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

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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. 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 a scanning tunnel microscopy image of graphite for students to come to understand the connection between macroscopic and submicroscopic levels of matter.

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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, nonvisible 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 our 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 states [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 "narrativelike" 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 our 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 and 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].

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

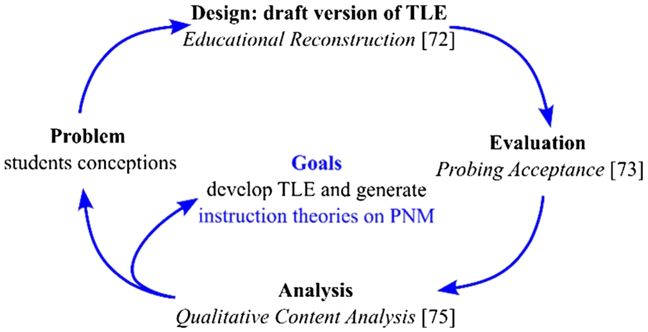

FIG. 1. Overview of the design-based research process. The terms in bold represent the steps of each cycle, beginning with the problem. The terms in italics represent the methods used in every step of the cycle (source: own illustration adapted from [68]).

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 Sec. 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 [72]. 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-learning sequences, 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 microteaching 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 Sec. 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

Because of an upcoming change of the national curriculum in Austria, only eighth-grade students (aged 13 to 14 yr) 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 min long. To allow time for a short introduction to the study, we limited the interviews to a duration of 40 min. On average, one interview lasted between 30 and 35 min.

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

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.

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, nonvisible[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 Sec. II. B, students need to be aware that proper explanation with the PNM requires using 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

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

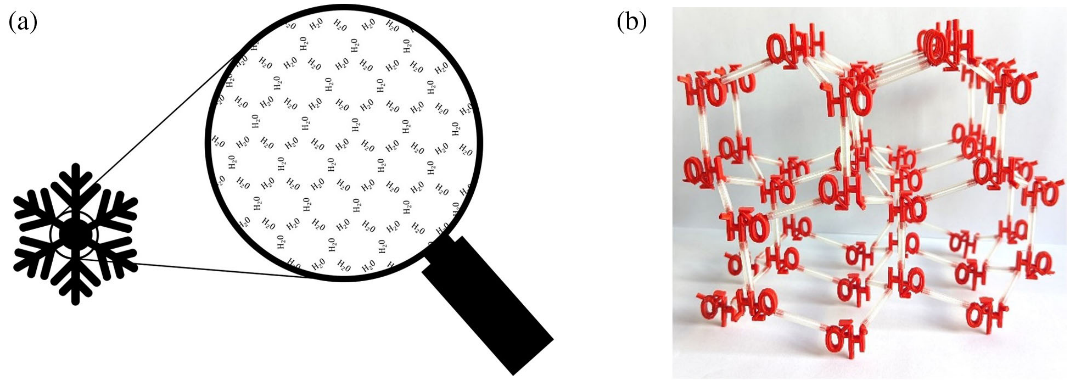

FIG. 2. (a) Typographic representation of ice I_h; (b) 3D-printed crystal structure of ice I_h (source: own illustration).

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 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. 2(b)].

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]

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. 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

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[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. Because of 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].

[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.

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, nonvisible 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.

salt crystals are shaped like cubes on a macroscopic scale due to the arrangement of the atoms.

E. Data analysis

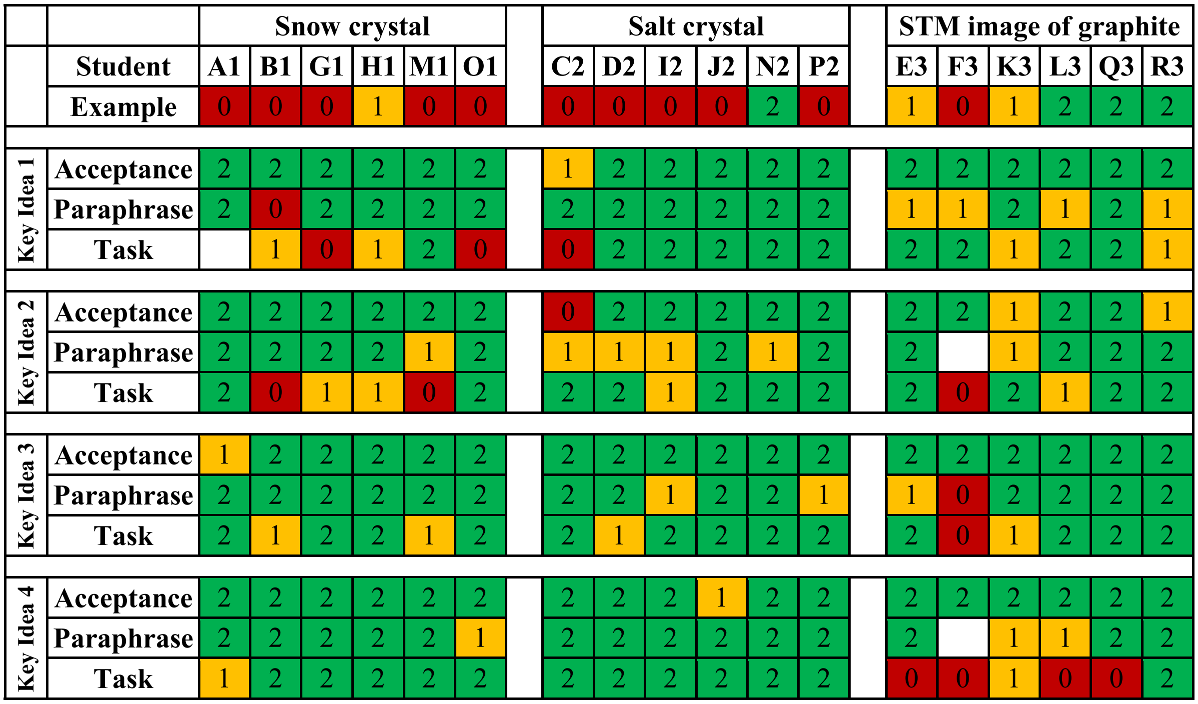
The interviews were analyzed using evaluative qualitative content analysis [74]. Concerning students' acceptance of the explanation, three deductive categories were used: "fully accepted," "accepted with restriction," and "not accepted." The paraphrases were rated as "correctly reproduced," "partially 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.

The first author rated all of the interviews using the described guidelines. Interrater 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

TABLE III. Students' answers in the interviews were rated using the scales shown below (adapted from [1]). 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.

	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.



		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 1	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 2	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 3	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 4	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 (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.

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.

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 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 a 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

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[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 [70]. 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.

> 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 a 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, nonvisible 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 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

TABLE IV. 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, nonvisible 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.

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 the gaseous state to scale [93].

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:

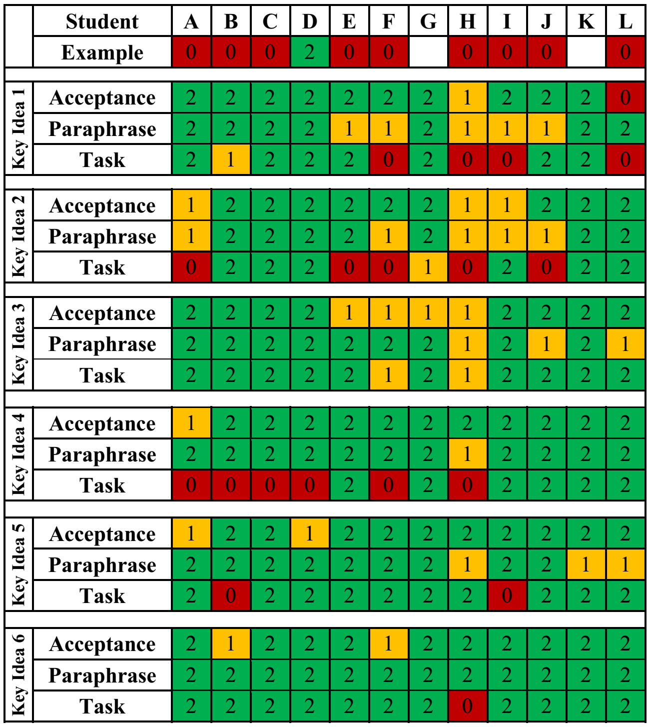
> I think when it, the water, freezes and falls down and turns then just so, then there are six because then it is not one ball, that just comes down so as snow, but it then flattens out more and more so and then it becomes a hexagon. (J:2)

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



	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 1	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 2	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 3	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 4	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 5	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 6	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 (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.

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).

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:

> 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

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

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, nonvisible 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.

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 min. 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.

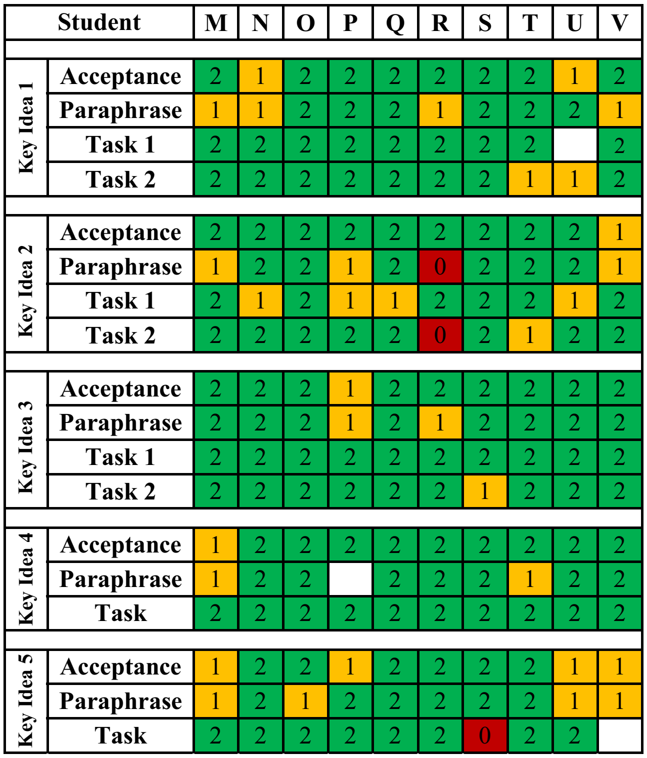
Finally, the tasks that were either too difficult or where students did not use the PNM were changed. For example, the task about the color of colloidal gold was omitted because half of the students had not answered it correctly. For key ideas 1, 2, and 3, a second task was added, to gain further insight 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.

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



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 2	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 3	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 4	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 5	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 (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.

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).

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?
Student 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. 6(b)]. 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. 6(a)]. 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 3 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.

V. DISCUSSION

Previous research on students' understanding of the PNM showed that students tend to view matter as

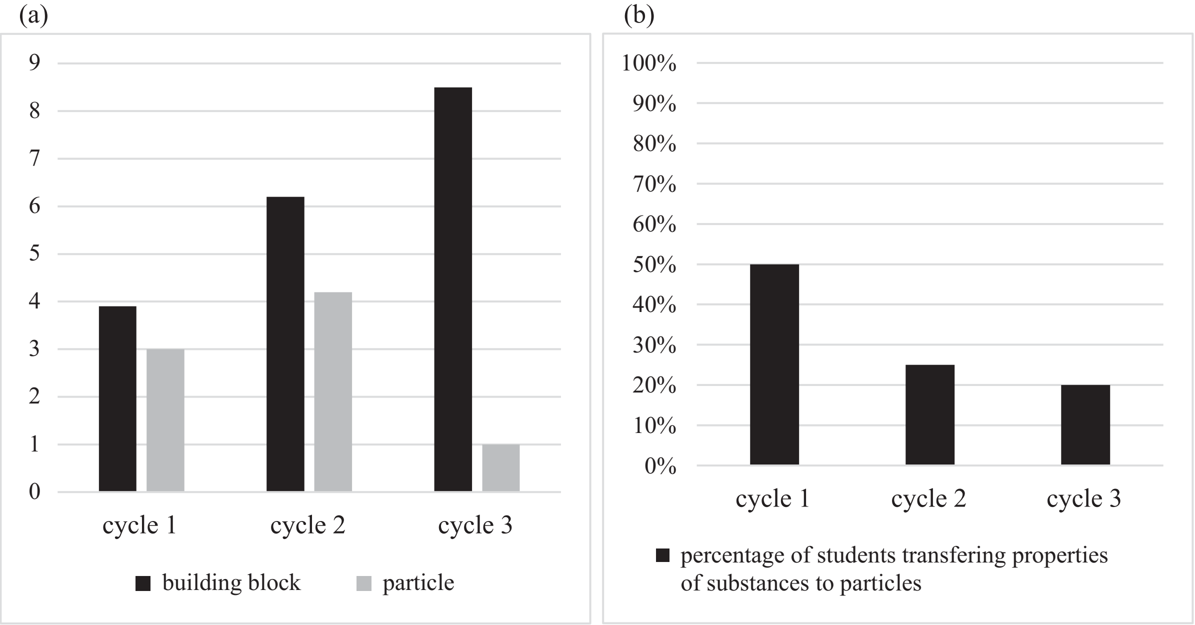


FIG. 6. (a) Use of the terms building block and particle per student during the three cycles of interviews. (b) Percentage of students applying the same properties to particles than to substances during the three cycles of interviews.

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. Because of 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 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. Because of 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 in 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 provided 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. Because of the interviews taking place during lessons of 50 min, 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 crystal 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 of 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 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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