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RESEARCH ARTICLE

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Rolling balls or trapping ions? How students relate models to real-world phenomena in the physics laboratory

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Abstract

The creation and use of models in science is of great importance for knowledge production and communication. For example, toy models are often used as idealized explanatory models in physics education. Models can be a powerful tool for exploring phenomena in ways that facilitate learning. However, careful consideration of instruction and explanations needs to be considered to guide how students relate models to real-world phenomena in subject-correct ways. A design experiment was conducted to investigate how upper secondary school students can use models for learning in the physics laboratory. The intervention used in the study was a laboratory exercise developed over three phases where students worked with a mechanical Paul trap and a simulation to understand the principle behind a real Paul trap. Each phase of the study consisted of three to five laboratory sessions. The data were analyzed using thematic analysis and the learning process was understood using the theoretical framework of variation theory. From the results, it was possible to identify patterns of variation for successful lab groups and critical aspects and features students need to discern to effectively modelize the mechanical Paul trap. The findings also indicate that having students work with models can be a meaningful clarificatory process to develop a deeper understanding of the use and limitations of models in science.

KEYWORDS
design-based research, Paul trap, physics laboratory, toy models, upper secondary physics education, variation theory

1 | INTRODUCTION

In science, models are everywhere. Consequently, there is a need to categorize and make sense of the role of different models (Bokulich, 2011; Godfrey-Smith, 2006, 2009; Hesse, 2017; Rosenblueth & Wiener, 1945; Toon, 2012). Some usually present in physics education are analog models, such as the billiard ball model of a gas (e.g., PhET, 2022) and electron orbits in an atom (e.g., Beiser, 2003); ideal models, such as perfectly isolated systems like the sun–moon–earth interactions (e.g., Chabay & Sherwood, 2015); and toy models, often seen as mechanical models such as the inflating balloon being analogous to the expanding universe and the lack of a "center" (e.g., Pålsgård et al., 2012), or the mechanical model for the Paul trap (Paul, 1990).

Using the theoretical framework of variation theory and a design-based approach, how students can use toy models to understand a real-world phenomenon is investigated by developing and iteratively revising a laboratory exercise. To this end, the current study focuses on exploring how a mechanical analog to the Paul trap, the mechanical Paul trap, as both a physical and computer-simulated model, can help upper secondary physics students learn the concept of trapping ions using varying electric fields, as in a real Paul trap. To relate the particular study to the discussion regarding the use of models in science education, the research question in focus is how interacting with a physical and simulated model of a mechanical Paul trap affects students' ability to understand how a real Paul trap qualitatively works.

This paper refers to the technique for trapping ions using a varying quadrupole electric field, developed by Nobel laureate Wolfgang Paul (1990) and collaborators, as either "Paul trap" or "real Paul trap." Furthermore, the two toy models for the Paul trap, a physical (mechanical) model and a computer simulation of the mechanical model, will be referred to as either "mechanical Paul trap" or "mechanical trap" and "simulation," respectively, with further clarifications as needed.

By reporting on the results from the design experiment study, contributions are made in three ways to both the physics education research community as well as the broader field of science education by identifying strategies and presenting an approach inspired by variation theory for how teachers can evaluate and improve laboratory exercises to fit their student groups better:

1. By constructing and evaluating a laboratory exercise in upper secondary physics classrooms, from the learners' point of view, using the toy models of the Paul trap and identifying critical aspects, suggestions are provided on how to use the artefacts to help students approach how a real Paul trap works.
2. Our use of variation theory contributes to the analytical toolset for structuring educational science laboratories to effectively reach the intended object of learning.
3. Our analysis provides further insight into the discussions on using models in science education.

1.1 | Models in science education

When investigating the scope of which young learners (middle schoolers) can judge the quality of scientific models, Pluta et al. (2011) found evidence of overlap between scientists' epistemic criteria, as proposed by Kuhn, and the investigated classes' ideas. The overlapping ideas were accuracy, explanatory scope, and the principle of parsimony (i.e., model complexity should be appropriate, see, e.g., Sober, 1981). The findings suggest using models and student-led inquiry in laboratory exercises as a possible effective teaching strategy. Earlier work by, among others, Harrison and Treagust (1998) suggests a similarly positive outlook on using students' notion of models and their development in the classroom to improve learning outcomes, even though their stance is that secondary school students' ideas on the quality of models are less developed than Pluta et al. (2011) suggests. Moreover, in a study by Schwarz et al. (2009), also set in middle school, issues regarding creating fruitful learning progressions for scientific practice using models are discussed. A vital issue identified but left unanswered was trying to motivate students to develop models to learn, as scientists do, rather than "doing school." Therefore, not fully grasping the meaning or usefulness of models in how they are used to develop knowledge influences students' abilities to evaluate a model (Schwarz et al., 2009). Thus, finding ways to make model development meaningful could be important for improving learning outcomes in science.

Further, in reviewing studies on using models in the science classroom, Coll et al. (2005) suggest that discussion-focused activities can enhance model-based learning from a sociocultural theoretical standpoint (Vygotskij, 1986). Lastly, Oh and Oh (2011) identifies the use of didactic transposition (Chevallard, 2006) as a way to identify how and why models can be used to bridge the gap between what should be taught and what students are ready to face. For example, when relating to teaching in secondary school, what is to be taught is informed by, but ultimately a subset of, some scholarly knowledge. Moving to a particular lesson, what is to be taught and what is learnt are further reduced to some essential sub-concepts. The back-and-forth process from scholarly knowledge to what is learnt can be related to the style of science referred to as model-based science (Giere, 1988; Godfrey-Smith, 2006) in the sense that when using a model in the physics classroom, it is a reduction, but supposed to resemble, some real-world phenomenon and as such existing in both scholarly knowledge and what is to be taught (see Figure 1). The model system is informed by the real-world phenomenon and specified by the model description, which is how a model is understood and described in the classroom, living both in what is taught and what is learnt.

1.2 | Variation theory

Originating from the phenomenographic approach, which started its development in the 1970s (e.g., Marton & Säljö, 1976) but first appeared by name in the literature with Marton (1981), variation theory began to see the light of day in the early 2000s following Marton and Booth (1997). Variation theory can be viewed as a learning theory and described in the words of Runesson (2006) as "Variation theory is a theory accounting for differences in learning, and it provides a way to describe the conditions necessary for learning" (p. 397). According to variation theory, one of the most fundamental questions to ask is what students need to be able to discern for the intended

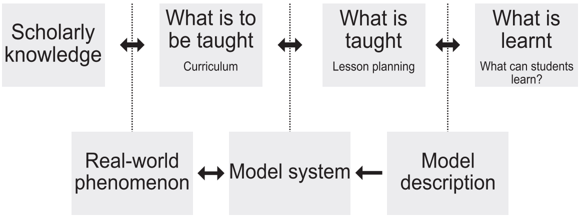

FIGURE 1 Visualizing the relation between the use of models in science (education) and transformations of an object of knowledge in different parts of the educational system. Adapted the process of didactic transposition from Chevallard and Bosch (2014) (top process) and how a scientist specifies a model system from Giere (1988) (bottom process).

learning to be possible (Marton, 2015). As such, variation theory recognizes that the most effective way to teach should be linked to the specific learning objective (the object of learning, see below), and it is in studying how learners develop in connection to the learning objective that proposals for how to teach the specific topic effectively can be made (Holmqvist et al., 2007).

Following is an expansion of two core concepts in variation theory, the object of learning and critical aspects, and a prototype to promote learning that serves as a basis for our analysis.

1.2.1 | Object of learning

To understand how students learn, it is essential first to understand what learning is made possible. Considering teaching as a rational activity, Lo et al. (2004) state that teachers must have their particular students' characteristics and physical conditions in mind when planning a lesson. Further, these conditions need to be translated into particular actions that help the current class in the current lesson to achieve specific goals. This relates to the object of learning, which can be thought of as a particular way of experiencing something which develops a particular capability. Marton (2015) suggests three ways the object of learning appears: intended (the aim), enacted (what is taught) and lived (what is learnt) object of learning. These distinctions are necessary since what learning is made possible is not necessarily synonymous with what the teacher or instructional designer thinks is possible to learn. Furthermore, the object of learning can seem synonymous with what is known in curriculums as a learning objective due to their lexical similarities. However, as Lo (2012) emphasizes, expected learning outcomes (learning objectives) easily lead to examination-oriented learning, whereas the object of learning focuses on the starting point and what students need to learn to achieve the desired learning objectives.

The current study focuses on the enacted (what the teacher and students are doing during the lesson) and lived object of learning (what the students learnt, as evident mainly from interviews and, to some extent, pre and posttests) to inform how to change the lab design (constructed from the intended object of learning). It is done by defining the object of learning in terms of its critical aspects, and much like Ingerman et al. (2009) focus on how the attended variations constitute student learning. By having this focus, we take on what is known in phenomenography as a second-order perspective (Marton & Booth, 1997), meaning that, as indicated previously, the students' experiences of the phenomenon are the focus, rather than the phenomenon itself. This has been shown to be a powerful way to identify qualitative different ways of experiencing a phenomenon (e.g., Booth & Ingerman, 2002; Ingerman et al., 2009; Marton & Booth, 1997; Patron et al., 2021).

1.2.2 | Critical aspects

Building on the definition of the object of learning used in this study, critical aspects are understood as what aspects are necessary to discern of a phenomenon to become aware of said phenomenon. More specifically, it is the aspects that the learner has to notice but is currently unable to (Marton, 2015). Further, a critical aspect can be seen as synonymous with a dimension of variation in the phenomenon (Pang & Ki, 2016), in the sense that critical aspects refer to a dimension of variation that needs to be experienced by the learner in order for them to be able to discern a particular phenomenon in a particular way (Kullberg et al., 2017; Lo, 2012).

When an aspect is varied, a dimension of variation is opened up by presenting a set of values, or features, in the aspect. If the aspect being varied is a critical aspect, then the dimension of variation is a critical aspect. Further, if certain features are required in order for the learner to discern a critical aspect, we call it a critical feature. According to Lo (2012, p. 30), when a child is learning to identify the color "red", it's important to focus on its critical aspects and features. For instance, if the critical aspect is color, one can show the child a red and a green ball to open up the dimension of variation. However, as the goal is to teach the child to recognize "red" specifically, it's important to discern the critical feature of "redness" by displaying different objects that are all red, thus separating red from ball. This example highlights the inseparable nature of critical aspects and features. Meaning that it is impossible to discern a critical feature without identifying what critical aspects the feature belongs to.

According to variation theory, the proper way to understand critical aspects can be problematic when put into practice, as revealed by Pang and Ki (2016). They highlight that teachers can interpret critical aspects as either the essential aspects defined by the tradition of the field or the curriculum or related to what students usually struggle with or tend to forget. By linking back to the relationship with phenomenography and the qualitatively different way of experiencing something, Marton and Booth (1997) note that this can be understood as a difference in what aspects are discerned and focused on simultaneously. Thus, pointing toward the relational nature of critical aspects, they visualize the critical differences between qualitatively different ways of experiencing something as a learner (Pang & Ki, 2016).

A synonymous view between critical aspects and dimensions of variation makes the core of the variation theory visible: variation. Holmqvist et al. (2007) make this clear by pointing out that "in the learning situation there must be a structure of relevance and variation to make it possible to discern critical aspects" (p. 186). Here, they are implying that it is not enough to open up dimensions of variation related to the critical aspects; it must be done purposely.

1.2.3 | A prototype for designing learning activities

Marton (2015) specifies that if the process of learning is seen as learning to see, one can understand the learning process through the following three-step process (patterns of variation), prefaced by some instantiation where the object of learning is presented:

1. Contrast. It focuses on studying different aspects of the studied concept separately by letting the studied (critical) aspect vary with certain values. The aim is to discern a critical aspect for understanding the object of learning.
2. Generalization. By letting the previously discerned aspect be invariant and varying other aspects, the goal here is to discard varied aspects as not relating to the object of learning.
3. Fusion. When going back and forth between Contrast and Generalization, multiple critical aspects can be identified. However, to fully understand the object of learning, students must experience variations in multiple critical aspects simultaneously, and fusion can occur when this is done.

As an example of this process in the physics laboratory, consider a student learning about Ohm's law $U = RI$ during a laboratory session using a simple electric DC circuit. Focusing on how a resistor affects the current flowing in the circuit, a possible beginning (Contrast) could be to let the student test multiple (including having no) resistors with different resistance to open up the dimension of variation of resistance. Next up, in the Generalization phase, as resistors can look quite different, the student might ascribe some physical properties of the resistor as a relevant aspect to how a resistor affects the current. Thus, letting the student try resistors that keep the resistance invariant but have different physical properties, such as size and seeing that those aspects do not affect the current in the circuit allows for a generalization to be made through experiencing sameness in resistance. Later, Fusion can occur when the student has made a similar exploratory journey regarding the dimension of variation of voltage and both critical aspects are simultaneously opened up as dimensions of variations to more deeply understand the object of learning, here being about understanding what affects the current in a simple DC circuit.

Another example linked to physics education can be found in Ling et al. (2006), which investigates patterns of variation used by a group of teachers participating in a learning study when teaching primary school students about the color of light. The intended object of learning in the study was defined as understanding the relationship between sunlight and the component colors. After conducting a pre-test, the researchers and participating teachers identified two critical aspects: The prism will not create a rainbow, it merely splits up sunlight; and there exists a part-whole relationship between sunlight and the colors of a rainbow. To improve learning outcomes, teachers participating in the study used the concept of patterns of variation to help students better discern the critical aspects. However, the results indicate that only the first critical aspect identified in this study was successfully discerned by the majority of the students. The analysis by Ling et al. (2006) indicates that this could be related to the fact that the second critical aspect was not properly contrasted. In fact, it seemed that the second critical aspect was taught using a pattern of variation on the Generalization level, skipping the seemingly essential contrast step.

2 | METHOD

2.1 | Design-based research

Design-based research is used within the physics education research community (Hake, 2008). Further, it is also one of the building blocks for the popular method used within variation theory called learning study (Holmqvist et al., 2007). The usefulness of design-based research within the field of education, where interventions are made in naturalistic classroom settings, can be considered in terms of its goals.

Conducting design experiments is about contributing to theory and informing practice (Bannan-Ritland & Baek, 2014; Brown, 1992; Joseph, 2004). Brown (1992) argues that conducting intervention studies in naturalistic classroom settings in cycles, systematically changing certain parameters, and exploring the actual outcome versus the expected can generate theoretical advancements that are not possible in a laboratory setting. However, the aforementioned positive sides of design-based research also have to be viewed as problematic regarding generalizability and meaningfulness (Kelly, 2004). With a focus on generating powerful hypotheses and contributing to the extension of conceptual frameworks within variation theory to the physics laboratory setting, this study provides a focus that helps mitigate these problems. Moreover, it should be noted that the researchers role in the development is crucial and that connections to existing theory must be ever-present (Barab & Squire, 2004). Lastly, the main type of questions that can be asked using a design-based approach revolves around what is happening and why it is happening (Shavelson et al., 2003). What is happening originates from the descriptions from observations and relates to the enacted object of learning, whereas why it is happening is understood from using the theoretical framework of variation theory to understand what students learnt from interviews and pre and posttests.

The current study uses variation theory as a theoretical framework but sticks to a design-based research approach instead of the more commonly used learning study approach. One main difference between these approaches is the clear focus on practising teacher involvement in all stages of the learning study cycle (Lo, 2012; Marton, 2015). The high involvement of participating teachers in a learning study presents some problems if wanting to conduct a learning study cycle in a limited course given in Swedish upper secondary schools such as Physics 2. First, for example, it introduces a lot more work for participating teachers having to be able to collaborate and co-plan between several different schools. Thus possibly decreasing the number of willing participants. Second, it may change the focus of the study away from the intended one, here being the use of toy models in a laboratory setting, to something the participating teachers feel more at home with to teach the intended object of learning. Furthermore, the distance between research and practice, a clear advantage of using learning study, is kept small in the present study because the researchers involved in the project all have a teacher or teacher-educator background. The study was conducted in three phases (see Figure 2). The first phase was considered a pre-study in which the laboratory equipment was thoroughly tested, and instruments for data collection were reviewed. Figure 2 also shows a condensed version of the different investigations students were tasked with conducting during the lab. The various parts will be described and explained further throughout the text.

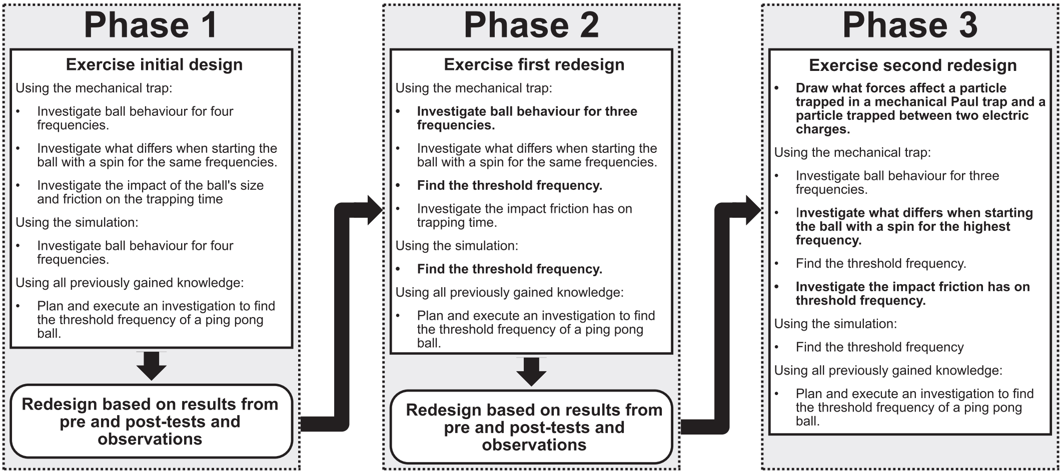

FIGURE 2 The design experiment cycle with an overview of the practical exercises included. After Phases 1 and 2, an initial analysis was based on the pre and post-tests and the observations. After Phase 3, all available data from all phases were analyzed to provide the study's final results.

2.2 | Participants

The setting for the current study is the course Physics 2, generally taken during the last year in Swedish upper secondary school (Swedish National Agency for Education, 2011). Six upper secondary schools in Sweden participated in the study: four public schools and two private ones. In the Swedish upper-secondary school system, private and public schools operate under the same regulations in terms of not being allowed to charge tuition fees, how students apply to them, and following the same curriculum. Within those, 8 teachers had 12 laboratory sessions, 3 during Phase 1, 5 in Phase 2, and 4 in Phase 3. Participating schools were chosen such that there would be a variation of big city schools versus suburban and smaller city and a spread in terms of socioeconomic status. The number of students in each laboratory session varied from 6 to 25, but most sessions spanned from 8 to 15 students. One hundred and nineteen students participated in the laboratory sessions. In total, there were 124 students enrolled in the classes who participated in the study. Two students from each session were interviewed in all but 2 sessions, 10 and 11, in which only 1 participated, meaning a total of 22 students were interviewed.

In designing the study, ethical considerations were made under the guidelines established by the Swedish Research Council (2017). Participating teachers and students received information regarding the purpose of the study, how data would be handled and used, and that participating was voluntary before giving their consent to participate in the study.

2.3 | Lab design

For the lab to have the potential to be utilized in the upper secondary physics classroom, several important factors had to be considered: First, it had to be of relevance to the current curriculum in the course. Second, the equipment has to be cheap, accessible and reliable. Third, the preparatory work before and after the laboratory session should be minimal for the teacher.

On the first point of consideration, the concept the students were supposed to learn about is how charged particles can be confined using charged rods (i.e., how a Paul trap works). In the Swedish upper secondary course Physics 2, students study movement in gravitational, electric and magnetic fields in two dimensions (Swedish National Agency for

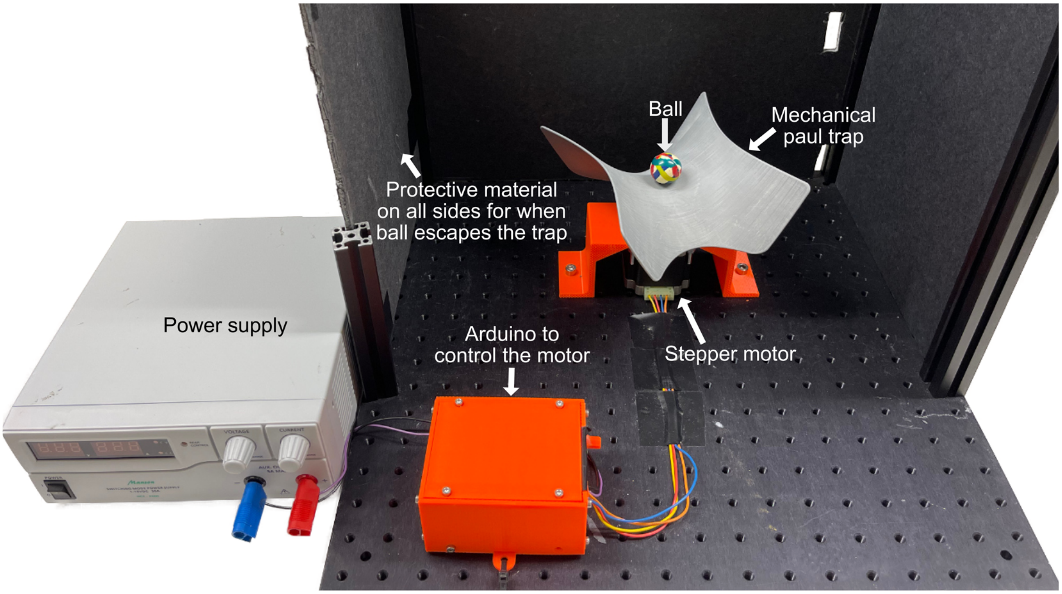

FIGURE 3 The experimental setup that students interacted with. To read the rotational frequency, they had a computer connected to the Arduino.

Education, 2011). Learning about Paul traps is relevant for understanding complex movement in electric fields. Further, the mechanical Paul trap also illustrates complex movement in a field, gravitational, thus allowing students to encounter similar complex movements in a gravitational field as they would have been able to identify in a real Paul trap.

Concerning the second and third points, five setups of the mechanical Paul trap were built using 3D-printed parts and an Arduino connected to a stepper motor to allow students to control the rotational frequency of the trap (Figure 3). The design of the mechanical Paul trap and the simulation is similar to the one proposed by Kilde Löfgren et al. (in press). The mechanical Paul trap allows one to experience how different objects behave when put on the surface of the 3D-printed saddle surface, either stationary or rotating at some frequency. For this lab, students had access to balls of varying sizes, densities, mass distribution and material and could change the rotational frequency of the trap between 0 and 4 Hz using steps of 0.1 Hz. Furthermore, the simulation allowed students to study a simplified version of the mechanical Paul trap in which there was no friction, the "ball" was considered a point particle, and the initial conditions were kept constant.

Before each laboratory session, the teacher in charge of the lesson was provided with a teacher guide consisting of: theoretical explanations regarding how a Paul trap works, what the similarities and differences are between it and the mechanical Paul trap, suggestions on their introduction of the lab and time management, some notes regarding the laboratory equipment, and suggested answers to the students' worksheet. In addition, the teachers had the opportunity to consult with one researcher and try the equipment before the session. The researchers provided all of the equipment needed for the laboratory session. Lastly, the student worksheet consisted of exercises that went from more closed to more open investigations as the session progressed, ending with an open-ended discussion question regarding the validity of the mechanical Paul trap as a model for a real Paul trap.

2.4 | Data collection and analysis

A pretest was made ~1 week before each lesson to establish that the concept of Paul traps and the mechanical model was indeed novel to the participating students. It was similar to the posttest conducted after the laboratory session to analyze how students' understanding of the mechanical Paul trap developed. The pre and posttests, analyzed using SPSS, and the field notes were the primary informers of how the student worksheets changed between the three phases. However, the same material had a more passive role during the final analysis as the interview transcripts provided the richest insight into the students' lived object of learning. Why the different types of data had varying importance over the study can be motivated by the fact that, as no studies have previously been made concerning upper secondary student perception when learning about Paul traps, it was warranted to gather data in such a way that multiple possible threads could be followed during the final analysis. Lastly, it should be noted that the response rate differed between the pre and posttests due to factors such as students not being present on one occasion or not choosing to answer the posttest (see Table 1).

To collect the qualitative data, the field notes and interview transcripts, one of the researchers took part in every lesson as an observer and interviewer. During each lesson, field notes were taken by focusing on two beforehand randomly selected lab groups, as well as taking notes on how the teacher interacted with the groups and started and ended the lesson. By having randomly selected groups to focus on, the potential for having a biased or unintentionally skewed set of observation data was avoided. Further, we argue that focusing only on two lab groups allowed the observations to examine how the groups worked in greater detail. Specifically, if and how their discussions around the tasks and interactions with the material changed during the lesson. The process of taking field notes was partially done during the lesson, where keywords and phrases regarding what happened were written down. In addition, shortly after each lesson, a more substantial written account of what happened was made, as well as some initial coding and highlighting of potential points of extra interest. Doing an initial analysis regarding qualitative data shortly after collection is an important step to keep the essence of the data (Bogdan & Knopp Biklen, 2007; Phillippi & Lauderdale, 2018). The choice of using field notes instead of video recording each lesson was made mainly for time-management reasons regarding available resources. This was important for the current study since there is a delicate process of how to divide the available time between each type of data collected and the analysis. In terms of validity, taking field notes could have the effect of being colored by the observing researcher's beliefs on what would be important to recognize (i.e., the intended object of learning). The aforementioned process of focusing on a limited number of randomly chosen groups during each session was used to combat this issue. Another point of consideration was regarding keeping the sessions close to normal classroom conditions. Then, filming the lesson can make the sessions feel less naturalistic for the students.

One student was randomly selected to be interviewed after the lesson within each observed group. The interviews followed a semi-structured approach and were audio-recorded so that the interviewer could focus on the conversation taking place. Similar to the field notes, an initial analysis was done soon after the interviews were conducted as the data was transcribed. Transcripts presented in the Section 3 of this study have been translated from Swedish to English. To keep the transcripts authentic, the translations were done as directly as possible to keep the grammatical structure students use and still make the sentences make sense in English. Transcripts are provided from different phases of the study and what student was in what phase can be seen in Table 2.

The final analysis of the data was done using thematic analysis (TA), following Braun and Clarke (2006, 2019). With a focus on the qualitative parts of the data (interview transcripts and field notes), emerging patterns and themes were also informed by previous initial data analysis that informed the design changes between the phases.

TABLE 1 Distribution of answers over the pre and posttests over the three phases.

Test	Phase 1 (n = *37*)	Phase 2 (n = *45*)	Phase 3 (n = *42*)
Pre	34 (92%)	45 (100%)	35 (83%)
Post	32 (86%)	33 (73%)	38 (90%)

Note: The given percentages are in relation to the total number of students enrolled in the classes participating in each phase.

TABLE 2 Distribution of the presented student transcripts over the three phases.

Phase 1	Phase 2	Phase 3
S4, S6, S7, S8	S2, S5	S1, S3, S9

Note: In total, nine interviewed students' transcripts are included as examples, labelled S1 through S9 in order of appearance.

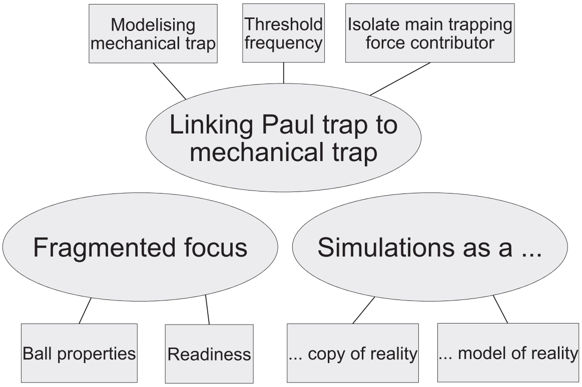

FIGURE 4 Identified themes from the thematic analysis.

By reanalysing all available data and then relating it to previous initial coding, it is possible to mitigate the fact that the initial analysis and coding of data may lead to prematurely partially closing or narrowing down the analysis (Vaismoradi et al., 2016). With a grounding in variation theory, the TA was theory-driven and themes were identified on a latent level, meaning that the analysis is already theorized (Braun & Clarke, 2006). A theory-driven approach allows the later stages of the analysis, in which the themes are abstracted, to become less dependent on the researchers' subjective judgment (Vaismoradi et al., 2016). Finally, by combining the initial analysis (resulting in the redesign between each phase) with the themes found using TA, it was possible to discern patterns of variation for groups that succeeded with the lab during Phase 3.

As with a phenomenographic approach (Marton, 1986), results from this study should be taken as something discovered in a specific context. The identified themes are colored by the researchers different experiences regarding the phenomenon, teaching and research. This introduces problems with the replicability of this study. However, the identified themes initially proposed by the main author were discussed in relation to the available data and accepted only after the whole research group agreed with the analytical process. After agreement within the group, identified themes with the presented data were also discussed with other colleagues. Thus, there is analytical replicability due to the high intersubjective agreement regarding the identified themes and increased credibility (Nowell et al., 2017).

3 | FINDINGS

The analysis identified what students needed to focus on to understand how a real Paul trap works using the mechanical Paul trap and the simulation and how the model can be problematic (see Figure 4). Further, the analysis also shows that students' views of what a simulation differs and that it is something teachers should be aware of. Finally, considering both the identified themes and how the laboratory exercise changed, patterns of variation for groups who succeeded with the laboratory exercise were identified.

3.1 | Linking Paul trap to the mechanical trap

In this section, we report on findings related to necessary discernments for students to make to better see the link between a real Paul trap and the mechanical Paul trap.

3.1.1 | Students' inability to recount the intended aim

To gauge what the students' experiences of what they were supposed to do during the lab were, they were asked to describe the lab to a hypothetical fellow student who did not attend. In doing so, students who, during the interviews, saw connections between the models and a real Paul trap generally provided short and nonmetaphorical answers. However, they did not typically mention any purpose but mentioned frequency as something important to think about during the lab:

S1: We used a Paul trap… Or a model of a Paul trap, as I understood it. And then we placed a ball on it and tried to put it as close to the middle as possible and test different frequencies to see when it stays.

S2: I would say that we… I don't know how to explain it, but it looked a little bit like a saddle. It was a square where two edges were pulled up and two down, and the goal was to find the frequency when it rotates so different balls could stay and not roll down the edges. And see how long you can get it to stay, at what frequencies is it possible.

One student in Phase 3 pointed more explicitly toward the intended object of learning:

S3: I would say that we tried to, understand the principle of a Paul trap. A mechanical one and how that phenomenon, I don't know how I should explain… Well when it stays in the middle from the beginning, when it's trapped, the ball. It was kind of like how electrical charges affect, like a real one.

As the lab session was led by each class' ordinary teacher, there were differences in how each lesson was started and framed. Student **S3** belonged to a group where the teacher stood out from the rest by being particularly thoughtful during the introduction of the lab to highlight the intended aim. Although some of the other teachers talked about links between the Paul trap and the mechanical model during the lesson, they did so without directly mentioning that this is something related to the focus or aim of the lab.

3.1.2 | Threshold frequency: The importance of critical features

When describing what they thought was the most important to investigate, varying the frequency to identify the threshold frequency was identified. The threshold frequency is a particular frequency where the trapping time suddenly increases significantly (see, e.g., Löfgren et al., in press). One student more clearly verbalized their thought process leading up to this realization:

S3: I thought you noticed how, for example weight affected. Like that you could have different frequencies for the light and the heavier. Meaning it was how you could have different high or low frequencies for different weights that was interesting… No, then it is probably the frequency that was the most important.

Others also indicated the importance of the frequency and mentioned the importance of seeing particular features in the dimension of variation of the frequency.

S1: I mean, the frequency, partly. Because had it only been a low frequency all the balls would have went out and then you wouldn't get a good understanding for it. And then a little bit with the size and such but… There I didn't really understand as much, what did what.

This particular kind of reasoning became apparent only in Phase 3, during both interviews and group discussions during the lab. During Phase 1, no task relating to the threshold was made explicit until the last task. That meant that no real chance was given to the students to experience the critical feature within the dimension of frequency in isolation. In Phase 2, this problem was partially handled by introducing the feature threshold frequency earlier and in isolation. However, students could notice this feature when the threshold frequency was separated from friction in Phase 3. When doing so, the link became easier to make between the Paul trap and the mechanical Paul trap.

3.1.3 | Trying to modelize the mechanical trap

To see past the differences between the models and a real Paul trap, students needed to view the mechanical model as a toy model of a real Paul trap. As a final guidance towards modelizing the mechanical Paul trap, students also interacted with a simplified computer simulation of the mechanical Paul trap. During Phases 1 and 2, groups generally struggled greatly with this. When asked whether one model was better than the other or if they complemented each other, students typically provided the following type of answers:

S4: Then I would say the simulation. Because when you trap an electron there is no friction. And then it is only a very small weight and a small size. Because in the simulation you couldn't set what type of ball we had in this case that were used in the simulation. But that was possible in the mechanical. But to compare between our experiment and a real Paul trap I think only the simulation would have been enough, but then you miss friction and weight differences. They weren't possible to investigate in the simulation.

S5: I think you could have understood it with only the computer or only, hmm, the mechanical trap. But the combination made the similarities to a real clearer.

However, some students during Phase 3 were able to use the previously discerned critical feature of threshold frequency to help see similarities between the real Paul trap and the mechanical models:

S3: It felt like you understood more with both. That it became a combination that made you really, understand that it can be trapped at some frequencies and at some others not.

If they felt they had the time, groups often chose to conduct extra investigations, usually after studying variations in friction. The groups who did this and had managed to disregard friction as affecting the threshold frequency (three groups in Phase 3) focused on studying the threshold frequency for different ball diameters. After discussions with their teacher, those groups identified this as that they varied the effective potential of the mechanical trap (see Figure 5) and identified a relation of that to the threshold frequency. Here the effective potential is defined as the relative path the ball's center of mass is allowed to travel, thus effectively changing the shape of the potential field affecting the ball.

3.1.4 | Isolating main trapping force contributor - nontrivial previous discernments

During all the lab sessions in Phase 3, a task was added where the students were asked to identify the relevant forces acting to keep the "particle" trapped in a real Paul trap and a mechanical Paul trap. Although no student

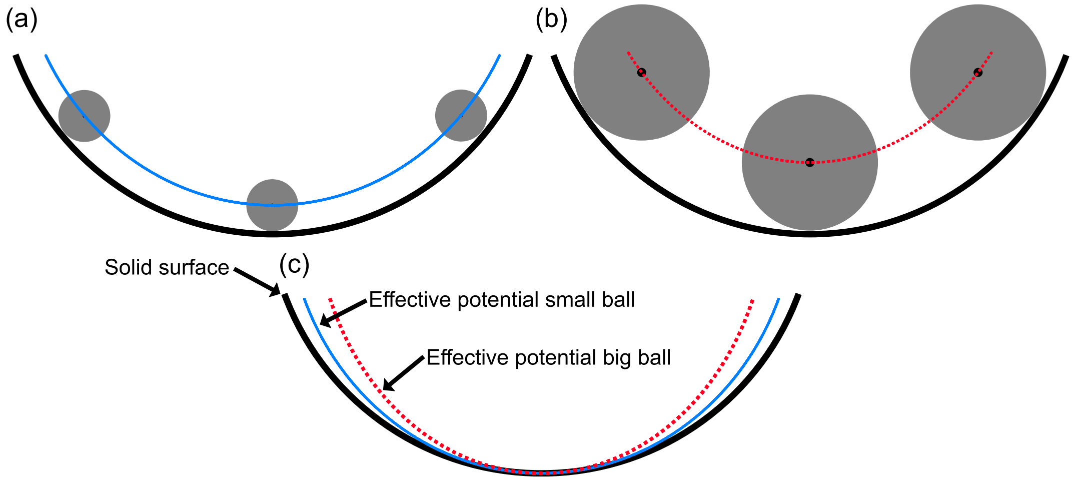

FIGURE 5 The effective potential (path of the center of mass) is exemplified for balls with different radii, (a, b), rolling on the same solid curved surface. In (c), the curves are layered with a common lowest point, illustrating that each ball's center of mass travels along different curved paths.

interviewed in Phase 3 made explicit mention of them, the ones who did manage to relate the models to a real Paul trap to understand the concept better were in groups and classes where both the group and the teacher during the introduction or at the end of the lesson discussed this. Further, during the laboratory work in all three phases of the study, lab groups who explicitly identified the likeness of the Coulomb force and Newtons force of gravity also managed to, to a greater extent, use the models as toy models to infer how a real Paul trap functions during group discussions.

In Figure 6, distribution of answers on the pre and posttest are compared for the questions regarding the main force contributors for the mechanical and the real Paul trap. When inspecting students understanding of how a mechanical Paul trap works in terms of what is to be regarded as the main trapping force contributor, there is a clear shift between the three phases. In the posttest in all three phases, students' answers all tend to be more towards the force of gravity, friction or normal force, that is, towards forces student relate to mechanical systems. However, only during Phase 3 did a significant change ($t[37] = 3.285$, $p < 0.05$) with a medium effect size ($d = 0.507$) according to Cohen's d (Cohen, 1988) occur, which points toward the correct answer (gravitational force). Turning the focus to understanding what force is used to trap ions in a real Paul trap, there is no as prominent move toward the correct answer (electric force). Therefore, compared with the observation data mentioned previously, this points toward that students in Phase 3 were guided by the intervention to discern the main force contributor for the models of the mechanical Paul trap only.

3.2 | Fragmented focus: Aspects critical to disregard

During four of the lessons, two in Phase 2 and two in Phase 3, the information provided by the teacher differed significantly from the rest. During these lessons, the teacher skipped some or almost all proposed background information about real Paul traps. The following interviews resulted in that no matter what was discerned by the students during the lab, they could not make the intended connections between the models and real Paul traps because it was a foreign concept for them to try to approach.

Some students ability to discern critical aspects was also hindered by other aspects, namely those relating to the physical properties of the different balls that could be used during the lab, usually relating to how the trapping

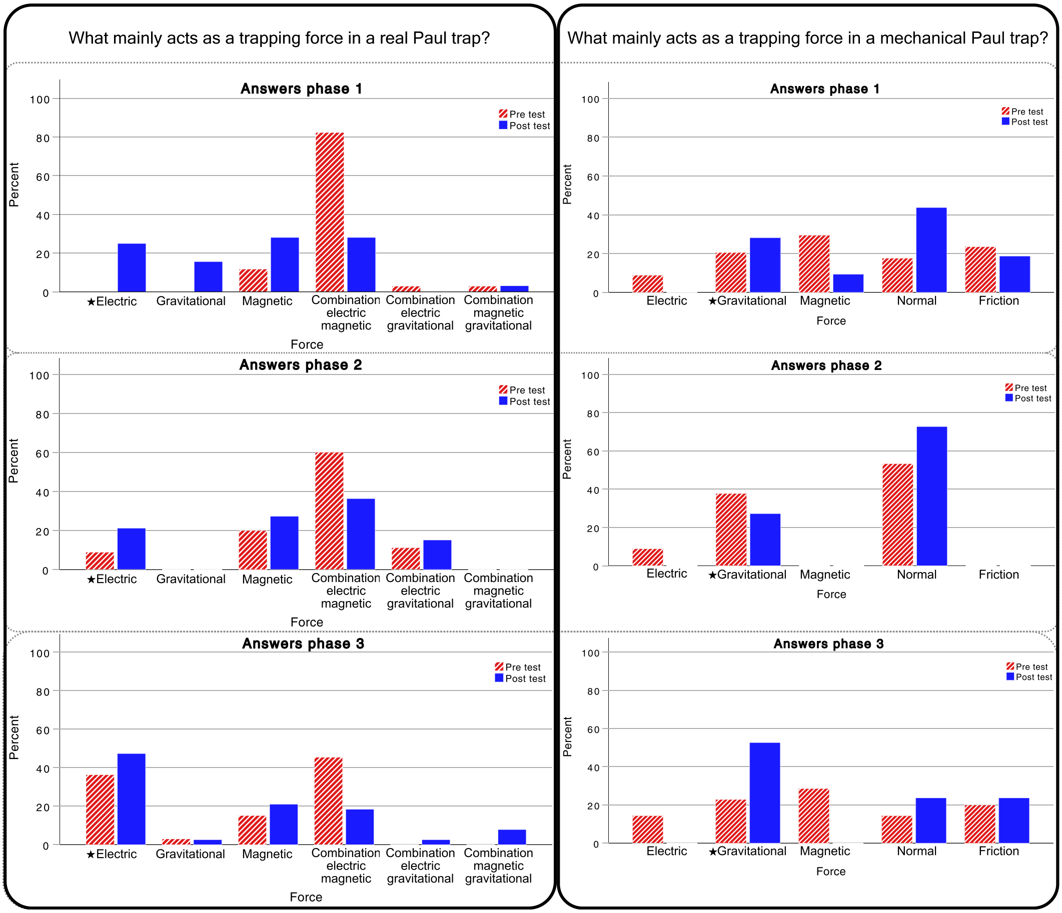

FIGURE 6 Student answers regarding what the main force contributor acting as a trapping force are in a real Paul trap and a mechanical Paul trap. The correct answer, marked with a star, was an electric force for the real Paul trap and a gravitational force for the mechanical Paul trap. As part of the evaluation regarding the intervention's effectiveness, a one-sample t test was conducted to evaluate if the relative increase of correct answers were significant, and if so, the effect according to Cohen's d. Regarding the real Paul trap, there is a small to medium significant change during Phase 1 ($t[31] = 3.215$, $p < 0.05$. $d = 0.44$) but no significant change during Phase 2 or 3 ($t[32] = 1.690$, $p > 0.05$ and $t[37] = 1.629$, $p > 0.05$). For the mechanical trap, there is no significant change during Phase 1 or 2 ($t[31] = 0.882$, $p > 0.05$ and $t[32] = -1.363$, $p > 0.05$), but a medium significant change during Phase 3 ($t[37] = 3.285$, $p < 0.05$. $d = 0.507$).

time in the mechanical trap was affected. When asked about what was the most important to investigate, these students provided answers along the following lines:

S6: I think it was… It could have been to test different balls. So that you not only see how it works, but also how different factors affect trapping time, which is what it's for. So I think that was probably the most important.

S7: It was that you tested different sizes or weights, so that you deepened, or understood the factors that mattered.

Continuing, when asked if there were anything they did not study that they would have if given another attempt or other material, more focus was drawn to irrelevant properties.

S6: …I don't think we studied balls with different mass properly. Or we did it but then it was size. And I guess that there were balls with same size but different masses, that was probably something we would have wanted to test actually.

S7: Hmm… The bouncy ball you maybe could have tried to bounce a little but, that we didn't do…. We only tested to spin it (the ball) in the same direction as the saddle rotated. We didn't try the other way.

Several groups also expressed these views during the laboratory sessions, mostly during Phases 1 and 2. As a result, the laboratory exercise was redesigned after Phase 1 and Phase 2, to allow students to be able to disregard these irrelevant aspects, namely ball properties. From the implemented changes and the fact that ball properties seemed to be disregarded by almost all groups during Phase 3, hints of a meaningful change can be seen in the design changes. Namely, it was important to introduce contrast in one particular property, friction, against a background of sameness in threshold frequency to disregard ball properties when modelising the mechanical Paul trap. When changing the friction in the mechanical trap, trapping time will decrease, but the threshold frequency will remain practically unchanged.

3.3 | Simulations as a copy or a model of reality?

A couple of questions were dedicated to how students would explain what a simulation is, both in general and in physics specifically. The students generally had trouble answering these questions, more so if they did not think they had previously seen or worked with simulations in school. Two different ways students viewed simulations as were identified, giving rise to different levels of credence or insight into how simulations can be made: copy of reality and model of reality. A noticeable distinction between these two views is that within the copy of reality camp, students struggled to a higher degree with seeing the mechanical Paul trap as a model of a real Paul trap.

The most commonly expressed view boiled down to simulations as a real-world copy in which it is possible to conduct experiments. Students ascribing to this view commonly referred to it in terms similar to the following examples:

S6: It is when you… replicate something you can do, in the real world. But digitally, and seeing what the results would be.

S8: It is a copy… Or humanity's attempt to copy how it would happen in reality, but having control over everything such as, air resistance, gravity, friction. . eh. . All types of forces is possible to, put in by yourself. But if you make a simulation so that it has to be as real as possible then its, just reality in a computer that makes it easier to calculate the dimensions of the actual investigation you should conduct.

Students who expressed that simulations are merely models of reality usually pointed toward the fact that simulations are visualizations of equations or some simplified version of reality, as exemplified by **S7** and **S9**:

S9: Maybe like a laboratory. Or backwards, like contrary to a laboratory that you go from having the answers…. As I understand it, a simulation is just a rewritten formula. Everything is in the little book we have (collection of formulas). But by having it, visualized, or animated you really see how the different factors contribute to the formula perhaps.

S7: First you have to start from reality and see what is happening, and you have to make some simplification of the system and see what. . eh. . variables that come about and such, and try to make as representative a model as possible in for example a computer program. And then you also have to… State its limitations because you can't. A model is just a model of reality, it's not the reality you represent.

TABLE 3 Highlighting the changes to the laboratory exercise that was made after Phase 1 and Phase 2.

Action	Motivation
Phase 1 → 2	
Removed 1 frequency to test in the trapped region	Save time
Added finding threshold frequency with mechanical trap and simulation	Introducing threshold frequency earlier during lab
Removed investigating impact of ball size	Remove focus on too complex aspect
Phase 2 → 3	
Added drawing what forces acts on particle trapped in bowl and between two charges	Draw focus towards previous knowledge
Changed investigation on spin to highest frequency	Save time
Changed friction investigation to its effect on threshold frequency	Help students generalize threshold frequency

Note: For more detail on included tasks in each phase, see Figure 2.

3.4 | An overview of the redesigns

During the first two phases of the intervention, the majority of the results can be seen as pointing towards that something critical seems to be missing for the intended learning to take place. In Table 3, the changes (bold parts in Figure 2) between Phases 1 and 2, and 2 and 3 are highlighted together with brief motivations. Each change was motivated by a combination of initial analysis of collected data, practical (lab time) limitations, and informed by variation theory.

For example, after Phase 1, it became clear that some values (features) in the dimension of variation of frequency were necessary (critical) for students to experience to discern the critical aspect properly. It was evidently not enough to include this in the last part of the exercise, where they were supposed to find the threshold frequency (but it was not stated explicitly) for another ball than what they used previously. However, it was not until the additional change after Phase 2, where frequency was generalized by separating friction from threshold frequency, that students, to a greater extent, could use the notion of threshold frequency to better identify similarities between the mechanical Paul trap and a real Paul trap. Another change, that was not thought of before seeing results from the pre and posttests, was regarding the students' struggle to identify the main force contributor acting as a trapping force in the mechanical and real Paul traps (see Figure 6). This was initially overlooked as similar discussions about relevant forces are handled extensively in a previous physics course. However, being situated in a new and unfamiliar specific context, it seemed that students needed some nudge in the direction of actually considering what are the relevant forces in the systems they are working with. This led to the introduction of the initial task implemented in Phase 3, where they had to bring previous knowledge into focus by explicitly drawing relevant forces acting on a particle in similar situations as in the mechanical and real Paul trap.

3.5 | Towards identifying patterns of variation

One of the core interests in this study, as with all action research related work, is to improve and inform practice. As such, and in line with having variation theory as a guiding principle, it is of interest to make sense of the varying experiences the students had reasoning about the lab and trying to find links between the mechanical Paul trap and a real Paul trap. We did this by identifying similarities in what students were successful in modelising the mechanical

Paul trap and juxtaposing that with the reasoning and workflow of struggling students. According to Marton (2015), it is necessary to find both students who are able to discern aspects of an object of learning and those who are not, to identify potential critical aspects. This idea, together with the fact that the mechanical Paul trap, is a model not commonly utilized within secondary physics education, meant that finding students struggling with the intervention is both expected and something that helps better pinpoint what aspects of the object of learning are in fact critical.

From the analysis, patterns of variation were identified that can be seen as building blocks towards helping students successfully modelize the mechanical model. The resulting patterns of variation can be found in Table 4 and following is an expanded explanation of them and their relation to previously presented findings. Starting from the top, including the task of drawing forces acting on particles seemed to be important, not to fully grasp what force is used as a trapping force, but rather to identify the two types of systems (models) being considered. Thus students will, in this step, be guided towards discerning the model-force relationship.

Meaning that what separates the models under consideration during the lab session is what the trapping force is (i.e., that the mechanical model and the simulation can be thought of as both being different representations of the mechanical model, as they are both using gravity as the main trapping force contributor). After coming to this realization, it seemed as though having a focus on trapping force was not needed during the rest of the lab, and that is why it is marked as not included in the following patterns of variation in Table 4.

Next is a contrast pattern followed by a generalization, both focusing on identifying the connection between frequency and trapping time. It was critical for students to identify this connection in part due to the chaotic nature of the mechanical Paul trap, where trapping time can fluctuate, although keeping the rotational frequency unchanged (see Löfgren et al., in press, for an example data collection run to identify the threshold frequency). Our suspicion, strengthened by data collected during Phase 3, is that it was by a combination of guiding students to discern the critical feature of threshold frequency together with identifying that friction has no observable effect on this feature that the connection between frequency and trapping time became more clear.

TABLE 4 Identified patterns of variation for successful groups during Phase 3.

Frequency	Trapping time	Ball initial	Friction	Model	Force	Effective potential	Pattern of variation and invariance
-	-	-	-	**V**	**V**	-	Bring previously discerned model and force relations into focus
V	**V**	i	i	i	-	i	Contrast frequency and see relation with trapping time
i	**I**	**V**	i	i	-	i	Generalization of frequency and trapping time relation by varying initial conditions of ball
v	**V**	-	i	i	-	i	Introducing the critical feature threshold frequency
V	**V**	-	**V**	i	-	i	Generalization of threshold frequency by varying friction
v	**V**	-	-	i	-	**V**	Contrast effective potential and see relation with threshold frequency by varying ball size
V	**V**	-	-	**V**	-	**V**	Modelizing mechanical model (Fusion)

Note: Not all successful groups performed the investigation corresponding to the second to last row, but the groups who did not skip it were all able to modelize the mechanical model. Frequency, trapping time, model and effective potential were all identified as being domains critical to experience variation within to successfully being able to discern them simultaneously in the last pattern of variation. The aspects in focus during each part are bold andcapitalized, a varied aspect is marked by v, and an invariant aspect is marked by i. Aspects not included are marked by -.

As a final note, we turn our attention to the point of being able to modelize the mechanical model and thus having it available to use as a tool to understand how a real Paul trap works. It is indicated that this seemed to happen to a high degree if: patterns of variation presented in Table 4 are offered so that the aspects critical to a particular student can be discerned both separately and together; and that the teacher is being mindful to both introduce the lab exercise in a way that the aim, or intended object of learning, is being presented in such a way that it becomes visible for the students, and shows flexibility during the lab. Then, if needed, a particular group of students may get guidance towards some discernment that seems to be critical for them not to miss out on, even though it may not be included among the particular tasks during the lab exercise.

4 | DISCUSSION

Toy models, despite their joyful tone, are far from trivial to use in teaching situations. Results from this study support this notion in that there were apparent struggles, especially when it came to Phases 1 and 2, where few managed to successfully create an internal idealized version of the mechanical Paul trap to qualitatively understand how a real Paul trap works. This process, which we call to be able to modelize the mechanical Paul trap, was identified as a crucial step to properly be able to link the real Paul trap and the mechanical Paul trap. This became apparent due to a combination of realizations regarding both the struggle and successes of students, viewed through the lens of variation theory.

The following discussion is divided into two parts. The first part starts from the results and the identified patterns of variation to discuss implications for teaching and learning in a laboratory environment. The second part aims to provide further to the theoretical discussion around models and modelling in science education, both by relating to the findings from this particular study and to previous research.

4.1 | Implications for teaching and learning in laboratory environments

From our results, we propose patterns of variation highlighting important steps and relations between the different tasks in the lab exercise during Phase 3 (see Figure 2) in Table 4, drawn from identifying differences between students who succeeded with the lab and those who did not. It should be noted that as with all models of learning processes, including the one presented in the introduction that follows Marton (2015) steps of instantiation, contrast, generalization, and fusion, the reality is more complex. However, it poses a good starting ground, and the general form can be extrapolated from the identified learning process.

Keeping the focus on the patterns of variation, there are several points to emphasize from the students' learning process. First, it was identified that during Phase 3, the groups who identified the relationship between the models and their particular trapping force via an initial fusion step also had an easier time later modelising the mechanical trap, meaning being able to use it as a means to understand the principle of a real Paul trap. However, this does not mean that the task helps students understand what is the main trapping force in the real and mechanical Paul trap, which is supported by Figure 6. Here hides an important highlight when it comes to critical aspects, object of learning and learning objects. Namely that, by identifying the need for students to attend to previously discerned aspects and use that for discerning something new (here being using the model-force relationship to see what representations that are presented during the lab should fall under the same model), it is not necessarily crucial to focus on whether it is being handled correctly in a general sense. It only needs to be understood in such a way that the current critical aspects can be discerned by the student. Thus we have a situation where the teacher would be encouraged to act differently depending on whether he or she has learning objectives (end of course goals) or a specific object of learning (specific aim) in mind. The former focus would promote an immediate intervention to try to combat the potential distribution of answers as seen in Figure 6. Whereas the latter would promote keeping the focus on providing a potential intervention in a way that, first and foremost, helps students towards seeing what different models are being utilized in the lab exercise and how the different representations can be linked to those models.

Second, much like Marton (2015) suggests, to understand the learning situation as a whole, it is relevant to experience both critical aspects to discern and aspects that are critical to disregard to generalize an aspect. When students were more clearly guided only to vary friction against a background of sameness of the feature threshold frequency was identified as an important generalization step, something only presented to students in the exercise during Phase 3. It seemed that it was critical to vary the friction by specifically varying the coefficient of static friction (i.e., the material of the ball) rather than varying the friction by changing the mass of the ball, as some tended to do. Changing other ball properties, such as size, also changes the effective potential of the trap, thus opening up more dimensions of variations than the students are ready to take on at that point during the lab.

Third, as the physics courses build on one another, students should continuously gain a deeper understanding of science and thus, among other things, develop knowledge about how models are used and developed in physics (Swedish National Agency for Education, 2011). Moving to the context of Physics 2, this will have the implication of students potentially having a large spread of depth regarding their development of this knowledge. This leads to students having a varying set of previously discerned dimensions of variations in physics modelling, which they might draw upon to make sense of the lab covered in this paper. That includes students' ability to judge the quality of modelling a real Paul trap with a mechanical trap. In our results, this appears in the way that students expressed varying meanings to the purpose of simulations and that some groups had little trouble using the notion of the effective gravitational potential that the ball and the mechanical trap surface jointly created for the ball's center of mass.

Moving away from patterns of variation, the evidence of student struggles presented in this study provides an opportunity to discussing model complexity and how to design laboratory exercises that appropriately meet and challenge students in ways appropriate to their current both practical and theoretical knowledge. In a recent review of research on laboratory work in schools, Gericke et al. (2022) point towards, amongst other things, the importance of the role of the teacher, the need for proper introduction of the phenomenon being studied (or appropriate guidance during the lab), and that the level of openness (level of inquiry) should be chosen deliberately on the intended learning goals.

Regarding the role of the teacher and introduction of the studied phenomenon, the current study (thanks to the naturalistic setting of the lab sessions) finds agreement with the points identified by Gericke et al. (2022). As Paul traps are, to the best of our knowledge, novel as something studied even qualitatively at the secondary physics education level, how the teacher introduced the phenomenon at the beginning of the lesson had a vital impact on students' ability to relate their findings and realizations during the lab and use that to understand how a real Paul trap works. This was particularly evident by the fact that many students were unable to recount what the intended aim, or actually important to had focused on during the lab was. We believe that this is related to the fact that few teachers chose to focus on thoroughly introduce the Paul trap at the beginning of the lab. A belief that is in agreement with findings from Gericke et al. (2022) and included in the general form of effective use of patterns of variation presented by Marton (2015).

Regarding the complexity of the model used in this study and the seemingly hard task of linking the mechanical Paul trap to how a real Paul trap works, it is relevant to draw upon the level of openness in laboratory work. Going from Phase 1 through to Phase 3 in this intervention, it is noticed how the level of openness seemed to decrease. At the same time, the number of lab groups that successfully managed to modelize the mechanical trap went up. The natural question to ask is whether there is any connection between these two trends? Drawing upon the previous discussion regarding identified patterns of variation, the answer is a cautious yes. This also falls in line with the discussion by Gericke et al. (2022), where it seems that even though guided inquiry is an evidently favorable way of structuring laboratory work, the level of openness and student-centered vs more teacher-centered is subject to change based on, amongst other things, the complexity and unfamiliarity of the phenomenon being studied. Based on the current study, we stand in favor of the argumentation that the level of openness and the use of student- vs teacher-centered approaches when planning laboratory work should be a mindful task planned by the class' teacher and taking the students' current knowledge and skills related to the intended object of learning for the lab exercise under careful consideration.

4.2 | On the use of models in science education

An essential goal of the laboratory exercise developed in this study was, when focusing on the lived object of learning, for the students to be able to modelize the mechanical trap. This is crucial as there are differences between the mechanical Paul trap and a real Paul trap, such as the inclusion of friction and how the potential changes over time to name a couple (see Löfgren et al., in press; Fan et al., 2016; Kirillov & Levi, 2016; Thompson et al., 2002 for further discussions on the quality of the model). From the patterns of variation presented in Table 4, it can be seen that students were guided by the tasks to update their model description successively. Thus step by step specifying the model system and creating an ideal model they can eventually use to make sense of the real-world phenomenon, a Paul trap (see Figure 1 for the relationship between real-world phenomenon, model system, and model description).

As pointed out by Oh and Oh (2011), models are considered subsets of scientific theories in model-based science, there to enrich with systems of explanations. Thus, it is reasonable for Godfrey-Smith (2006) to assert that model-based science should not be associated with idealization. However, working to construct ideal models is important to include in the physics classroom, as they are part of scientific communication. Levy (2018) specifies idealizations as intentional misrepresentations and closely connected to the constructor's knowledge and intentions. Levy also notes that how Newtonian mechanics is being used today is to be seen as an idealization since it, by intention, falsely describe gravitational interactions.

Finally, returning to Oh and Oh (2011), who suggest that students should engage in the construction and revision of models, results from the current study contribute to this view and suggest that, much like has been found previously (e.g., Coll et al., 2005; Harrison & Treagust, 1998; Schwarz et al., 2009) that involving students in model construction could be a good practice to promote learning. Both in terms of drawing upon previously discerned dimensions of variations, which have also been pointed out by Euler et al. (2020) in the context of working with a digital learning environment in physics, and providing the students with an opportunity to see the explanatory power as well as the limitations of idealized models such as the mechanical Paul trap being a toy model for a real Paul trap.

5 | CONCLUSIONS AND OUTLOOK

This study aimed to investigate if and how the mechanical Paul trap and a simulation could be used in a laboratory setting as artefacts to learn how a real Paul trap qualitatively works, within the context of the Swedish upper secondary course Physics 2. To do this, variation theory was used as a theoretical framework, thus deeming it necessary to identify the critical aspects to define the object of learning. The design experiment over three phases identifies an instruction process in terms of patterns of variation that made it possible for students to learn qualitatively how a real Paul trap works by exploring and developing an idealized model using a mechanical Paul trap.

The patterns of variation students exhibited who successfully used the mechanical Paul trap to understand a real Paul trap follow the general pattern suggested by Marton (2015). However, it can also be understood in terms of Figure 1 and how the students successively updated their model description, further specifying the model system and eventually were able to use it as an idealization of a real Paul trap (the real-world phenomenon). The results indicate that it was crucial that the students first got some introduction to a real Paul trap since the model system is not only created by the model description but also informed by the real-world phenomenon.

Science education is riddled with models, often various forms of idealized ones thereof. Our study shows agreement with Oh and Oh (2011) and Coll et al. (2005) in that the use of models can develop students understanding of them and their limitations when they are engaged in constructing and revising. We want to add to this discussion that, as indicated by our findings, working with idealized models could be a meaningful clarificatory process to help students better understand the use and limitations of models. However, further research in this area is needed, and our study can serve as an example of how variation theory is a fruitful approach to exploring the use of models as a tool for teaching conceptual understanding in the science laboratory.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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