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

Florian Budimaier,
Martin Hopf

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*

Florian Budimaier
University of Vienna and University College of Teacher Education Vienna, Austria
Martin Hopf
University of Vienna, Austria

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

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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 (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 behaviour 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

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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.

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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

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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.

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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 cannot 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

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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 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:

Interviewer: Okay well, how would you explain that again in your own words, what's happening. Could you repeat that again? […]

Respondent: 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 cannot 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)

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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

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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:

I: Could you repeat what I have just explained to you about this experiment and also try to explain it in your own words.
R: 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 cannot 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)?

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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.

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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

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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.

Declaration of Interest

Authors declare no competing interest.

Note

This paper discusses only relevant parts of the collected data. Full transcripts are available upon request to the first author.

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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)

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Experiment	Description	Reference
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 CO2 will inflate within an hour until it bursts because CO2 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

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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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Florian Budimaier *(Corresponding author)*
MS, University of Vienna and University College of Teacher Education Vienna, Austria.
E-Mail: florian.budimaier@univie.ac.at
Website: https://aeccp.univie.ac.at/
ORCID: https://orcid.org/0000-0003-2625-2639

Martin Hopf
PhD, Professor of Physics Education Research, University of Vienna, Universitätsring 1, 1010 Wien, Austria.
E-Mail: martin.hopf@univie.ac.at
Website: https://aeccp.univie.ac.at/
ORCID: https://orcid.org/0000-0003-3273-0000