Going through a phase: Infrared cameras in a teaching sequence on evaporation and condensation

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Phase transitions are everyday occurring phenomena, but students often find them difficult to comprehend, not least in terms of the principles of thermal physics. To be able to explain phase transitions in primary school, teachers need to understand various concepts and phenomena, such as condensation, evaporation, energy, and temperature. As energy is absorbed or released during phase transitions, changes in temperature can occur. Infrared (IR) cameras can thus be utilized to visually observe and explore surface phenomena such as condensation and evaporation. In line with the resources framework, we have designed a teaching sequence which involves both everyday experiences and observations through IR cameras, and which is designed to encourage students to leverage common resources associated with evaporation and condensation. In testing our teaching sequence, we presented three thermal phenomena to a group of pre-service teacher students. Two of these phenomena, namely, walking out of a shower and sitting in a sauna, were anchored in embodied experiences to hopefully activate the students' resources and to make the students pay attention to the thermally relevant aspects. The third phenomenon was less familiar, involving the condensation of water on a piece of paper. The result shows that the students managed to carry out the sequence with the three phenomena and applied an explanatory model across all three to consistently explain evaporation. However, the lack of a more general model of chemical bonding and an overreliance on the second law of thermodynamics seem to have acted as barriers for the students' forming of a coherent understanding of both evaporation and condensation.
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I. INTRODUCTION

Thermal physics is full of phenomena that are difficult to perceive, but nevertheless relatable to common everyday experience. A possible approach, which addresses such difficulties involves the use of educational technology: for example, simulations that bring forward microscopic aspects or measurement equipment that enhance our physical senses. In our research, we explore the affordances of infrared (IR) cameras in learning activities, involving thermal phenomena, as they are great tools for visualizing temperature distribution and changes.

IR cameras detect infrared radiation (typically in the 7–14 μm range) and display the temperature of a surface both numerically and along a color scale, assuming an emissivity parameter ε, for objects in the field of view. Typically, higher temperatures are represented as red and white, and lower temperatures as blue, in line with everyday notions.[1] The use of IR cameras in teaching and learning thermal science has been explored in multiple studies.[2–4] They have shown that students, through the use of IR cameras, learn how to identify aspects of thermal phenomena relevant to a science context. For example, having students notice reflections on a window of the infrared radiation emitted from their bodies provides a starting point for the study of the emissivity of different materials.[2] This can be considered a pedagogical affordance of the IR cameras.[5,6] However, research has yet to explore the implications of integrating the IR cameras systematically in teaching sequences. In this study, we have developed and implemented a teaching sequence on phase transitions for primary (elementary) school pre-service teacher students. The IR cameras are particularly suited for such students, as they allow for conceptual and qualitative exploration of thermal phenomena. Science education for primary teacher students in Sweden is often taught by university teachers from physics, chemistry, and biology departments. This presents challenges in that physicists have to adapt the physics content to a level that is appropriate for students who lack the kind of specialization in mathematics and science from upper secondary school typically required to appreciate a quantitative approach.

II. STUDENTS' UNDERSTANDING OF THERMAL PHENOMENA

Physics and chemistry education research has documented that students often have difficulties learning thermal science and thermodynamics.[7,8] For example, Loverude *et al.* investigated whether introductory physics students could predict and explain the temperature change during adiabatic compression of an ideal gas.[9] Most students predicted correctly that the temperature would increase. However, they were so committed to the importance of the ideal gas law that they could not recognize the relevance of the first law of thermodynamics, even when they were given cues to consider energy and work. They also associated the decreased volume with increased temperature, without considering the interaction between the gas and its surrounding. The conclusion was that students' "confidence in [the ideal gas law] seemed to be a significant barrier to consideration of the first law of thermodynamics."[10] In chemistry, many students believe that energy is released when chemical bonds break, as if energy were a kind of glue that holds atoms together or a kind of stored fuel. These students fail to realize that it requires energy to break bonds and that energy is released when bonds form.[11,12] Dreyfus *et al*. show how the idea that energy is stored in chemical bonds, which is used in biology teaching of processes involving ATP, provides an additional challenge for subsequent physics teaching.[13] This idea from biology, of chemical bonds storing energy, thus acts as a barrier for further learning in physics. Conceptual difficulties among students have also been found in relation to phase transitions: students in science teaching and engineering often maintain the belief that a phase transition is always driven by a temperature gradient.[14,15] This could potentially be explained by students' difficulties in relating the concept of energy to the concept of a phase transition.[14]

Within the conceptual change tradition, a common educational approach has been to confront students with their misconceptions, and make them change their understanding to something more in line with established scientific explanations.[16] In contrast, within the resources framework, put forward by, e.g., Hammer and Redish in physics education research, it is suggested that we can build productively on students' preconceptions of natural phenomena, grounded in intuitive understanding.[17,18] Students' understandings constitute conceptual and epistemological resources that are activated and coordinated in different ways depending on the context. Resources are filtered in students' attention, through a process which Redish identifies as framing: "If we can extract elements that are correct from students' common understanding, we can build on these elements to help students reorganize their existing knowledge into a more complete and correct structure."[19] Knowledge structures that are both intuitive and in line with scientific reasoning have been named anchors.[20]

In designing a teaching sequence, we wanted the students to draw from their previous physical experiences of phase transitions, such as evaporation of water from their skin when they walk out of the shower, and from the use of IR cameras as an intuitive visualization technology for incorporating energy in their understanding of phase transitions. This was meant to be used when the students were presented with a phenomenon not accessible by the sense of touch, but visible with IR cameras. In this way, visualization technology provides the opportunity for students to activate resources that may be coordinated with their previous understanding in a productive way.

III. METHODS AND INSTRUCTION

In this study, we present a teaching sequence on the topic of phase transitions. Acknowledging the basic ideas of the resource framework, the sequence starts with something familiar and embodied, and moves on to a related phenomenon that may be unfamiliar in an everyday context.

The teaching sequence was carried out with a group of pre-service primary school teacher students at a Swedish university who are required to take a full semester of science—with a conceptual approach—supplemented with theory on teaching and learning of these subjects. The content is designed to support the future teaching according to the national Swedish curriculum, which includes phase transitions.[21] We intervened just after a lecture on energy in which the students had discussed concepts such as phase transitions, heat, temperature, and the laws of thermodynamics. In doing so, we hoped to give students opportunities to activate resources from the ongoing course.

To prime the students for aspects relevant in this sequence (phase transitions and energy transfer), we gave students a handout of information similar to what was available during their lecture (see Fig. 1). To probe the students' resources in each part (labeled A–C, below), we asked them to discuss each case, predict the outcome of a phenomenon similar to the case, observe, and then explain what they had just observed. The last part included additional observations to be explained, covering the concepts of evaporation, condensation, and dynamic equilibrium. The approach is an adaptation of predict-observe-explain (POE) in that we designed the teaching sequence so each prediction could be based on the explanation made for the previous phenomena and the lecture in which they had recently participated.[22] In the light of criticism against the POE approach from, e.g., Ref. 23, the tasks were designed so that students' predictions would not rely exclusively on their intuition. Instead, the predictions were connected to one another, to previously taught content, and to the students' everyday experience. Therefore, in line with the resources framework, we expected that the students would be able to draw on these experiences as fruitful conceptual and epistemological resources.

Ten students, divided into two groups of five students each, conducted the tasks. They were given handheld FLIR C2 IR cameras (a model that uses the same type of sensor as FLIR One), and the following instructions were provided orally, and presented as PowerPoint slides, in sequence after the interaction with the previous phenomenon had finished:

In this sequence, you will be asked to predict, observe and explain four phenomena (A–D). Try to base every prediction, after the first phenomenon, on what you have learned from the previous phenomena.

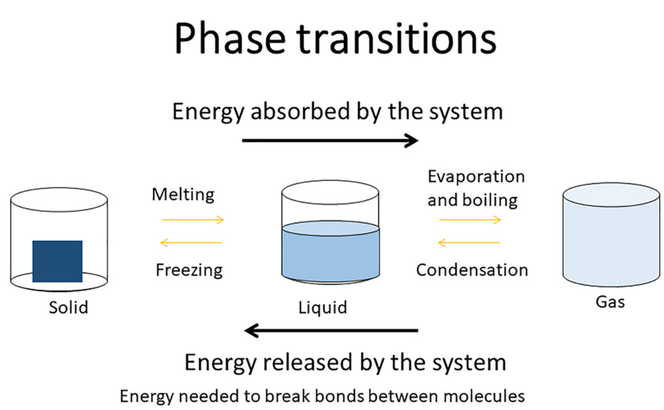

Fig. 1. A summary of how phase transitions relate to energy.

A. The sauna

- You are sitting in a sauna and someone throws water on the rocks.
- How will it feel? Why?
- Predict what happens when you hold a hand above a kettle with boiling water.
- Observe the instructor with IR cameras when he/she holds a surface over the kettle. What do you see? Explain what is happening.

B. The shower

- You have just taken a shower and step outside the shower curtain.
- How does it feel? Why?
- Predict what happens when water at room temperature is sprinkled on your arm.
- Observe, with an IR camera, your skin when some water, at room temperature, is sprinkled on it.
- What do you feel? Why does it feel that way? Explain the phenomenon.

C. Paper on cup

- A cup of room temperature water is standing on a table.
- What is happening to the water?
- What would happen if you would put a sheet of dry paper on top of the cup, covering the opening (the paper is not touching the liquid water in the cup)?
- Observe, with an IR camera, the surface of water in a cup that has been standing on a table for a while to reach a temperature close to the temperature of the room.
- Explain your observation.
- Observe, with an IR camera, a piece of dry paper being put on top of a cup containing water close to room temperature.
- Explain the phenomenon.
- Predict what would happen if the paper was moved over to an empty cup.
- Observe the paper, with an IR camera, when moved over to an empty cup.
- Explain.

In addition to these three tasks involving evaporation and condensation, task D related to what happens when salt is poured on an ice cube. This turned out to be too challenging for the students as the phenomenon was too loosely connected to the previous exercises. We therefore decided to focus our analysis on the students' interaction with the first three tasks. In addition, our account of the students' interaction focuses on the group that managed to come up with the most coherent explanation of the phenomena.

IV. PUTTING THE TEACHING SEQUENCE INTO PRACTICE

A. The sauna

The first task was designed to encourage the students to discuss how it feels when water is thrown on the hot stones in a sauna (which most Swedes have experienced). The nearly immediate feeling of warmth is primarily due to vaporization of water on the stones and the subsequent condensation on the skin.[24] The formation of hydrogen bonds between the water molecules during condensation releases energy, which leads to an increase in the skin's temperature (although the actual temperature of the air in the sauna is fairly constant, typically around 80 °C). From a macroscopic perspective, the perceived warmth of the sauna can be described in terms of heat of condensation.

When asked what this feels like, the pre-service teacher students (TS 1-5) successfully drew on their experience of feeling warmth, but had difficulties in explaining the scientific process behind the warm sensation. The students used two lines of reasoning in their explanations:

(1) the water vapor turns into a liquid when in contact with a human body and transfers energy to that body;
(2) the water on the skin functions as insulation so that no energy is transferred to the surroundings.

The latter is shown in the following transcript (translated from Swedish):

TS 5: "It is the energy that the steam has that is transferred…"

TS 2: "It goes from gaseous to liquid state when it lands on us."

[…]

TS 4: "Maybe it [the liquid] functions a bit like insulation for the skin which keeps its own heat so that we experience it as even warmer. That we don't give our own heat as fast. Like wearing a coat."

To empirically study a similar phenomenon, the students were asked to predict what would happen when they held their hand above the water vapor from an electric kettle. They responded that gaseous water would rise and turn into a liquid when contacting the hand due to the temperature difference between the water and the hand. They explained that, as the water vapor turned into liquid water, it would transfer thermal energy to the hand. TS 1 added that the hand should feel wet if their prediction was correct.

Using an IR camera to observe a hand held above the kettle with boiling water (Fig. 2), the students concluded that the hand got warm and wet. After a while, when the water had stopped boiling, TS 4, the student that had held her hand above the kettle stated that "[…] it feels cold. The feeling you get when you step out from the shower into the room and…get cold." We can thus see that the evaporation of water from the hand was associated with the situation of stepping out from the shower. We were happy to see the students had already spontaneously related the kettle task to the next one we had prepared.

The final explanation of the phenomenon has two arguments:

(1) Water in its gaseous state heats the palm of the hand and condenses. In line with the second law of thermodynamics, there is heat transfer from an object of higher temperature, the steam, to an object of lower temperature, the skin. The phase transition is caused by a transfer of kinetic energy from the water vapor to the palm of the hand.
(2) The cause for the hand feeling cold after a while is that when that heating stops, there is a larger difference between the temperature of the hand and the surroundings than before which makes it feel cold when heat is transferred from the hand to the surroundings.

When trying to explain the phenomenon, the students recall the laws of thermodynamics:

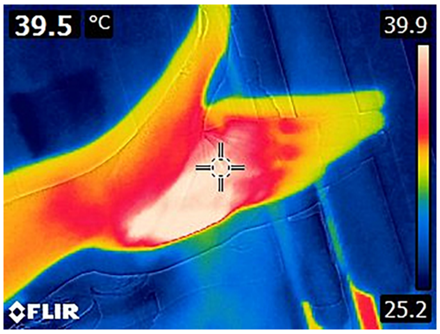

Fig. 2. Condensation of water vapor on the palm of the hand, which leads to a temperature increase.

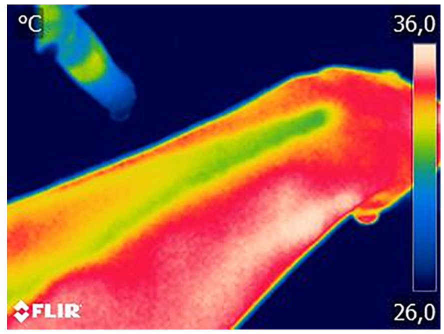

Fig. 3. Water evaporating from an arm, which leads to a temperature decrease.

TS 4: "But these four laws. It is 0, 1… this thing about equilibrium, that the energy wants to be distributed equally, like you said, it is colder in the room and that our body releases heat and we are cooled down too. This law about energy."

We interpret this as an attempt at supporting the first argument of the explanation with the second law of thermodynamics. In the previous lecture, the law was defined as, "Heat is always transferred spontaneously from a warmer to a colder body." However, in the students' explanations, they failed to recognize that energy also is released during condensation in the formation of intermolecular bonds.

B. The shower

In the second part, the students were asked to explain the feeling of walking out in the bathroom after a shower. Behind the shower curtain, the air is humid, and water molecules both condense on the skin and evaporate from it. Outside, the air is less humid, leading to less condensation and therefore a changed balance; many more hydrogen bonds between water molecules at the skin will break than be formed, and thus more energy will be transferred from the body. Due to the change in humidity, it feels colder outside, even if the temperature of the air remains the same.

As mentioned above, TS 4 had already referred to this situation. The students ended up relying on the second law of thermodynamics to predict the outcome:

TS 2: "Then the heat would go out from the bathroom to the cold. It is that rule […]"

TS 2: "The second…"

TS 5: "The second law of thermodynamics!"

TS 2: "So the heat goes…"

TS 3: "Out from the bathroom. And above all, you have gained a higher temperature than before so it will feel colder in the bathroom than it really is. You will experience it as colder because you are warmer."

To test their reasoning, we followed up with the question: "What would happen if it [the water] would be the same temperature as your body?," to which they replied that it would not feel the same at all. If the water had been the same temperature as the body, they did not think it would feel cold.

The observational step in the investigation of the phenomenon involved sprinkling a small amount of room temperature water on an arm (see Fig. 3). The students' experience of this was that it felt cold and they explained that it would feel cold until all water had evaporated. When one of the students, TS 3, disagreed with the others based on how the water on the arm was not transitioning into a gaseous state, another student, TS 2, replied, "If you leave a glass of water, [the water] will evaporate. That is what is so confusing, it does not need to be at the boiling point." Again, by referring to water evaporating in a glass, the students spontaneously pointed forward to the next part of the teaching sequence.

Another factor that the students referred to was the movement of warm, humid air and the cold, dry air in the room. In this way, they considered convective heat transfer, but did not relate this to the phenomenon of evaporation.

In the end they did not really come to any final explanation as seen in this statement:

TS 1: "It is surely this thing evaporation that we are supposed to get at."

The students tried to make the most out of their experience when discussing the first two phenomena and at times their understanding seemed to be in line with physics reasoning. However, by the end, they fell back to trying to explain it with the second law of thermodynamics or just giving up on explaining it at all.

C. Paper on cup

In the third part of the sequence, the students were presented with a task based on an experiment originally proposed by Charles Xie as "Seeing evaporation, condensation, and latent heat" (here called Paper on cup).[4] The students were asked to predict what would happen when a piece of paper was placed just above a surface of water in a cup slightly below room temperature.

Due to evaporation, a cup of water will become cooler than the air temperature. The molecular explanation is that it requires energy to break bonds as the vaporized water molecules are released and that they carry more kinetic energy than those in the liquid state they leave behind in the cup. The actual temperature depends on the rate of evaporation and condensation. The more the molecules evaporate, rather than condense, the lower the temperature of the cup falls (typically, less than 2 °C below).

When we place a piece of paper on top of the cup, water molecules evaporating from the cup encounter the cellulose molecules of the paper surface. Because cellulose molecules are hydrophilic, the water molecules form hydrogen bonds with them (a process known as adsorption in surface physics). A certain amount of potential energy is converted into kinetic energy in this hydration process, raising the temperature of the paper. When more water molecules arrive, they form hydrogen bonds with the initial layer of water. As a result, these water molecules condense, converting more potential energy into kinetic energy to warm the paper up even further. At the same time, water molecules from the layer will evaporate into the air. When the amount of water molecules evaporating from the layer is equal to the amount of water molecules condensing into the layer, a dynamic equilibrium is reached, causing the temperature of the paper to become the same as that of the air, within a minute.

If we move the paper to an empty cup, we will break the dynamic equilibrium; no net flux of water vapor compensates for the evaporation from the paper. As a result, the temperature of the paper will decrease.

The students activated two resources from their personal experiences outside class to predict the outcome: Having a cup with water on the bedside table overnight, from which water evaporates, and the discovery of condensed water on a plate that was covering soaked lentils.

Eventually, the students predicted that the water would evaporate from the water surface and that this water vapor would wet the paper as it was "trapped" between the paper and the liquid water in the cup. The students predicted that, as the water vapor came into contact with the paper, the energy required to evaporate the water would be released as heat which would, in turn, increase the temperature of the paper. Finally, they argued that evaporation occurs because of how the second law of thermodynamics was defined in class, namely, that heat is transferred from warm to cold.

After having observed the phenomenon with an IR camera (see Fig. 4), TS 1 exclaimed, "It turned red!" and, "The paper got warm!" The explanation for this initial temperature increase of the paper was similar to their prediction: as the water vapor (in their words, the heat) inside the cup rose, it carried energy that was released to the paper, which then functioned as a sort of insulation for the water vapor. When the temperature of the paper became close to the temperature of the surroundings, we asked them to discuss what would happen if the paper were to be moved over to an empty cup. The students predicted that, since "energy was moved from the water to the paper," it should now be moved off from the paper again. Here they related the phenomenon to what happens when you step out from a sauna or the shower: evaporation requires energy and thus makes you feel colder. TS 3 summarized this: "There is still water here [in the paper] when you move the paper and for the water to evaporate, energy is required." Here the students finally coordinated the three resources in a productive way to understand evaporation: the condensed water on the skin evaporating when stepping out from the sauna, the evaporation of water from the skin when stepping out from the shower, and the evaporation of water from the paper all require energy.

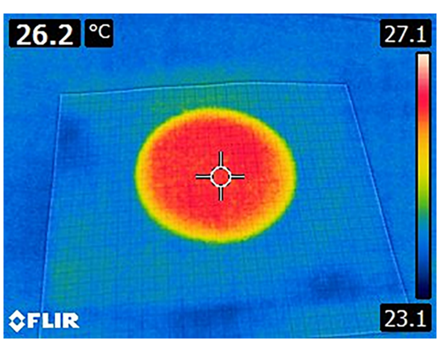

Fig. 4. Condensation of water vapor onto the inside surface of a paper put on a cup with water, which leads to a temperature increase.

V. DISCUSSION AND CONCLUSION

If carefully chosen, everyday situations that exemplify the critical aspects of the content to be taught can be used to activate and coordinate resources that students bring into the classroom in a productive way. We propose that the first two parts, relating to students' experiences of sitting in a sauna and walking out of a shower, served as anchors for the third part, condensation and evaporation on a paper.[20] It is remarkable that the students spontaneously connected to the next part of the teaching sequence before having been introduced to them when trying to explain the phenomena; they drew on the experience of a shower while explaining the observation in part A, and drew on experiencing the result of evaporation from a cup of water while explaining the observation in part B.

However, as opposed to what we had expected, the students struggled to provide coherent explanations during the first two, more experientially grounded parts. It was not until they engaged in the study of the paper on the cup that they managed to come up with a coherent account. In particular, for part C, the students explained that evaporation requires energy both in the context of the paper on the cup and water on their skin. They related the latter context to both the case of the shower and the sauna.

In other words, the students coordinated their resources in a productive way to apply an explanatory model and managed to relate the phenomena to one another through experiential familiarity with each. The fact that the students spontaneously related the situations to one another suggests that they experienced the sequence as a coherent whole. This would also support the hypothesis that our designed activity helps the students to activate and coordinate resources in a way that productively builds on the critical aspects of the phenomena. Like Redish argues, when students experience content as coherent, it is easier for them to tie that content to previous experiences and to activate the appropriate knowledge in a consistent way.[18]

Overall, the students provided a consistent argument throughout the sequence, based on two resources from their previous studies in physics:

(1) A kinetic explanatory model, where the kinetic energy of the molecules determines the state of the water, and phase transitions are associated with a decrease or increase of kinetic energy, but without considering potential energy at the molecular level.
(2) The second law of thermodynamics, activated as a resource by the students to explain any spontaneous process, in terms of heat transfer from an object of higher temperature to an object of lower temperature.

However, coherence is not sufficient. In the students' final explanation of the evaporation and condensation phenomena, the idea that energy is required for evaporation and released during condensation was not central to their line of reasoning. In particular, the kinetic explanatory model fails to recognize that potential energy is transformed into kinetic energy when water molecules condense or are absorbed on a surface. In this study, both the second law of thermodynamics (limited to heat being transferred from a warmer to a colder body) and the kinetic model prevented the students from fully understanding the evaporation and condensation in the phenomena. We see this as similar to how the ideal gas law was shown to be a barrier for students to explain the increased temperature during adiabatic compression.[9] Without considering that energy is released when bonds form, it is not plausible that condensation of water vapor on a paper at room temperature would lead to a temperature increase. Therefore, the students provided an alternative explanation: that energy is transferred from hot water vapor to the cold paper, and the vapor turns into liquid in the process.

In practice, it was important that this sequence was part of a larger teaching unit. For students to apply a microscopic model for the release of energy in condensation, we think that a more thorough introduction to the energy of chemical bonds would be needed. As a smaller modification, the over-reliance on the second law of thermodynamics might have been confronted if the students had experienced that it soon also feels cold when they are sprinkled with water at body temperature or higher due to evaporation. However, we do think that this teaching sequence is useful for restricting students' frame of phase transitions,[25] and for identifying their explanatory models. From this perspective, we see the approach of grounding the teaching of phase transitions in the students' embodied experiences of related phenomena as fruitful, also in the case of the other group of five students, which did not achieve the same level of coherence in their explanations as the group we chose to focus on here.

In addition, the teaching sequence relies on the use of IR cameras in all three parts. When studying water sprinkled on the skin, the students could confirm that the cold sensation when walking out of a shower is measurable in terms of decreased surface temperature. Similarly, the students were able to appreciate that condensation of water vapor from a kettle leads to a temperature increase. In contrast, students lacked prior embodied experiences of temperature changes during condensation and evaporation on a piece of paper, and such phenomena are not easily measurable with a thermometer. In this last phenomenon, IR cameras become an indispensable measurement and visualization tool,[4] which provides pedagogical affordance in the study of thermal phenomena.[6]

In conclusion, through participation in a teaching sequence with the help of IR cameras, students were able to coordinate resources from their embodied experience and previous teaching to deliver an explanatory model for evaporation. Reliance on the second law of thermodynamics acted as a barrier for considering the role of potential energy in phase transitions, and thereby explaining condensation.

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