the teachers' manual for students who demonstrated a high level of interest. These materials could include a more detailed description of how crystal structures are formed.

All teachers felt that most of their students understood what they were taught during the TLS. Teachers C and D mentioned that the learning materials and the hands-on nature of the TLS were beneficial to their students' learning. Teacher B felt that when talking to the students, the majority of them seemed to understand the content. However, they may soon forget if they do not review and reinforce this knowledge.

None of the four teachers reported making any major changes to the TLS. They used all of the student worksheets and presentation slides provided by the researchers. Only the experiments demonstrating the expansion of an evaporating liquid in a food bag did not work well for the teachers.

Teachers A and B reported that it did not work at all, no matter what they tried. They showed the video of the experiment instead. Teacher C also had some difficulties at first, but managed to make the experiment work for the students. Teacher D did not let the students do the experiment themselves because there was not enough time and they had to try more than once to get it to work. It seems that this hands-on activity is difficult for teachers to use in the classroom, although they said that it would be helpful for students learning the PNM if it worked.

V. DISCUSSION

The purpose of the study was to evaluate whether a TLS developed based on domain-specific design principles would promote students' use of the PNM. Domain-specific design principles are "local theories" [60], meaning they are not generalized theories, but rather practical guidelines within the context in which they operate [13]. They inform instructional activities in a particular context to promote learning [67]. In this stud,y the four domain-specific design principles in Table I were intended to guide students' application of the PNM.

The non-generalized nature of the design principles makes it challenging to determine which of these principles is responsible for which outcome. The higher performance of students in the posttest can be attributed to the collective influence of all domain-specific design principles. However, it is not possible to determine which one had the greatest impact on students' use of the PNM. Some of the key ideas, in particular, make use of a design principle. For instance, the concept of empty space between particles is elucidated to students through the use of various typographic representations. Consequently, it can be posited that typographic representations influenced students' acceptance of this idea more frequently in the posttest. Similarly, the emphasis on the emergent properties is of paramount importance for students to comprehend temperature. As evidenced by the fact that the majority of students in the posttest connected temperature with the movement of particles, an understanding of the concept of emergence might have facilitated their ability to apply the PNM correctly. Comparable to the study by Henderson *et al.* [56], explaining to students the concept of emergence seems to have helped them to argue within the appropriate ontology.

Only some of the results from the previous study could be replicated in the classroom setting. Crystal structures appeared to be a fruitful context for the introduction of the PNM, as students in the interviews as well as in the posttest were able to apply the PNM within that context. Even the students in class 5, who scored poorly on the posttest, predominantly applied the PNM in connection with crystal structures.

However, regarding phase transitions, there are differences between the previous and the current study. In the previous study, students were able to explain what happens to the building blocks during phase transitions when specifically asked to do so in the interviews. In this study, students were also asked to use the building blocks for their explanation of phase transitions, but most of them did not do so. It remains unclear why students did not use the PNM for their explanation of melting and boiling point. It is possible that the examples provided for the items were not optimal, as students may perceive the melting of a substance and the heating of another substance without undergoing a phase transition as two distinct phenomena. Consequently, they may adhere to the continuous model, as it is more familiar to them and they can justify the observed differences in melting and boiling points. However, the same examples were also utilized in interviews with students in the previous study. In this instance, students encountered only minor difficulties in utilizing the PNM to elucidate phase transitions.

The Students in this study showed what has been termed "level confusion" [22] or "hybrid conceptions" [25]. They employed the same properties for submicroscopic particles as they did for macroscopic objects. This conception appeared to be most prevalent in connection with solids, as more than half of the students imagined expanding iron particles causing the expansion of a railroad track. This phenomenon might be attributed to students' belief that particles cannot move in a solid.

Conversely, students in general accepted the idea of moving particles in gases. Only a minority of students in this study argued that particles expand in a gas. This finding is consistent with the observation that students have difficulties explaining phase transitions with the PNM. They do not perceive the different phases of matter as the same particles having different velocities and bonding, but rather as three distinct entities. This kind of student' conception has already been documented by Johnson and Papageorgiou [68].

A. Limitations of the study

The objective of this study was to assess the feasibility of utilizing the developed TLS in instructing the PNM to 8th-grade students from Austria. As such, it represents a study of feasibility, rather than a comprehensive quantitative study. The study involved four teachers and six classes comprising a total of 130 students from three distinct schools in Vienna. The participation of teachers and their respective classes was entirely voluntary. All students received the same instructional approach, and there were no control groups. Conducting an RCT with a large, randomly selected sample would have enhanced the reliability and objectivity of the study. Teachers were provided with guidelines outlining the most crucial aspects of the TLS. These guidelines also included detailed lesson plans. Additionally, they received all necessary materials (students' worksheets, presentation slides, experimental materials) for implementing the intervention. However, the researchers did not observe teaching. It is therefore not possible to conclude that all students were taught exactly in the same way. However, it can be argued that during the follow-up interviews, none of the teachers made any remarks about teaching in a way that differed from what was described in the guidelines.

The results of the six classes differed from each other. Five of the classes showed a significant improvement in the posttest, while class 5 scored worse in the posttest than in the pretest. Class 4 exhibited the greatest improvement in mean test scores between the pretest and posttest. The use of a single worksheet by teacher B for grading students' performance may have contributed to the high learning gain observed in class 4. However, it remains unclear whether this alone can explain the significantly higher learning gain observed in class 4 compared to the other classes.

If we assume that all teachers adhered to the guidelines as they stated, another source of variation in student outcomes may be due to differences in the time required to teach the intervention. As the intervention was planned for four consecutive lessons, teachers would need between two and four weeks, depending on the number of lessons in a week. However, in the interview, teacher C stated that they did not teach the TLS in four consecutive school lessons as planned but had to interrupt the TLS to teach something else. After more than a month, the intervention was completed and the posttest was administered. This may be the reason for class 5 scoring worse on the posttest than on the pretest.

Another limitation is the students' attitudes towards the study. Teachers reported that students did not take it as seriously as their regular teaching, as they were aware that the pretest and posttest would not be relevant for their grade. Consequently, students frequently failed to consider their responses in depth or even to respond to open-ended questions at all. It can be posited that had their results on the posttest been relevant for their grade, students would have invested more effort in providing accurate responses.

VI. CONCLUSION

In general, teachers were satisfied with the materials of the TLS and found them useful for teaching. Students overall used the PNM more after the intervention. Therefore, it can be concluded that the domain-specific design principles promote students' use of the PNM. These results suggest that the TLS can be used for teaching the PNM in 8th-grade classes. In the case of the Austrian physics curriculum, the TLS can serve as a basic introduction to the PNM in the context of thermodynamics. However, the

TLS might also be used in other physics or chemistry contexts. As the TLS focuses on the most fundamental ideas of the PNM, it might also be expanded to cover a broader range of physics concepts, such as heat transfer and diffusion. As the term "building blocks" encompasses atoms, molecules, and ions, it is possible to delve deeper into the distinctions between these terms and their underlying concepts.

As previously mentioned in the limitations section, the objective of this study was to assess the viability of implementing the TLS in 8^{th}-grade physics classes. The presented results cannot be generalized, as the sample size was limited and not randomly selected. Future research should therefore focus on testing the TLS with a larger number of randomly selected students in an RCT. In reverse, a more qualitative follow-up study could investigate the effects of the different design principles used in the TLS in more detail. As for the results of this study, it is often not possible to determine which of the domain-specific design principles proves most effective in fostering students' use of the PNM. Moreover, the reason for the apparent dependence of students' use of the PNM on the phases of matter could be investigated. Science education research might also focus more on investigating the teaching of the concept of emergence, as it is key for explaining many phenomena in science education.

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APPENDIX: POSTTEST[9]

Please create the following code: **YOUR CODE:** | *Example* **CODE:**

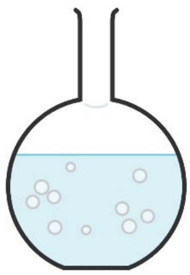
the first two letters of your **mother's first name**			***first*** name of your mother: ***Maja***	M	A
the first two digits of **your own birthday** (01-31)			own birthday: ***06.10.2010***	0	6
Second and third letter of **your own first name**			own first name: ***Thomas***	H	O

1) Please tick in each line:

	incorrect	**correct**
The building blocks of a solid substance are completely immobile at room temperature.	❐	❐
There is empty space between the building blocks of a substance.	❐	❐
When iron melts, the iron building blocks become soft.	❐	❐
A railroad track expands when heated because the iron building blocks expand.	❐	❐
The building blocks of a warm iron ball move faster than the building blocks of a cold iron ball.	❐	❐

Always tick one answer to the following five questions :

2) Water is boiling in a glass container. After the water has evaporated, what is between two adjacent water blocks in the container?



❐ empty space
❐ air
❐ water vapor

3) What happens to a single water building block when water vapor is heated?

❐ The water building block becomes faster.
❐ The water building block expands.
❐ The water building block loses density.
❐ The water building block becomes slower.

[9] The Posttest has been translated from the German original using a translation software.

4) A balloon filled with helium is pushed to the bottom of the swimming pool. It immediately becomes smaller. How can this decrease in volume be explained?

- ❐ The cold water causes helium to become liquid.
- ❐ The helium building blocks are getting smaller.
- ❐ Helium building blocks migrate through the rubber skin of the balloon into the water.
- ❐ The distances between the helium building blocks become smaller.

5) Although every snow crystal looks different, all snow crystals always have six points . The following three statements attempt to explain why this is so. Tick which of the three statements you agree with most !

- ❐ Mike claims: "I think a snow crystal looks like this because the building blocks of water always assemble in this shape when it is cold."
- ❐ Lisa says: "I think a snow crystal looks like this because the building blocks of water also have this shape."
- ❐ Anna says: "I think a snow crystal looks like this because little ice balls are deformed when they fall through the air."

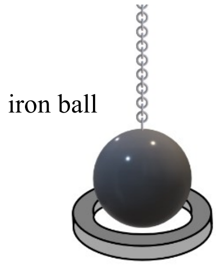
6) Diamond and graphite consist only of carbon building blocks. Nevertheless, they have other properties: diamond is extremely strong, whereas graphite breaks relatively easily. The following three statements attempt to explain why this is so. Tick which of the three statements you agree with most.

- ❐ Mike claims: "Diamond has different properties than graphite because its density is much higher than graphite".
- ❐ Lisa says: "Due to the different arrangement of the building blocks. Diamonds have a stable crystal structure in contrast to graphite .
- ❐ Anna says: "Diamond and graphite consist of the same building blocks but the individual building blocks have been changed in nature. That's why diamond and graphite look different and have different properties."

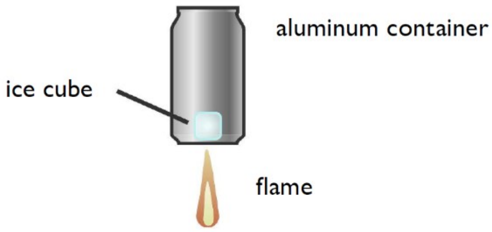
Please answer the following questions with at least one complete sentence.

7) In this picture you can see three cuboid pyrite crystals. Why do they have such a rectangular shape? Justify an answer using the building blocks of matter!

8) The iron ball does not fit through the iron ring at room temperature. Describe what could be done to get it through. Justify your answer with the building blocks of matter!

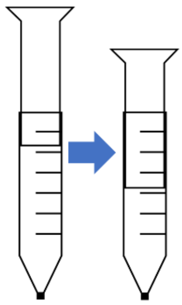


9) If you hold an aluminum container with an ice cube in it over a candle flame, the ice cube begins to melt, but the aluminum container does not. Explain why this is so using the building blocks of matter!



10) If you heat salt water to boiling point and wait for the water to evaporate, the salt will remain at the bottom of the vessel. Explain why this is so using the building blocks of matter!

11) A syringe is filled with air and tightly closed so that no air can escape. Nevertheless, the syringe can be compressed to some extent. Explain why this is possible using the building blocks of matter!



Thank you for participating!

5. Results

The doctoral research project was conducted in accordance with the methodological framework of DBR. The project's objectives were twofold: to develop products for teaching the PNM and to generate new theoretical findings in this field. Both objectives were met, as evidenced by the development of a new TLS on the PNM and the evaluation of domain-specific design principles. As is characteristic of DBR, the development of the TLS and the generation of new theoretical findings were closely connected.

A. Theoretical findings on teaching the PNM

In the DBR project generating new theoretical findings was closely linked to the design principles. While the general design principles were stipulated at the beginning of the project, the domain-specific design principles (see Table 1) were developed throughout several cycles of design, evaluation, and analysis. Through this process, general theories about teaching and learning could be connected to teaching and learning the PNM. For example, the development of the TLS was based on well-known students' conceptions. As students tend to transfer the properties of macroscopic objects to atoms and molecules, the term "particle" was avoided, as it comes from "to part" and therefore implies that a macroscopic object is split up until very small particles remain[10]. These particles would then still have the same properties as the macroscopic object.

To further address the aforementioned students' conception a ontological conceptual change strategy should be employed. In this approach, students should learn to perceive physical phenomena as emergent rather than direct-causal. To illustrate this emergent ontology, examples from everyday life, such as the formation of a picture on a screen, can be used. Furthermore, the use of "building block" should also contribute to students' understanding of the emergent properties of the PNM. The properties of substances emerge from the properties of the building block, rather than the other way around. Data from the interview study suggests that the more students use the term "building block", the less they transfer the properties of substances to particles.

The TLS was designed in a way that learning starts with students' subjective perceptions and leads to abstract scientific concepts. Students should initially consider the specific characteristics of crystals before learning that the formation of crystals can only be explained by applying the PNM. Therefore, students must again utilize the emergent ontology. To explain why, for instance, salt crystals always form a cubic shape, it is necessary to consider that the sodium and chloride ions form a cubic lattice structure. Data from the interview study and the classroom intervention have shown that students can connect the formation of crystals with the PNM.

To demonstrate that the shape of the crystals is not determined by the shape of the individual building blocks, it is important to use learner-friendly representations. In the investigated sample, students preferred typographic representations over spherical or continuous representations of matter. Typographic representations use chemical symbols and formulas instead of colored ball-shaped objects to represent atoms and molecules. They can be used in illustrations as well as in 3D-printed models.

Domain-specific design principles	
DP 1:	Using crystal structures as a starting point for the introduction of the PNM.
DP 2:	Use of "building blocks" instead of "particles".
DP 3:	Stressing the emergent aspects of the PNM.
DP 4:	Using typographic representations instead of ball-shaped drawings of atoms and molecules.

Table 1. Domain-specific design principles in the TLS.

[10] This is also the same in German: the term „Teilchen" (particle) comes from „teilen" (to part).

To facilitate student engagement in learning about the PNM, it is essential to view them as active participants in the learning process. This entails encouraging them to make their own observations and engage in discussion with their peers. Subsequently, the teacher should strive to integrate students' observations and reasoning in their explanations of the key ideas. The four teachers who conducted the intervention study highlighted that students in their classes derived enjoyment from collaborative problem-solving and experimentation. One of the teachers also explicitly stated that students working with the materials alone or in groups was one of the strengths of the TLS.

B. The TLS

In parallel with the generation of the theoretical findings described above, a TLS on the PNM was developed. The method of educational reconstruction (Kattmann et al., 1996) was employed to formulate key ideas, with content knowledge as well as knowledge on teaching and learning the PNM being used. As described in the instruction not all of these key ideas were established at once; rather, they were developed throughout several iterations of design, evaluation, and redesign.

The final version of the TLS consists of seven key ideas. As illustrated in Table 2 the key ideas are also closely aligned with the domain-specific design principles. For instance, in each key idea, atoms and molecules are referenced as fundamental building blocks. Moreover, several of the key ideas are linked to the emergent properties of matter. Key idea 2 introduces the concept of emergence, while key idea 3 explains how some properties of matter, such as strength, emerge from the bonding of the building blocks. Key idea 4 explains how temperature emerges from the movement of the building blocks. Finally, key ideas 5 and 7 combine the concepts of bonding and movement of the building blocks to explain how phase changes emerge.

Key ideas
KI 1: Everything that can be touched is imagined to be composed of very many, small, non-visible building blocks.
KI 2: The properties of a building block are not the properties of the object.
KI 3: The bonding of the building blocks determines the properties of the object.
KI 4: The movement of the building blocks determines the temperature of an object.
KI 5: At the melting point, the bond becomes flexible and the rigid structure disappears.
KI 6: There is nothing between the building blocks.
KI 7: At the boiling point, the bonding of the building blocks ceases and they move away from each other.

Table 2. Key ideas in the TLS

Further implications from the domain-specific design principles were used for the design of the TLS. For example, the first key idea is introduced in the context of crystal structures. Students are initially presented with a video demonstrating the formation of crystals and are asked to make assumptions about why these crystals always form in the same way. The teacher then presents students with the idea that everything that can be touched is imagined to be composed of very many, small, non-visible building blocks. The formation of the crystals can only be explained by applying this idea. For that students first need to understand that the properties of the building blocks are not the properties of the object. This is demonstrated by three different examples: 1) one building block of a three-dimensional puzzle does not have the same shape as the puzzle as a whole, 2) one pixel on a display does not show the same picture as the whole display and 3) one building block of salt does not have the same rectangular shape as the salt crystal. These examples demonstrate the basic idea of emergence without the use of the term itself.

To further illustrate the distinction between the building blocks and the objects they compose typographic representations are used. For example, the building blocks of salt are depicted as *Na* and

Cl[11]. Building blocks are not solely utilized for textbook-like depictions (see Fig. 3a) but also in 3D-printed crystal structures (see Fig. 3b). A number of these 3D-printed structures are employed in particular in connection with key idea 3, to show students the bonding of the building blocks. Students work in pairs and receive either a 3D-printed crystal structure of diamond or graphite. By examining these structures, students should recognize that although both materials are composed only of carbon atoms they can have very different properties due to the different bonding. This should also reinforce the notion that the properties of the building blocks are distinct from those of the macroscopic objects.

a) **b)**

Figure 3. Two ways of using typographic representations showing the crystal structure of salt
(source: own illustration using a picture of salt crystals by Cristian V., Wikimedia commons, CC BY-SA 4.0)

Although the tubes representing the bonds between the building blocks in the 3D-printed crystal structures are rigid the building blocks can be moved slightly. This allows the concept that the building blocks are in constant motion, even when the object is in a solid state, to be demonstrated to students. To prove this assumption a demonstration is conducted by the teacher: an iron ball that exactly fits through an iron ring is heated with a flame. When the temperature is sufficiently elevated, the iron ball no longer fits through the ring anymore. This observation can only be explained by postulating that the iron building blocks move more rapidly when the temperature rises, causing the ball to expand.

In the subsequent step, the concepts of the constant motion and the bonding of the building blocks are integrated. To illustrate the distinctions between the solid and liquid states, 3D-printed models are employed once more. First, students are presented with a model, which demonstrates the rigid hexagonal structure of the water molecules in ice I_h. Students are then shown second model using the same H_2O symbols but this time they are connected by short pieces of silicon tubing. This modification makes the connection between the building blocks becomes flexible, demonstrating their behavior when water is in a liquid state. To further investigate the melting process, students do a small hands-on activity in which they place an ice cube in an aluminum can and place the can over a candle. Based on their observations, students should make assumptions about why the ice cube melts but the aluminum can does not.

The sixth key idea introduces the idea that there is nothing between the building blocks. Since students tend to think that there is air between the building blocks they need to be convinced otherwise. First, the teacher demonstrates what happens when 200 ml of water and 40 ml of salt are mixed. Counter-intuitively the mixture does not have a volume of 240 ml, there is less salt water than the volume of water and salt combined. This contradiction then leads to the idea that there is empty space between the

[11] More accurately would be Na^+ and Cl^- because the salt crystal is formed by an ionic bond. In order not to overwhelm students with more information about charges and the subatomic structure this information is omitted in the TLS. However, it can already be added at this point or later on. In that case the typographic representations can be easily adapted to the teacher's preferences.

building blocks so that they can move closer together. In the following hands-on activity students should use this ides when answering the question of why air can be compressed in a syringe.

a) **b)**

Figure 4. a) Model experiment demonstrating the behavior of particles in water vapor; b) 3D-printed H_2O symbols used in the model experiment (source: own illustration).

The final key idea brings together all of the previous key ideas to explain evaporation. To demonstrate the spacing of the building blocks when an object is in a gaseous state, students are shown a model experiment[12] (see Fig. 4a). The model consists of a plastic bag and small 3D-printed H_2O symbols (see Fig. 4b) The number and size of the symbols are to scale with the volume of the bag. When shaken, the symbols move around in the bag, showing the increase in distance between the liquid and gaseous states. With this model in mind, students should then carry out a hands-on experiment: a small pouch (normally used for baby food) is filled with several drops of methylated spirits. The pouch is sealed tight and then immersed in hot water. As long as the temperature of the water is above the boiling point of the methylated spirits (78 °C), the pouch quickly expands rapidly as the methylated spirits evaporate and increase in volume. When the pouch is removed from the water, it quickly contracts as the methylated spirits condenses.

[12] For a detailed description of the model experiment see Hull et al. (2023).

6. Discussion

The aim of the doctoral research program was to find new ways of teaching the PNM to students at the lower secondary level. The research process was structured by a total of five research questions. Based on the findings described in the articles and summarized in Chapter 5, these questions are answered in the next subchapter, followed by the limitations of the study and concluding remarks about the project.

A. Answers to the research questions

The main question guiding the research in the dissertation project was how to improve students' understanding of emergent properties in the context of the PNM. Similar to the findings of Chi et al. (2012), data suggest that students need to be explicitly taught the concept of emergence. As the participating students in the research project were primarily thirteen to fourteen years old the term *emergence* was not used but rather the idea was explained to them through simple examples. In general, the students found this idea to be sensible and plausible. However, when asked solve problems related to the emergent nature of the PNM, students in some cases still used macroscopic properties for particles. For example, most students agreed with the statement "A railroad track expands when heated because the iron building blocks expand" in the posttest of the intervention study. In contrast, only a few students argued that a water building block increases in size during the expansion of water vapor.

The second research question asked for experiments that would convince students of the PNM. Five of these experiments that are commonly used in the classroom were selected from the literature (Fischler & Rothenhagen, 1997; Harrison & Treagust, 2006; Sieve, 2016). The selection of the experiments was based on their popularity in the literature as well as being easy to carry out with materials that are available at every school. Students' understanding of these experiments was assessed in interviews following the method of probing acceptance. Data suggest that none of these five experiments should be used to introduce the PNM. This could lead to the conclusion that experiments in general are not the best way to start with the teaching of the PNM. Understanding what happens in the experiment and simultaneously learning about particles seems to be too demanding for secondary school students. However, this does not mean that experiments cannot be a part of teaching and learning the PNM. Rather, they should not be used as an introductory motivation to the topic.

Students' difficulties in learning the PNM through experiments led to the search for other ways to introduce the topic. In the second cycle of the interview study, three different arguments were used to introduce students to the PNM: 1) the formation of snow crystals, 2) the formation of salt crystals, and, 3) an STM image of graphite. Data suggest that all three arguments promoted students' use of a particulate model more than experiments. However, students were able to connect the macroscopic to the submicroscopic levels of matter in the context of the snow and salt crystals but not in the context of the STM image of graphite. Therefore, the hypothesis by Franzbecker and Quast (1975) on using crystal structures to introduce the PNM seems to be accurate within the limitations of the doctoral research project, as students understand the connections between macroscopic and submicroscopic levels of matter.

Another important aspect of teaching the PNM are representations of the particulate model, since the particles themselves are non-visible. Typically, atoms and molecules are represented by colored spheres (Bunce & Gabel, 2002). It has been argued that this type of representation fosters misconceptions because students often have difficulties interpreting models and think of them as copies of the real world. This could lead students to think that atoms and molecules look like small colored spheres. To avoid this type of misconception and to emphasize the model character of such depictions this study made use of typographic representations. Instead of using spheres, atoms were represented by the name of the element (e.g. *Fe* for iron) and molecules by the molecular formula (e.g. H_2O for water).

Similar to the study by Wiener et al. (2015), most of the students in the interview study accepted the idea of typographic representations. The majority of the students preferred the typographic representations compared to spherical and continuous representations of matter.

The final research question (RQ 5) asked whether a TLS based on domain-specific design principles can promote students' use of the PNM. This question was addressed by an intervention study with 130 students from three schools in Vienna. The analysis of the pre- and posttest shows that on average students use the PNM more often in the posttest. However, this cannot be said for all aspects of the PNM that are covered by the TLS. While students significantly more often accept the idea that there is empty space between the particles and that temperature emerges from particle motion, they do not use the PNM when asked to explain melting and boiling point. This is surprising since the respective questions specifically asked students to use the PNM. Why students experience difficulties remains an open question, especially since the students in the interviews were able to use the PNM when asked by the interviewer.

B. Limitations

In evaluating the results of the doctoral research project, it is important to remember that it was a study of feasibility conducted by a single researcher, not a large-scale research project involving multiple researchers and a large number of schools. Therefore, the number of participants is limited. A total of 60 students participated in interviews and 130 students participated in the intervention study. All the students were from three different schools in Vienna. The limited number of schools participating in the study in part was, in part, due to regulations of the federal government enacted on response to the COVID-19 pandemic. Furthermore, the participation of students in the research project was entirely voluntary. To enhance reliability and objectivity a larger sample of randomly selected students should have been chosen. The doctoral research project merely aimed to develop and evaluate a TLS that demonstrated positive results within the selected sample.

According to the physics curriculum for a secondary school in Austria, the TLS was designed for 8th grade. Consequently, the evaluation was also carried out with students from 8th grade[13]. Data suggesting a positive effect on students' use of the PNM is only applicable to students in grade 8. It was not investigated whether the TLS can also be used with students in other age groups.

Four domain-specific design principles form the theoretical foundation of the TLS. These theory-driven principles have been subject to rigorous evaluation throughout the research project, and the results indicate a positive effect on students' use of the PNM. The selection of the domain-specific design principles was based on decisions made by the researcher, informed by a review of pertinent literature and research results. However, the available data were limited, with only a fraction of experiments on the PNM being investigated. Furthermore, a different set of principles could have been evaluated. It is important to note that not every significant aspect of teaching the PNM could be included in the research project.

C. Conclusion and implications

Overall the TLS developed during the doctoral research project seems to be understandable for students and useful for teaching the PNM. All teachers participating in the study indicated that they would use at least some aspects of the TLS again if they had to teach the topic in one of their classes. None of them reported difficulties in using the TLS in the classroom. Some of the domain-specific

[13] Except for the first cycle in the DBR project, as a change in the curriculum was announced by the Austrian ministry of education after the interviews took place.

design principles were new to them, especially the use of the term “building block” instead of “particle”. However, the results indicate that as students become more familiar with the term "building block," their hybrid conceptions of matter become less pronounced. The introduction of crystal structures into the teaching of the PNM was also a novel concept for both teachers and students, yet they generally adapted well to this idea. Both teachers and students expressed positive sentiments regarding the typographic representations, particularly the 3D-printed models of crystal structures. In light of the students' enhanced performance in the posttest and the teachers' positive feedback, the TLS may be utilized in future instruction of the PNM. However, further research is still necessary.

As previously stated, the doctoral research project represents a study of feasibility. Based on the limited data available all conclusions drawn in this project are only valid within the investigated sample. To determine if the TLS enhances learning of the PNM within the population a large-scale study with a randomly selected sample would be necessary. Moreover, the efficacy of teaching the PNM with the TLS should be contrasted with that of "traditional teaching" of this topic.

However, the outcomes of the study also prompt further inquiries for future research on teaching and learning the PNM. As previously discussed, the reasons behind the apparent dependence of hybrid conceptions of matter on the phases of matter remain unclear. An in-depth qualitative study might provide new insights into this question. Moreover, the concept of emergence has only recently been incorporated into science education research, particularly in the context of teaching the PNM and other topics in physics. Further research could not only enhance our understanding of how this concept can be effectively utilized in teaching but also provide additional evidence to support the assumption that a significant proportion of students' conceptions are based on an ontological misunderstanding. The application of the concept of emergence to explain other phenomena, such as heat transfer or pressure, to students may not only contribute to the advancement of science education research but could also be utilized to expand the TLS developed in this research project. In this way, the TLS may become a comprehensive introductory course in thermodynamics for students in lower secondary school.

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7. Appendix

A. Abstract

Students often assume that atoms and molecules have the same properties as macroscopic objects. For example, they imagine that during the thermal expansion of a substance, its particles also expand. The reason for this is often the application of the wrong ontological category: students see a direct causal connection between the atomic level and the macroscopic level instead of an emergent connection. The latter describes how the properties of a system arise from the behavior of its parts, whereby the properties of the parts differ from those of the system. An understanding of the particulate nature of matter (PNM) therefore requires an understanding of emergence.
To familiarize students with the emergent nature of the PNM, a teaching-learning sequence (TLS) was developed in a design-based research project. Over four cycles, key ideas were tested using the method of probing acceptance with a total of 60 students. The results of the qualitative content analysis of the interview transcripts led to the formulation of domain-specific design principles. This showed that students are already able to understand the basic principle of emergence in lower secondary school. In addition, crystal structures seem to be better suited for introducing the PNM than many of the commonly used experiments. Likewise, students prefer typographic representations to the spherical representations usually found in textbooks.
The final version of the TLS was taught by four teachers in six classes with a total of 130 students. The intervention lasted four lessons and was accompanied by a pre- and posttest. The tests contained both open-ended and closed-ended items, whereby seven tasks were identical in both tests. With the help of these seven tasks, significance tests (t-test, Wilcoxon signed rank test) were used to determine the influence of the intervention on the students' use of the PNM. In five of the six classes, there was a statistically significant improvement in the use of the PNM in the posttest. The largest effect sizes were found concerning the acceptance of empty space between the particles and linking particle movement with temperature. In contrast, students hardly ever used the PNM in connection with phase transitions. At the end of the intervention, all participating teachers stated that they wanted to use the TLS again in their future lessons.

B. Zusammenfassung

Schüler:innen gehen häufig davon aus, dass Atome und Moleküle die selben Eigenschaften wie makroskopische Gegenstände haben. Beispielsweise stellen sie sich vor, dass sich bei der thermischen Ausdehnung eines Stoffes dessen Teilchen ebenfalls ausdehnen. Ursache für diese Vorstellung ist häufig die Anwendung der falschen ontologischen Kategorie: Schüler:innen sehen zwischen atomarer Ebene und Stoffebene einen direkt-kausalen anstatt eines emergenten Zusammenhangs. Letzterer beschreibt das Entstehen von Eigenschaften eines Systems aus dem Verhalten seiner Einzelteile, wobei sich die Eigenschaften der Teile von denen des Systems unterscheiden. Das Verständnis des Teilchenmodell setzt somit ein Verständnis von Emergenz voraus.

Um Schüler:innen die emergente Natur des Teilchenmodells näher zu bringen, wurde in einem Design-based Research Projekt ein Lehr-Lern-Arrangement (LLA) entwickelt. Über vier Zyklen hinweg wurden zentrale Konzeptideen in Akzeptanzbefragungen mit insgesamt 60 Schüler:innen überprüft. Die Ergebnisse der qualitativen Inhaltsanalyse der Interview-Transkripte führten zur Formulierung themenspezifischer Designprinzipien. Dabei hat sich gezeigt, dass Schüler:innen bereits in der Sekundarstufe I in der Lage sind das grundlegende Prinzip von Emergenz zu verstehen. Darüber hinaus scheinen Kristallstrukturen besser für die Einführung des Teilchenmodells geeignet als viele der häufig dazu verwendeten Experimente. Ebenso bevorzugen Schüler:innen typografische Darstellungen gegenüber den meistens in Schulbüchern vorzufindenden kugelförmigen Darstellungen.

Die finale Version des LLA wurde schließlich von vier Lehrpersonen in sechs Klassen mit insgesamt 130 Schüler:innen unterrichtet. Die Intervention umfasste vier Unterrichtsstunden und war von einem Pre- und Posttest begleitet. Die Tests enthielten sowohl offene als auch geschlossene Items, wobei sieben Aufgaben in beiden Tests ident waren. Mit Hilfe dieser sieben Aufgaben konnte über Signifikanztests (T-Test, Wilcoxon-Vorzeichen-Rang-Test) der Einfluss der Intervention auf die Verwendung des Teilchenmodells durch die Schüler:innen ermittelt werden. In fünf der sechs Klassen verbesserte sich die Anwendung des Teilchenmodells im Posttest statistisch signifikant zum Pretest. Die größten Effektstärken zeigen sich hinsichtlich der Akzeptanz des leeren Raumes zwischen den Teilchen sowie der Verknüpfung von Teilchenbewegung und Temperatur. In Zusammenhang mit Phasenübergängen wandten Schüler:innen dagegen kaum das Teilchenmodell an. Am Ende der Intervention gaben alle teilnehmenden Lehrpersonen an, das LLA in ihrem zukünftigen Unterricht wieder einsetzen zu wollen.

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Alternative Darstellungsformen des Teilchenmodells

Florian Budimaier & Martin Hopf

Abstract Deutsch

Das Teilchenmodell stellt einen zentralen Aspekt naturwissenschaftlicher Bildung dar, jedoch bereitet es Schülerinnen und Schülern häufig Lernschwierigkeiten. Insbesondere die Unterscheidung der Eigenschaften von makroskopischen Objekten und submikroskopischen Teilchen fällt ihnen schwer. Diese Problematik wird durch Abbildungen, welche Teilchen explizit makroskopische Eigenschaften zuordnen, noch verstärkt. Im Rahmen einer Studie mit 20 Schülerinnen und Schülern der Sekundarstufe wurde daher eine alternative Darstellungsform des Teilchenmodells untersucht. Die Ergebnisse legen nahe, dass typografische Darstellungen – insbesondere für leistungsstärkere Schüler*innen – hilfreicher sind als die in Schulbüchern verbreiteten kugelförmigen Darstellungen.

Schlüsselwörter

Akzeptanzbefragung, Qualitative Inhaltsanalyse, Teilchenmodell, Typografische Darstellungen

Abstract English

The particle model is a central aspect of science education, but it often causes learning difficulties for students. In particular, they find it difficult to distinguish between the properties of macroscopic objects and submicroscopic particles. This problem is exacerbated by illustrations that explicitly assign macroscopic properties to particles. Therefore, an alternative representation of the particle model was investigated in a study with 20 secondary school students. The results suggest that typographic representations are more helpful than the spherical representations commonly found in textbooks, especially for high-achieving students.

Keywords

particulate nature of matter, probing acceptance, qualitative content analysis typographic representations

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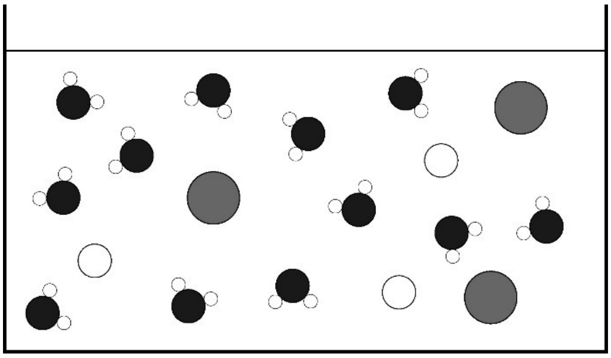
Ausgangslage

Das Teilchenmodell gilt als eines der zentralen Konzepte im naturwissenschaftlichen Unterricht (vgl. National Science Teaching Association 2017; OECD 2019). Nicht nur bildet es die Grundlage für ein Verständnis des Aufbaus der Materie, es ist auch ein zentrales Element für den Umgang mit vielen gesellschaftlich bedeutsamen Kontexten wie beispielswiese dem Klimawandel und der Energiewende. Auch im neuen österreichischen Lehrplan für Physik in der Sekundarstufe I zählt das Teilchenmodell zu den zentralen fachlichen Konzepten (vgl. BMBWF 2023, S. 2). Dabei wird betont, dass sich unter der Annahme alles besteht aus Teilchen, das Verhalten von physikalischen Systemen voraussagen lässt. Eine exaktere Definition des Teilchenmodells findet sich bei de Vos und Verdonk (1996, S. 659): „All matter consists of entities called particles. Individual particles are too small to be seen. They behave as hard, solid, and (except in chemical reactions) immutable objects. Their absolute dimensions and shape are usually irrelevant.“[14]

Eine Vielzahl an Forschungsarbeiten hat gezeigt, dass das Teilchenmodell zu den schwierigsten Themen im naturwissenschaftlichen Unterricht gehört (vgl. Hadenfeldt, Liu & Neumann 2014, S. 182). Falsche Vorstellungen vieler Schüler*innen über das Teilchenmodell resultieren häufig daraus, dass sie wissenschaftliche Modelle nicht korrekt auf beobachtbare Phänomene anwenden können (vgl. Mikelskis-Seifert & Fischler 2003, S. 78). Dies führt dazu, dass Schüler*innen Atomen und Molekülen dieselben Eigenschaften zuschreiben wie der Substanz, die sie aufbauen. Beispielsweise existieren Vorstellungen, wonach Atome eine Farbe haben (vgl. Albanese & Vicentini 1997, S. 253) oder sich die Größe von Wassermolekülen bei Phasenübergängen ändert (vgl. Griffiths & Preston 1992, S. 618f.; Lee et al. 1993, S. 261). Wenn diese Schüler*innen – wie Grosslight et al. (1991, S. 804) vorschlagen – davon ausgehen, dass Modelle einfache Kopien der Realität sind, scheint es offensichtlich, dass in ihrem mentalen Modell ein Wassermolekül die gleichen Eigenschaften wie flüssiges Wasser hat. Daher würden sie argumentieren, dass das Wassermolekül blau ist wie der Ozean und sich ausdehnt, wenn das Wasser verdunstet, da Gase mehr Raum benötigen als Flüssigkeiten.

Harrison und Treagust (2006) argumentieren, dass diese fehlerhaften mentalen Modelle der Schüler*innen oft aus den Darstellungen des Teilchenmodells in Lehrbüchern resultieren. Diese Darstellungen, wie beispielweise jene in Übersicht 1, lassen den falschen Schluss zu, dass sich Moleküle im Inneren einer Substanz befinden und dass sich immer etwas zwischen ihnen befindet (vgl. ebd., S. 60). Auch bezüglich der Abstände zwischen den Teilchen widersprechen Schulbücher öfters der wissenschaftlichen Lehrmeinung (vgl. Treagust et al. 2010, S. 144). Während das korrekte Verhältnis für die Abstände zwischen den Teilchen in Festkörpern, Flüssigkeiten und Gasen etwa 1:1:10 beträgt (vgl. de Vos & Verdonk 1996, S. 660), gehen Darstellungen in Lehrbüchern meist von einer engeren Anordnung der Teilchen aus. Adbo und Taber (2009, S. 771) konnten zeigen, dass die mentalen Modelle schwedischer Schüler*innen der Sekundarstufe II hinsichtlich der Struktur der Teilchen in den drei Aggregatzuständen häufig mit Darstellungen in Lehrbüchern übereinstimmen. Schüler*innen nehmen daher in der Regel an, dass in Festkörpern die Teilchen miteinander in Kontakt stehen und zwischen zwei Teilchen in Flüssigkeiten etwa ein Teilchen und in Gasen etwa drei bis vier Teilchen Platz haben (vgl. Treagust et al. 2010, S. 144).

[14] De Vos und Verdonk (1996, S. 659) führen neben dieser noch sieben weitere Konzeptideen an, um die grundlegenden Eigenschaften des Teilchenmodells zu beschreiben. Dabei gehen sie unter anderem auf die Bewegung der Teilchen, ihre gegenseitige Anziehung sowie die Abstände zwischen den Teilchen in den drei Aggregatzuständen ein.



Übersicht 1: Teilchenmodell einer Flüssigkeit, welches impliziert, dass die Teilchen sich innerhalb einer Substanz befinden (adaptiert nach Harrison & Treagust 2006, S. 60, Quelle: eigene Darstellung)

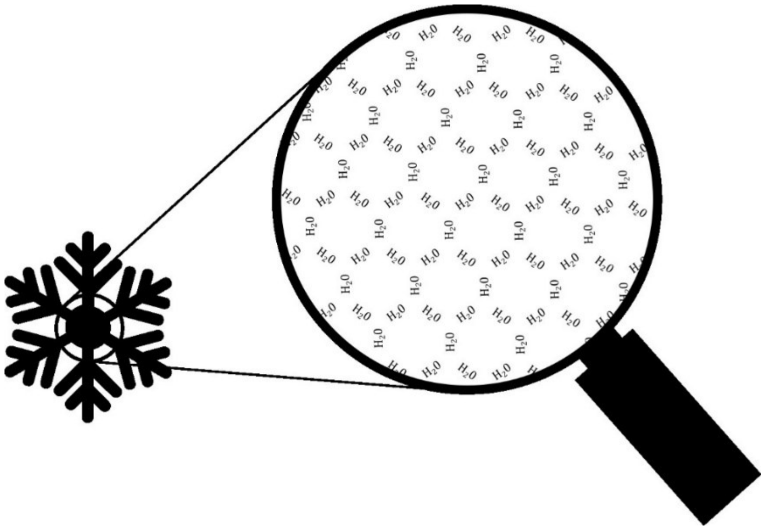
Sollte man in Anbetracht all dieser Schwierigkeiten modellhafte Darstellungen des Teilchenmodells im Unterricht verwenden? Aus der Theorie multimedialen Lernens geht hervor, dass Menschen nur eine begrenzte Menge an Information auf einmal über einen visuellen oder auditiven Kanal verarbeiten können (vgl. Mayer 2009, S. 66). Eine Kombination mehrerer unterschiedlicher Darstellungsformen kann daher das Physiklernen fördern, weil verschiedene Sinneskanäle gleichzeitig aktiviert werden, anstatt einen Kanal zu überlasten (vgl. Opfermann, Schmeck & Fischer 2017, S. 6). Wenn zum Beispiel eine mündliche Erklärung über das Teilchenmodell durch eine visuelle Darstellung (Diagramm, Grafik usw.) unterstützt wird, kann eine erfolgreiche konzeptionelle Veränderung erreicht werden (vgl. Adadan, Irving & Trundle 2009, S. 1765; Chiu & Chung 2013, S. 161). Da Atome und Moleküle nicht direkt beobachtet werden können, müssen sie entweder durch visuelle Modelle (z. B. Kugel-Stab-Modell) oder Symbole (z. B. H_20 für ein Wassermolekül) dargestellt werden (vgl. Gilbert & Treagust 2009, S. 4).

Wiener et al. (2015, S. 315) halten visuelle Modelle von Teilchen für sehr problematisch. Wie bereits erwähnt, kann die Darstellung von Atomen als kreisförmige, farbige Objekte zu zahlreichen Missverständnissen führen. Daher schlagen sie einen typografischen Ansatz vor, bei dem alle Teilchen durch Buchstaben oder Wörter dargestellt werden. Auf diese Weise sollte der Modellcharakter betont und die Übertragung von makroskopischen Eigenschaften auf submikroskopische Teilchen reduziert werden. In einer Studie mit 20 Schülerinnen und Schülern der zweiten Klasse einer allgemeinbildenden höheren Schule (AHS) haben Wiener et al. (2015, S. 320) festgestellt, dass ihre Idee in dieser Gruppe gut akzeptiert wurde und dabei falsche Vorstellungen von Schülerinnen und Schülern zum Teilchenmodell vermindert werden konnten.

Forschungsfragen und Ziele

Anschließend an den soeben beschriebenen Forschungsstand konzentriert sich diese Studie auf die fachlich inkorrekten Vorstellungen von Schülerinnen und Schülern im Zusammenhang mit Darstellungen in Schulbüchern. In der einfachsten Version des Teilchenmodells wird ein Atom als Kreis und ein Molekül als Summe kreisförmiger Objekte dargestellt (vgl. Bunce & Gabel 2002, S. 913). Um verschiedene Elemente oder Moleküle voneinander zu unterscheiden, werden sie mit unterschiedlichen Farben versehen oder in verschiedenen Größen gezeichnet. Manchmal wird auch Farbe verwendet, um bestimmte Eigenschaften hervorzuheben, zum Beispiel sind *heiße* Teilchen rot und *kalte* Teilchen blau. Diese Darstellungen können jedoch bei Schüler*innen zur Annahme führen, Atome und Moleküle hätten eine beobachtbare Farbe oder Form.

Um derartige Vorstellungen zu vermeiden, wurde im Rahmen der Studie eine neue Art der Darstellung, basierend auf der Idee typografischer Darstellungen von Wiener et al. (2015, S. 315f.) entwickelt. In der Elementarteilchenphysik stellen Wiener et al. (2015, S. 316) Quarks, Gluonen und die aus diesen aufgebauten Teilchensysteme mit Buchstaben dar (z. B. *u* für up-Quark). Diese Idee wurde im Kontext des Teilchenmodells weiterentwickelt und Atome und Moleküle durch die jeweiligen chemischen Symbole dargestellt (z. B. *H_2O* für Wassermoleküle). Bei der Gestaltung der Darstellungen wurde auch darauf geachtet, dass sie mit physikalischen Erkenntnissen übereinstimmen. Beispielsweise beträgt das Verhältnis der Abstände zwischen den Teilchen in Festkörpern, Flüssigkeiten und Gasen 1:1:10 (vgl. de Vos & Verdonk 1996, S. 660). Zudem bilden Wassermoleküle in Eis eine hexagonale Struktur[15] (vgl. Salzmann & Murray 2020, S. 586). Übersicht 2 zeigt ein Beispiel einer typografischen Darstellung, welches diese Erkenntnisse berücksichtigen.



Übersicht 2: Typografische Darstellung von Eis (Quelle: eigene Darstellung)

Wie bei allen Formen grafischer Darstellungen gibt es jedoch auch hier Grenzen: Die meisten Stoffe des täglichen Lebens bestehen nicht nur aus einem Element oder einem einfachen Molekül wie H_2O. Während Wasser oder Luft leicht mit ihren chemischen Symbolen dargestellt werden können, ist dies bei anderen Stoffen wie Fett, Kunststoffen oder Holz nicht der Fall. Dies schränkt die Anzahl der möglichen Beispiel, die mit den Schülerinnen und Schülern diskutiert werden können ein. Für die hier vorgestellte Studie wurde nur Wasser[16] verwendet, weil es für das tägliche Leben besonders relevant ist.

Wie soeben dargelegt, liegt das Forschungsinteresse der hier präsentierten Studie darin, die Funktionalität der entwickelten typografischen Darstellungen für den Unterricht über das Teilchenmodell zu überprüfen. Dementsprechend lautet die Forschungsfrage wie folgt:

*Wie beurteilen Schüler*innen typografische Darstellungen im Vergleich zu anderen Darstellungen des Teilchenmodells?*

Basierend auf einer gemäßigt konstruktivistischen Betrachtung von Lernen wird hinsichtlich der Beantwortung der Fragestellung davon ausgegangen, dass Schüler*innen nicht als *tabula rasa* in den Unterricht kommen (vgl. Haagen-Schützenhöfer 2016, S. 13). Vorerfahrungen und Vorwissen beeinflussen den Lernprozess. Es sollte daher untersucht werden, ob sich typografische

[15] Tatsächlich bildet Eis verschiedene Strukturen. Friert Wasser bei normalem Druck (1 bar) und Temperaturen knapp unterhalb des Gefrierpunkts (0 °C) bildet sich Eis I_h, das eine hexagonale Struktur aufweist. Bei Temperaturen unterhalb von -22 °C bilden sich auch kubische Strukturen (Eis I_c). Nach Salzmann und Murray (2020, S. 586) sind insgesamt 18 verschiedene Kristallstrukturen von Eis bekannt.

[16] Wasser verhält sich jedoch anders als fast alle anderen Stoffe, da es im flüssigen Zustand die höchste Dichte aufweist. Schüler*innen müssen darauf aufmerksam gemacht werden, dass die meisten Stoffe beim Schmelzen an Volumen zunehmen, während Wasser dichter wird. Dieses Beispiel kann auch als Ausgangspunkt für einen kognitiven Konflikt genutzt werden, um einen Konzeptwechsel herbeizuführen (vgl. Posner et al. 1982, S. 214). Schüler*innen gehen häufig davon aus, dass Teilchen in Flüssigkeiten größer sind als in Festkörpern (vgl. Griffiths & Preston 1992, S. 618f.). Dieses Beispiel zeigt aber, dass diese Annahme nicht stimmt und das Volumen eines Körpers nicht mit dem Volumen der Teilchen zusammenhängt.

Darstellungen hinsichtlich dieser Vorerfahrungen als anschlussfähig erweisen und welche Vorstellungen Schüler*innen mit den einzelnen Darstellungsformen verbinden.

Untersuchungsdesign

Die soeben gestellte Forschungsfrage wurde im Rahmen einer Studie[17] zum Teilchenmodell untersucht. Das genaue Vorgehen wird im Weiteren beschrieben.

Erhebungsmethoden

Die Untersuchung der typografischen Darstellungen wurde anhand von Interviews nach der Methode der Akzeptanzbefragung (vgl. Jung 1992, S. 278; Wiesner & Wodzinski 1996, S. 252) durchgeführt. Bei dieser Methode handelt es sich um eine Kombination aus einem Micro-Teaching und einem Einzelinterview mit dem Ziel, Lernschwierigkeiten zu eruieren. Anstatt den Schülerinnen und Schülern nur Fragen zu stellen, werden zentrale fachliche Konzepte, auch *Key Ideas* (vgl. Haagen-Schützenhöfer 2016, S. 21) genannt, vom Interviewenden erklärt. Nach der Erklärung werden die Schüler*innen vom Interviewenden gefragt, ob diese für sie logisch und nachvollziehbar war. Im Anschluss sollten die Schüler*innen die Erklärung noch einmal in eigenen Worten wiederholen. Durch diesen Schritt können mögliche Verständnisschwierigkeiten aufgedeckt werden. Abschließend sollten die Schüler*innen noch mindestens eine Aufgabe lösen, um zu zeigen, dass sie die Erklärung auch in einem neuen Kontext anwenden können.

Intervention

In der vorliegenden Studie wurden zwei Key Ideas untersucht. Dabei ging es um die Ideen, dass alles aus sehr kleinen, nicht-sichtbaren Bausteinen besteht sowie, dass das Verhalten all dieser Bausteine die Eigenschaften eines Stoffes bestimmt. Zu beiden Key Ideas gab es jeweils eine Aufgabe mit typografischen Darstellungen. Dabei wurden diese noch mit zwei weiteren Darstellungen – einem kugelförmigen Teilchenmodell und einem kontinuierlichen Modell der Materie – ergänzt. Bei der ersten Aufgabe wurden die Schüler*innen gefragt, welche der drei gezeigten Darstellungen ihrer Meinung nach am besten zeigt, wie eine Schneeflocke aufgebaut ist. In derselben Art und Weise sollten die Schüler*innen bei der zweiten Aufgabe beurteilen, welche der drei gezeigten Darstellungen am besten das Schmelzen einer Schneeflocke veranschaulicht. Übersicht 3 zeigt alle verwendeten Darstellungen.

Bei der Auswahl der Stichprobe wurden mehrere Faktoren berücksichtigt. In Österreich sieht der Physik-Lehrplan für die AHS das Teilchenmodell in der zweiten und sechsten Klasse vor. Da Vorstellungen von Schülerinnen und Schülern über die Teilchennatur der Materie auch in der Sekundarstufe II vorherrschen (vgl. Adbo & Taber 2009, S. 783; Treagust et al. 2010, S. 161), war ein Vergleich zwischen der Sekundarstufe I und der Sekundarstufe II von Interesse.

Die Auswahl der Schüler*innen wurde durch die Covid-19-Pandemie beeinflusst, die den Besuch von Schulen aufgrund der Beschränkungen durch die österreichische Bundesregierung unmöglich machte. Da der Erstautor jedoch Lehrer an einem Wiener Gymnasium ist, war es möglich, die Studie an dieser Schule durchzuführen. Die Schule befindet sich in einem Bezirk mit sehr hohem sozioökonomischem Status und die Schüler*innen werden im Allgemeinen von ihren Eltern in ihrem Lernen stark unterstützt. Sowohl von der Direktion als auch von den Eltern der teilnehmenden Schüler*innen wurde das Einverständnis eingeholt. Zwanzig Schüler*innen[18] aus vier verschiedenen Klassen haben sich freiwillig zur Teilnahme an den Interviews bereit erklärt. Die Stichprobe war zu gleichen Teilen in Schüler*innen der zweiten und sechsten Klasse AHS aufgeteilt. Die Schüler*innen beider Gruppen hatten zuvor bereits im Physikunterricht etwas über das Teilchenmodell gelernt.

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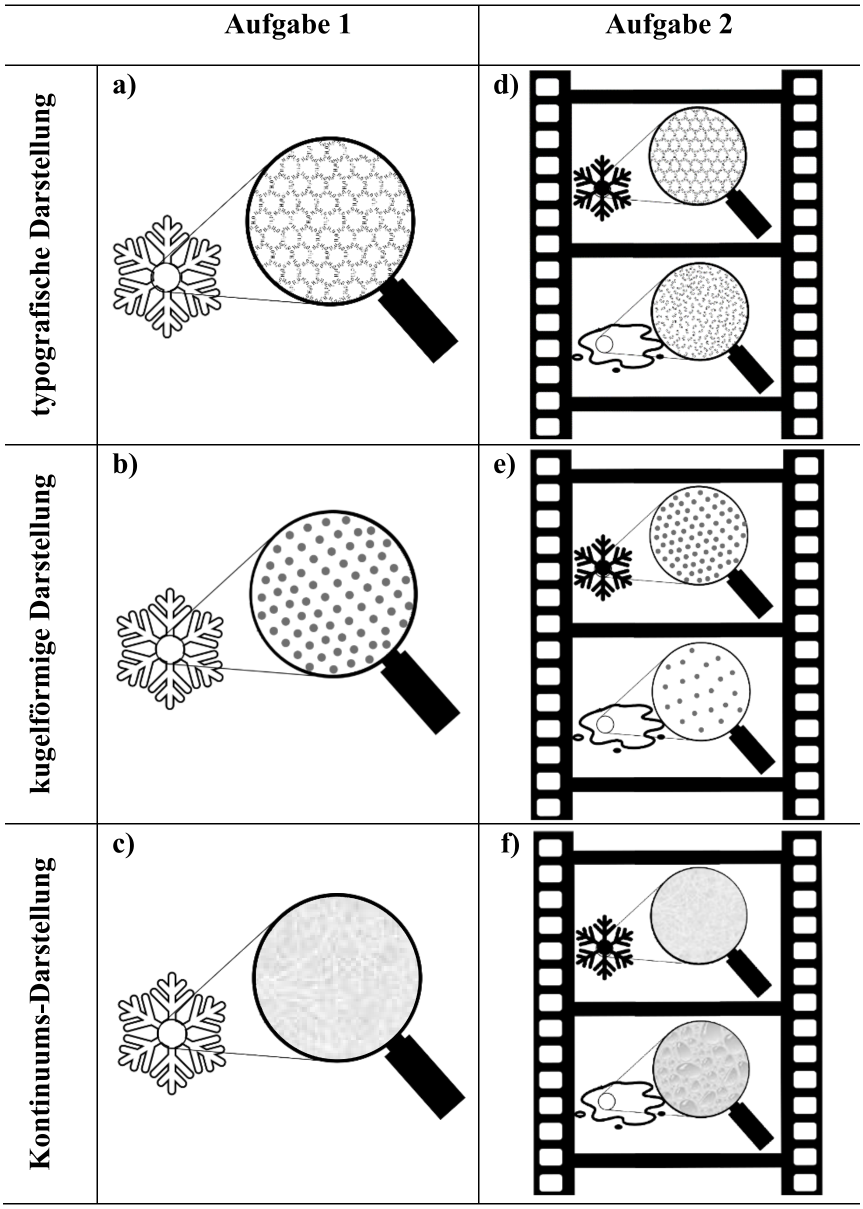
[17] In diesem Artikel wird der Teil der erhobenen Daten präsentiert, der sich auf die typografischen Darstellungen bezieht. Weitere Ergebnisse der Studie sind bereits in Budimaier und Hopf (2022) und Hull et al. (2023) publiziert. Die vollständigen Transkripte der Interviews sind auf Anfrage bei Budimaier erhältlich.

[18] 12 Schülerinnen und 8 Schüler.

Auswertungsmethoden

Die Auswertung der Akzeptanzbefragungen erfolgte mittels evaluativer qualitativer Inhaltsanalyse (vgl. Kuckartz & Rädiker 2022, S. 157ff.). Hinsichtlich der Aufgaben wurden drei Codierungen verwendet, welche sich auf mentale Modelle zum Teilchenmodell nach Johnson (2006, S. 115f.) stützten. Entschieden sich die Schüler*innen für die kontinuierliche Darstellung, erhielt ihre Antwort die Codierung *Kontinuumsmodell*. Die kugelförmige Darstellung, welche die Übertragung makroskopischer Eigenschaften auf Atome nahelegt, erhielt die Codierung *Hybridmodell*. Die typografische Darstellung, welche besonders den Modellcharakter betont, erhielt die Codierung *Teilchenmodell*. Alle Antworten wurden vom ersten Autor codiert, anhand von zwei Interviews wurde auch die Interrater-Reliabilität erhoben und κ = 0,74 errechnet. Gemäß Landis und Koch (1977, S. 165) stellt dies eine erhebliche Übereinstimmung dar.



Übersicht 3: Darstellungen aus der Akzeptanzbefragung (Quelle: eigene Darstellung)

Forschungsergebnisse

Mehr als die Hälfte der Schüler*innen erachtete typografische Darstellungen als, im Vergleich zu den beiden anderen Darstellungen, besser geeignet, um den Aufbau der Materie zu veranschaulichen (siehe Übersicht 4). Dies ist bemerkenswert, weil die Darstellung als kugelförmiges Modell vielen Schülerinnen und Schülern bereits aus ihren Physiklehrbüchern vertraut war, wie folgende Aussage illustriert: „Die typischen Darstellungen sind die, weil Moleküle werden dargestellt als (.) eben als kleine Kügelchen auch im Physikbuch“ (M3:24)[19]. Es zeigen sich jedoch Unterschiede im Antwortverhalten, wenn die gesamte Leistung der Schüler*innen in der Akzeptanzbefragung in die Analyse miteinbezogen wird. Jene Schüler*innen, welche im Laufe der Akzeptanzbefragung ein größeres konzeptuelles Verständnis gezeigt hatten, wählten im Vergleich durchschnittlich doppelt so oft das typografische Modell. Demnach sind die typografischen Darstellungen besonders attraktiv für Schüler*innen, welche bereits ein elaborierteres Verständnis des Teilchenmodells aufweisen. Dies ist unabhängig von Alter und Geschlecht der Schüler*innen. Es konnten keine nennenswerten Unterschiede zwischen der zweiten und der sechsten Klasse AHS, sowie zwischen Schülerinnen und Schülern festgestellt werden.

	Typografische Darstellung	**Kugelförmige Darstellung**	**Kontinuums-Darstellung**
Schneeflocke	13	5	2
Schmelzen	10	8	2
Gesamt	**23**	**13**	**4**

Übersicht 4: Anzahl der Schüler*innen, die eine bestimmte Darstellung bevorzugen
(Quelle: eigene Darstellung)

Auf die Frage, warum sie das typografische Modell am überzeugendsten finden, argumentierten viele Schüler*innen, dass die Darstellung gut zeigt, wie die Moleküle „vernetzt“ (M3:24), „verkettet“ (K6:20) oder „zusammengebunden“ (B3:38) sind. Es scheint somit, dass Schüler*innen das typografische Modell als besonders gut geeignet für die Darstellung der Struktur von Festkörpern erachten. Um einen exemplarischen Einblick in die Überlegungen der Schüler*innen zu geben, werden im Folgenden zwei prototypische Antworten jeweils anhand eines Fallbeispiels dargestellt.

Modellwechsel

Als letzte Frage zur ersten Key Idea sind den Schülerinnen und Schülern drei Zeichnungen gezeigt worden, welche die Struktur einer Schneeflocke darstellen sollen. Nummer eins stellte das typographische Modell dar, Nummer zwei ein kontinuierliches Modell und Nummer drei ein kugelförmiges Modell (siehe Übersicht 3a-c). Der Interviewende forderte die Schüler*innen auf, aus diesen drei Darstellungen jene auszuwählen, welche ihrer Meinung nach am besten den Aufbau der Schneeflocke zeigt. Bob[20] begründete seine Wahl des typografischen Modells (siehe Übersicht 3a) dabei wie folgt:

> „Also ich finde, dass es die Nummer eins am besten darstellt, weil wir, also weil die halt, weil es Bausteine sind und die nicht wie bei der Nummer drei also solche Abstände haben sie dann direkt zusammen sind und so halten. Und bei der Nummer zwei, also die Nummer zwei verstehe ich nicht ganz weil (.) also hier kann ich sehen, dass es kleine Teilchen sind, aber der Nummer zwei nicht“ (R2:30).

Demgemäß schien bei Bob die Vorstellung vorhanden zu sein, dass in einer festen Substanz die Teilchen miteinander in Kontakt stehen. Es ist jedoch fraglich, ob die Aktivierung dieser Vorstellung wissenschaftlich korrekte Vorstellungen über die atomare Bindung behindern könnte.

Am Ende der Diskussion von Key Idea Nummer zwei wurden den Schülerinnen und Schülern erneut drei Zeichnungen gezeigt. Diese stellten die Strukturveränderung der Materie beim Schmelzen einer Schneeflocke dar, wobei am Ende nur noch eine Wasserpfütze übrig bleibt. Dabei entsprach Nummer eins dem kontinuierlichen Modell, Nummer zwei dem typographischen Modell und Nummer drei dem kugelförmigen Modell (siehe Übersicht 3d-f). Der Interviewende forderte die Schüler*innen wiederum auf, aus diesen drei Darstellungen jene auszuwählen, welche ihrer Meinung nach am besten den

[19] Zur Anonymisierung der Teilnehmer*innen wurde für jede Person eine Kurzbezeichnung erstellt (z.B. *M3*). Die Zahl nach dem Doppelpunkt kennzeichnet den Absatz im Transkript, dem das Zitat entnommen ist.
[20] Alle Namen sind Pseudonyme.

Schmelzvorgang zeigt. Bob entschied sich, im Gegensatz zu seiner Antwort auf die vorherige Frage, hier jedoch für das kugelförmige Modell (siehe Übersicht 3e):

„**Bob:** Diesmal ist es die Abbildung Nummer drei.

Interviewer: Und kannst du mir auch begründen warum?

B: Weil man da einfach deutlich sieht, dass die Teilchen weiter auseinander sind. Also weil bei dem sieht man es schon ein bisschen, aber wenn wir jetzt nur so ganz kurz darauf könnte man das auch mit dem verwechseln.

I: Okay, weil die zwei Bilder bei zwei zu ähnlich sind.

B: Ja also halt während bei dem, da merkt man sofort, da sind weniger Teilchen und ein größerer Abstand ist da“ (R2:56-60).

Bob merkt deutlich an, dass ihm die Nummer drei am besten gefällt, weil man „deutlich sieht, dass die Teilchen weiter auseinander sind“ (R2:58). Auch dies deckt sich mit den Erkenntnissen aus der Literatur hinsichtlich der Vorstellungen von Schülerinnen und Schülern über die Abstände zwischen den Teilchen. Im Gegensatz zur naturwissenschaftlichen Sichtweise nimmt gemäß vieler Schüler*innen der Abstand zwischen den Teilchen von fest zu flüssig zu.

Hierarchie der Modelle

Alice betrachtete die drei verschiedenen Darstellungen des Aufbaus der Materie als hierarchisch strukturiert, wie sich aus ihrer folgenden Aussage ablesen lässt:

„Ich würde jetzt auf jeden Fall sagen, dass das hier die realste, also Nummer zwei [kontinuierliche Darstellung, Anmerkung F.B. & M.H.] ist die realste Vorstellung, weil so sehen es wir. So könnte man, also Nummer drei [kugelförmige Darstellung, Anmerkung F.B. & M.H.] könnte man beschreiben, als die nächstkleinere Stufe, weil das besteht aus Teilchen, weil wir wissen alles besteht aus Teilchen und dann Nummer eins [typografische Darstellung, Anmerkung F.B. & M.H.] sehe ich jetzt hier schon die genaue chemische Zusammensetzung aus Wasser und das ist hier halt dann so ein Netz“ (F2:32).

Es scheint, dass für Alice der Modellcharakter dieser Darstellungen, trotz deutlicher Hinweise des Interviewers, nicht klar geworden ist. Sie sah die Darstellungen nicht als drei verschiedene Möglichkeiten, die Struktur der Materie zu veranschaulichen, sondern als Bilder der Realität, die auf verschiedenen Skalen zeigen *wie es wirklich ist*.

Darüber hinaus gab es für Alice nicht nur eine Hierarchie zwischen den Darstellungen, sondern auch zwischen Teilchen auf der einen Seite und Atomen und Molekülen auf der anderen:

„**A:** Es ist vielleicht falsch gewählt gewesen dieses Vokabel, aber es ist eigentlich alles ein Teilchen, nur Teilchen sind für mich trotzdem größer, ich, oder molekular kann man sagen, auf jeden Fall noch nicht atomare Ebene.

I: Okay, also das heißt du würdest sagen ein Teilchen ist größer als ein Atom oder als ein Molekül, das ist eine größere Einheit.

A: Nein, theoretisch nicht, aber in meiner Vorstellung irgendwie schon“ (F2:66-68).

Dies zeigt, dass bei Alice eine Art Zwiespalt im Denken über das Teilchenmodell bestand. Obwohl sie die wissenschaftlichen Fakten bereits kannte und in der Lage war, sie anzuwenden, hatte sie immer noch Vorstellungen, die im Widerspruch zu ihrem Wissen standen.

Die beiden soeben exemplarisch aufgezeigten Erkenntnisse traten nicht nur bei Alice und Bob auf, sondern waren jeweils bei mehreren teilnehmenden Schülerinnen und Schülern zu beobachten. So wechselten insgesamt fünf Schüler*innen von der ersten zur zweiten Frage vom typografischen zum kugelförmigen Modell. Außerdem erkannten insgesamt vier Schüler*innen eine Hierarchie zwischen den drei vorgestellten Modellen. Drei davon gaben an, die typografische Darstellung sei am genauesten, gefolgt von der kugelförmigen Darstellung und der Kontinuums-Darstellung. Eine Person reihte jedoch die Kontinuums-Darstellung an erster Stelle, gefolgt von der typografischen und der kugelförmigen Darstellung.

Interpretation und Diskussion

In der hier vorgestellten Studie wurde die Nützlichkeit typografischer Darstellungen für Lernprozesse im Kontext des Teilchenmodells untersucht. Dabei hat sich gezeigt, dass die Mehrheit der befragten Schüler*innen typografische Darstellungen als bessere Darstellung des Aufbaus der Materie erachtet haben als kugelförmige oder kontinuierliche Modelle. Leistungsstärkere Schüler*innen wählten besonders häufig das typografische Modell. Dies deckt sich mit den Ergebnissen von Ezema et al. (2022, S. 203) wonach kognitive Fähigkeiten einen positiven Einfluss auf den Konzeptwechsel beim Lernen über das Teilchenmodell haben.

Schüler*innen dieser Studie bevorzugten das typografische Modell vor allem bei der Darstellung von Festkörpern, da es die Struktur der Moleküle und deren Bindung zeigt. Dies ist in Einklang mit den Ergebnissen von Treagust et al. (2010, S. 144), wonach in der Vorstellung vieler Schüler*innen die Teilchen im Festkörper in Kontakt miteinander stehen. Ebenso konnte das Ergebnis von Treagust et al. (2010, S. 144) bestätigt werden, dass Schüler*innen im Allgemeinen davon ausgehen, dass der Abstand der Teilchen zueinander beim Übergang vom festen in den flüssigen Zustand zunimmt.

Des Weiteren wurde die Schwierigkeit der Modellbildung von Schülerinnen und Schülern (vgl. Mikelskis-Seifert & Fischler 2003, S. 78) auch in dieser Studie deutlich. In der Annahme, dass es eine starke Korrelation zwischen ihren eigenen mentalen Modellen über die Teilchen und der Realität gibt (vgl. Harrison & Treagust 1996, S. 532) konstruierten manche Schüler*innen eine Hierarchie zwischen den in der Studie vorgestellten Darstellungen des Aufbaus der Materie. Grund dafür könnte auch die generelle Unzufriedenheit mit Modellen von Schülerinnen und Schülern sein, verbunden mit dem Wunsch zu wissen wie *es wirklich ist* (vgl. Fischler & Schecker 2018, S. 147ff.).

Einschränkungen

Hinsichtlich der Aussagekraft der erhobenen Daten muss angemerkt werden, dass alle Schüler*innen, welche an der Studie teilgenommen haben, dieselbe Schule besucht haben und von derselben Physik-Lehrkraft unterrichtet wurden. Dieser Lehrkraft zufolge hatten die meisten der Schüler*innen, die sich freiwillig zu einem Interview bereit erklärten, gute Noten und großes Interesse an Physik. Wären Schüler*innen zufällig ausgewählt worden, hätten diese möglicherweise schlechtere Leistungen erbracht als jene in der untersuchten Stichprobe.

Des Weiteren wurden den Schülerinnen und Schülern drei verschiedene Darstellungen zum Aufbau der Materie vorgestellt, welche entsprechend den Erkenntnissen aus der Literatur erstellt wurden. Daraus lässt sich jedoch nicht zwangsläufig schließen, dass die von den Schülerinnen und Schülern im Rahmen der Studie als beste Darstellung gewählte Form auch generell die beste Variante zur grafischen Darstellung des Teilchenmodells ist. Zudem zeigen die Antworten der Schüler*innen, dass die typografischen Darstellungen noch weiter verbessert werden sollten, um beispielsweise nicht den Eindruck zu vermitteln, die Teilchen wären miteinander in Kontakt.

Bei der Anwendung der typografischen Darstellungen ergibt sich das Problem, dass diese nur auf eine begrenzte Menge an Beispielen beschränkt sind, da die Summenformeln vieler Substanzen komplex sind. Eine mögliche Lösung wäre, sich zu Beginn auf einige alltägliche Stoffe mit einfacher Summenformel (z.B. Wasser oder Luft) zu beschränken. Mit fortschreitendem Wissen der Schüler*innen aus dem Chemieunterricht könnten dann auch komplexere Beispiele verwendet werden.

Ausblick

Die Ergebnisse der hier präsentierten Studie legen nahe, dass typografische Darstellungen des Teilchenmodells im Unterricht verwendet werden können, da sie – innerhalb der hier untersuchten Stichprobe – auf breitere Akzeptanz stießen als die in Schulbüchern verbreiteten kugelförmigen Darstellungen. Entsprechend der Rückmeldungen der Schüler*innen sollten jedoch noch kleinere Verbesserungen an den Darstellungen vorgenommen werden. So sollte immer ein deutlicher Abstand zwischen den Symbolen sein, damit nicht der Eindruck entsteht, diese würden einander berühren. Des Weiteren sollten Schüler*innen explizit darauf hingewiesen werden, dass die Abstände zwischen den Bausteinen beim Schmelzen nicht merklich zunehmen. Im für den Alltag sehr wichtigen Beispiel Wasser nehmen die Abstände sogar ab, was mit der hexagonalen Struktur von Eis I_h zu tun hat. Die hier präsentierten typografischen Darstellungen ermöglichen es, diese Anomalie des Wassers darzustellen und mit Schülerinnen und Schülern zu diskutieren.

Abschließend wollen die Autoren dieses Beitrags Lehrkräfte und Fachdidaktiker*innen der Naturwissenschaften dazu ermutigen, typografische Darstellungen in der schulischen Praxis sowie in weiteren Studien zu erproben. Aufgrund der Vielfalt an naturwissenschaftlichen Konzepten, welche mit dem Teilchenmodell in Verbindung stehen, sind verschiedene Anwendungsmöglichkeiten denkbar. Um nur einige zu nennen: Temperatur, Druck, Wärmetransport oder der Aufbau von Kristallen. Letzteres Thema wird von den Autoren in einer Folgestudie noch weiter untersucht werden. Darüber hinaus sollten die hier vorgestellten oder ähnliche Beispiele mit einer größeren Gruppe von Schülerinnen und Schülern getestet werden. Ebenso können die Ergebnisse dieser und möglicher weiterer Studien für Autorinnen und Autoren von Physikschulbüchern von Bedeutung sein, insbesondere hinsichtlich der Implementierung des zentralen Konzepts *Teilchen* im neuen Lehrplan für Physik der Sekundarstufe I.

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D. Teacher's manual

Die Bausteine der Materie

Ein Unterrichtskonzept für die Sekundarstufe I

Handreichung für Lehrkräfte

Einleitung

Das Teilchenmodell zählt im neuen Lehrplan Physik für die Sekundarstufe I zu den zentralen fachlichen Konzepten. Dabei wird betont, dass sich unter der Annahme „Alles besteht aus Teilchen", das Verhalten von physikalischen Systemen voraussagen lässt. Betrachtet man die im Lehrplan verankerten Kompetenzbereiche genauer, so findet sich das Teilchenmodell vor allem im Bereich „Wetter und Klima" in der vierten Klasse. Das vorliegende Unterrichtskonzept ist daher als grundlegendes Teilchenmodell für die Thermodynamik im Bereich von „Wetter und Klima" gedacht.

Ausgehend von der Beobachtung natürlicher Phänomene, anhand des konkreten Beispiels der Kristallstrukturen, werden Schüler:innen mit der Idee des diskreten Aufbaus der Materie vertraut gemacht. Entsprechend der Vorgaben des Lehrplans wird dabei besonders darauf fokussiert, welche Eigenschaften eines physikalischen Systems sich aus dem Verhalten der Teilchen ableiten lassen. Schüler:innen fällt es tendenziell sehr schwer, diese Verbindung herzustellen, weshalb das im Unterricht besonders betont und öfters wiederholt werden muss.

Das Unterrichtskonzept ist das Ergebnis eines mehrjährigen Forschungsprozesses. Anhand von Erkenntnissen aus der Fachdidaktik wurden dabei die zentralen Konzeptideen entwickelt und in insgesamt 60 Einzelinterviews getestet. Durch eine mehrfache Überarbeitung konnte das Konzept schrittweise verbessert und auf Lernschwierigkeiten gezielt eingegangen werden. Als abschließender Schritt wird nun überprüft, ob die Ergebnisse aus den Einzelinterviews sich auch im Unterricht mit einer Klasse reproduzieren lassen.

Für die Mithilfe bei dieser letzten Phase des Forschungsprozesses möchte ich mich sehr herzlich bedanken. Ich wünsche viel Erfolg bei der Umsetzung der Unterrichtsstunden und freue mich über eine kurze Rückmeldung zu den Erfahrungen mit dem Unterrichtskonzept.

Florian Budimaier

Das Wichtigste auf einen Blick

Besonderheiten des Unterrichtskonzepts

Das Unterrichtskonzept orientiert sich an Erkenntnissen aus der Physikdidaktik, welche beispielsweise in Schulbüchern bisher kaum berücksichtigt werden. Daraus ergeben sich Unterschiede zum „klassischen“ Unterricht über das Teilchenmodell. Den folgenden vier Aspekten wurde bei der Entwicklung des Unterrichtskonzepts besondere Aufmerksamkeit geschenkt:

1. Kristallstrukturen dienen als Ausgangspunkt für den Einstieg in das Teilchenmodell
2. Es wird der Begriff „Bausteine“ statt „Teilchen“ verwendet
3. Betonung der Unterschiede zwischen Eigenschaften der Bausteine und der Gegenstände
4. Bausteine werden nicht mit Kugeln sondern mit Buchstaben dargestellt

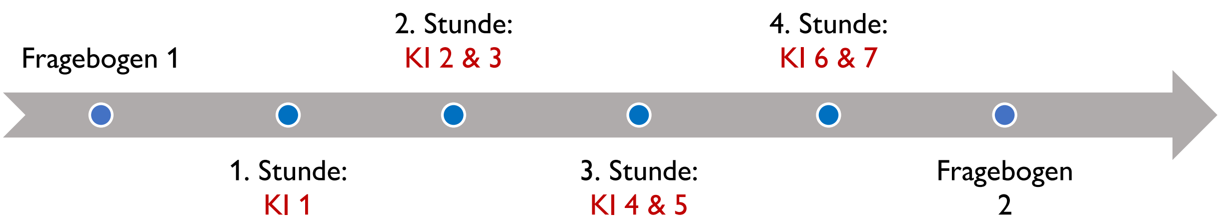
Zentrale Konzeptideen (KI)

Unter Berücksichtigung der soeben genannten besonderen Aspekte, wurde die Struktur der Unterrichtskonzept erarbeitet. Diese ist in sieben zentralen Konzeptideen zusammengefasst. Das Verständnis dieser Konzeptideen stellt die Lernziele für die Schuler:innen dar. Wichtig ist dabei die vorgegebene Reihenfolge, welche anhand der Ergebnisse aus der Interviewstudie festgelegt wurde, beizubehalten.

1. Alles, das man angreifen kann, stellt man sich aus sehr vielen, kleinen, nicht-sichtbaren Bausteinen zusammengesetzt vor.
2. Die Eigenschaften eines Bausteins sind nicht die Eigenschaften des Gegenstands.
3. Die Bindung der Bausteine bestimmt die Eigenschaften des Gegenstands.
4. Die Bewegung der Bausteine bestimmt die Temperatur eines Gegenstands.
5. Am Schmelzpunkt wird die Bindung flexibel und die Struktur der Plätze löst sich auf.
6. Zwischen den Bausteinen ist nichts.
7. Am Siedepunkt trennt sich die Bindung der Bausteine auf und sie entfernen sich voneinander.

Ablauf

Um das Stundenausmaß auf lediglich vier Unterrichtsstunden zu beschränken, wurden die zentralen Konzeptideen in einer möglichst kompakten Form aufbereitet. Darüber hinaus wird noch jeweils ein Teil einer Unterrichtsstunde vor und nach dem Unterrichtskonzept für einen Fragebogen benötigt. Sämtliche für den Unterricht benötigen Materialien werden zur Verfügung gestellt.



Besonderheiten des Unterrichtskonzepts

1. ### Kristallstrukturen als Ausgangspunkt für den Einstieg in das Teilchenmodell

   Die Ergebnisse der Studie legen nahe, dass Schüler:innen häufig verwendete Experimente zum Teilchenmodell, wie die Beobachtung der Brownschen Molekularbewegung unter dem Mikroskop nicht verstehen. Schüler:innen gelingt es dabei auch in der Sekundarstufe II noch nicht die Beobachtungen aus dem Experiment mit der Vorstellung, dass alles aus Atomen aufgebaut ist zu verknüpfen.

   Als Alternative wird daher in diesem Unterrichtskonzept die **Beobachtung von Kristallstrukturen** als Einstieg in das Teilchenmodell verwendet. Die Suche nach einer Erklärung für das Phänomen, dass Kristalle von Natur aus regelmäßige Formen haben wird dabei genutzt, um die Existenz der Bausteine der Materie zu motivieren.

2. ### Bausteine statt Teilchen

   Anknüpfend an frühere Forschung wird auf den Begriff „Teilchen" verzichtet. Dies liegt einerseits an der Mehrdeutigkeit des Begriffs: Teilchen kann auch nur einen kleinen Teil von etwas bezeichnen. Zum Beispiel wäre im alltäglichen Sprachgebrauch auch ein Staub- oder Salzkorn ein Teilchen. Des weiteren legt der Begriff die Idee des Atoms als „letztes Teilungsstück" nahe. Die führt aber eher zu Lernendenvorstellungen, wie der Übertragung von makroskopischen Eigenschaften auf Atome und Moleküle. Daher wird vom Atom als „ersten Aufbaustein" ausgegangen und Atome, Moleküle und Ionen gleichermaßen als Bausteine bezeichnet.

3. ### Betonung der Unterschiede zwischen Eigenschaften der Bausteine und der Gegenstände

   Eine der häufigsten Vorstellungen von Schüler:innen zum Teilchenmodell ist, dass die Bausteine der Materie dieselben Eigenschaften haben, wie die Gegenstände, die aus ihnen aufgebaut werden. Daher werden die unterschiedlichen Eigenschaften der Bausteine und der Gegenstände besonders in den Fokus gestellt und durchgehend betont. Dabei ist es auch wichtig, sprachlich konsistent zu sein. Es sollte nie von Bausteinen höherer Temperatur oder wärmeren Bausteinen gesprochen werden, sondern nur von schnelleren Bausteinen. Auch verdampfen die Bausteine nicht. Sondern: sie lösen die Bindungen zu anderen Bausteinen aufgrund ihrer schnelleren Bewegung.

4. ### Darstellung der Bausteine mit Buchstaben

   Wie bereits erwähnt tendieren Schüler:innen dazu den Bausteinen Eigenschaften wie Farbe, Temperatur oder Form zu verleihen. Dies wird häufig noch durch die Art der Darstellungen von Bausteinen in Lehrbüchern verstärkt. Meistens werden diese als verschiedenfarbige Kugeln dargestellt, wobei die Farbe beispielsweis das Element oder auch die Temperatur angibt. Um derartige Vorstellungen nicht weiter zu fördern, wird in diesem Unterrichtskonzept auf typografische Darstellungen zurückgegriffen, die bereits aus der Elementarteilchenphysik bekannt sind. Atome werden durch das Elementsymbol (z.B. *Fe* für Eisen), Moleküle durch ihre Summenformel (z.B. H_2O für Wasser) dargestellt. Diese Darstellung wurde auch bei der Herstellung von 3D-gedruckten Modellen genutzt.

Übersicht der zentralen Konzeptideen

1. Unterrichtsstunde

1. Alles, das man angreifen kann, stellt man sich aus sehr vielen, kleinen, nicht-sichtbaren Bausteinen zusammengesetzt vor.

Ausgangspunkt für das Unterrichtskonzept ist die Beobachtung, dass die meisten Dinge in der Natur eher unregelmäßige Formen haben, es aber auch vereinzelt Dinge mit einer sehr regelmäßigen Form gibt. Kristalle sind Materialien mit sehr regelmäßigen Formen, die in der Natur vorkommen. So sind die Salzkristalle beispielsweise rechteckig und Schneekristalle haben immer eine sechseckige Form bzw. bilden sechs Zacken aus.

Beispiel 1: https://www.youtube.com/watch?v=ZTG8FCJZL3M (00:00 – 00:50)
Salzwasser wird unter ein Mikroskop gegeben und gewartet, bis das Wasser verdunstet ist. Betrachtet man die Videoaufnahme im Zeitraffer, so erkennt man, dass sich scheinbar von selbst rechteckige Salzkristalle bilden.

Beispiel 2: http://www.snowcrystals.com/videos/1aMonoMovie.mp4
Dieses Video zeigt die Entstehung eines Schneekristalls im Labor. Am Rand der Aufnahme sind kleine Wassertropfen zu erkennen, die nach und nach gefrieren. Das Video ist wiederum im Zeitraffer abgespielt. Man erkennt, dass sich scheinbar von selbst die sechs Zacken des Schneekristalls ausbilden.

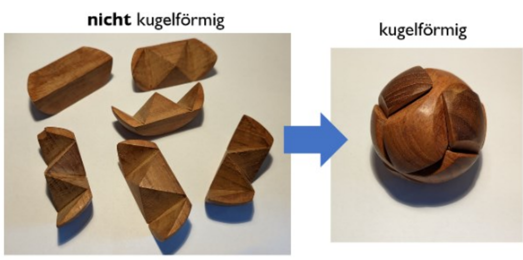
Anhand der Videos wird die Frage aufgegriffen, wie es möglich ist, dass Dinge scheinbar „von selbst" entstehen. Auch die Form der Kristalle kann auf grundlegende Prinzipien zurückgeführt werden, den nicht-sichtbaren Bausteinen. Nicht-sichtbar bedeutet, dass die Bausteine zu klein sind, um selbst mit einem Mikroskop gesehen zu werden. Klein bedeutet, dass 10 000 000 Bausteine aufgereiht nur 1 mm lang sind. Da diese so klein sind, setzt sich schon ein einziger Wassertropfen aus 100 Trilliarden Bausteinen zusammen.

2. Unterrichtsstunde

2. Die Eigenschaften eines Bausteins sind nicht die Eigenschaften des Gegenstands.

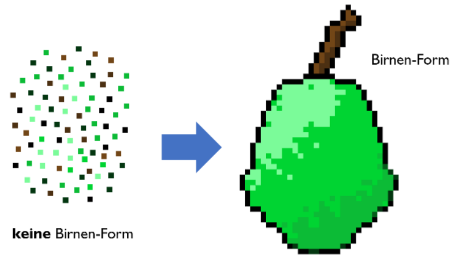
Aus dem Verhalten der Bausteine können Eigenschaften der Gegenstände, die sich aus diesen Bausteinen zusammen setzen abgeleitet werden. Jedoch machen Schüler:innen dabei oft den Fehler die Eigenschaften der makroskopischen Ebene direkt auf die submikroskopische Ebene zu übertragen. Um dem vorzubeugen, sollte anhand einige Beispiele darauf eingegangen werden, dass die Eigenschaften der Bausteine nicht die Eigenschaften der Gegenstände sind.

Beispiel 1:
Wenn man dieses Holzpuzzle richtig zusammensetzt ergibt sich die Form einer Kugel. Jedoch sind die einzelnen Bausteine des Puzzles nicht kugelförmig, sondern haben eine ganz andere Form.



Beispiel 2:

Ein Bild auf einem Display setzt sich aus lauter farbigen Punkten, den Pixeln, zusammen. Wenn man die Pixel richtig zusammen setzt, ergeben sich alle möglichen Formen, wie hier zum Beispiel eine Birne. Ein einzelnes Pixel hat aber nicht die Form einer Birne, sondern ist quadratisch.

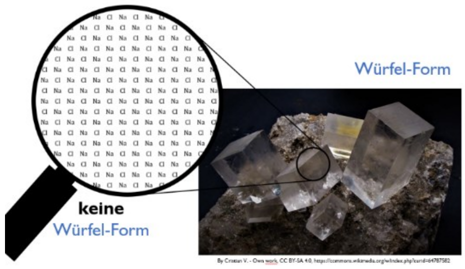


Quelle: eigene Darstellung basierend auf Nickpick910 - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=17969690

Im Anschluss wird die Idee „die Eigenschaften der Bestandteile sind nicht die Eigenschaften des Ganzen" auf die Bausteine übertragen.

Beispiel 3:

Ein Salzkristall setzt sich aus Natrium und Chlor-Bausteinen zusammen. Der Salzkristall ist würfelförmig. Die Bausteine des Salzkristalls sind jedoch nicht würfelförmig. Die Würfelform des Salzkristalls ergibt sich durch die Bindung der Bausteine.



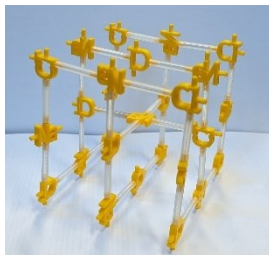
Quelle: eigene Darstellung basierend auf: Cristian V. - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=64787582

3. Die Bindung der Bausteine bestimmt die Eigenschaften des Gegenstands.

Die Bausteine haben andere Eigenschaften als die Gegenstände, die aus ihnen zusammengesetzt sind. Trotzdem bestimmt die Bindung der Bausteine Eigenschaften der Gegenstände. So kann man zum Beispiel die regelmäßige Form von Kristallen oder ihre Festigkeit mit der Bindung der Bausteine erklären.

Beispiel 1:

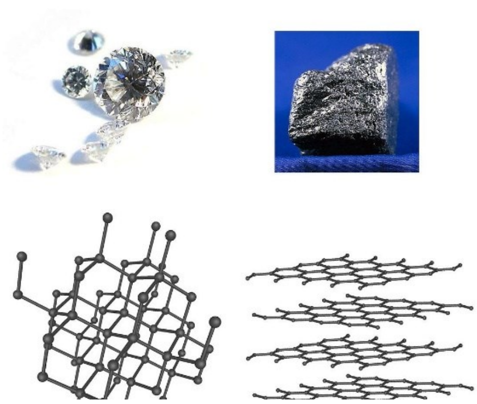
Dieses Modell zeigt die Struktur der Bausteine von Salz. Dabei bindet sich immer ein Baustein von Natrium an Bausteine von Chlor. Dadurch dass sie sich sehr regelmäßig aneinander binden entsteht ein würfelförmiges Gitter.



2. Unterrichtsstunde

Beispiel 2:

Durch unterschiedliche Strukturen bei der Bindung der Bausteine können aus einem Typ von Baustein ganz verschiedene Dinge entstehen. Zum Beispiel entsteht sowohl Diamant als auch Graphit aus Kohlenstoff-Bausteinen. Während Graphit ein weiches Material ist, das man zum Beispiel für Bleistiftminen verwendet, ist Diamant das härteste Material in der Natur. Diese unterschiedlichen Eigenschaften kommen nur durch die Bindung der Bausteine zustande.



Quelle: User:Itub - Self-made derivative work (see below), CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1755521

4. Die Bewegung der Bausteine bestimmt die Temperatur eines Gegenstands.

Eine weitere Eigenschaft, die sich auf das Verhalten der Bausteine zurückführen lässt ist die Temperatur. Schüler:innen gehen häufig davon aus, dass sich die Bausteine in einem Festkörper nicht bewegen. Daher ist es wichtig zu betonen, dass auch wenn die Bausteine aneinander gebunden sind, sie sich ständig an ihrem Platz hin- und herbewegen. Die Stärke der Bewegung der Bausteine bestimmt die Temperatur eines Gegenstands.

Beispiel:

Auch wenn wir die stärkere Bewegung der Bausteine nicht sehen können, so können wir ihre Auswirkung beobachten. Denn wenn sich die Bausteine mehr bewegen, dann brauchen sie auch mehr Platz. Dazu wird folgender Versuch gezeigt: eine Eisenkugel passt genau durch einen Eisenring. Erhitzt man die Kugel passt sie jedoch nicht mehr durch den Ring. Die Kugel hat sich ausgedehnt, weil die Bausteine sich schneller bewegen und mehr Platz brauchen.

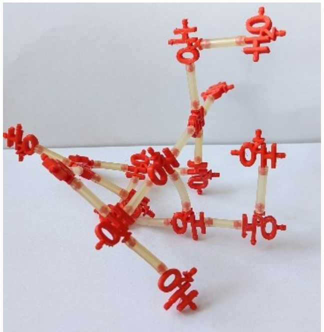
5. Am Schmelzpunkt wird die Bindung flexibel und die Struktur der Plätze löst sich auf.

Bringt man nun die zwei zuvor besprochenen Eigenschaften der Bausteine, nämlich ihre Bindung und ihre Bewegung zusammen, dann kann man damit wieder neue Phänomene erklären. Übersteigt nämlich die Bewegung der Bausteine einen bestimmten Wert, dann beginnt sich ihre regelmäßige Struktur aufzulösen. Entgegen der Vorstellung vieler Schüler:innen ändern sich die Abstände zwischen den Bausteinen dabei aber kaum, sie sind noch immer aneinander gebunden. Die Bindung ist aber flexibler, sodass sich die Bausteine mehr bewegen können.

3. Unterrichtsstunde

Beispiel:

Zur Demonstration der Unterschiede zwischen Festkörper und Flüssigkeiten gibt es wiederum zwei Modelle. Das erste zeigt die Struktur von Eis, das zweite von flüssigem Wasser. Während im festen Zustand die hexagonale Geometrie des Eises zu erkennen ist, gibt es im flüssigen Zustand keine bestimmte Struktur mehr. Die Bindung im Modell wird hier nicht durch feste Rohre sondern durch Schlauchstücke realisiert, um die Flexibilität der Struktur zu erhöhen.

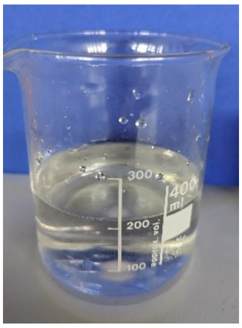


Den Vorgang, dass sich die starre Struktur auflöst, nennt man Schmelzen. Die Temperatur, bei der das passiert heißt Schmelzpunkt. Je stärker die Bausteine aneinander gebunden sind, desto höher ist der Schmelzpunkt. Zum Beispiel schmilzt Eis bei 0 °C aber Eisen erst bei 1535 °C. Das liegt daran, dass die Bausteine im Eisen viel stärker aneinander gebunden sind als im Eis.

6. Zwischen den Bausteinen ist nichts.

Die bisher betrachteten Modelle und Darstellungen zeigen, dass zwischen den Bausteinen immer noch Platz ist. In der Vorstellung vieler Schüler:innen befindet sich Luft[21] zwischen den Bausteinen. Sie argumentieren häufig, dass ja nicht „Nichts“ zwischen den Bausteinen sein kann. Daher wird anhand von zwei Beispielen demonstriert, dass sich das Volumen bei gleichbleibender Anzahl an Bausteinen verändern kann[22].

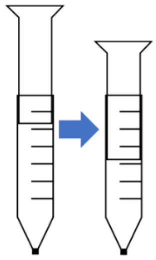
<u>Beispiel 1:</u>



In ein Becherglas werden 200 ml Wasser gefüllt. In einem kleineren Gefäß werden 40 ml Salz abgemessen. Löst man die 40 ml Salz in den 200 ml Wasser auf, ergeben sich nicht 240 ml Wasser, sondern nur etwa 220 ml. Das liegt daran, dass die Bindungen im Salz getrennt werden und sich die Wasserbausteine um die Natrium- und Chlorbausteine herum anlagern. Dabei ist der Abstand zwischen den Bausteinen kleiner, als wenn Salz und Wasser getrennt voneinander vorhanden sind.[23]

<u>Beispiel 2:</u>

Eine mit Luft gefüllt Spritze wird vorne fest verschlossen, sodass keine Luft mehr herauskommt. Trotzdem lässt sich die Luft in der Spritze auf circa die Hälfte zusammendrücken. Dabei verringert sich der Abstand zwischen den Luft-Bausteinen solange bis die Abstoßung zwischen den Bausteinen überwiegt und die Luft nicht mehr weiter komprimiert werden kann.



Anhand der beiden Beispiele sollte gezeigt werden, dass es möglich ist, dass die Bausteine unterschiedlich viel Abstand voneinander haben und daher unterschiedlich viel Platz einnehmen. Das ist umso mehr der Fall, je weiter die Bausteine voneinander entfernt sind. Deshalb lassen sich Gase gut komprimieren, Festkörper und Flüssigkeiten dagegen nur wenig. Die Vorstellung des leeren Raums zwischen den Bausteinen ist auch eine wichtige Voraussetzung für die nächste Konzeptidee.

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[21] Manchmal wird auch Sauerstoff genannt, wobei beide Begriffe als synonym betrachtet werden.

[22] Möchte man dabei auf die Dichte eingehen, sollte erwähnt werden, dass neben dem Abstand zwischen den Bausteinen auch die Masse eines einzelnen Bausteins relevant ist.

[23] Oft wird argumentiert, die Natrium- und Chlor-Ionen füllen Lücken zwischen den Wassermolekülen aus. Das ist aber nicht korrekt, da die Verringerung des Abstands durch die Anziehung zwischen Ladungen zustande kommt. Der partiell positiv geladene Wasserstoff im H_2O-Molekül und die negativ geladenen Chlor-Ionen ziehen sich dabei gegenseitig an, ebenso der partiell negativ geladene Sauerstoff im H_2O-Molekül mit den positiv geladenen Natrium-Ionen.

7. Am Siedepunkt trennt sich die Bindung der Bausteine auf und sie entfernen sich voneinander.

Übersteigt die Bewegung der Bausteine einen anderen bestimmten Wert, dann können sie ihre Bindung sogar trennen und sich frei herumbewegen. Der Abstand zwischen zwei Bausteinen steigt dabei durchschnittlich auf das Zehnfache an. Über alle drei Raumrichtungen summiert ergibt sich dabei eine Volumenzunahme um circa das Tausendfache.

Beispiel:

Das Verhalten der Bausteine beim Verdampfen und im gasförmigen Zustand wird mit einem Modellexperiment verdeutlicht. Dieses besteht aus einem Plastiksack, in dem sich kleine H_2O-Symbole befinden, welche die Bausteine von Wasser darstellen. Das Modell zeigt millionenfach vergrößert und näherungsweise maßstabsgetreu den Abstand zwischen den Bausteinen. Wichtig ist dabei erneut zu betonen, dass sich zwischen den Bausteinen nichts befindet, also auch keine Luft! Durch schütteln des Modells lässt sich die Bewegung der Bausteine simulieren.

Der Vorgang, bei dem die Bausteine ihre Bindung trennen und sich voneinander entfernen nennt man Verdampfen. Die Temperatur, bei der das passiert ist der Siedepunkt. Je stärker die Bausteine aneinander gebunden sind, desto größer ist der Siedepunkt. Wasser siedet zum Beispiel bei 100 °C, Eisen bei 3000 °C. Das liegt daran, dass die Bausteine im Eisen stärker aneinander gebunden sind.

Übersicht zu den Unterrichtstunden

Die folgende Übersicht zeigt den ungefähren Ablauf der einzelnen Unterrichtsstunden. Dieser dient als Orientierung und kann gerne auch entsprechend eigener Vorlieben und den Anforderungen der jeweiligen Klasse adaptiert werden. Wichtig ist nur, dass die Besonderheiten des Unterrichtskonzepts beachtet und alle sieben zentralen Konzeptideen in der vorgegebenen Reihenfolge unterrichtet werden. Auch die Arbeitsblätter und PowerPoint-Präsentationen können gerne abgeändert werden. Bitte Änderungen dokumentieren, damit am Ende klar ist, was wie unterrichtet wurde. Den Überlegungen von Lehrkräften sowie den Rückmeldungen von Schüler:innen kommt für die Evaluation des Unterrichtskonzept eine große Bedeutung zu.

1. Stunde

Zentrale Konzeptidee

1. Alles, das man angreifen kann, stellt man sich aus sehr vielen, kleinen, nicht-sichtbaren Bausteinen zusammengesetzt vor.

	Lehrperson	Schüler:innen	Material
1.	Stellt das Thema des Unterrichtskonzepts vor: Woraus besteht alles? – Zeigt Folie mit Bildern von Dingen aus der Natur. Fragt SuS nach Besonderheiten. *Teilchen/Bausteine sollten zu diesem Zeitpunkt noch nicht erwähnt werden*	Überlegen zuerst kurz alleine wie sie die Frage beantworten. Teilen dann die Überlegungen mit der/dem Sitznachbar:in und der Klasse	PowerPoint 1 - Folie 1
2.	Sammelt Ergebnisse der Schüler:innen. Erklärt die Besonderheit von Kristallstrukturen und zeigt einige Beispiele	Beschreiben kurz ihre Beobachtungen vor der Klasse	PowerPoint 1 - Folie 2
3.	Erklärt Aufgabenstellung; gibt Arbeitsblätter aus, wobei in jeder Bank immer zwei verschiedene Arbeitsblätter vorhanden sein sollten Gibt Hilfestellungen *Alternativ können die Videos von der Lehrperson gezeigt werden*	Bearbeiten zuerst ein Beispiel (Salzkristalle, Schneekristalle) am Arbeitsblatt alleine und erklären sich die Schlussfolgerungen dann gegenseitig	AB 1 - *Wie entstehen Kristalle?* Smartphone/Tablet
4.	Geht darauf ein, dass zum Verständnis des Aufbaus von Kristallen die Vorstellung notwendig ist, dass alles aus Bausteinen aufgebaut ist. Ruft Fragen in der PowerPoint oder direkt auf Mentimeter auf https://www.mentimeter.com/app/presentation/alzk3hrk9ewchox75uxpis8apw7irjds erklärt Aufgabenstellung kommentiert die Antworten der Schüler:innen	Melden sich mit ihrem Smartphone oder Tablet bei Mentimeter an und nennen drei Begriffe, die sie mit „Bausteine der Materie" verbinden	PowerPoint 1 – Folie 5 & 6 Smartphone/Tablet
5.	Fasst die Antworten der Schüler:innen zusammen. Erklärt mit Hilfe der PowerPoint (Folie 7 & 8) die Vorstellung dass „alles, das man angreifen kann, aus sehr vielen kleinen, nicht-sichtbaren Bausteinen zusammengesetzt ist".	Stellen Fragen bei Unklarheiten *Optional: schreiben den Merksatz von PowerPoint 1 - Folie 7 ins Heft*	PowerPoint 1 – Folien 7 & 8

2. Stunde

Zentrale Konzeptideen

1. Die Eigenschaften eines Bausteins sind nicht die Eigenschaften des Gegenstands.
2. Die Bindung der Bausteine bestimmt die Eigenschaften des Gegenstands.

	Lehrperson	**Schüler:innen**	**Material**
1.	Erklärt das Prinzip „die Eigenschaften der Bestandteile sind anders als die Eigenschaften des Ganzen“ anhand von zwei Beispielen. Wendet dieses Prinzip dann auf die Bausteine am Beispiel Salzkristall an.	Stellen Fragen bei Unklarheiten	PowerPoint 2 – Folie 2 - 4
2.	Erklärt Aufgabenstellung, gibt Hilfestellungen *Bei Bedarf bzw. wenn noch Zeit ist können die Concept Cartoons auch im Plenum nachbesprochen werden*	Entscheiden sich für eine Aussage im Concept Cartoon und begründen ihre Wahl vergleichen dann mit der Nachbarin/dem Nachbarn	AB2 - Concept Cartoons PowerPoint 2 – Folien 5 & 6
3.	Erklärt am Beispiel Salzkristall, wie die Bindung der Bausteine die Eigenschaften des Gegenstands bestimmt.	Stellen Fragen bei Unklarheiten *Optional: schreiben Merksatz von PowerPoint 2 - Folie 7 ins Heft*	3D-Modell Salzkristall PowerPoint 2 – Folie 7
4.	Erklärt Aufgabenstellung; gibt Arbeitsblätter aus, wobei in jeder Bank immer zwei verschiedene Arbeitsblätter vorhanden sein sollten Gibt Hilfestellungen	Erklären sich gegenseitig wie die Festigkeit von Diamant und Graphit entsteht	3D-Modelle AB3 - *Wie entstehen die Eigenschaften der Dinge?*
5.	Sammelt Ergebnisse und erklärt noch einmal kurz, wie die unterschiedlichen Eigenschaften der Bausteine zustande kommen	stellen die Ergebnisse ihrer Überlegung kurz im Plenum vor	PowerPoint 2 – Folien 8 & 9
	Vorbereitung für 3. Stunde: Eiswürfelform mit Wasser füllen und einfrieren		

3. Stunde

Zentrale Konzeptidee

1. Die Bewegung der Bausteine bestimmt die Temperatur eines Gegenstands
2. Am Schmelzpunkt wird die Bindung flexibel und die Struktur der Plätze löst sich auf.

	Lehrperson	**Schüler:innen**	**Material**
1.	Erklärt, dass die Bewegung der Bausteine die Temperatur eines Gegenstands bestimmt Zeigt Experiment mit der Kugel (*alternativ kann ein Video des Experiments gezeigt werden; siehe PP 3 – Folie 2*) fasst Zusammenhang zwischen Temperatur, Bewegung der Bausteine und Volumen des Gegenstands zusammen	Beobachten Experiment, stellen Vermutung an, was passiert, wenn die Kugel erhitzt wird. *Optional: schreiben Merksatz von PowerPoint 3 - Folie 4 ins Heft*	Metallkugel, Metallring, Gasbrenner; PowerPoint 3 – Folien 2 - 4
2.	Gibt Hilfestellungen wenn Zeit ist können die Aufgaben mit Hilfe der PowerPoint im Plenum nachbesprochen werde	Bearbeiten Arbeitsblatt in Einzelarbeit	AB4 - *Temperatur* PowerPoint 3 – Folien 5 & 6
3.	Erklärt Schmelzvorgang und verwendet dazu die 3D-Modelle und die PowerPoint geht auf den unterschiedlichen Schmelzpunkt der Stoffe ein und erklärt die Ursache mit den Bausteinen	Stellen Fragen bei Unklarheiten	3D Modelle Wasser und Eis PowerPoint 3 - Folien 7 & 8
4.	Erklärt Aufgabenstellung, teil Gruppen ein; gibt Materialien aus gibt Hilfestellungen wenn Zeit: Fragen im Plenum nachbesprechen	Führen Experiment in Gruppen von 3-4 Personen durch und beantworten Fragen	Aluminium-Becher, Eiswürfel, Teelichter AB5 - *Experiment: Schmelpunkt von Eis*

4. Stunde

Zentrale Konzeptideen

1. Zwischen den Bausteinen ist nichts.
2. Am Siedepunkt hört die Bindung der Bausteine auf und sie entfernen sich voneinander.

	Lehrperson	Schüler:innen	Material
1.	Zeigt Experiment (alternativ kann in der PP ein Video des Experiments gezeigt werden) und geht auf den leeren Raum zwischen den Bausteinen ein	Beobachten Experiment Stellen Vermutung auf, wie sich der Füllstand im Becherglas verändert, nachdem das Salz aufgelöst wurde	Becherglas, Salz, kleiner Messbecher, Löffel (Video: PowerPoint 4 – Folien 2 & 3) PowerPoint 4 – Folien 4 & 5
2.	Erklärt Aufgabenstellung Stellt Spritzen zur Entnahme bereit Gibt Hilfestellungen	Führen Experiment alleine oder zu zweit durch Beantworten Fragen auf dem AB	Spritzen AB6 – *Experiment: Warum lässt sich Luft zusammendrücken?*
3.	Erklärt Verdampfen und Siedepunkt Erklärt mit Hilfe des Modellexperiments, was auf der Ebene der Bausteine passiert	Stellen Fragen bei Unklarheiten	PowerPoint 4 – Folie 7-9 Modell Wasser 6 l Plastiksack + 38 H_2O Modelle
4.	Erhitzt Wasser im Wasserkocher Gibt Materialien aus Das Einfüllen des heißen Wassers sollte am besten von der Lehrperson gemacht werden, da Verbrühungsgefahr besteht *Alternativ kann der Versuch als Video (in PP) gezeigt werden*	Führen in Gruppen von 3-4 Personen Versuch mit dem Quetschbeutel durch und beantworten Fragen	Becherglas 600 ml, Wasserkocher, Brennspiritus, leerer Quetschbeutel, Spritzen (als Pipette) AB7: Sieden im Quetschbeutel
5.	Fasst Ergebnisse des Experiments zusammen, demonstriert die Bewegung der Bausteine beim Eintauchen/Herausziehen des Quetschbeutels in das heiße Wasser mit dem Modellexperiment	Stellen Fragen bei Unklarheiten	6 l Plastiksack + 38 H_2O Modelle Video: PowerPoint 4 – Folie 10

E. Students’ worksheets

Wie entstehen Salzkristalle?

Auf dem Bild rechts siehst du einige Salzkristalle, wie man sie in einem Bergwerk finden kann. Das besondere an den Salzkristallen ist, dass sie scheinbar von selbst in einer regelmäßigen rechteckigen Form entstehen. Die Salzkristalle wurden genauso wie sie auf dem Bild zu sehen sind in der Natur gefunden und nicht von Menschen bearbeitet.

By Cristian V. - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=64787582

Doch wie kommt es zu dieser regelmäßigen Form?

Sieh dir dazu das Video zur Entstehung von Salzkristallen unter dem Mikroskop an. Im Video werden einige Tropfen Salzwasser auf eine dünne Glasplatte gegeben. Diese Tropfen werden dann in das Mikroskop gegeben und gefilmt. Beobachte dabei, welche Formen die Salzkristalle annehmen.

Video zur Entstehung von Salzkristallen unter dem Mikroskop

Scanne den QR-Code, um das Video zu sehen oder gib folgenden Link im Browser ein: **https://bit.ly/3ZN2l3l**

Sieh dir das Video bis zu Minute 00:50 an.

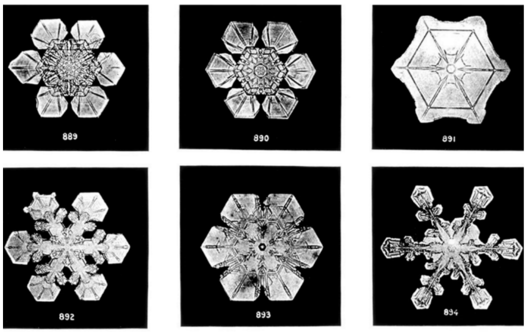
1. Beschreibe deine Beobachtungen aus dem Video und gehe dabei auf die Form der Kristalle ein!

2. Erkläre zuerst deine Beobachtungen deinem/deiner Nachbar:in.
   Fasse dann seine/ihre Beobachtungen zur Form der Kristalle kurz zusammen.

3. Überlegt gemeinsam, welche Gemeinsamkeiten es zwischen den beiden Beispielen gibt. Fasst eure Überlegungen in Stichworten zusammen.

Wie entstehen Schneekristalle?

Auf dem Bild rechts siehst du einige Schneekristalle. Das besondere an den Schneekristallen ist, dass sie scheinbar von selbst in einer regelmäßigen sechszackigen Form entstehen. Die Schneekristalle wurden genauso wie sie auf dem Bild zu sehen sind in der Natur gefunden und nicht von Menschen bearbeitet.



Von Wilson Bentley - Plate XIX of Studies among the Snow Crystals, Gemeinfrei, https://commons.wikimedia.org/w/index.php?curid=22130

Doch wie kommt es zu dieser regelmäßigen Form?

Sieh dir dazu das Video zur Entstehung von Schneekristallen unter dem Mikroskop an. Um den Kristall herum siehst die kleine Wasser-Tröpfchen, die dann gefrieren. Beobachte dabei, welche Form der Schneekristall annimmt.

Video zur Entstehung von Schneekristallen unter dem Mikroskop

Scanne den QR-Code, um das Video zu sehen oder gib folgenden Link im Browser ein: **https://bit.ly/4152sbv**

Sieh dir das Video bis zum Ende an.

1. Beschreibe deine Beobachtungen aus dem Video und gehe dabei auf die Form der Kristalle ein!

2. Fasse zuerst die Beobachtungen deines/deiner Nachbar:in zur Form der Kristalle zusammen. Erkläre ihm/ihr dann deine Beobachtungen.

3. Überlegt gemeinsam, welche Gemeinsamkeiten es zwischen den beiden Beispielen gibt. Fasst eure Überlegungen in Stichworten zusammen.

Eigenschaften der Bausteine

Schneekristalle haben immer eine sechszackige Form. Hier siehst du drei Personen, die versuchen zu erklären, wie diese Form entsteht. Kreuze die Aussage an, die deiner Meinung nach am besten erklärt, wie diese Form entsteht.

Wie entsteht die sechszackige Form des Schneekristalls?

○ Ich denke ein Schneekristall sieht so aus, da sich die Bausteine von Wasser wenn es kalt ist immer in dieser Form zusammensetzten.

Mike

○ Ich denke ein Schneekristall sieht so aus, da die Bausteine von Wasser ebenfalls diese Form haben.

Lisa

○ Ich denke ein Schneekristall sieht so aus, da kleine Eiskügelchen beim Hinunterfallen durch die Luft so verformt werden.

Anna

Begründe, was genau dich an dieser Aussage überzeugt:

Eigenschaften der Bausteine

Salzkristalle haben immer eine viereckige Form. Hier siehst du drei Personen, die versuchen zu erklären, wie diese Form entsteht. Kreuze die Aussage an, die deiner Meinung nach am besten erklärt, wie diese Form entsteht.

Wie entsteht die viereckige Form des Salzkristalls?

○ Ich denke ein Salzkristall sieht so aus, da die Bausteine von Salz ebenfalls diese Form haben.

Mike

○ Ich denke ein Salzkristall sieht so aus, da er unter hohem Druck zusammengepresst wurde.

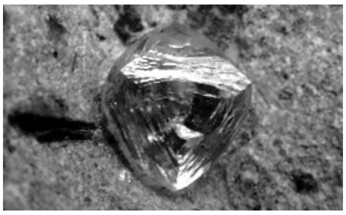
Lisa

○ Ich denke ein Salzkristall sieht so aus, da sich die Bausteine von Salz in dieser Form zusammensetzen.

Anna

Begründe, was genau dich an dieser Aussage überzeugt:

Wie entstehen die Eigenschaften der Dinge?

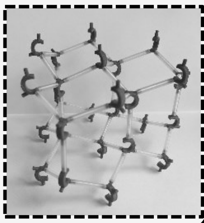


Von StrangerThanKindness - Eigenes Werk, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=14173725

In dem Bild rechts siehst du in der Mitte einen Diamanten. Diamant ist durchscheinend und das härteste Material, das es gibt. Diamanten werden wegen ihrer großen Festigkeit zum Schneiden von Steinen verwenden, zum Beispiel beim Graben von Tunneln. Diamant setzt sich zu hundert Prozent aus Kohlenstoff-Bausteinen zusammen, es kommen keine anderen Bausteine vor.

Woher kommt die hohe Festigkeit von Diamant?

Sieh dir dazu das 3D-gedruckte Modell der Kristallstruktur von Diamant an. Die Kohlenstoff-Bausteine werden mit dem Buchstaben C dargestellt. Sie haben eigentlich nicht diese Form und diese Farbe. Auch die Verbindungen zwischen den Bausteinen gibt es nur im Modell. Was das Modell jedoch gut zeigt ist, wie die Kohlenstoff-Bausteine im Diamant angeordnet sind. Dabei sind alle Kohlenstoff-Bausteine fest miteinander verbunden.

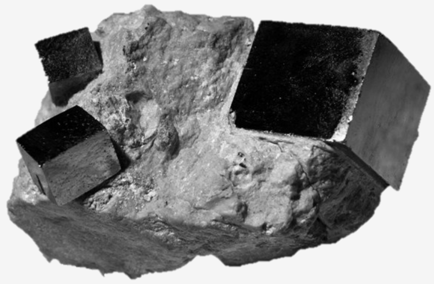


1. Beschreibe, welche Eigenschaften von Diamant sich mit Hilfe des Modells erklären lassen.

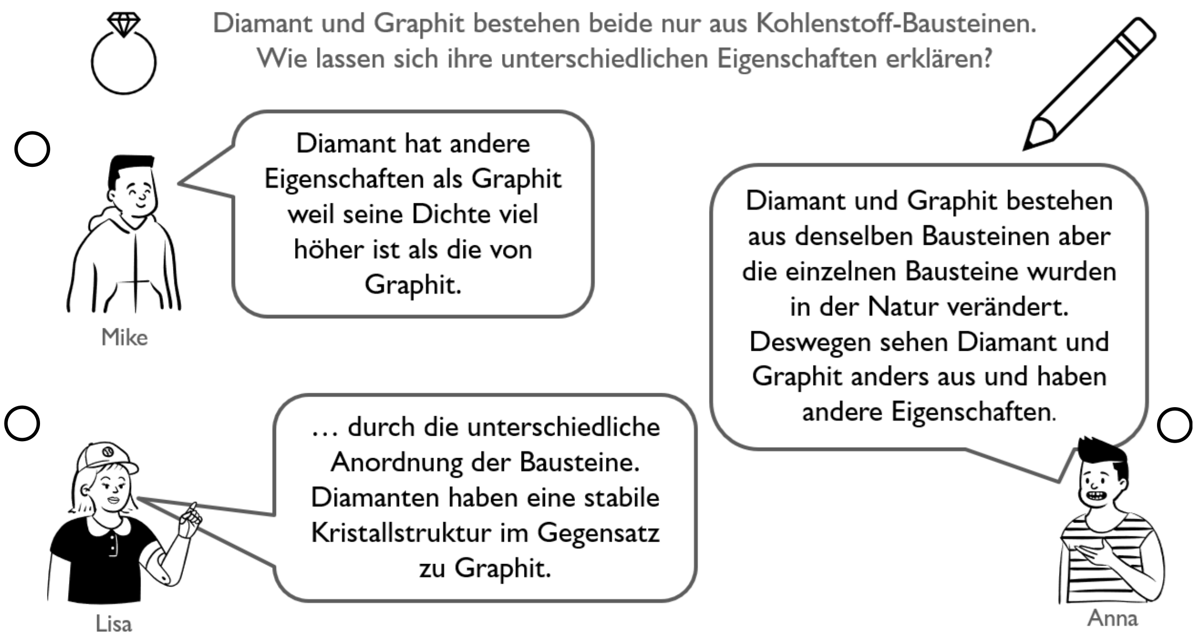
2. Erkläre zuerst deine Beobachtungen zum Diamant-Modell deinem/deiner Nachbar:in. Fasse dann seine/ihre Beobachtungen zum Graphit-Modell kurz zusammen.

3. Versucht gemeinsam zu erklären, warum Diamant besonders fest und Graphit nicht, obwohl beide zu hundert Prozent aus Kohlenstoff-Bausteinen bestehen.

4. Auf diesem Bild siehst du drei quaderförmige Pyrit-Kristalle. Erkläre warum diese so eine rechteckige Form haben.



5. Diamant und Graphit bestehen jeweils nur aus Kohlenstoff-Bausteinen. Trotzdem haben sie ganz andere Eigenschaften. Diamant ist extrem fest, Graphit dagegen weich und spröde. Die folgenden drei Aussagen versuchen zu erklären, warum das so ist. Kreuze die Aussage an, die deiner Meinung am besten erklärt, warum Diamant und Graphit so unterschiedliche Eigenschaften haben.

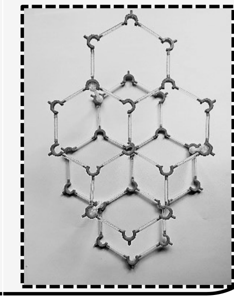


Begründe, was genau dich an dieser Aussage überzeugt:

Auf dem Bild siehst du die Spitze eines Bleistifts. Diese besteht aus Graphit. Graphit hat eine dunkelgraue Farbe und ist nicht sehr fest, er bricht leicht auseinander. Aus diesem Grund verwendet man es auch zum Schreiben: wenn man mit dem Bleistift über das Papier fährt löst sich der Graphit leicht von der Spitze. Graphit setzt sich zu hundert Prozent aus Kohlenstoff-Bausteinen zusammen, es kommen keine anderen Bausteine vor.

Woher kommt die geringe Festigkeit von Graphit?

Sieh dir dazu das 3D-gedruckte Modell der Kristallstruktur von Graphit an. Die Kohlenstoff-Bausteine werden mit dem Buchstaben C dargestellt. Sie haben eigentlich nicht diese Form und diese Farbe. Auch die Verbindungen zwischen den Bausteinen gibt es nur im Modell. Was das Modell jedoch gut zeigt ist, wie die Kohlenstoff-Bausteine im Graphit angeordnet sind. Diese sind in einer flachen Schicht fest aneinander gebunden. Es liegen immer viele dieser flachen Schichten übereinander. Diese Schichten lassen sich leicht voneinander trennen, da die Bausteine einer Schicht nur sehr schwach mit denen der nächsten Schicht zusammen hängen.

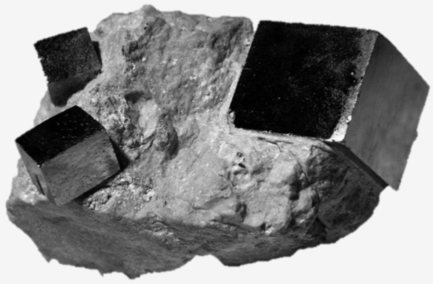


1. Beschreibe, welche Eigenschaften von Graphit sich mit Hilfe des Modells erklären lassen.

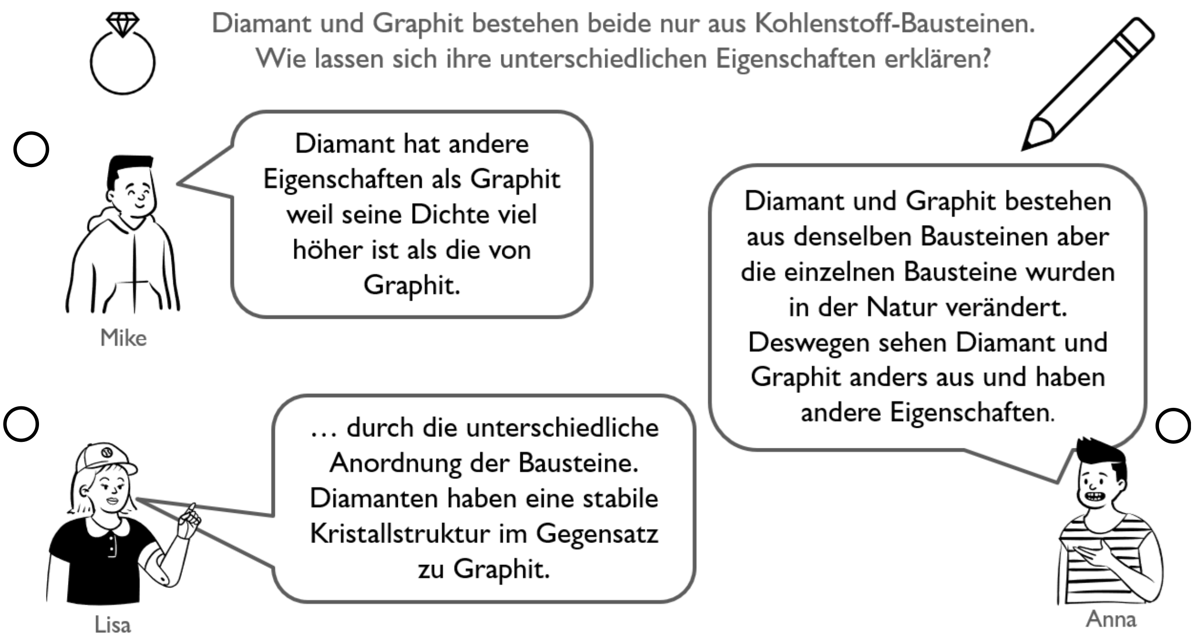
2. Fasse zuerst die Beobachtungen deines/deiner Nachbarin:in zum Diamant-Modell kurz zusammen. Erkläre ihm/ihr dann deine Beobachtungen zum das Graphit-Modell.

3. Versucht gemeinsam zu erklären, warum Diamant besonders fest und Graphit nicht, obwohl beide zu hundert Prozent aus Kohlenstoff-Bausteinen bestehen.

4. Auf diesem Bild siehst du drei quaderförmige Pyrit-Kristalle. Erkläre warum diese so eine rechteckige Form haben.



5. Diamant und Graphit bestehen jeweils nur aus Kohlenstoff-Bausteinen. Trotzdem haben sie ganz andere Eigenschaften. Diamant ist extrem fest, Graphit dagegen weich und spröde. Die folgenden drei Aussagen versuchen zu erklären, warum das so ist. Kreuze die Aussage an, die deiner Meinung am besten erklärt, warum Diamant und Graphit so unterschiedliche Eigenschaften haben.



Begründe, was genau dich an dieser Aussage überzeugt:

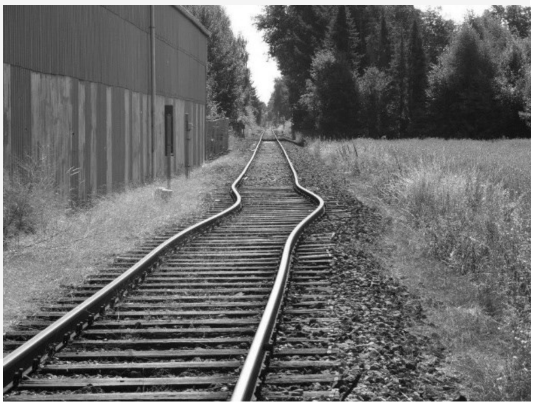
Temperatur

Die Bewegung der Bausteine bestimmt die Temperatur eines Gegenstands. Je stärker sich die Bausteine bewegen, desto höher die Temperatur. Weil die Bausteine wenn sie sich stärker bewegen mehr Platz brauchen, dehnen sich Gegenstände beim Erwärmen aus. Das passiert auch bei festen Gegenständen, da sich die Bausteine dort an ihrem Platz etwas hin und her bewegen können.

1. Die Eisenkugel passt bei Zimmertemperatur gerade nicht durch den Eisenring. Beschreibe, was man tun könnte, damit sie durchpasst. Gehe dabei auf die Bausteine der Materie ein!

2. An den beiden Enden von Brücken findet man häufig eine Metallschiene mit ineinandergreifenden Zacken (siehe Bild). Beschreibe, wozu diese Metallschiene eingebaut wird. Gehe dabei auf die Bausteine der Materie ein!

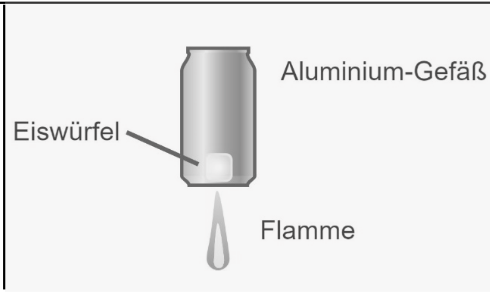
3. An heißen Sommertagen passiert es in seltenen Fällen, dass sich Bahngleise verbiegen (siehe Bild). Erkläre, warum das passiert. Gehe dabei auf die Bausteine der Materie ein!



Experiment: Schmelzpunkt von Eis

Material: Aluminium-Gefäß, Teelicht, Streichhölzer, Eiswürfel

Durchführung: Zünde das Teelicht an. Gib den Eiswürfel in das Aluminium-Gefäß und halte es über die Flamme. Das Gefäß sollte dabei nicht die Flamme berühren. Halte das Gefäß am oberen Ende fest, da es in der Nähe der Flamme heiß werden könnte.



Beobachte was bei dem Experiment mit dem Eiswürfel und dem Aluminium-Gefäß passiert!

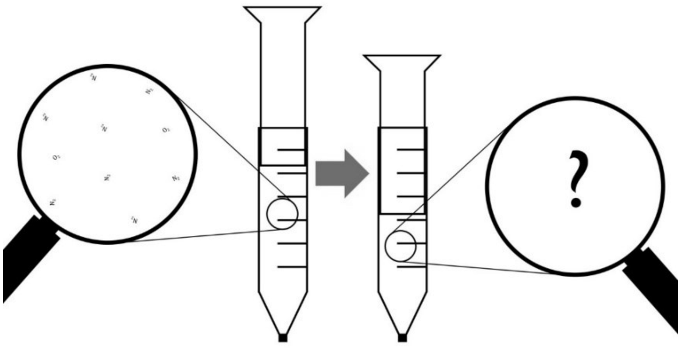
1. Was hat den höheren Schmelzpunkt, Eis oder Aluminium? Begründe deine Wahl!

2. Erkläre, warum der Schmelzpunkt von Eis und Aluminium sich unterscheidet. Gehe dabei auf die Bausteine der Materie ein!

Experiment: Warum lässt sich Luft zusammendrücken?

Material: Spritze (20 ml)

Durchführung: Ziehe die Spritze auseinander, sodass sich der hintere Teil bei 15 ml befindet. Verschließe die Öffnung der Spritze fest mit einem Finger. Es sollte keine Luft nach außen kommen können. Drücke dann die Spritze zusammen.



Begründe, warum sich die Spritze zusammendrücken lässt, obwohl keine Luft nach draußen kann. Gehe dabei auf die Bausteine der Materie ein!

Experiment: Was passiert beim Sieden im Quetschbeutel?

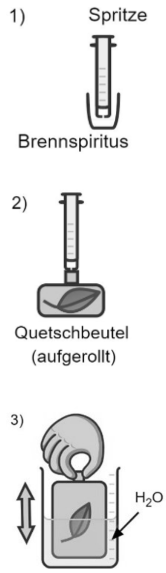
Material: Becherglas 400 ml, leerer Quetschbeutel, Brennspiritus, Spritze, heißes Wasser

Durchführung:

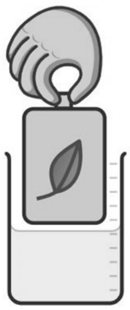
1) Drücke den Kolben der Spritze ganz nach vorne in die Spritze hinein. Tauche dann die offene Spitze der Spritze in den Brennspiritus. Ziehe den Kolben vorsichtig einige Millimeter nach hinten, sodass sich die Spritze ein wenig mit dem Brennspiritus füllt.

2) Schraube den Quetschbeutel auf und rolle ihn zusammen, um die Luft herauszudrücken. Tropfe nun aus der Spritze 8 Tropfen Brennspiritus in den Quetschbeutel. Verschraube den Quetschbeutel fest und rolle ihn wieder auseinander.

3) Fülle das Becherglas zur Hälfte mit heißem Wasser. Tauche dann den Quetschbeutel vorsichtig in das heiße Wasser. Achte darauf nicht mit den Fingern in das heiße Wasser zu tauchen. Ziehe dann den Quetschbeutel wieder heraus. Wiederhole das Eintauchen und Herausziehen mehrere Male.



1. Vervollständige die Tabelle!

	Beobachtung	**Was passiert mit den Bausteinen?**
		
		

2. Begründe, ob der Siedepunkt von Brennspiritus größer oder kleiner ist, als der von Wasser.

Acknowledgements

In conclusion, I would like thank all of my colleagues, friends, and relatives for their invaluable support throughout the completion of my doctoral thesis. I am particularly grateful for the opportunity to conduct my research project over the past few years. During this period, I not only gained a wealth of knowledge for myself but also had the privilege of meeting new people with whom I shared a passion for physics education research. Their work and accomplishments have been a source of inspiration for me.

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I would like to sincerely thank all the teachers and students who participated in the interviews and intervention study, without whom my research would not have been possible.

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